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INVESTIGATION OF HIGH POWER MHD GAS LASERS

Bert Zauderer, et al

General Electric Company

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13. ABSTRACT This report presents the results obtained during the period January 1974 to June 1975 in the study of MHD powered gas lasers. Key results of the work thus far are:		Air Force Advanced Research Projects Agency
1. The shock tunnel was substantially modified during the past 18 months to improve the quality of the experiments. The cesium injecting system was completely replaced, the secondary (reflecting) diaphragm relocated to the rear of the laser channel, a primary double diaphragm arrangement was installed and a new CO₂ probe laser acquired. 2. The gain measurements previously reported were repeated with substantial improvement in the signals. 3. An MHD channel was operated at 19% enthalpy extraction which at the time was the best any MHD experiment operating at reasonable temperature had achieved.		

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4. An optical resonator and associated diagnostics and alignment hardware was completed and installed on the shock tube.

5. The shock tube was operated as a CO_2 gas dynamic laser to check and develop the resonator and diagnostics.

6. A CO_2 mixture with 1% xenon as a seed was operated with lasing output in the presence of electric currents and a magnetic field. This was the primary task of the present contract - to get lasing from a magnetohydrodynamic plasma containing carbon dioxide.

7. Preliminary experiments were done using various gas mixtures containing carbon monoxide and the problems associated with CO MHD lasing identified.

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FINAL REPORT

**INVESTIGATION OF
HIGH POWER MHD GAS LASERS**

Contract No. N0014-73-C-0243
(1 Jan. '73 - 30 June '75)
Program Code: 3E20

Contract Value \$324,292

January 1974 to June 1975

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Dr. Bert Zauderer - Manager, MHD Programs

Eric Tate - Scientist, MHD Programs

Dr. C. H. Marston - Research Engineer, MHD Programs

(Telephone: (215) 962-2677/6)

Scientific Officer

J. Satkowski

General Electric Company

Space Sciences Laboratory

Space Division

P.O. Box 8555

Philadelphia, Pennsylvania 19101

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FOREWARD

The work discussed herein is being performed at the General Electric Company, Space Division, Space Sciences Laboratory, King of Prussia, Pennsylvania, under the auspices of the Office of Naval Research and the Defense Advanced Research Projects Agency. Mr. J. Satkowski of ONR and Mr. J. Meson of DARPA are the technical monitors.

The studies presented cover the period from January 1974 to June 1975 and represent the final report on this project.

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

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1. Key Results of the Past 18 Months

1. The shock tunnel was substantially modified during the past 18 months to improve the quality of the experiments. The cesium injecting system was completely replaced, the secondary (reflecting) diaphragm relocated to the rear of the laser channel, a primary double diaphragm arrangement was installed and a new CO_2 probe laser acquired.

2. The gain measurements previously reported were repeated with substantial improvement in the signals.

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4. An optical resonator and associated diagnostics and alignment hardware was completed and installed on the shock tube.

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7. Preliminary experiments were done using various gas mixtures containing carbon monoxide and the problems associated with CO MHD lasing identified.

II. PUBLICATIONS OF THE PAST 18 MONTHS

1. B. Zauderer, E. Tate, C. H. Marston, "Electrode Studies and Recent Results of Non-Equilibrium MHD Generator Experiments," GE TIS Report 74SD217.
2. E. Tate, C. H. Marston, B. Zauderer, "Large Enthalpy Extraction Experiments in a Non-Equilibrium MHD Generator", GE TIS Report 74SD226. (To be published in Applied Physics Letters).
3. B. Zauderer, "Closed Cycle MHD Potential Impressive", Electrical World, March 15, 1974.
4. B. Zauderer, E. Tate, and C. H. Marston, "Electrode Studies and Recent Results of Nonequilibrium Generator Experiments", 14th Symposium on Engineering Aspects of MHD, University Tennessee Space Institute, April 1974.
5. B. Zauderer, E. Tate, and C. H. Marston, "CO₂ MHD Laser, Analysis, Design and Shock Tunnel Experiments", 14th Symposium on Engineering Aspects of MHD, University of Tennessee Space Institute, April 1974.
6. E. Tate, C. Marston, B. Zauderer, "Large Enthalpy Extraction Experiments in a Non-Equilibrium MHD Generator", Applied Physics Letters, Vol. 25, No. 10, 15 November 1974.
7. E. Tate, C. H. Marston, B. Zauderer, "Large Enthalpy Extraction Results in a Non-Equilibrium MHD Generator". VI International Conference on MHD Electrical Power Generation. Vol. III, Page 89, June 1975.
8. Lasing in fast flowing CO₂ - He - Xe mixtures in the presence of electrical and magnetic fields - to be published.

III. CONTRACT EFFORT AND RESULTS

1. Introduction

This program is directed towards the utilization of a shock-tunnel driven supersonic channel to perform a study of gases suitable for MHD laser operation. Under the previous contract¹ MHD laser gain exceeding 0.2%/cm has been achieved in the GE/ONR shock tunnel using a mixture of 78% Helium, 18% Argon and 4% CO₂ plus 0.1% Cs seeding and a 70 He/29 Ne/1 Xe 4% CO₂ mixture. Long relaxation times and non-emitting electrodes required use of some external voltage augmentation to achieve the necessary plasma conditions in the available generator length. The results were also reported to the 14th Symposium on Engineering Aspects of MHD (1974) and the paper is included as Appendix A.

This gain measurement represents the first step in the achievement of an MHD laser, in which thermal energy is converted to optical energy in a single, static, channel at efficiencies potentially much greater than those possible in a gas dynamic laser. In a CO₂ gas dynamic laser, for example, the energy source is vibrationally excited nitrogen and this, combined with CO₂ quantum efficiency places an upper bound on overall conversion of about 4%. The MHD laser on the other hand has an upper bound of about 10%, which represents the combination of MHD generator enthalpy extraction (thermal to electric conversion) and electric discharge laser efficiency.

The MHD laser channel has a long (11"), narrow (0.125") throat through which the gas, brought to a suitable temperature and pressure by shock compression, flows into an expansion region where it is accelerated to a high velocity and the static gas temperature is lowered to $\approx 2000^{\circ}\text{K}$ in the case of CO₂. Addition of a small amount of easily ionizable species and the generation of electrical current by the MHD generator process (a voltage is generated by the conducting plasma flowing through a magnetic field) creates free electrons at a temperature well above the static gas temperature. These free electrons can pump a molecular species present in the gas to provide a population inversion.

Population inversion can be detected by a gain measurement in which a laser beam at the frequency of interest is passed through the plasma; if an inversion exists, the beam will be enhanced. During the present contract the gain measurements were considerably refined. The measurement was developed to an accuracy of 1% (signal to noise ratio of one). The flow starting time was considerably reduced by relocating the secondary (reflecting) diaphragm from the front of the channel to the rear. This also eliminated the passage of aluminum particles past the observation windows which also improved the signal.

Of primary importance to MHD laser operation is the efficiency with which the thermal energy of the reservoir gas (in this case the gas in the reflected shock region) is converted to electrical power (enthalpy extraction). The GE/ONR shock-tunnel facility is also used to study MHD generator channels. Recently, 19.3% enthalpy extraction from a non-equilibrium plasma was obtained (the best obtained in an open cycle combustion generator 100 times larger has been 8%). The details of this work are given in Appendix B. While operating the generator channel, the diagnostic equipment for the laser channel was extensively revised, mechanical changes were made to the channel and a mirror system to obtain laser output was designed. The foregoing and other experimental revisions will be described in the following sections.

The next experimental stage was to verify the gain measurements and fully prove the concept by actually getting laser operation. The accomplishment of this will be described in section 4.

2. Experimental Revisions and Additions

(a) Carbon monoxide nozzle

A nozzle for operation with carbon monoxide has been designed and fabricated. Carbon monoxide requires a lower gas temperature for lasing. The slit height is consequently .025" to give a more rapid expansion than the CO₂ nozzle. The method of characteristics was used to design a sharp edge nozzle for expanding the flow to M=8, which corresponds to a static temperature of 2000°K.

As detailed in Reference 1, deflection of the nozzle block designed for use with CO_2 caused an intolerable perturbation of the flow until additional external support was added. The smaller throat height of the CO nozzle means that slight changes in the throat height are even more critical. For this reason, the nozzle has been designed as a single assembly with a center support which will be inserted into the channel through the stagnation region. Figure 1 is a photograph of the CO nozzle.

(b) Cesium Injection System

The experimental observation that electrode conduction is enhanced by the presence of large ($> 1\%$) concentrations of cesium provided the necessary impetus for a complete redesign of the cesium injection system. This new system was a factor contributing to the achievement of 19.3% enthalpy extraction and it will be utilized for future laser channel experiments.

(c) Secondary Diaphragm Relocation

The desire to precoat the electrodes with cesium immediately prior to an experiment necessitated a relocation of the downstream diaphragm from the front of the MHD generator channel to the rear. This made possible the location of the cesium injection port at the rear of the channel with a nozzle pointing upstream so that the cesium particles would flow over the electrodes. This precoating was also a factor contributing to the 19.3% enthalpy extraction. A side benefit was that the flow started much quicker, as shown by pressures and current measurements. Success with the downstream diaphragm on the MHD generator channel encouraged a trial of the same technique on the laser channel even though its much smaller throat raised some doubt as to whether the flow would start properly. The rear of the laser channel was machined to accept a specially fabricated diaphragm holder. Changing this diaphragm conveniently had been made possible by mounting the dump-tank on tracks and using hydraulic cylinders to move it back and forth.

(d) Primary Double-Diaphragm

Since the laser channel was first operated, a double diaphragm arrangement at the shock-tunnel driver end has been installed. The two diaphragms are separated by a six inch long intermediate chamber which is pressurized. The driver-tube is then pressurized to the exact pressure desired. The intermediate chamber is then evacuated and both diaphragms immediately burst. This gives precise control over the burst pressure (and hence shock Mach number) and time of burst, which is required for optimum cesium seeding.

(e) New Wire Electrode Plates

Experiments with the laser channel and results with the generator channel have shown the desirability of using wire electrodes mounted parallel to the magnetic field. Fiberglass-epoxy plates with electrodes of this type have been fabricated and one of these plates is shown in Figure 2.

(f) Gain Diagnostics

A source of inaccuracy in the gain measurements has been the stability (both mechanical and electrical) of the probe laser. A new Sylvania 3 watt CO₂ laser was received. However, this laser had unacceptable 120 cycle ripple on its output. Since its delivery, two more power supplies were requested from Sylvania and the third power supply met the requirement of $<0.2\%$ short term amplitude stability. This laser is also inherently mechanically more stable as it is three times shorter than the laser previously used. The output stability of this laser has made possible tracking down and eliminating vibration sensitivity in all the other components of the gain measurement optical system. A total gain of 1% can now be measured with a signal to noise ratio of <1 . Further refinements of the gain measurements are expected when a pyroelectric detector (flat response at 10.6 microns) and a Hg-Cd: Te detector (greater sensitivity than Au-Ge at 10.6 microns) are used.

3. Gain Measurements

Following the improvements in the gain diagnostics and the relocation of the secondary diaphragm more gain measurements have been made. A series of experiments were performed with the diaphragm switched from front to rear on alternate runs. The results of these experiments are shown in Figure 3. Figure 3(a) and 3(b) show detector outputs for front diaphragm and rear diaphragm experiments, respectively. The gas mixture was 50% Argon/50% Helium to give a molecular weight of 22 to simulate the normal GDL mixture of 48% N_2 /40% He/12% CO_2 . A comparison of 3(a) and 3(b) shows that the initial several milliseconds of absorption is almost certainly beam bending due to a very disturbed flow caused by aluminum pieces obstructing the throat. The high frequency spikes are also absent in 3(b) and these were, therefore, (as suspected all along) a result of aluminum particles interrupting the probe beam. Figure 3(c) and 3(d) are a similar comparison for a mixture containing CO_2 (48% N_2 /40% He/12% CO_2). Figure 3(c) is a gain measurement typical of all those reported previously (although with a considerably improved signal to noise ratio) and was made with a front diaphragm location. Figure 3(d) is a detector signal with the diaphragm at the rear. The signal rises quickly ($\approx 400 \mu\text{sec}$) to its peak value and then decays slowly with time back to the base line. The initial several milliseconds absorption and the high frequency transients are absent. There is still a small initial beam bending as the shock front passes the windows. The second "absorption" is caused by the reflected shock from the rear diaphragm. This shock is clearly observed by pressure transducers. A typical pressure transducer trace is shown in Figure 4. A reflected shock was also present in the MHD generator experiments when a rear diaphragm was used. The vertical scale for Figure 3 (all oscillograms) is 50 mv/cm and the total detector output varied between 0.5 and 1.0 volts. One centimeter deflection on 3(d) represents 10% gain. Figure 5 is the detector output for an experiment in which the probe laser was off and the detector gave zero output so no spurious infra-red radiation was present. These measurements indicate that the gain diagnostic procedure is accurate. The

next step was to do these measurements with currents and magnet field applied to He/Ne/Xe + CO₂ and He/Ar/Cs + CO₂ plasmas to see if the previous measurements done in these gases could be verified. This was much more difficult than the GDL measurements as electromagnetic radiation was present. The clean probe laser output made it possible to reduce the detector pick-up to less than 1 millivolt by trying various combinations of shielding and cable routing while repetitively pulsing currents through the electrodes. Figure 6 is a typical gain measurement in an 8l Helium/19 Argon + 6% CO₂ + Cs plasma. The other conditions are shown on the figure. The vertical scope gain was at 50 mV/cm which is large compared to the noise pick-up. These measurements showed that the facility can be accurately employed (with appropriate channel throats and suitable probe laser) for investigation of other potential lasing media.

4. Laser Experiments

a) Resonator

An investigation of laser resonator configurations was done. A spherical 99.5% reflecting mirror and a flat 98% reflecting output coupler was chosen as the resonator configuration offering the best compromise between enclosed mode volume and alignment tolerance. The resonator configuration was not chosen to maximize power output but to (a) give as much stability as possible because of the vibrations present and (b) to ensure oscillation at small gains (i.e. to ensure that the gain/pass would exceed the window and mirror losses). The resonator is shown in Figures 7, 8, 9. The mirror and coupler were mounted outside the channel and Brewster angle windows were mounted on the channel. All optical components (except for the concave mirror which is a dielectric coated copper mirror) were made of zinc selenide. Zn Se has several advantages over other materials for use in the infra-red but the primary reason for its use is that it is transparent to visible radiation. This facilitated alignment and a He-Ne laser was used for alignment. As it was expected that mechanical vibration of the optical components would be the major difficulty in getting laser power extraction, a massive aluminum table was fabricated and the optical components, including the detector mounted on it.

b) Gasdynamic Laser Experiments

Initial testing of the system was done using a "standard" gas-dynamic CO₂ laser mixture of 40 He/48 N₂/12 CO₂. An oscillogram of the lasing output is shown in Figure 10 with a gain measurement (Figure 10) obtained under the same conditions for comparison. The lasing output has the same profile as the gain measurement but of course with no absorption spikes. The detector and circuitry for each measurement was the same; therefore, the less steady laser output is attributed to mirror and/or window vibration. Figure 11 shows the lasing output (a) and two experiments to eliminate the possibility of spurious infra-red radiation. In Figure 11b the 99.5% reflecting mirror was covered and the detector output was zero; in

Figure 11c a chopper was located on the 99.5% mirror side of the resonator and it can be seen that the detector output returns to zero when the path is blocked.

c) Xenon Seeded Experiments with Applied Currents and Magnetic Field

Experiments with applied currents were done with 70 He/29Ne/1Xe with the addition of various amounts of CO₂. Figure 12 shows the detector response for consecutive experiments in which the CO₂ concentration was increased from 2% to 5%. Oscillation starts at a CO₂ concentration of 4% and as it is estimated that the optical losses (including the 2% exiting the output coupler) are 3.2% then the path length of 27 cms. would indicate a gain/cm of .12% which is in agreement with gain measurements obtained under identical plasma conditions. This gas mixture does exhibit a freezing of the CO₂ vibrational levels and, therefore, will lase without the application of currents. Presently, the experimental effort is mostly directed at separation of this combined GDL and EDL lasing. The currents are applied by twelve isolated sources. The axial spacing from the window and the current density are the two main parameters being varied.

As the primary objective of this program is eventual generation of current (to provide pumping of an upper laser level) by the MHD generator effect, it is therefore essential to show that lasing can be maintained in the presence of a magnetic field. The present optical bench and associated equipment was designed primarily to be a stable base for the resonator and thus perform satisfactorily despite the mechanical vibrations present in shock-tube operation. Compromises in mechanical stability necessary for operation at large magnetic fields were not made. The magnetic field strength used was, therefore, kept below 0.8 Tesla and only the top half of the split solenoid was employed. Nevertheless, the field does move the bench enough during a run to cause misalignment. This is illustrated in Figure 13. The top oscillogram (a) is the magnetic field profile. Figure 7(b) shows normal GDL operation and 7(c) shows GDL operation with B field. Comparing 7(b) and 7(c) shows that the bench moves out of alignment

shortly after peak-field and moves back into alignment several milliseconds thereafter. When the bench moves back into alignment, the magnetic field is at about 80% of its peak value so the movement is mostly an eddy current effect which subsides after the magnet is crow-barred from a fairly fast (≈ 3.5 ms) sinusoidal rise to a slow exponential decay. A similar comparison for the xenon seeded mixture with applied currents is shown in 7(d) and 7(e). Figure 7(e) is of primary importance as it shows laser operation of a molecular species in the presence of electrical currents and a magnetic field.

5. Carbon Monoxide Experiments

As the time and money available on the contract after the completion of the CO_2 experiments was very limited, a detailed research program was ruled out. Gain measurements over various wavelengths in the 5 micron range would have been very prolonged. A decision was, therefore, made to simply pick an appropriate gas mixture containing CO and to replace the $10.6 \mu \text{CO}_2$ resonator optics with 5μ optics and look directly for lasing. If one starts at a stagnation temperature of 2000°K , then expansion of the flow to Mach 8 is needed to lower the temperature to $\approx 120^\circ\text{K}$ which is appropriate for CO operation. A Mach 8 nozzle was installed. The first series of experiments were checks on the aerodynamic performance of the Mach 8 nozzle. It was suspected that with the low channel pressure, after expansion to Mach 8, the dump tank volume would be insufficient to give a large enough pressure ratio to ensure flow starting. This proved to be the case so the Mach 8 nozzle was removed and the Mach 5 throat re-installed. To get the desired 100°K in the channel, the stagnation temperature must, therefore, be lowered to 1000°K . This implies an incident shock Mach number of 2. At Mach 2 the stagnation pressure to initial pressure ratio is only 15; therefore, to get 10 atmospheres stagnation (to give sufficient CO number density in the channel after expansion through the nozzle) the shock-tube must be loaded initially to 500 Torr. This was not a practical operating point for the shock-tube as the cesium injection system was not designed to operate above 100 Torr initial pressure and the secondary reflecting diaphragm creates problems. Nevertheless, thirty runs were made a high initial

pressures. This was done by simply loading the shock-tube statically to the desired initial pressure with gas that had been passed over hot cesium. The discharge provided by the improvised seeding system was non-steady and a uniform discharge is a necessity for lasing. Lasing was not achieved with CO but enough experience was obtained on the MHD behaviour of plasmas containing CO that it is felt that the experimental modifications necessary for operation with CO are understood.

The conclusions arrived at are that a Ludwieg tube (in which a high pressure vessel is attached directly to the channel) and an alternative seeding method are more appropriate for CO operation.

IV. REFERENCES

1. B. Zauderer, E. Tate, and C. H. Marston, "Investigation of High Power MHD Gas Lasers", General Electric Co., Contract No. N00014-73-C-0243, 1973.



FIGURE 1 Mach 8 sharp edge nozzle for use with CO

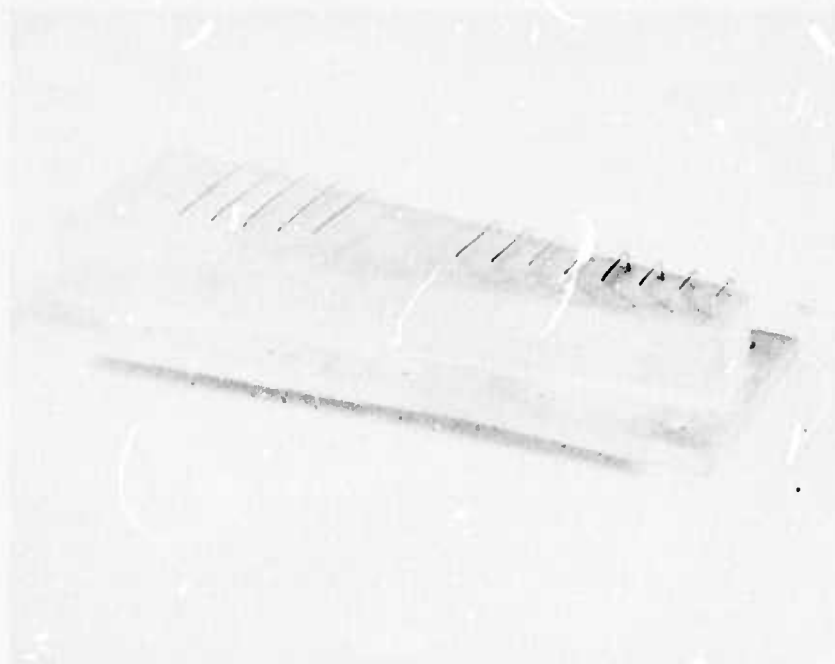
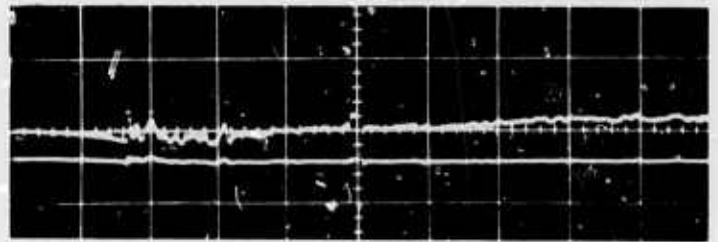
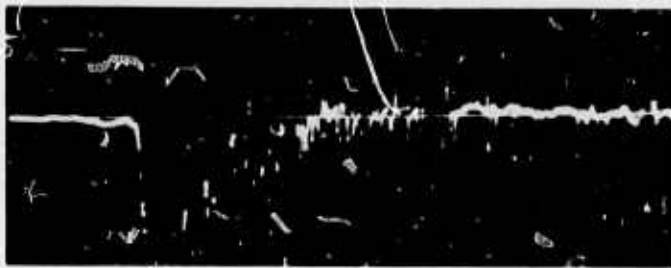
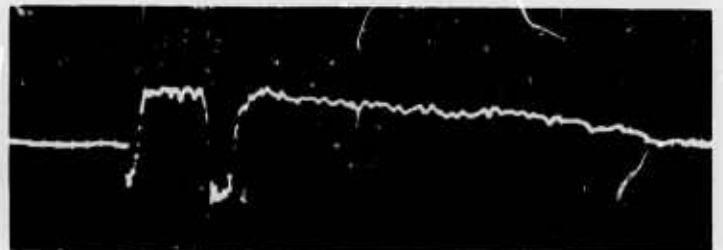


FIGURE 2 A wire electrode plate.



(a) front diaphragm - no CO_2

(b) rear diaphragm - no CO_2 (Upper trace)



(c) front diaphragm - with CO_2

(d) rear diaphragm - with CO_2

All oscillograms 2 ms/cm horizontal axis

All oscillograms 50 mV/cm vertical axis - D. C. level 500 -1000 mV

A vertical deflection indicates gain.

FIGURE 3 Detector outputs for front and rear diaphragm experiments

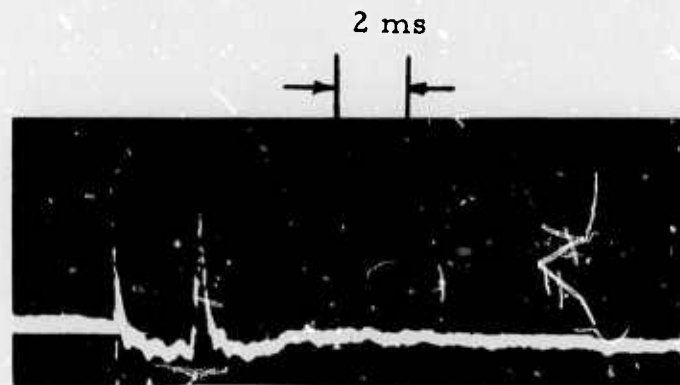


FIGURE 4 Pressure measurement showing initial and reflected shocks in MHD laser channel

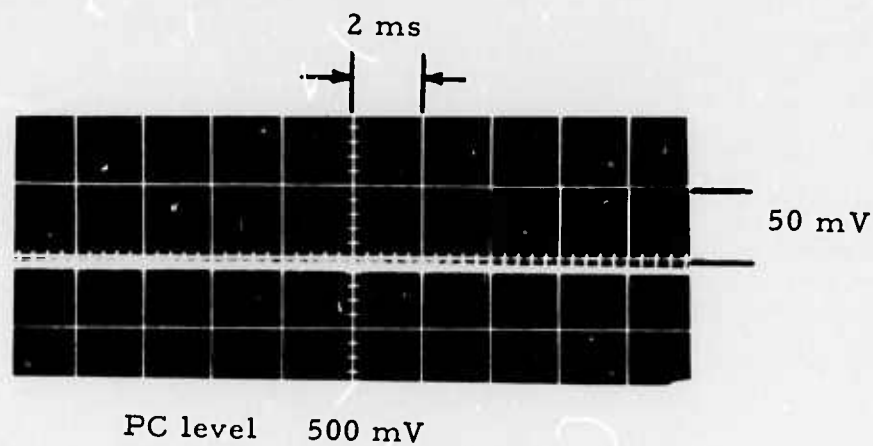
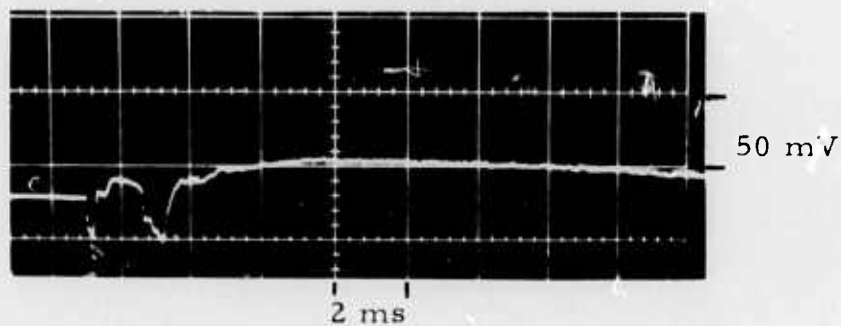


FIGURE 5 Detector output with probe laser off



INCIDENT MACH NO. 2.9
STAGNATION TEMPERATURE 2100°K
A VERTICAL DEFLECTION INDICATES GAIN

FIGURE 6 Detector output for 81 Helium/19 Argon + 6 CO₂ + Cs
with currents applied through 12 electrode pairs.

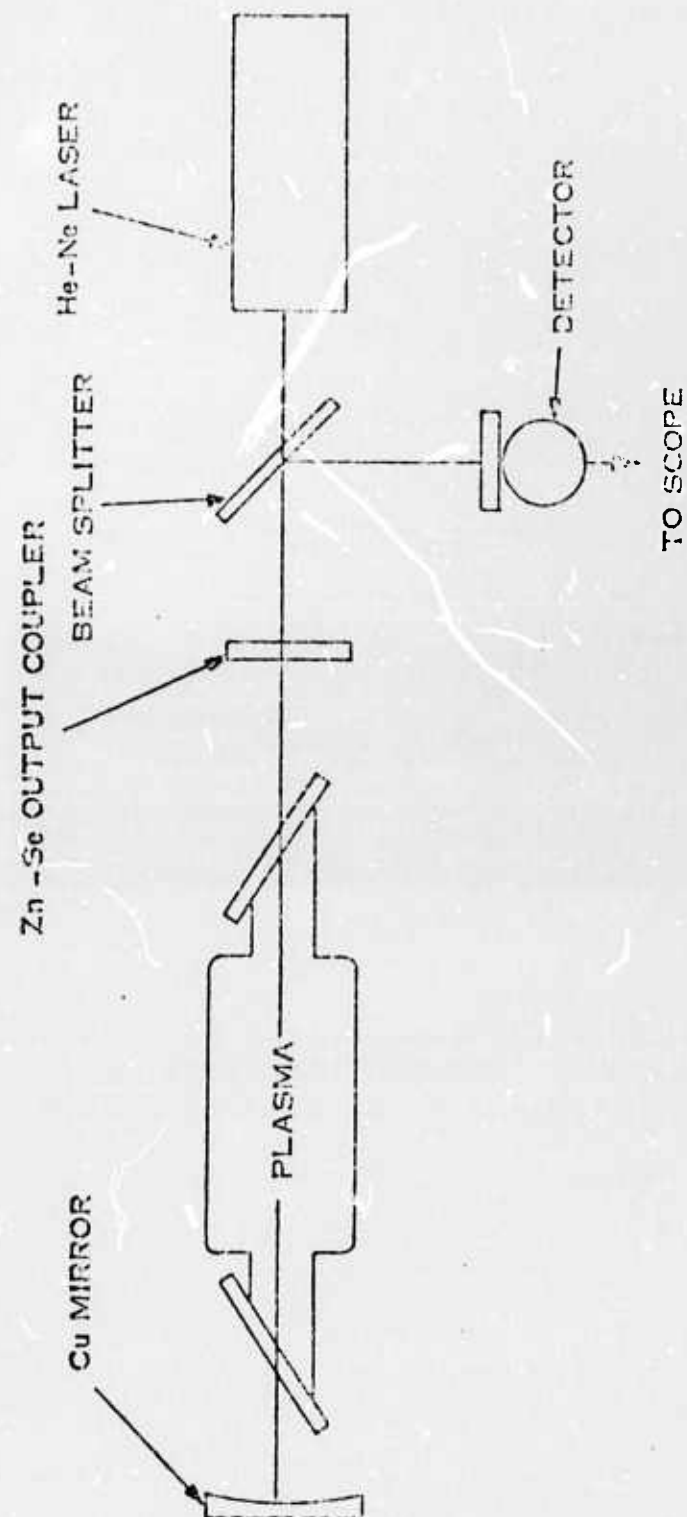
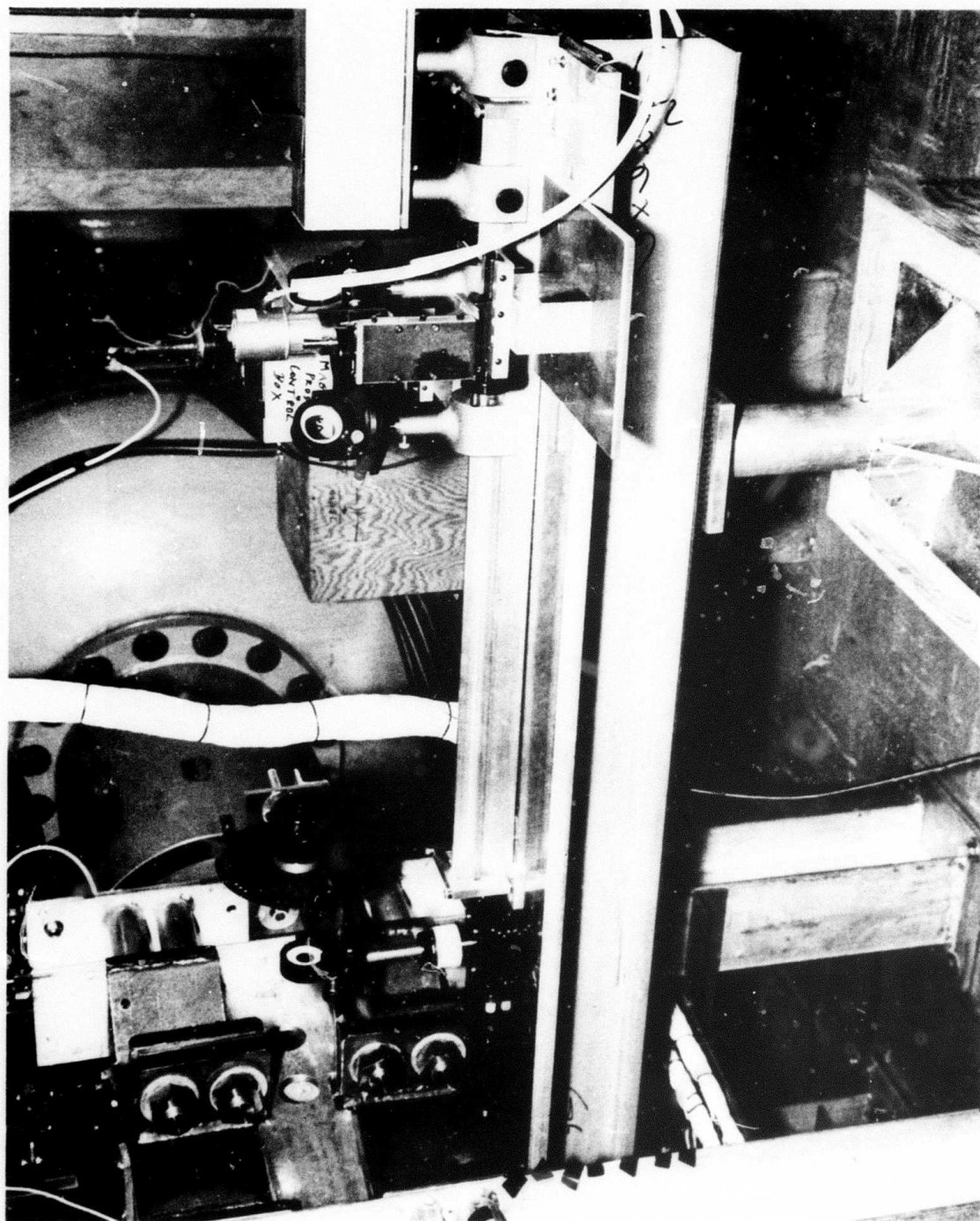
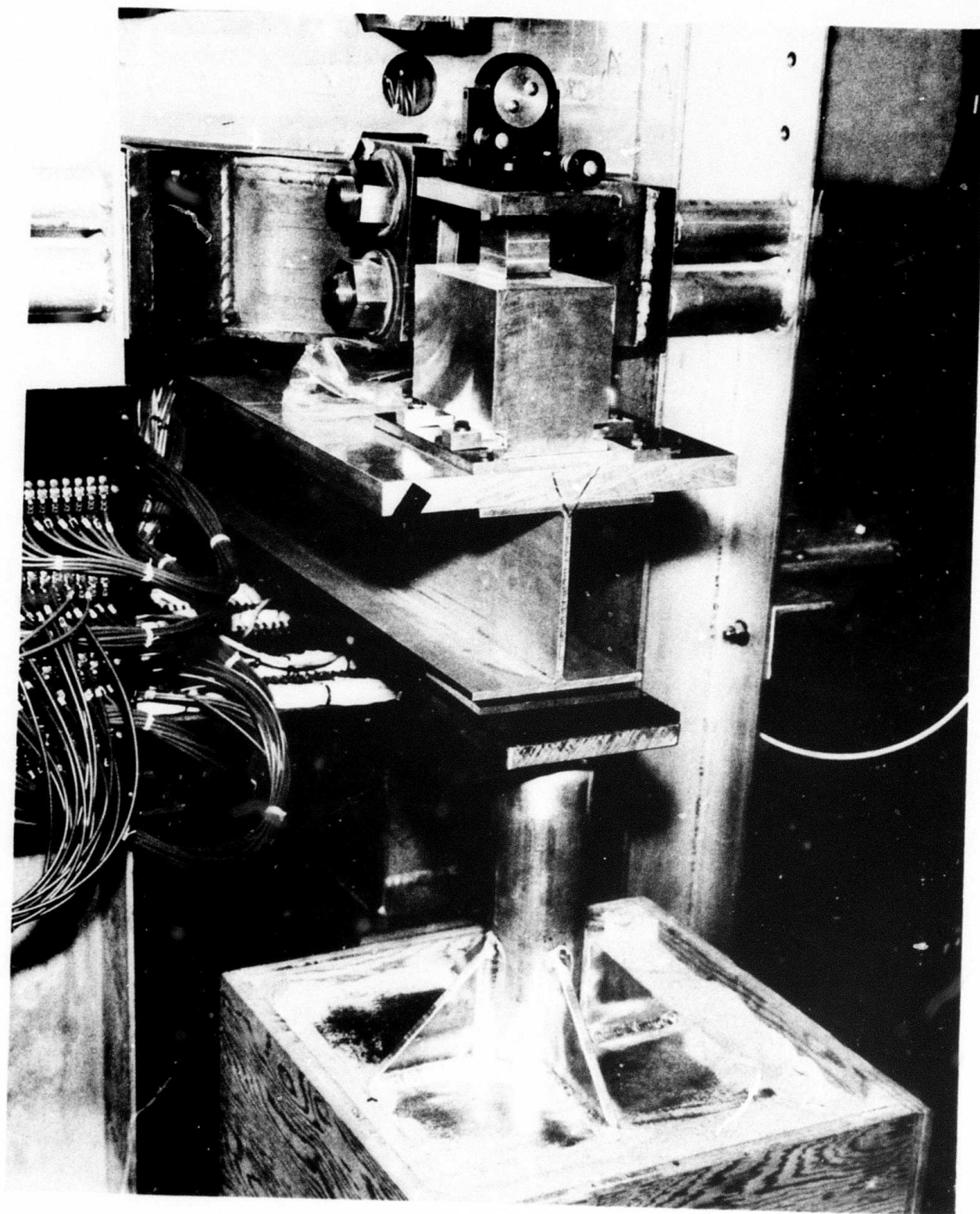


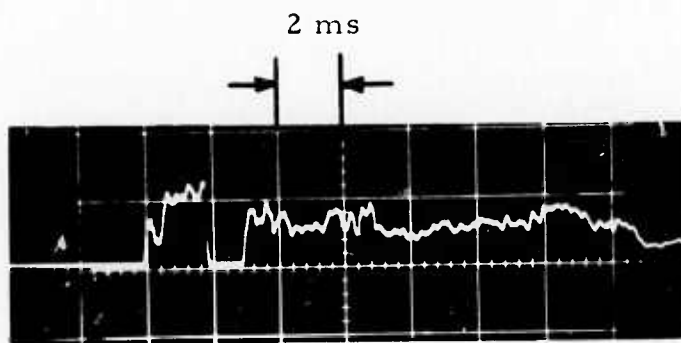
FIGURE 7 SIMPLIFIED SCHEMATIC OF MHD LASER CHANNEL OPTICS



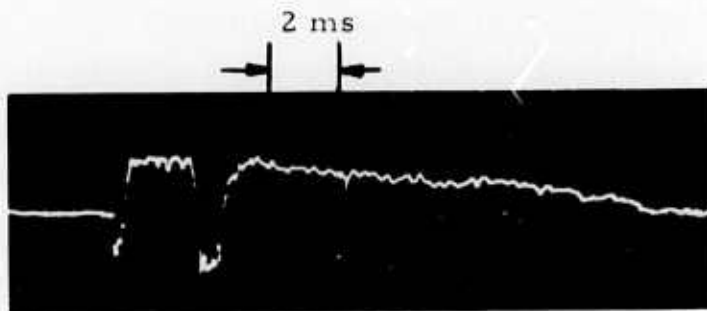
View of Output Coupler Side of Laser Resonator and Detectors



View of 99.5% Mirror Side of Laser Resonator

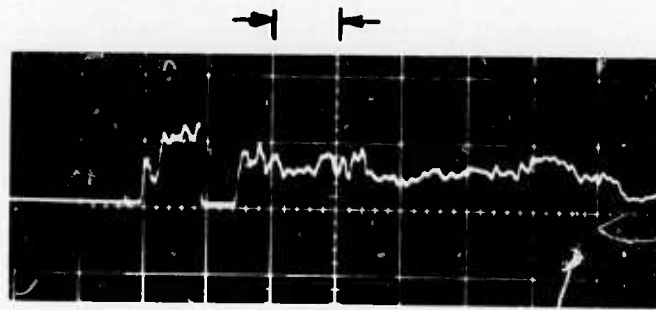


(a) GDL Lasing Output

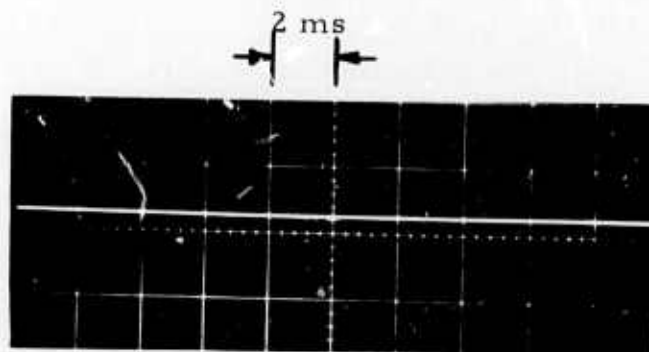


(b) GDL Gain Measurement

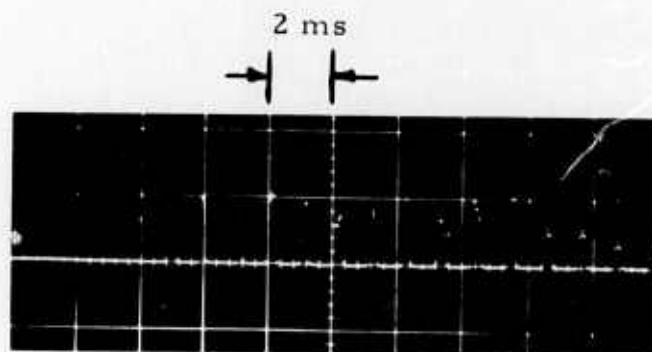
FIGURE 10 Comparison of GDL Lasing and GDL Gain



(a) UNCHOPPED SIGNAL



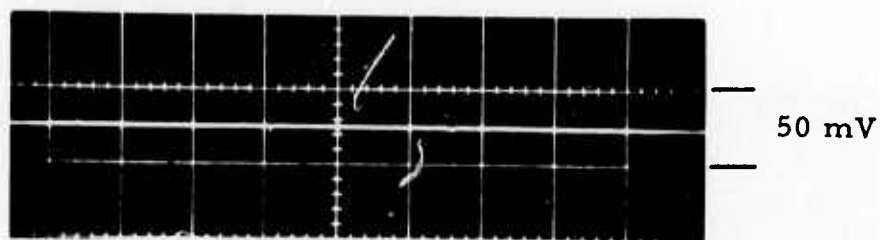
(b) SIGNAL WITH 99.9% MIRROR BLOCKED OFF



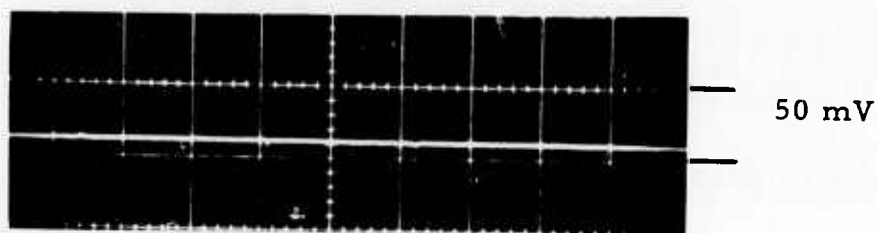
(c) CHOPPED SIGNAL

LASING OUTPUT SIGNAL OPERATING AS A GAS DYNAMIC LASER

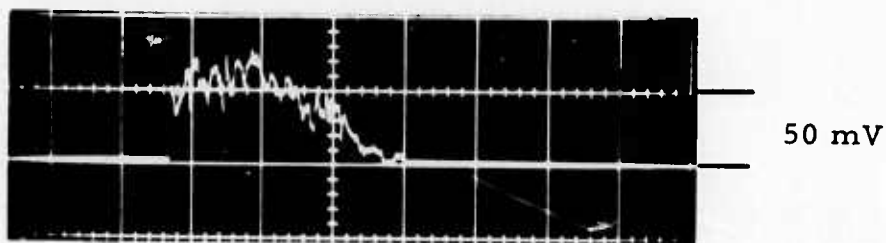
FIGURE 11



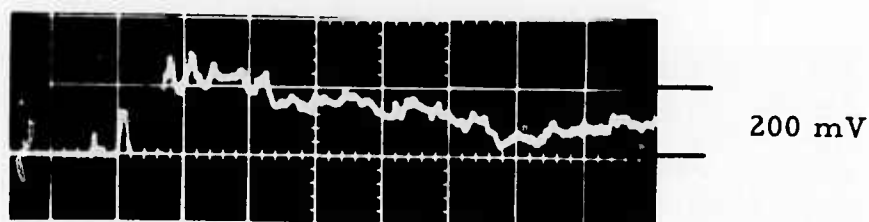
(a) CO_2 Concentration 2%



(b) CO_2 Concentration 3%



(c) CO_2 Concentration 4%



(d) CO_2 Concentration 5%

All Osillogram at 2 ms/cm

FIGURE 12

Xenon Mixture Lasing Outputs with Applied Currents and Various Percentages of CO_2

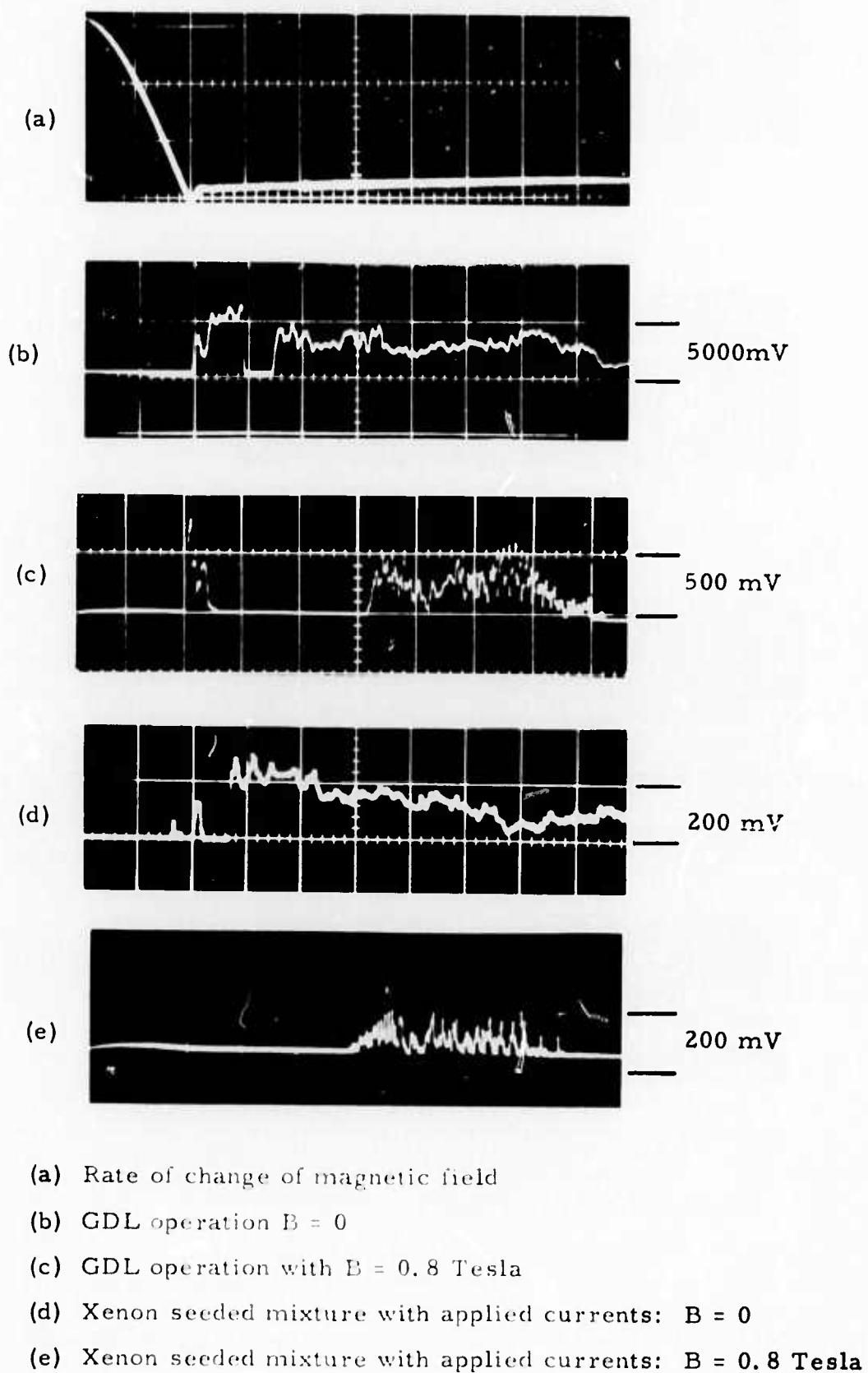


FIGURE 13 Lasing outputs with and without magnetic field

APPENDIX A

14th SYMPOSIUM ON ENGINEERING ASPECTS OF MHD (1974)

CO₂ MHD LASER: ANALYSIS, DESIGN AND SHOCK TUNNEL EXPERIMENTS

B. Zauderer, E. Tate and C. H. Marston
General Electric Company
King of Prussia, Pa.

Abstract

MHD laser gain exceeding 0.2%/cm has been achieved in the GE/ONR shock tunnel using a mixture of 78% Helium, 18% Argon and 4% CO₂ with either 1% Xe or 0.1% Cs added to the basic mixture for seeding. Long relaxation times and non-emitting electrodes required use of some external voltage augmentation to achieve the necessary plasma conditions in the available generator length. The MHD laser analysis, design of a channel based on that analysis, and experimental results to date will be discussed.

CO₂ was chosen as the laser medium because it has a reasonably high quantum efficiency (~41%), requires pumping to energy levels comparable to expected electron energy in an MHD generator (a few tenths of an electron volt) and is reasonably well understood as a result of the large effort which has been directed toward development of both gas dynamic and electric discharge lasers.

I. Introduction

Successful operation of an MHD laser requires satisfactory resolution of a number of conflicting requirements. To cite a few examples: the presence of a molecular species, such as CO₂, tends to degrade generator performance, thus, the concentration of the laser medium must be kept as low as practical, consistent with the absolute concentration required to achieve laser gain; static temperature must be low enough to avoid equilibrium thermal population of the lower laser level yet stagnation temperature must be sufficient to meet energy flux requirements; cesium seed can react chemically with CO₂ and CO₂ may lower electron temperature by quenching excited Cs atoms. The absolute electron concentration must be sufficient for adequate current density yet low enough to avoid exciting a large fraction of the CO₂ molecules to the lower laser level. These and other conflicts were resolved in the design and operation of a special laser channel in the GE/ONR shock tunnel facility.

II. Analysis and Design

A fairly simple model was formulated to describe the MHD laser and gas dynamic flow conditions in order to establish bounds on the pertinent parameters and achieve sufficient understanding of the situation to design an effective channel.

Effective electrical conductivity, assuming a Faraday channel and including the effect of plasma turbulence was taken as

$$\sigma_{\text{eff}} = 2\sigma/R_e \quad (1)$$

Where R_e is the Hall parameter ($\beta \gg 2$). The electron energy equation⁽¹⁾, modified by an inelastic collision loss factor δ_{eff} can be written for a one-dimensional perfect gas compressible flow in a short circuited channel as

$$\frac{3}{2} \delta_{\text{eff}} \left[\frac{T_e}{T_g} - 1 \right] = \gamma M^2 g_e \quad (2)$$

where T_e and T_g are electron and gas temperatures, γ is the specific heat and M the Mach number. A weighted average δ_{eff} was calculated from data for cross-sections⁽²⁾ and inelastic losses⁽³⁾

$$\delta_{\text{eff}} = \left(\frac{\sum_j \delta_j X_j Q_{ej}/M_j}{\sum_j X_j Q_{ej}} \right) \left(\sum_j X_j M_j \right) \quad (3)$$

For reasonable assumptions concerning stagnation temperatures, electron temperatures, and static gas temperatures, a design Mach Number of 4.5 and a CO₂ concentration < 5% were established with the aid of equations 1 - 3. Gas pressure was initially specified assuming a Hall parameter limited to ~10 by ion slip, and a magnetic field of 2.5 Tesla.

The electron density range within which a population inversion can be achieved was estimated by considering the rates of excitation and deexcitation of the appropriate laser levels by collision with electrons and with helium atoms. The electron rate constants of Bell and Bradley⁽⁴⁾ were used in the original analysis but those of Nighan and Brown⁽⁵⁾ give similar results. A range of 10^{12} to 5×10^{12} was estimated, neglecting the effect of laser power output. This estimate is also consistent with the results of Nighan and Brown.

A source of concern in MHD laser operation is quenching of cesium resonance radiation by molecular species since this will have the effect of lowering electron temperature and reducing electrical conductivity. Mnatsakanyan⁽⁶⁾ showed that a large increase in δ_{eff} for Nitrogen which resulted from the addition of cesium to a nitrogen argon mixture, could be attributed to quenching. Also, reaction of cesium and CO₂ to form CO and cesium oxides must be considered. These effects can be minimized by keeping the cesium concentration as low as possible and in any event much less than the CO₂ concentration.

Nozzle design and channel were established so as to minimize length of channel needed for re-

laxation to non-equilibrium, steady state and for sufficient MHD interaction.

A sharp cornered nozzle was used. The nozzle section is a removable steel insert approximately 2 1/2 inches in the flow direction. Most of the expansion takes place in this section although there is also some divergence built into the fiber-glas-epoxy MHD channel. Since the channel is relatively broad in the y direction and shallow in the z direction, a pair of Helmholtz coils were used to provide the magnetic field.

III. Experimental Set-up

The channel and magnet assembly are shown in Fig. 1 as they looked prior to completion of external electrode wiring and connection of the magnet to its capacitor bank power supply. Electrodes are segmented in both the x and y directions and consisted initially of 19 rows of flush mounted tungsten cylinders with up to 11 electrodes in each row. To reduce electrode loss, each electrode was later drilled to accept a short protruding tungsten pin.

Instrumentation for small signal gain measurement is shown in Fig. 2. A single mode beam from a small CO₂ probe laser was directed through germanium windows approximately 13 cm from the nozzle exit. Two gold-doped germanium detectors and a beam splitter mirror permitted continuous monitoring of the laser output during a run. A considerable effort was necessary to:

- Isolate detectors and probe laser from shock induced mechanical vibration.
- Modify the laser power supply to achieve 1% short term amplitude stability with single mode operation.
- Eliminate electromagnetic interference by the use of multiple shields for the detectors combined with careful grounding of all circuitry.

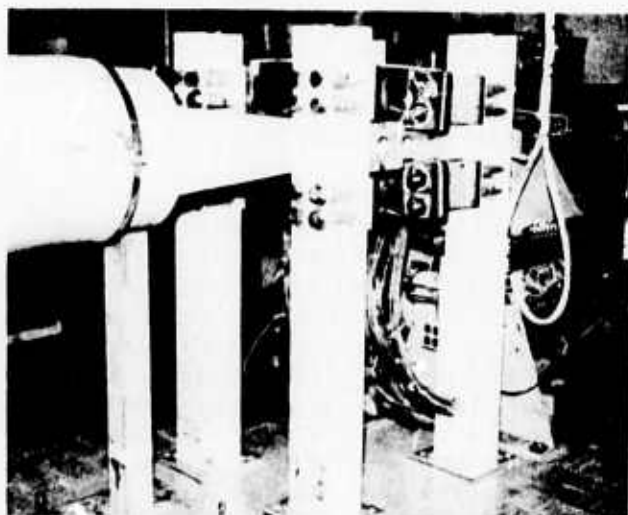


Fig. 1. Photograph of the Assembled MHD Laser Channel and Magnet. The View is in the Upstream Direction Toward the Shock Tube.

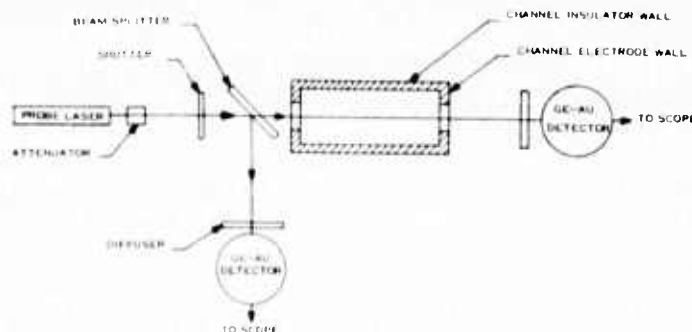


Fig. 2. Instrumentation for Laser Gain Measurements.

Fig. 3 shows the detector signal after completion of these modifications.

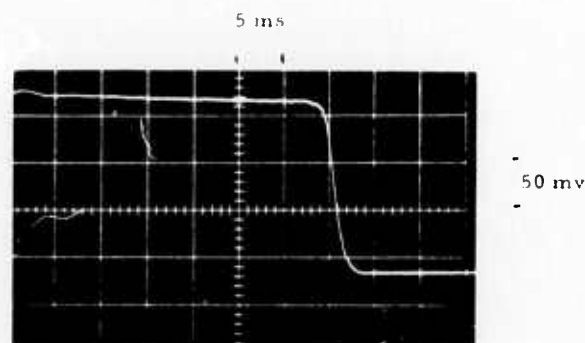


Fig. 3. Detector Signal With No CO₂ in Test Gas. Effect of Shock Wave Can Be Seen at Extreme Left. Mechanical Shutter Cuts Off Signal at About 30 ms.

IV. Gas Dynamic Laser Measurements

Gas dynamic laser gain tests were performed to check out the CO₂ laser gain equipment without the complication of interference from electrical and magnetic fields and to establish the gas dynamic operating characteristics of the channel.

The GDL mixture selected was 12% CO₂ + 48% N₂ + 40% He at 12 atm. and 1500° K stagnation conditions. Numerical analyses of the supersonic expansion indicated that the small signal gain should be about 0.2%/cm at the viewing port in the channel, but in the initial experiments only absorption was observed during the 2 ms test time except for a small initial spike. This measurement plus high static pressure in the channel led to the suspicion that the channel walls and the nozzle were being spread apart during the test time by the gas stagnation pressure. Direct measurement showed that nozzle flexing during the first two milliseconds of the test time was large enough (about 50% of the throat height) to reduce the gain to zero.

After strengthening the nozzle and extending the test time to 14 milliseconds by using a sphere at the end of the driver, more GDL experiments were done, Fig. 4. The longer test-time still gave absorption for about 6 milliseconds but then gain was

observed, thus providing the desired checkout of the diagnostics.



Fig. 4. Gas Dynamic Laser Gain With Reinforced Nozzle and With Sphere to Extend Test Time to 14 ms.

V. MHD Laser Measurements

A variety of mixtures were run in preliminary MHD laser experiments, Table I, but the two that yielded reproducible gain measurements were:

- . 78% He, 18% Ar, 4% CO₂ with 0.1% Cs seed added
- . 68% He, 27% Ne, 4% CO₂, 1% Xe

The use of Xe as a source of electrons eliminated the chemical reaction and possible quenching effects associated with cesium and enabled us to show experimentally that with a 4% mole fraction of CO₂ (sufficient for a concentration of 10¹⁶ cm⁻³) laser gain was feasible. Once that was achieved, we returned to cesium seed to improve MHD performance and found that seed levels of 0.1% cesium were effective.

Quenching was not a serious problem but most of the cesium reacted with the CO₂ to form cesium oxides prior to firing the shock tunnel. A light scattering measurement showed that concentration of cesium aerosol dropped by a factor of 5 to 7 when CO₂ was present in the gas mixture. Products of the reaction are not certain, but on the assumption that they are primarily CO and Cs₂O, the reaction is weakly exothermic at room temperature⁽⁷⁾. Subsequent shock heating decomposed the oxide and, as evidenced by a current density of about .3 a/cm², sufficient free electrons were available. From this we conclude that in gas containing both CO₂ and cesium the CO₂ mole fraction must be much larger than the cesium mole fraction so that most of the CO₂ will remain unreacted.

The computer code developed for MHD generator analysis⁸ which uses the Shkarovsky-Lau conductivity model⁹ was modified to include CO₂ as a constituent of the plasma. Vibrational interaction was accounted for in an approximate way by considering the energy difference and rate⁵ for interaction of free electrons with the CO₂ 010 vibrational level. While this does not give us a prediction of the CO₂ vibrational inversion, it did provide an estimate, Table II, of the gas dynamic and MHD conditions at which gain was measured.

Voltage augmentation was required to maintain electrode conduct on. Due to the short axial length of the channel, external voltage augmentation was used to obtain required ionization build-up. As has been explained elsewhere⁽¹⁰⁾, a discharge transverse to a gas flow is subject to extinction by gas convective effects in the ionization relaxation region. Thus, a voltage which is considerably greater than the discharge sustaining voltage must be applied across the electrodes in the channel. The use of non-emitting electrodes in this experiment further increased the ratio of ignition voltage to sustaining voltage.

Once the discharge was ignited, all but 100 volts of the augmentation voltage appeared across the external load resistors. Improvements in the electrode configuration and/or surface treatments are expected to permit operation of the generator at large CO₂ concentrations without any external supplement to the internally developed generator voltage.

Also of interest is the very high value of $\omega\tau$ ($\omega\tau = 39$) at which the MHD channel was successfully operated. Most non-equilibrium MHD generators operate in $\omega\tau$ range of 1 to 10.

Figure 5 shows measured gain. Note that it takes approximately 8 milliseconds to establish the flow. Total test time is about 14 ms but stagnation pressure is dropping near the end of that time so the gain tends to decrease. The relatively long test time is a result of the very small throat size required to give sufficient expansion for proper MHD laser flow conditions. Test time is limited by arrival of expansion waves from the driver end of the tube rather than by drain time, even though a sphere is used at the end of the driver to delay propagation of the expansion waves.

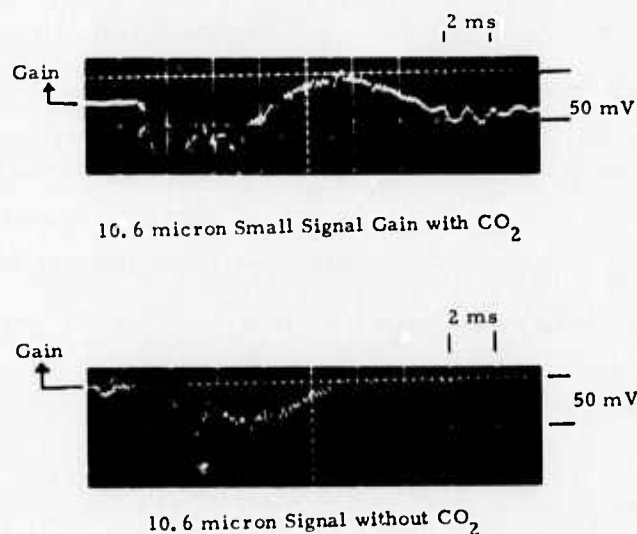


Fig. 5. 10.6 Micron Signal With and Without CO₂

Table I. Table of Various Gas Mixtures Tested in The MHD Laser Channel

Test Gas	% C _s	% CO ₂	% N ₂	% Gain	Comments
81% He/19% Ar ↓	1.0	All Conditions		0	$n_{C_s} n_{CO_2}$ Hence No Gain
	0.1	2.3	0	0	n_{CO_2} Too Small
	0.1	2.5	2.5	0	n_{CO_2} Too Small
	0.1	3.9	0	4-9	n_{CO_2} Sufficient for Gain
	0.1	0	0	0	NO CO ₂ Hence No Gain
70% He/19% Ne/1% Xe ↓	0	0.25	0	0	n_{CO_2} Too Small
	0	0.50	0	0	
	0	2.00	0	0	
	0	0.50	0.50	0	
	0	1.80	1.80	0	
	0	1.70	0	0	n_{CO_2} Sufficient For Gain
	0	3.80	0	~ 6	
	0	4.10	0	~ 6	
	0	0	0	0	NO CO ₂ Hence No Gain

Table II. MHD Laser Operating Conditions

Mixture: 78% He, 18% Ar, 4% CO₂, 0.1% Cs

Gas Dynamic Conditions: $M = 5$ $u = 2370$ m/sec
 $T_o = 1880^\circ K$ $T_{static} = 1960^\circ K$
 $p_o = 3.4$ atm $p_{static} = 6.9$ torr

MHD Conditions: $B = 1.66$ tesla
 $j = 0.29$ a/cm²
 $V_{ext} = 1800$ V, $R_{ext} = 1000 \Omega$, $I = 1.7$ a
 $V_{net} = 100$ V (Net Augmentation)
 $u_{By} = 1080$ V (Induced Internally)

Calculated Properties*: $n_e = 5.8 \times 10^{12}$ cm⁻³ $n_{CO_2} = 1.0 \times 10^{16}$ cm⁻³
 $T_e = 2085^\circ K$
 $\omega\tau = 39$
 $\sigma_{eff} = 1.6$ mho/m

* Shkarofsky-Lau Conductivity Model Plus CO₂ - 010 Vibration Energy

VI. Conclusion

Achievement of laser gain in an MHD channel with external voltage augmentation is the first step toward the development of a device capable of transforming thermal energy to coherent optical energy in a single gas dynamic channel. The test condition provides a bench mark from which to work for further improvements in electrode configuration, magnetic field and other variables to reduce the required external augmentation to a preionizer section or eliminate it altogether.

VII. Acknowledgements

The authors wish to thank Mr. L. D. DeDominicis for his contributions to the design of the channel and magnet assembly and Messrs. W. Frey and F. McMenamin for their assistance in performing the experiments. This work was supported in part by the Defense Advanced Research Projects Agency and by the Office of Naval Research.

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APPENDIX B
APPLIED PHYSICS LETTERS

LARGE ENTHALPY EXTRACTION EXPERIMENTS
IN A NON-EQUILIBRIUM MAGNETOHYDRO-
DYNAMIC GENERATOR

E. Tate, C. H. Marston, and B. Zauderer

General Electric Co.
Space Sciences Laboratory
King of Prussia, Pa.

A measure of the performance of a magnetohydrodynamic generator is the enthalpy extraction (power out/heat in) which generally must exceed 20% to operate efficiently in a thermodynamic Brayton power cycle. For the first time 1.82 megawatts, which represented 19.3% enthalpy extraction, was achieved in a non-equilibrium plasma, magnetohydrodynamic generator. Cold electrodes were used. Theoretical calculations show that 30% enthalpy extraction could be achieved with thermionically emitting electrodes.

Enthalpy extraction (electrical output/thermal input) of 20% is generally accepted as the minimum needed for successful development of Magnetohydrodynamic (MHD) generators. This is true of both the closed cycle (non-equilibrium, noble gas) and open cycle (combustion gas) types,^{1, 2} although recent calculations³ indicate that, in open cycle systems a somewhat lower value is acceptable if the combustion air can be preheated to 3000°F in a heat exchanger directly fired by the corrosive MHD generator exhaust.

An enthalpy extraction of 19.3% has recently been achieved in a shock-tunnel driven magnetohydrodynamic (MHD) Faraday generator. This was done by utilizing the non-equilibrium ionization concept in which Joule heating preferentially excites the plasma electrons so that their density is characteristic of a temperature higher than the gas temperature as a whole. The test gas was neon seeded with cesium.

A one foot diameter, sixty foot long shock tunnel was used to process the test gas to pressures of 4 - 5 atmospheres and temperatures of 3000 - 3500°K. The gas flowed through a convergent - divergent nozzle before entering the generator (see Figure 1). The gas traversed the generator in 400 microseconds and as the total test time was 10 milliseconds, the flow thus reached steady state conditions.

The MHD generator has entrance dimensions of 10.3 x 7.8 cm. and exit dimensions of 25.4 x 19.1 cm. to give an area ratio of 6 to 1.

The generator entrance was 20 cm. downstream of the throat. Previous experiments⁴ had also shown that wire electrodes parallel to the magnetic field and mounted away from the electrode walls resulted in lower electrode losses (than flush mounted electrodes) and did not disturb the supersonic flow in a drastic manner. The electrodes were 40 mil tungsten wires protruding 0.5 cm. from the electrode walls. There were 74 pairs of electrodes with the last dozen locations having two pairs at each axial location.

The magnet was of saddle-coil construction. To maximize the peak field, within the constraint of 1 megajoule available from the capacitor bank power supply, the windings were diverged in two directions with the same angular divergences

as the generator walls. The rise time (quarter cycle) was 4 milliseconds, the magnet being crow-barred at the quarter cycle point at which time the test gas entered the MHD generator.

Seed was introduced by flowing cold test gas over a hot bath of cesium. Particles of order 1 micron diameter were entrained and the mixture was then introduced into the shock-tube. After loading the shock-tube, the test had to be completed within one minute, otherwise the larger cesium particles fell, to the bottom of the shock tube. A double diaphragm driver arrangement provided the precise timing control necessary. The cesium injection system was designed to supply a greater concentration of cesium than necessary for plasma conductivity enhancement as previous experience had shown that large concentrations ($\approx 1\%$) of cesium enhanced electrode conduction. Changes (from previous experiments) made to enhance electrode conduction were to relocate the cesium injection system to the rear of the MHD generator. This provided a cesium flow directly over the electrodes, thus depositing a cesium layer upon them prior to the start of an experiment. A thin aluminum diaphragm separated the rear of the generator from a large vacuum dump tank.

The conditions for 19.3% enthalpy extraction were as shown in Table 1. Although the stagnation temperature was 3520°K , it should be noted that the gas static temperature (after flowing through the convergent - divergent nozzle) at the first electrode was only 2020°K and at the generator exit was only 1200°K . Previous work⁵ has shown that enthalpy extraction in a non-equilibrium MHD generator is a very weak function of the gas stagnation temperature.

The theoretical analysis showed (using the experimental load resistors to determine the current) that the electron temperature rose quickly in the generator to 2700°K and fell off to 2400°K at the generator exit. This effect is strongly illustrated by the power distribution curve shown in Figure 2. The current rose quickly to a large value after several electrode pairs and reached a maximum at a distance equal to one third of the generator length. The discontinuity in power near the downstream end of the generator was caused by a change from single electrode pairs loaded with 1.7 ohms to double electrode pairs each loaded with 1.7 ohms to give, in effect, 0.85 ohms at those axial locations. The theoretical analysis predicted a net enthalpy extraction of 20% which was in good agreement with the actual output. The measured electrode drop of 150 volts was used as an input to the theoretical analysis. The theoretical analysis gave a gross enthalpy extraction (the sum of the power lost due to the 150 volt electrode loss and the power delivered to the load) of 30%. At this value strong aerodynamic loading (i. e. flow deceleration) caused choking of the flow near the generator exit. The choking was not a serious problem because lowering the power output of the generator by a small amount ($\approx 5\%$) removed the choking effect.

Run 424 which gave a net enthalpy extraction of 11.3% is shown (see Figure 2) for comparison with Run 182A⁶. Run 424 was made prior to the changes in experimental setup previously described but under similar conditions of pressure, temperature and magnetic field. Because the interaction was smaller, power output was uniform throughout the generator. The Mach number at the entrance of the generator was 1.5. At open circuit the exit Mach number was 3. At the 19.3% enthalpy extraction condition, the Mach number decreased in the channel and the analysis indicated it approached unity near the channel exit.

The experimentally measured enthalpy extraction varied linearly with magnetic field (see figure 3). The theoretical net extraction was in agreement with the experiment if a 150 volt loss was used above 17 kilogauss. The voltage loss was gradually decreased to 80 volts at 12 kilogauss. The theoretical gross enthalpy rose with magnetic field and then levelled off as the aerodynamic loading became strong enough to approach choking conditions. This occurred at slightly over 30% enthalpy extraction. An obvious conclusion is that, as the magnetic field is increased, a greater percentage of the gross enthalpy was delivered to the external load resistors because the voltage loss became a smaller proportion of the total voltage available. The computed turbine efficiency of this generator was 60%. Due to the electrode losses (which could of course be eliminated with thermionic emission) the net isentropic generator efficiency was 40%. At about 70% isentropic efficiency and 30% enthalpy extraction, power plant efficiencies of around 50% would be attainable.

It should be noted that these experiments indicate that 30% enthalpy extraction could be achieved in a generator with thermionically emitting electrodes. This is far better than had been thought possible and places the closed cycle MHD generator in the enthalpy extraction range accessible to turbines.

ACKNOWLEDGEMENT, FOOTNOTES, AND REFERENCES

* Sponsored in part by the Office of Naval Research and by the Defense Advanced Research Projects Agency.

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6. Letter A Suffix denotes new series of runs beginning April 1973.

FIGURE AND TABLE CAPTIONS

- FIGURE 1 Schematic drawing of the MHD generator.
- FIGURE 2 Variation of power output per electrode location versus axial
electrode location.
- FIGURE 3 The variation of experimental and theoretical enthalpy extractions
with magnetic field.
- TABLE 1 The generator conditions pertaining to the extraction of 19 percent
of the thermal input power, run 182A.