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EXPERIMENTAL MHD RESULTS RELEVANT TO ADVANCED PROPULSION CONCEPTS

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Abstract *The MHD power generation results obtained in a hypersonic shock tunnel at Mach 30 and 10.200 K are relevant to the development of advanced propulsion systems. The interaction of high velocity air plasma with transverse magnetic field strengths of 2300 and 6500 Gauss were investigated in the shock tunnel. The incident shock Mach number varied from 10 to 32 with corresponding plasma temperatures from 3600 to 11.000 K. At Mach 30, the observed open circuit potentials across the electrodes agreed with the theoretical values. By varying the external load for a shock Mach number of 30, the current from the plasma with 2300 Gauss field varied from zero to 115 A. The observed potential decreased linearly with increasing current indicating a nearly constant plasma resistance. The maximum power extracted from the plasma was 7.8 kW with an external load of 1,85 Ohm. But with the 6500 Gauss field, the voltage across the electrodes with different external resistance decreased nonlinearly with increasing current flow. Also, the plasma resistance across the electrodes decreased drastically with corresponding increase in the electrical conductivity at high current flows. A power of 151 kW was extracted from the Mach 30 plasma with room temperature copper electrodes, which was much greater than the theoretical prediction.*

Key Words: *Magnetohidrodynamics, Hypersonics, Shock tunnel, Laser propulsion*

1. INTRODUCTION

In the early 60's there was an active interest on the problem of the interaction of high velocity plasma with a magnetic field, (Rosa, 1962, Nagamatsu & Sheer, 1961, Nagamatsu *et al*, 1962, Way *et al*, 1961, Steg & Sutton, 1960). The need for better understanding of the MHD phenomena arose from the interest in thermonuclear reactions, astrophysics, electric power generation, space propulsion, and application of MHD for aerodynamic control of ICBM nose cones and the Apollo vehicle. Numerous analytical and only limited experimental papers were published on the hypersonic MHD phenomena. Nagamatsu & Sheer (1961), and Nagamatsu *et al.* (1962), initiated an investigation to study the interaction of air plasma, produced by strong shock waves, with transverse magnetic field strengths of 2300 and 6500 Gauss across a 101,6 mm, diameter, 30,5 m long shock tube (Nagamatsu *et al*, 1959). This simple arrangement for the MHD investigation was selected to permit the correlation of existing theories with the experimental results, and the information will be useful in the field of MHD power generation and for flight applications.

In the present, interest in MHD for aerospace applications has regrown spurred by the need to drastically decrease the cost of launching transatmospheric vehicles. A laser or microwave beamed energy with a MagnetoHydroDynamic (MHD) fanjet to accelerate the vehicles to orbital Mach number of 25 has been proposed by Myrabo, et al. (1995). The inlet of this hypersonic engine is a novel device that enable active control of a Lightcraft, which is a vehicle that derives its power for flight propulsion from a beam of electromagnetic energy (laser or microwaves). In this concept the control of the external hypersonic aerodynamics is is possible by means of the laser induced Air Spike (Myrabo et al, 1995, Myrabo and Raizer, 1994). The principle function of Air Spike is to replace the traditional sharp conical forebody, normally proposed for streamlining an aerospace plane and precompressing the inlet air for the "scramjet" engine. Myrabo and Raizer (1994) have shown that continuous wave and pulsed lasers, with appropriate average power, frequency rate and focal length can be used to support the spike.

Toro *et al.* (1997, 1998) conducted experiments in the RPI 61 cm diameter Hypersonic Shock Tunnel (Minucci & Nagamatsu, 1991) with a 152,4 mm. diameter blunt body Lightcraft model with 152,4 mm. long slender plasma torch at the stagnation point. This simulated the "Directed-Energy Air Spike" produced by laser beam at hypersonic Mach numbers of 10 to 20. Plasma torch powers up to 135 kW were used. With the Air Spike the detached bow shock wave was changed to conical shock wave with corresponding decrease in the surface pressure, aerodynamic drag, and heat transfer to the model.

For the lift-off of the Lightcraft, Myrabo *et al.* (1995, 1998) and Mead *et al.* (1998) suggested the concept of Pulsed Detonation Engine (PDE) cycle. This engine develops laser-generated thrust upon the aftbody of the Lightcraft. Laser energy is focused by the parabolic shaped aftbody mirror towards the center of the cowl surrounding the body and detonation waves are produced. In October, 1998, Myrabo *et al.* (1998) deflected a 10 kW Pulsed Laser Vulnerability Test System (PLVTS) pulsed carbon dioxide laser (1 kJ per pulse, 30 ms pulse with a 10 Hz) at the High Energy Laser System Test Facility (HELSTF), White Sands Missile Range, New Mexico by a 45 degree mirror to the rear of the 14 cm diameter, 50 gm model to produce the detonation waves at the cowl surface. With PDE cycle the 50 gm model was accelerated vertically at approximately 2.3 g's to an altitude of 4,3 m. More recently, spin-stabilized free-flight launches outside the laboratory have been accomplished to altitudes approaching 30 m by Mead *et al* (1998).

In another proposed concept, a Rocket-Induced MHD Ejector engine (RIME) t for a single-stage-to-orbit has been suggested by Cole *et al* (1995) to accelerate future transatmospheric vehicle from take-off to orbital velocity, Mach 25. The rocket engine, fueled by liquid hydrogen and liquid oxygen, is the source of energy for the entire system. It provides the very high velocity flow of ionized gas through the MHD generator (Rosa, 1962, Nagamatsu & Sheer, 1961, Nagamatsu *et al*, 1962). The MHD accelerator is designed and operates similarly to the MHD generator, except that a high potential is imposed on the electrodes in opposition to the force which will accelerate both the ions and electrons in the direction of the flow.

Both above advanced propulsion concepts share the same need for developing propulsion MHD flight systems and have motivated the present work.

2. EXPERIMENTAL APPARATUS

2.1 Shock tunnel

The shock tube portion of the Hypersonic Shock Tunnel (Nagamatsu *et al*, 1959) was used to conduct the magnetohydrodynamic experiments. At the end of the 30,5 m long driven tube a 101,6 mm internal diameter Herkolite™ insulating tube was connected and the tube discharged into the large 5,7 m^3 dump tank, as depicted in Fig. 1. All of the tests were made with combustion of stoichiometric mixtures of hydrogen and oxygen with an excess of helium (Nagamatsu *et al*, 1959, Nagamatsu & Martin, 1959) to produce strong shock waves in air. By varying the pressure in the driven tube with constant driver conditions, it was possible to produce shock waves of varying strengths, Mach = 10 – 32.

2.2 Magnetic field coils

Two identical coils with an inside diameter of 12,7 cm and outside diameter of 24,1 cm were mounted normal to the axis of the Herkolite™ section of the driven tube, as depicted in Fig.1. They were wound from copper strip with a thickness of 0,254 mm and a width of 8,9 cm. One hundred and seventy turns of this copper strip were used for each coil. Initial investigations (Nagamatsu & Sheer, 1961) were conducted with magnetic field strength across the tube of 2300 Gauss with a current of 385 A through the coils supplied by a welding generator. By adding an iron core, surrounding the magnetic coils, the magnetic field strength across the tube was increased to 6500 Gauss (Nagamatsu *et al*, 1962).

2.3 Instrumentation and electrode system

For each shot the shock wave position as a function of time was determined by means of 12 ionization gages located along the driven tube. The outputs from these gages were fed into a modified Tektronix 535 oscilloscope with a crystal controlled signal generator and display chassis. These shock velocity measurements were supplemented by Berkeley counter which measured the shock wave traversal time over the 76,2 cm sections of the driven tube.

Piezoelectric gages, located just ahead of the magnetic field, Fig. 1, were used to monitor the pressure increase across the shock wave. However, the response time of the quartz gages was too slow to obtain the absolute magnitude of the pressure rise across the shock wave at high shock velocities.

Microwave equipment with wavelengths of 4 mm and 3 cm (X-band), Fig. 1, was used to probe the plasma just upstream of the magnetic coils. For the longer wavelength the reflected and transmitted signals across the plasma were displayed on the oscilloscope. The transmitting and receiving horns were located very close to the Herkolite™ tube which is highly transparent to these microwave frequencies.

The electrode system consisted of two copper discs of 1,27 cm^2 in area mounted flush with the inside of the Herkolite™ tube for a magnetic field strength of 2300 Gauss (Nagamatsu & Sheer, 1961).A larger pair of copper discs, with an area of 3,94 cm^2, were used for the magnetic field strength of 6500 Gauss (Nagamatsu *et al*, 1962). The electromotive force developed across these opposing electrodes was also placed on a Tektronix oscilloscope. Electrical resistance across these electrodes was connected with short leads to minimize the impedance of the current. From the voltage across the external resistance, the current being extracted from the high velocity plasma was determined. The range of external resistance used in the investigation with the 2300 Gauss (Nagamatsu &

Sheer, 1961) was from 0,2 to 10^6 Ohm and for the 6500 Gauss investigation (Nagamatsu *et al*, 1962) the resistance was from 0,76 to 10^6 Ohm.

3. AIR PLASMA CHARACTERISTICS AND THEORETICAL ELECTRICAL CONDUCTIVITY

3.1 Air plasma characteristics

The air in the driven tube was initially at room temperature but the pressure was varied to obtain the desired shock Mach number with the driven conditions held nearly constant for all the shots. By assuming the air after the incident shock wave to be in equilibrium, the equilibrium composition and thermodynamic properties were obtained from the results in Gilmore (1955), Hilsenwrath & Beckett (1956), and Ziemer (1960). These results in conjunction with the collision cross-sections for the different species were used to calculate the effective electrical conductivity of the air plasma.

3.2 Theoretical prediction of electrical conductivity

For the calculation of the electrical conductivity of the plasma, the electrons, ions, and neutral atoms were assumed to be at the same temperature and the plasma to be neutral with no magnetic or electric fields (Lanm & Lin, 1958, Sakuntala *et al*, 1960, Mullaney *et al*, 1960). These assumptions are reasonable because the plasma is produced by a normal shock wave. The "free path kinetic theory" (Alfren, 1950, Cobine, 1958, Spitzer, 1950) approach has been used to derive the approximate equation for the conductivity of partially ionized air plasma (Nagamatsu & Sheer, 1961). However, when the magnetic field is large and the plasma density is very low, the theoretical electrical conductivity of the shock heated air for equilibrium conditions is decreased (Chapman & Cowling, 1952, Way, 1960). For these conditions the collisions interval between the ions, electrons and neutral species are large compared with the cyclotron frequencies around the lines of magnetic force. For a gas containing electrons and positive ions interacting with a weak magnetic field, the electric current will be mainly due to the motion of the electrons. The indication of the decrease in the conductivity due to the magnetic field is given by the product of the electron cyclotron frequency and the collision interval of the electrons in the ionized gas (Lin, 1959).
Therefore, the theoretical conductivity in the direction of the electric field, which is perpendicular to the magnetic field, has to be corrected as suggested by Chapman & Cowling (1952) in order to provide the effective conductivity.

4. EXPERIMENTAL RESULTS

4.1 Induced electromotive force

The induced voltages for the investigations (Nagamatsu & Sheer, 1961, Nagamatsu *et al*, 1962) were appreciable because of the high shock velocities and strong magnetic field strengths of 2300 and 6500 Gauss. Representative voltage traces for a high external resistance of 10^6Ohm with magnetic field strengths of 2300 and 6500 Gauss and a shock Mach number of approximately 30 are presented in Fig. 2. The equilibrium temperature behind the shock wave was 10.200 K for an initial pressure in the shock tube of 65 microns of mercury and room temperature. For this condition the induced plasma velocity was $9{,}78 \times 10^5$ cm/sec and the corresponding electron number density was $6{,}54 \times 10^{15}$ electrons/cm^3. Only few microseconds were required for the induced potential across the electrodes to be established for both magnetic field strengths. For magnetic field of 2300 Gauss the induced voltage decayed slowly with time but for 6300 Gauss the voltage after approximately 10 μsec decreased more rapidly, Fig. 2.

In Fig. 3 the observed potentials across the electrodes for an external resistance of 1.0×10^{6} Ohm are plotted as a function of shock Mach number for applied magnetic field strengths of 2300 and 6500 Gauss normal to the plasma flow. At higher Mach numbers the agreement between the theoretical and the observed potential is excellent for both magnetic fields. These results indicate that the plasma velocity across the tube cross-section is nearly uniform and that the boundary layer at wall must be thin immediately behind the shock wave. For shock Mach number less than 27 with 2300 Gauss (Nagamatsu & Sheer, 1961) the observed induced voltages were less than the theoretical prediction, Fig. 3, because of the delay behind the shock wave in dissociating and ionizing the air at lower Mach numbers with lower temperatures. For a magnetic field strength of 6500 Gauss (Nagamatsu *et al*, 1962), Fig. 3, the agreement between the experimental induced potentials and theoretical predictions were very good for shock Mach numbers of 15 to 31, and the potential across the electrodes was 667 V for Mach 30 shock wave.

4.2 Current from plasma produced by Mach 30 shock wave

A systematic variation of external resistance across the electrodes was made for a shock Mach number of approximately 30 and magnetic field strengths of 2300 and 6500 Gauss in Nagamatsu & Sheer (1961), and Nagamatsu *et al* (1962).

To determine the length and the duration of the high temperature plasma behind the Mach 30 shock wave, microwaves of 4 mm and 3 cm, X-band, were transmitted across the plasma. For the 3 cm wavelength, the transmitted signal is cut-off completely for about 10μsec, indicating that the plasma frequency is higher than the microwave frequency (Nagamatsu & Sheer, 1961, Nagamatsu *et al*, 1962). This time is approximately the passage time across the electrodes of the nearly uniform heated plasma. After the passage of heated plasma, the microwave signal is not attenuated because the free electron concentration in the gas is very low due to the mixing of the driven gas with the driver gas. Once the free electron concentration becomes small, it is not possible to maintain high current flow from the plasma.

The current extracted from the plasma was determined from the observed potential across the load and the resistance for magnetic field strengths of 2300 and 6500 Gauss and Mach 30 shock wave. For 2300 Gauss field, the external resistance was varied from 0,2 to 10^6 Ohm, and the voltage decreased with increasing current like a battery or a generator, Fig. 3. With an external resistance of 0,2 Ohm the maximum current was 115 A with a potential of 21 V. This current was obtained from the 1,27 cm diameter copper electrodes at nearly room temperature, and the current density corresponds to 90,8 A/cm^2.

The external load resistance was varied from 0,766 to 10^6 Ohm for magnetic field strength of 6500 Gauss (Nagamatsu *et al*, 1962) with 2,24 cm diameter copper electrodes mounted flush to the inner wall of the Herkolite™ tube. A rather interesting and unexpected variation of the voltage with current was observed, Fig. 4. At low currents the voltage decreased nearly linearly with current, similar to the 2300 Gauss results. But for currents greater than 150 A, the voltage decreased very slowly with the current indicating that the electrical conductivity of the plasma was increasing with the current flow. This type of variation of voltage with current has been observed for an electric arc as discussed in Cobine (1958). With an external resistance of 0,766 Ohm the maximum current was 447 A with copper electrodes with an area of 3,94 cm^2 at room temperature and the current density corresponds to 113 A/cm^2. Similar non-linear increase of the electrical conductivity was observed for argon and air plasma at 10.000 K and transverse magnetic field strength of 10500 Gauss with 2,54 cm $\times$ 7,62 cm copper electrodes.

4.3 Electrical power extracted from plasma produced by Mach 30 shock wave

From the measured potential across an external load, the maximum power, for different loads, were calculated. To that end, the product of the voltage *V* across the load and the current flow *I* was used to compute the power. These results were obtained for the plasma produced by a shock Mach number of approximately 30 and transverse magnetic field strengths of 2300 and 6500 Gauss. The electrical power outputs across the load are plotted in Fig. 5 as a function of the current flow through the circuit. For 2300 Gauss field, a maximum power of 7,8 kW was obtained from the plasma with a current flow of nearly 65 A through the external load of 1,85 Ohm with 1,27 cm diameter electrodes. When the external resistance was less than 1,85 Ohm, the power output from the plasma decreased. The solid curve in Fig. 5 for 2300 Gauss is based upon the slope of the voltage as a function of the current in Fig. 4.

Also in Fig. 5, the electrical power output across the load is plotted as a function of the current flow through the circuit for a magnetic field of 6500 Gauss with 2,54 cm diameter electrodes. For the range of external resistance that was used in the investigation, the power continues to increase as a function of the current to a value of 155 kW for a current of 400 A. At the lower current flow the power is tending to vary like a parabola, which is the case for a constant plasma resistance across the electrodes, but for current greater than about 150A, the power seems to vary linearly with the current. This means that the conductivity of the plasma is also increasing with the current flow. These results are not in agreement with the MHD power generation experiments conducted at lower velocities and lower temperatures (Way, 1960, Mullaney, 1960). In previous experiments (Nagamatsu & Sheer, 1961) with a lower magnetic field of 2300 Gauss, the power output from the plasma was a parabola with a maximum power output of 7.8 kW, with 1,27 cm copper electrodes, Fig. 5. Evidently the induced voltage at the lower field strength was not large enough to produce the nonlinear variation of the electrical conductivity encountered with the 6500 Gauss field.

One of the significant results from the investigation is the fact that it is possible to extract high current density from a cold copper cathode for both magnetic field strengths of 2500 and 6500 Gauss (Nagamatsu & Sheer, 1961, Nagamatsu *et al*, 1962). In Cobine (1958), the thermionic work functions for different materials are tabulated. For clean copper surfaces the work necessary in Volts to remove a unit change of electrons from surface is 4,38 V. Thus, at room temperature the electron emission from the cold copper cathode would be negligible. However, in actual case for a plasma, produced by a Mach 30 shock wave, moving through magnetic fields of 2300 and 6500 Gauss, it was possible to extract currents from 115 A (Nagamatsu & Sheer, 1961) to 447 A (Nagamatsu *et al*, 1962), respectively. This result would indicate that for flight applications of magnetohydrodynamics for generating power and producing thrust by accelerating the plasma (Myrabo et al, 1995, Cole, 1995), it may not be necessary to heat the cathode to obtain large current flows. Therefore, further experimental and analytical investigations must be conducted to understand these interesting phenomena for a high-velocity plasma.

5. CONCLUSIONS AND FURTHER RESEARCH

With the combustion driver shock tube technique, it was possible to produce air plasma with an equilibrium temperature range of 3600 to 11,000 K and the corresponding shock Mach number varied from 10 to 32. At the higher temperatures the air was completely dissociated and highly ionized.

As the high velocity air plasma moved through the transverse magnet fields of 2500 and 6500 Gauss, an electromotive force was generated across the shock tube. For a nearly open circuit condition the induced potentials across the electrodes agreed well with the theoretical predictions at high Mach numbers.

For the plasma produced by a Mach 30 shock wave, the voltage across the electrodes with different external loads decreased linearly with increasing current flow from zero to 115 A with 1,27 cm diameter copper electrodes. And for 6500 Gauss field with 2,24 cm diameter electrodes, the voltage across the electrodes decreased linearly with increasing current flow through the circuit from zero to approximately 80 A. At higher current extractions from the plasma the voltage variation with current becomes nonlinear, similar to that observed for electric arcs. The plasma resistance decreased drastically at high current flows.

Very high current flows with copper electrodes at room temperature were observed. For two copper electrodes with an area of 3,94 cm^2 facing each other across the tube it was possible to extract 447 A from the plasma with 6500 Gauss field.

The electrical conductivity, determined from the effective plasma resistance across the electrodes, for a Mach 30 shock wave and magnetic field of 2300 Gauss was found to be lower than the theoretical value corrected for the cyclotron motion of the electrons. On the other hand, for the magnetic field of 6500 Gauss, the electrical conductivity was found to be greater than the theoretical value corrected for the electron cyclotron frequency.

With a magnetic field strength of 2300 Gauss with 1,27 cm diameter electrodes and a plasma produced by Mach 30 shock wave, a maximum power of 7,8 kW was extracted from the plasma with the external load resistance equal to the plasma resistance of 1,85 Ohm. But for a magnetic field of 6500 Gauss with 2,24 cm diameter electrodes, a power of 155 kW was extracted with room temperature copper electrodes. Due to the increase in the conductivity with current flow, the extractable electrical power from the plasma was much greater than the theoretical predictions.

To increase the MHD knowledge for high velocity and temperature plasmas, investigations are being conducted in the RPI 24-in. diameter Hypersonic Shock Tunnel. A Lightcraft model with MHD accelerator, located at the periphery of the model, and a two-dimensional wedge model, with 1,2 Tesla permanent magnet for accelerating the air plasma, are being currently tested at free stream Mach numbers of 8 to 25 and stagnation temperatures to 4100 K.

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REFERENCES

Alfren, H., Cosmical Electrodynamics, Clarendon Press, Oxford, England, 1950.

Chapman, S., and Cowling, T.G., The Mathematical Theory of Non-Uniform Gases, Univ. Press, Cambridge 1952.

Cobine, J., Gaseous Conductivity, Dover Publications, Inc., New York, 1958.

Cole, J., Campbell, J., and Robertson, A., “Rocket-Induced Magnetohydrodynamic Ejector:A Single-Stage-to-Orbit Advanced Propulsion Concept,” AIAA Paper 95-4079, September 1995.

Gilmore, F.R., “Equilibrium Composition and Thermodynamic Properties of Air to 24,00K,” Rand Corp. Rep., RM-1543, August 24, 1955.

Hilsenwrath, J., and Beckett, C.W., “Table of Thermodynamic Properties of Argon-Free Air to 15,000 K,” Arnold Engineering Development Center Rep., AEDC-TN-56-12, September 1956.

Lanm, L. and Lin, S.C., “Electrical Conductivity of Thermally Ionized Air Produced in a Shock Tube,” J. App. Phys., 28, July 1958, pp.754-59.

Lin, S.C., “Rate of Ionization Behind Shock Waves in Air,” AVCO Res. Lab Res. Note 170, December 1959.

Mead, F.B. Jr., Myrabo, L.N., and Messitt, D.G., “Flight and Ground Tests of a Laser-Boosted Vehicle, “ AIAA Paper 98-3735, July 1998.

Minucci, M.A.S., Nagamatsu, H.T. , “An Experimental Investigation of Hypersonic Shock Tunnel Testing at an Equilibrium Interface Condition of 4100 K: Theory and Experiment,” AIAA Paper 91-1707, June 1991.

Mullaney, G.J. and Dibelias, N.R., “Power Extraction in a MHD Generator Using Flame Gases Seeded with Large Concentrations of Potassium,” General Electric Chem. Res. Dept, Memo C-60-75, June 1960.

Myrabo, L.N., Mead, D.R., Raizer, Y.P., Surzhikov, and Rosa, R.J., “Hypersonic MHD Propulsion System Integration for a Manned Laser-Boosted Transatmospheric Aerospacecraft,” AIAA Paper, June 1995.

Myrabo, L.N., Messitt, D.G., and Mead, F.B. Jr., “Ground and Flight Tests of a Laser Propelled Vehicle,” AIAA Paper 98-1001, January 1998.

Myrabo, L.N, and Raizer, Y.P., “Laser-Induced Air Spike for Advanced Transatmospheric Vehicles, “AIAA Paper 94-2451, June 1994.

Nagamatsu, H.T., Geiger, R.E., and Sheer, R.E.Jr., “Hypersonic Shock Tunnel,” ARS H., 29, May 1959, pp.332-40.

Nagamatsu, H.T., and Martin, E.D., “Combustion Investigation in the Hypersonic Shock Tunnel Driver,” J. App. Phys., 30, July 1959, pp1018-21.

Nagamatsu, H.T., and Sheer, R.E.Jr., “Magnetohydrodynamics Results for Highly Dissociated and Ionized Air Plasma,” The Physics of Fluids, Vol. 9, September 1961, pp.1073-1084.

Nagamatsu, H.T., Sheer, R.E. Jr., and Weil, J.A., “Non-Linear Electrical Conductivity of Plasma for Magnetohydrodynamic Power Generation,” ARS Paper 2632-62, November 1962.

Rosa, R.J., “Magnetohydrodynamic Generators and Nuclear Propulsion,” ARS Journal, August, 1962, pp.1221-1230.

Sankuntala, M., VonEngel, A., and Fowler, R.G., “Ionic Conductivity of Highly Ionized Plasmas,” Phys. Rev. 118, June 15, 1960, pp.1459-65.

Spitzer, J., Physics of Fully Ionized Gases, Interscience Publ., NY 1950.

Steg, L. and Sutton, G.W., “The Prospects of MHD Power Generation,” Astronautics 5, August 1960, pp.22-25.

Toro, P.G.P., Myrabo, L.N., and Nagamatsu, H.T., “Experimental Investigation of Hypersonic ‘Directed-Energy Air Spike’ Inlet at Mach 10-20,” AIAA Paper 97-0795, January 7,1997.

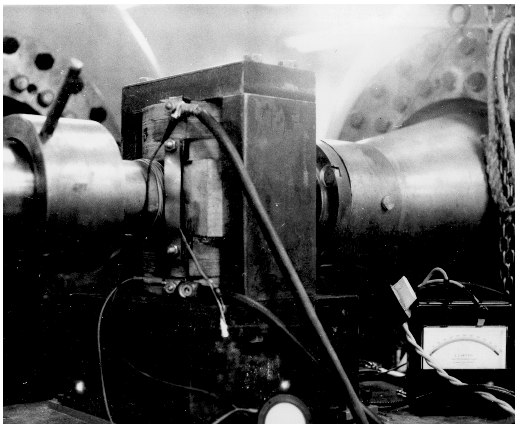
Toro, P.G.P., Myrabo, L.N., and Nagamatsu, H.T., “Pressure Investigation of the Hypersonic ‘Directed Energy Air Spike’ Inlet at Mach Number 10 with Arc Power up to 70 KW,” AIAA Paper 98-0991, January 1998.

Way, S., “Magnetohydrodynamic Power Generation,” Westinghouse Research lab., Scientific Paper 6-40509-2-P2, April 1, 1960.

Way, S., DeCorso, S.M., Hundstud, R.L., Kenney, G.A., Stewart, W., and Young, W.E., “Experiments with MHD Power Generation,” Trans. Am. Soc. Mech. Eng., J. Eng. Power 83, Series A. October 1961, pp.394-408.

Wharto, C.B. and Slager, D.M., “Microwave Determination of Plasma Density Profiles,” J. App. Phys., 31, February, 1960, pp.428-30.

Ziemer, R.W., “Extended Hypervelocity Gas Dynamic Charts for Equilibrium Air,” Space Technology Lab Inc. TR-60-0000-09093, April 14, 1960.



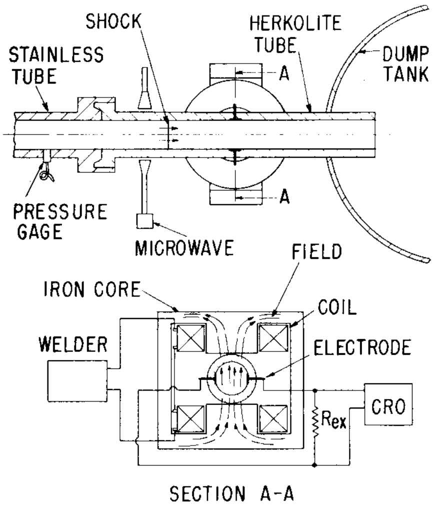
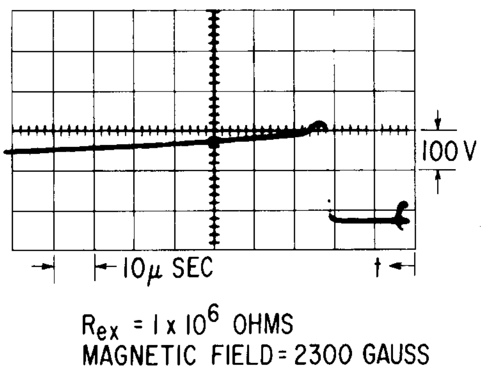


Figure 1-Photograph of the experimental apparatus (left) and a schematic view depicting the location of the intrumentation (right)



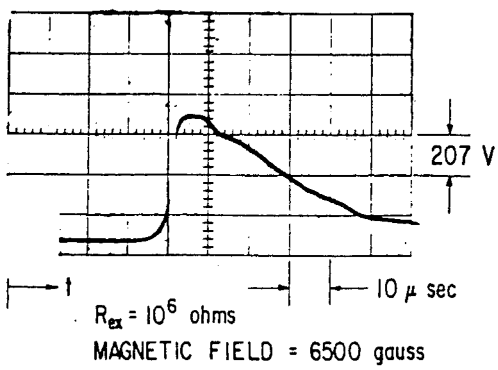


Figure 2-Oscilloscope record of induced potencial for shock Mach number of 30 and magnetic field strenghts of 2300 Gauss (left) and 6500 Gauss (right).

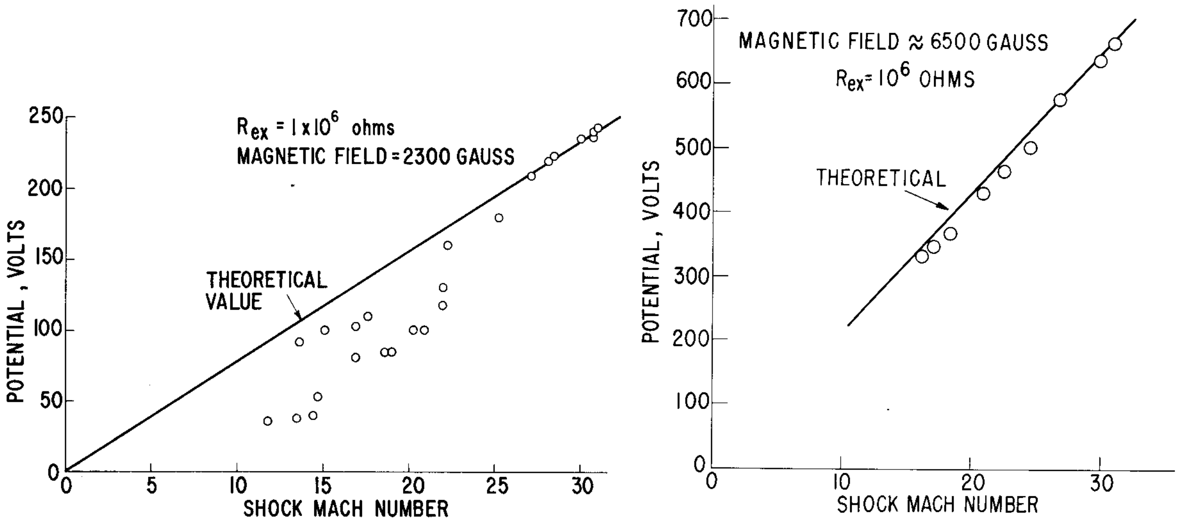


Figure 3 -Potential across electrodes as function of shock Mach number for magnetic field strengths of 2300 Gauss (left) and 6500 Gauss (right)

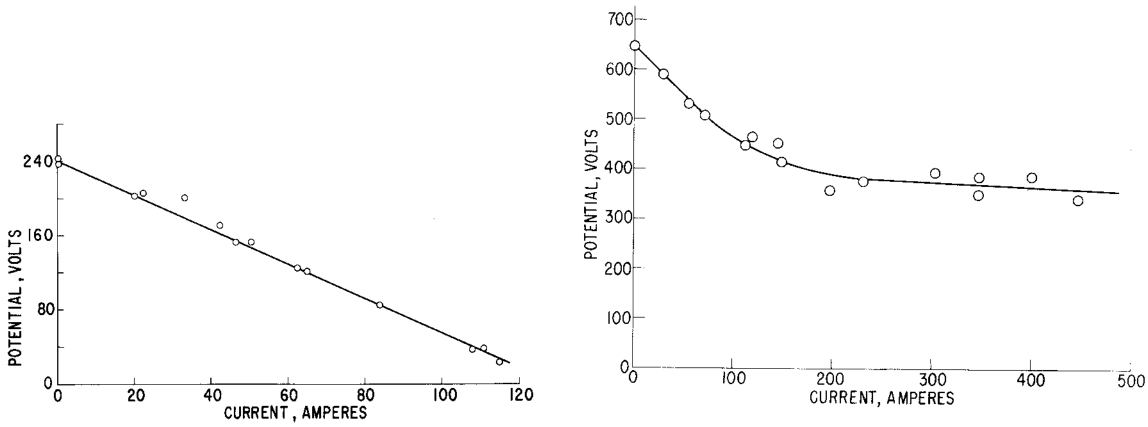


Figure 4-Potential-current characteristics for plasma produced by Mach 30 shock wave and magnetic field strengths of 2300 Gauss (left) and 6500 Gauss (right)

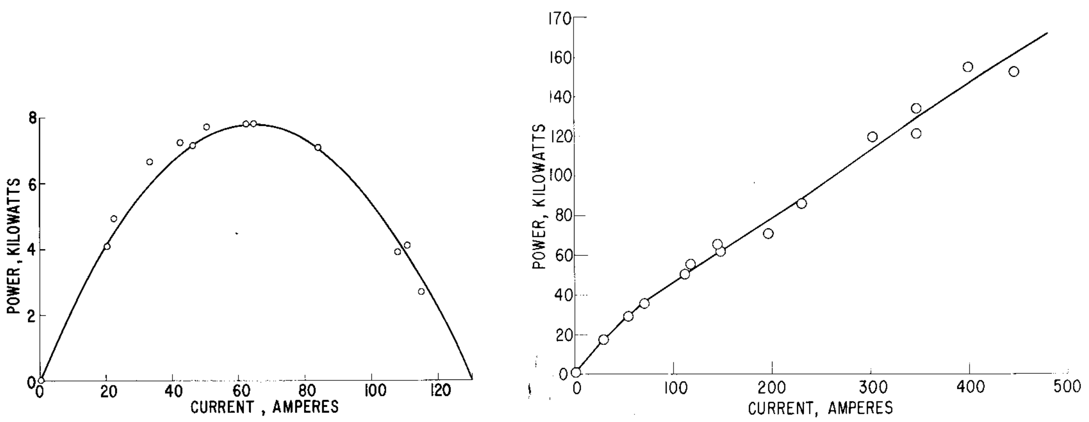


Figure 5-Power output vs. current for plasma produced by a Mach 30 shock wave and magnetic field strengths of 2300 Gauss (left) and 6500 Gauss (right)