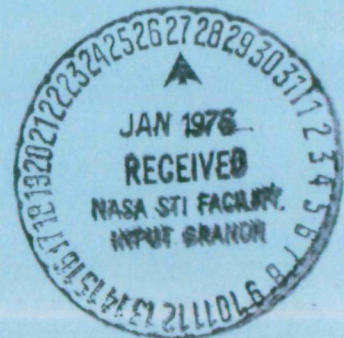


# CLOSED-CYCLE MHD POWER GENERATION

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## CLOSED-CYCLE MHD SPECIALISTS MEETING

NASA-Lewis Research Center  
Cleveland, Ohio  
June 16-17, 1975



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## FOREWORD

The 1975 Closed-Cycle MHD Specialists Meeting was held on June 16th and 17th at the NASA Lewis Research Center in Cleveland, Ohio. It was the sixth in a series of annual meetings organized under the auspices of the Joint European Nuclear Energy Agency/International Atomic Energy Agency International Liaison Group on MHD Electrical Power Generation. The purposes of the meetings are to exchange information on recent closed-cycle MHD research, assess the current status of the research, and suggest the direction of future research.

The meeting was informal in character. The first portion consisted of presentations in which each attendee discussed his closed-cycle MHD research. The second portion was a workshop session devoted to making a realistic assessment of the potential benefits, problem areas, and future applications of closed-cycle MHD systems. The attendees, who represented nine countries and the International Atomic Energy Agency, also toured the MHD facilities at the NASA Lewis Research Center.

Among the experimental results presented at the meeting were the following:

- (1) The achievement of 24-percent enthalpy extraction and a power density of  $140 \text{ MW/m}^3$  in shock tube experiments with a gas stagnation temperature of 3300 K at Eindhoven University
- (2) Measurement of 9-, 16.5-, and 19.3-percent enthalpy extractions at gas stagnation temperatures of 2150, 2600, and 3500 K, respectively, in shock tube experiments at General Electric
- (3) The enhancement of power output in the regime of fully ionized seed with a recovery  $B_{\text{eff}}$  of up to 4 in disk MHD experiments at Tokyo Institute of Technology
- (4) Improved performance (power = 1200 W, power/volume =  $0.33 \text{ MW/m}^3$ ) in the steady-state facility at the NASA Lewis Research Center

Results were also presented that indicate that the closed-cycle MHD community is actively preparing for the next phase of research. Among these presentations were designs for a  $50\text{-MW}_{\text{th}}$  blowdown facility at General Electric and a  $5\text{-MW}_{\text{th}}$  blowdown facility at Eindhoven University. Results were presented for successful initial tests of a refractory regenerative heat exchanger at General Electric. Detailed system studies for fossil-fired closed-cycle MHD systems were presented for the first time at this meeting.

Discussions in the workshop session did treat the advantages, disadvantages, and basic research problems associated with closed-cycle MHD systems, but centered around the need to advance closed-cycle MHD research into the next stage of development. A summary of the workshop session is included at the end of these proceedings.

The 1976 meeting will be held in the U. S. A. , and it will be coordinated with the 15 EAM Symposium. The organizer of the meeting will be either M. I. T. or the Mitre Corporation.

Finally, I would like to thank Joseph J. Etzkin, James A. Burkhart, J. Marlin Smith, and Stephanie Black for their assistance in the details of organization and operation of the meeting.

Ronald J. Sovie  
Editor  
NASA Lewis Research Center  
Cleveland, Ohio

## MHD PROJECT AT OBSERVATORIO NACIONAL DE FÍSICA CÓSMICA DE SAN MIGUEL

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The experimental project that is at present being developed at the Observatorio Nacional de Física Cósmica de San Miguel and Comisión Nacional de Estudios Geo-Heliofísicos involves a disk geometry MHD generator, in which the conductive fluid is obtained by means of a shock tube. The main parts of the experimental equipment are

- (1) Shock tube
- (2) Cesium seed
- (3) MHD generator
- (4) Magnetic field
- (5) Electrical and optical diagnostics

### SHOCK TUBE

The shock tube consists of a stainless steel tube with a diameter of 15 cm and a total length of 11 m, 3 m of which correspond to the high-pressure tube and 8 m to the low-pressure section. As a consequence of the reflected shock wave, the tube provides a plasma with a temperature of 2000 K, a length of 0.80 m, and a duration of 3 to 4 msec. The thermal power obtained is 10 MW. The driver gas employed is essentially  $H_2$  with a percentage of  $N_2$  in order to adapt the shock wave, at a pressure  $P_4 \approx 14$  atm, the tube being uniform (at the diaphragm section). The driven gas is argon seeded with cesium. The pressure is initially  $P_1 = 0.1$  atm and with the reflected wave reaches  $P_5 \approx 10$  atm. The shock wave Mach number is 3. The high- and low-pressure sections are separated by means of a copper diaphragm with a thickness of 0.5 mm. This diaphragm is weakened with two traces at an angle of  $90^\circ$ . The firing is done by means of a mechanical device.

## CESIUM SEED

The cesium seed is made near the diaphragm that separates the high- and low-pressure sections. Before the firing of the diaphragm, in order to obtain an argon plus cesium plasma a "cloud" of cesium particles is formed. With this purpose, an oven containing 1 or 2 grams of cesium at a temperature of  $350^{\circ}\text{C}$  is employed to obtain an area of liquid cesium of  $100\text{ cm}^2$ . Argon cooled with liquid nitrogen at a temperature of about  $-100^{\circ}\text{C}$  is then blown over the free surface of the cesium through a tube 3 mm in diameter. The particles thus formed, together with a larger argon flow, enter a cyclone whose walls are cooled to a temperature of about  $0^{\circ}\text{C}$  so that the heaviest particles can be separated. The gas mixture enters the low-pressure section and is there circulated at the working pressure  $P_1$ . A mechanical vacuum pump with a capacity of 1000 liters/min was employed for this purpose. The presence of this cloud at the tube end is recorded through the absorption of a light beam that runs along the tube diameter and is detected by a phototube. Once the right conditions of pressure and light absorption are obtained, the diaphragm is fired.

## MHD GENERATOR

The main parameters at the generator inlet are

$$T_0 = 2000\text{ K}$$

$$G = 7\text{ kg/sec}$$

$$P_0 = 10\text{ atm}$$

$$M = 2.5$$

$$\text{seed fraction} = 0.1\text{ percent}$$

The generator dimensions are

|                                      |      |
|--------------------------------------|------|
| Radius at inlet, cm . . . . .        | 8    |
| Radius at outlet, cm . . . . .       | 20   |
| Radius at cathode, cm . . . . .      | 25.5 |
| Distance between walls, cm . . . . . | 2.5  |
| Radius of diffuser, m . . . . .      | 1.36 |

The 2-T magnetic field is powered by an 80-kJ condenser bank in an iron electromagnet. The whole generator-diffuser assembly is made of stainless steel, reinforced with iron beams. The first pressure tests showed that the generator-diffuser assembly would not withstand the final pressure after the shock. The assembly was reinforced,

and the final pressure was lowered by eliminating the nozzle at the diaphragm section, which resulted in a shock tube with uniform section. The first stage was devoted to producing the argon plus cesium plasma, and at present we are trying to test the uniformity and fraction of seeding before starting with preionization.

The generator has 10 single and 10 double radial probes, in order to measure the distribution of potential and Hall electric field. It also has 16 pairs of tungsten probes for the preionization of the plasma at the nozzle exit and a few millimeters before the anode in the supersonic region ( $M = 2.5$ ). Some experiments have been performed by applying a voltage of 30 to 40 V between probes, which gives a current of 25 A.

The generator has four observation windows. Two of these windows are usually employed for pressure measurements. The electrical insulation has been provided by covering the metal surface of the generator with a thin layer of epoxy paint (300  $\mu\text{m}$ ).

### MAGNETIC FIELD

The magnetic flux density will be about 22 000 G. It will be produced with an iron electromagnet with a saturated nucleus ( $\approx 18\,000$  G) plus a pulsed coil fed by an electrolytic condenser bank (1.5 faraday; 350 V). The iron nucleus will be fed by a quasi-continuous coil ( $\tau = 60$  sec) which is powered by the main line through rectifiers. The volume of the magnetic field is  $3000\text{ cm}^3$ , and the electromagnet gap is 5 cm.

### OPTICAL AND ELECTRICAL DIAGNOSTICS

The optical method employed for measuring the electronic temperature of the argon plus cesium plasma behind the reflected incident wave is based on the detection of a cesium resonant line ( $\lambda = 4555\text{ \AA}$ ). At the conditions of the observed plasma this line behaves as optically thick. This fact allows the comparison of the cesium emission with the emission of a black body (strip filament lamp) whose emission is calibrated against temperature. The measurements that have been made show good agreement with the temperature obtained on the basis of the Rankine-Hugoniot relations for the incident and reflected wave, with a difference between the methods of about 10 percent.



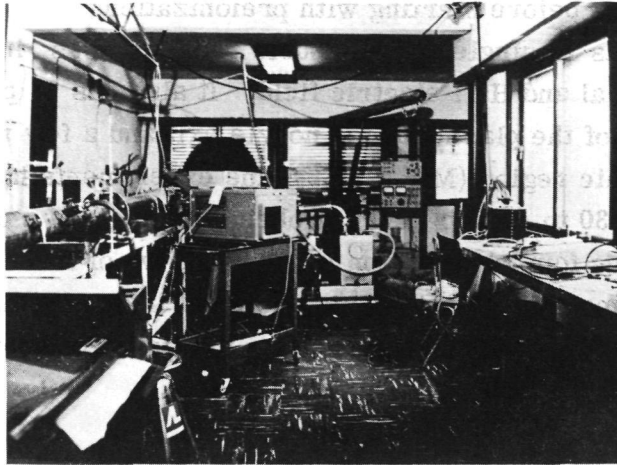


Figure 1.

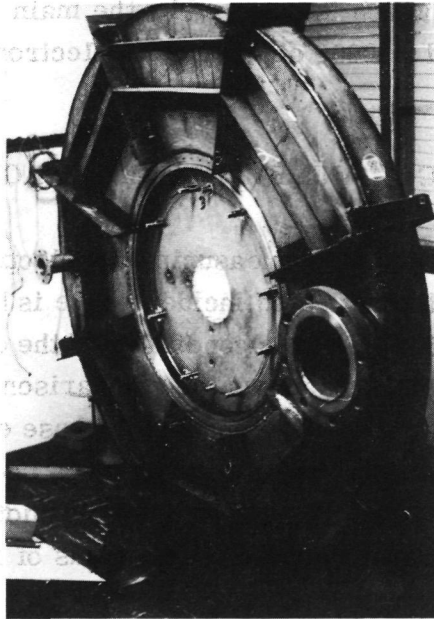


Figure 2.

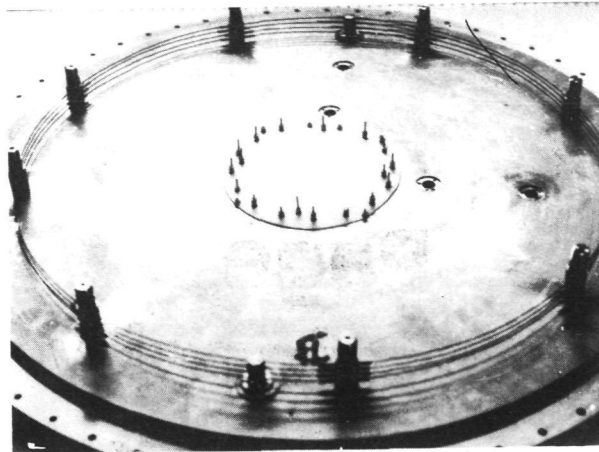


Figure 3.

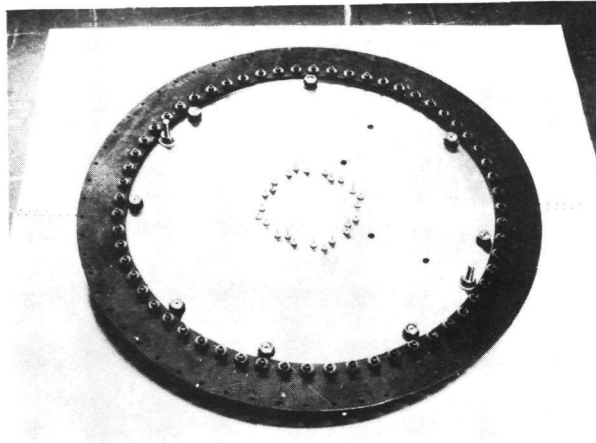


Figure 4.

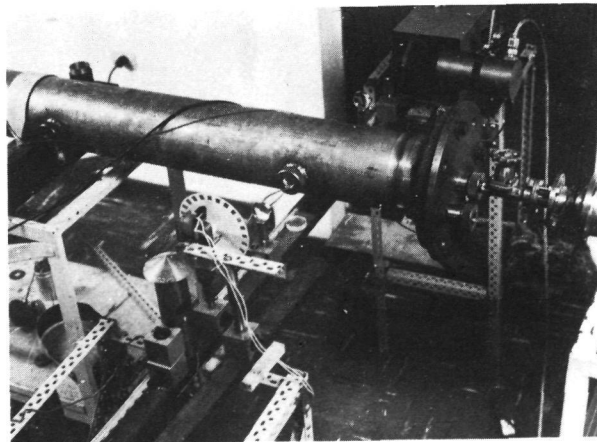


Figure 5.

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## MHD IN AUSTRALIA

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### EXPERIMENT AT UNIVERSITY OF SYDNEY

An experimental facility was set up in Australia in 1962 at the University of Sydney. The facility was supported initially by the Electrical Research Board and the Australian Utilities and later by the Australian Institute of Nuclear Science and Engineering. The installation was primarily oriented toward closed-cycle MHD and is described in reference 1. It originally employed a 40-kW arc torch as the heat source; the system has been run mainly with argon seeded with alkali compounds in powder form and pure alkali vapors. Molecular gases like  $N_2$  have also been studied.

Recently the installation has been extended by coupling the arc torch to a 40- to 100-kW rf induction plasma heater. This rf heater is to be used to preheat and preionize the seed material and to establish controllable initial operating conditions under extended continuous operations. Provision has been made to simulate combustion gases.

The experiments were originally concerned with the study of materials and plasma conductivity, but later work concentrated on boundary layers and their effect on MHD generator performance (ref. 2). For this purpose special generator ducts have been developed where electrode surface temperature can be controlled externally, and seeding systems for powder seed and liquid alkali metals have been set up.

Boundary layers on electrodes and the limitation on surface temperature imposed by long life requirements are very critical factors limiting electric current through a generator. It has been established that currents of practical order of magnitude can be generated only if arc spots form on the electrodes when molecular gases are used as MHD fluids. In noble gases diffuse current emission is possible, but impurity levels are critical (ref. 3).

It has been shown that generator performance, in terms of output power and life of the duct, can be improved considerably if the electrode surfaces are designed properly.

Reference 4 presents the latest results which have been obtained in the experimental facility described in reference 1. This work was concerned with different electrode materials and their effect on current transfer through the duct. With alkali salts as seeding

materials the transfer depends critically on breakdown conditions on the electrode surface, and these are predominantly controlled by impurities.

The general work on MHD is relevant in Australia considering the relative importance of fossil fuels and the possible use of MHD for the conservation of fuels and for the reduction of pollution. The economic situation is discussed in the next section.

MHD as applied to nuclear energy sources is also relevant if we consider the enormous uranium resources in Australia. As large as they are, however, we should still be concerned with their efficient use as well as the considerable thermal heat wastage associated with a nuclear plant.

## POWERPLANT CONCEPTS AND ECONOMICS

### Peaking Plant

The load characteristics in electric utility systems are such that there is a need for a base powerplant providing for continuing demand as well as a plant that provides for varying load, for peak loads, and for emergencies. A plant with a capacity factor below the normal range of 0.5 to 0.8 for the base load, that is, below about 4000 hr/yr of operating time, has to satisfy requirements that differ from those for a base-load plant. A peaking plant should have a low capital cost, and this becomes more and more important as the operating period per year decreases. At the same time fuel costs and plant efficiency would become less important with decreasing capacity factor, and exotic fuels may not be ruled out.

Other desirable features for peaking are fast startup and rapid response to control action in order to cope with sudden changes in load and disturbances. Plants presently used are hydro or gas turbine plants and less efficient, slower, older steam plants.

An MHD peaking plant should be simple, and several proposals have been considered in the literature (see, e.g., ref. 5). We may consider a fossil-fuel-fired MHD generator using liquid oxygen and exhausting directly into a stack. With pure oxygen there is no need for preheating, and NO pollution is no problem. The plant still has to cope with slag and seed removal, but otherwise no bottoming cycle need be involved since efficiency is not critical.

A more novel proposal (ref. 2, pp. III-6 and III-7) involves the use of hydrogen as fuel burnt with oxygen. The exhaust gas, being steam vapor, can be handled readily and must be condensed only. This allows operation down to subatmospheric pressure, and as a consequence we can improve efficiency. Hydrogen fuel is presently considered as one of the possible byproducts in several proposals for use of solar energy; hence, these studies are not unreasonable.

The economics of different MHD peaking plants have been studied by several research groups (ref. 5). Capital costs are favorable, especially when large power ratings and rapid response are required. Gas turbines are close competitors, especially for intermediate capacity factors up to 0.25 (i. e. , 1500 to 2000 hr/yr). For such conditions further studies are needed in order to determine optimum economical conditions for oxygen enrichment, if air is used, together with the optimum degree of preheating and waste heat recovery.

### Base-Load Application

The application of MHD to base-load power generation has been one of the primary goals of all the work that has gone into the development programs. A large number of independent studies have been made of the economics involved, and most of them have considered the binary MHD-steam cycle. As an alternative to the steam cycle some studies have looked at the use of gas turbines in the bottoming cycle.

The fuels considered are coal, oil, charcoal, and gas. Potassium seed is preferred over cesium because of cost. Preheat temperature and magnetic field strength are the important parameters, and with present day technology it can be expected that a station efficiency of 50 percent can be achieved, as shown by many studies (e. g. , ref. 5, p. 330). This implies an air preheat temperature of 1550 K and a magnetic field strength of 5 T on the average; that is, a superconducting magnet would be required. With an advancement in MHD technology, with an increase in air preheating to 2000 K and magnetic fields to 7 T, it should be possible to reach 60-percent efficiency.

MHD plants can compete economically with existing plants under given conditions and specifically with steam stations, since it is expected that the capital cost per kW of an MHD plant should be roughly the same as that of a steam plant of early design. In more detail we may consider the economics of different competing plants in a situation as it would apply in the state of New South Wales in Australia. For this comparative study a powerplant is chosen with a binary cycle (i. e. , MHD topping and steam bottoming). It is also assumed that 50 percent of the total power output is generated by the MHD cycle.

In figure 1 the annual costs of this MHD-steam base-load station are compared with costs for a conventional coal-fired steam plant and a nuclear plant. The lowest curve applies for the coal-fired steam plant at a fuel cost of 0.2¢/3kWh, an overall capital cost of \$160/kW installed, and a maintenance cost of roughly \$2.5/kW. These conditions are close to the optimum costs achieved in 1974 and apply approximately for capacity factors ranging from 0.5 to 0.8. General conditions for the other curves in figure 1 are indicated in table I.

It should be noted that nuclear power is uneconomical at this stage in New South Wales and the cost of coal has to rise by a factor of 2.5 before the nuclear plant becomes

fully competitive. The position of MHD is also indicated in terms of worst permissible conditions. The high efficiency of MHD-steam stations means that the cost curves are flatter. For competitive costs over the capacity factor range 0.5 to 0.8 the MHD-steam curves cut the zero line above the curves for the steam plant. This means that for the MHD plant the capital costs can be very much higher than for the steam plant under the conditions stated when about 50 percent of the station output is generated by MHD. Actual costs per kW are deduced from figure 1, as shown in table II, which indicates possible costs of \$240/kW to \$300/kW for the MHD plant. This cost can rise even higher with increasing costs of coal. However, then the position of nuclear power becomes critical, for the 0.5¢/kWh conventional steam plant loses its competitiveness with the nuclear plant even at a low capacity factor of 0.5. However, the MHD plant can still be competitive with the nuclear plant if its capital cost can be reduced to a value below that for the steam plant. Detailed analyses in the U. S. A. and the U. S. S. R. indicate that the capital cost of the MHD plant should in fact be lower, because of the structural simplicity of the MHD plant and despite the need for inverters.

Despite enormous reserves of uranium in Australia, we find coal to be also relatively abundant, and nuclear power is not expected to become economically competitive until the mid-1990's in most parts of Australia. Consequently, the cost aspect is not so important as factors like efficiency and pollution. Of particular interest would be the peaking plant; however, this would have to compete with modern gas turbines, which can also be used for intermediate loads.

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TABLE I. - ASSUMPTIONS FOR FIGURE 1<sup>a</sup>

| Powerplant         | Capital cost, \$/kW | Depreciation life, yr | Total operating cost, ¢/kWh | Maintenance cost, \$/kW |
|--------------------|---------------------|-----------------------|-----------------------------|-------------------------|
| Nuclear            | 300                 | 25                    | 0.15                        | 3.0                     |
| Conventional steam | 160                 | 30                    | <sup>b</sup> 0.2            | 2.5                     |
|                    |                     |                       | <sup>c</sup> .3             | 2.5                     |
|                    |                     |                       | <sup>d</sup> .5             | 2.5                     |
| MHD-steam          | See table II        | 25                    | 2/3 of coal                 | 3.0                     |

<sup>a</sup>Capital and other costs are referred to present day dollars. Maintenance costs, flat rate, valid for capacity factors from 0.50 to 0.80. Interest rate, 8 percent. MHD used as topping cycle with conventional steam; power division, 1:1.  
<sup>b</sup>Current average cost in New South Wales, Australia.  
<sup>c</sup>Increased cost assumed caused by progressive scarcity, 1985.  
<sup>d</sup>Long term increase.

TABLE II. - MAXIMUM PERMISSIBLE CAPITAL COST FOR MHD AS TOPPING PROCESS FOR CONDITIONS SPECIFIED IN TABLE I AND FIGURE 1 AND 60- PERCENT MHD-STEAM STATION EFFICIENCY

| Capacity factor | Capital cost, \$/kW   |                       |
|-----------------|-----------------------|-----------------------|
|                 | With coal at 0.3¢/kWh | With coal at 0.5¢/kWh |
| 0.5             | 240                   | 256                   |
| .6              | 260                   | 278                   |
| .7              | 278                   | 300                   |
| .8              | 296                   | 322                   |

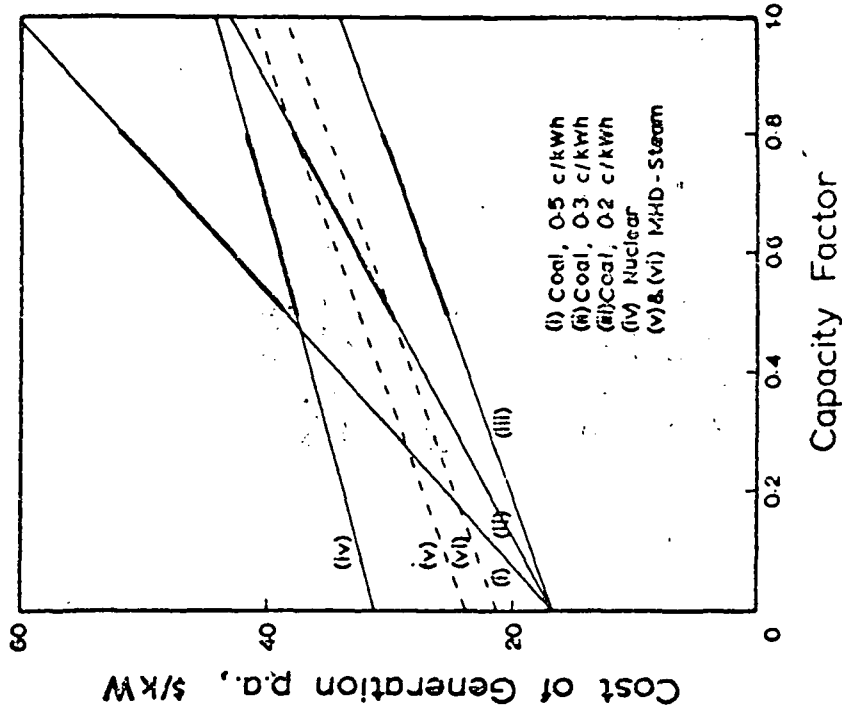


Figure 1. - Cost of generation as function of capacity factor for base load plant.



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SHOCK TUBE EXPERIMENTS WITH PURE ARGON AT INSTITUT DE MECANIQUE  
DES FLUIDES DE MARSEILLE

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The goal of the program at the Institut de Mecanique des Fluides de Marseille has been to study the performance of a nonequilibrium Faraday MHD generator using shock-heated argon as the working fluid in order to simulate the nonequilibrium ionization occurring at the entrance of closed-cycle MHD generators.

In the experiments the aerodynamic and electric parameters of the gas at the generator entrance and the electric configuration of the generator are optimized so as to allow observation of the aspects of pure magnetically induced ionization in the flowing gas. Most of the phenomena which can prevent the magnetically induced ionization in small scale experiments have no important effect under the conditions of our experiments. In particular,

(1) The total voltage drop at the electrodes is small compared with the generator emf. The 17 pairs of electrodes are cold and flush-mounted. (The segmentation ratio is 1/8.)

(2) Since the nonequilibrium relaxation time is small compared with the transit time of the gas throughout the generator, a stationary state tends to be reached toward the last pairs of electrodes.

(3) During the ionization process (across the first pairs of electrodes) the electromagnetic interaction parameter is small. The thermal power of the flow is 10.6 MW.

Current density profiles along the duct and image converter photographs of the induced discharge are obtained for different values of the applied magnetic field.

The main results that have been obtained from this study are the following:

(1) Pure magnetically induced ionization is obtained in a linear Faraday segmented generator using a high-pressure supersonic argon flow.

(2) The nonequilibrium steady state which is obtained in the flowing gas is stable. It is in good agreement with the laminar two temperature model (as in the case of a pure discharge without a magnetic field for identical gas conditions).

(3) As shown in figure 1, the induced discharge has a filamentary structure in the first part of the generator (unsteady regime), but in the second part of the generator (steady regime), the plasma seems to be homogeneous.

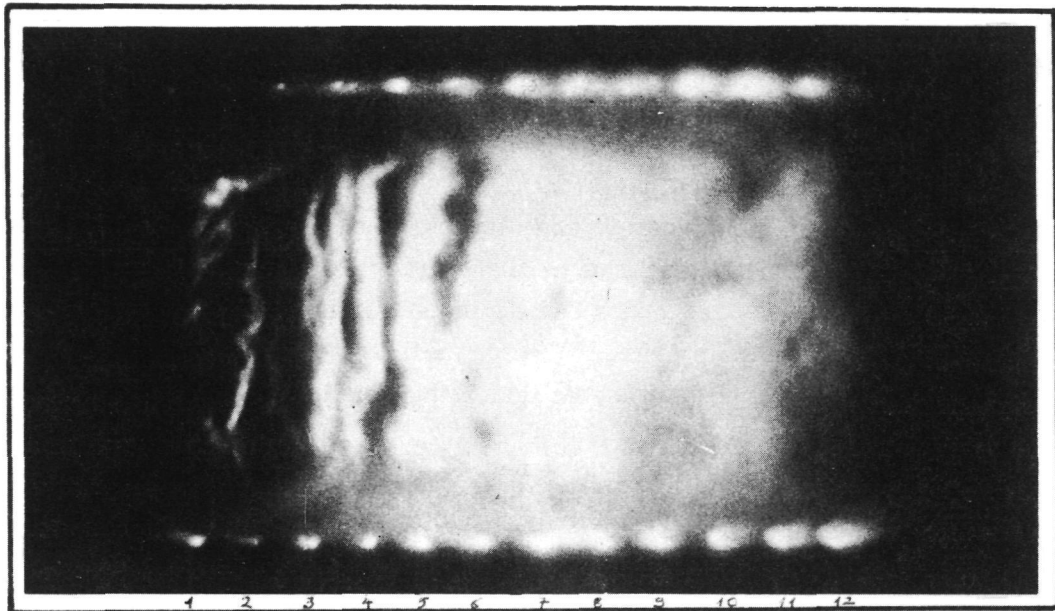


Figure 1. - Induced discharge in argon.  $T_e$ , 6100 K;  $p$ ,  $1.6 \times 10^5$  N/m<sup>2</sup>;  $u$ , 1920 m/sec;  $B$ , 2T; 12 electrode pairs<sup>g</sup>(short circuit).

## CLOSED-CYCLE MHD RESEARCH AT TOKYO INSTITUTE OF TECHNOLOGY

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At present the main subjects of our closed-cycle MHD research are the physical problems connected with the seeded plasma and its flow in the magnetic field. Current and planned closed cycle MHD programs at Tokyo Institute of Technology consist of the following items:

- (1) Suppression of ionization instability
- (2) Investigation of effects of Lorentz force on the boundary layer and the flow field
- (3) Investigation of discharges in the flow field, current conduction phenomena at electrodes, and heat transfer in the magnetic field
- (4) Methods of combining closed-cycle MHD with nuclear energy, including fusion energy

In regard to the first item, after we observed the recovery of  $\beta_{\text{eff}}$  at open circuit in the disk generator in March 1974, we conducted generation experiments and observed the enhancement of power output in the regime of fully ionized seed with recoveries of  $\beta_{\text{eff}}$  up to 4. In our next programs we will (a) measure  $\beta_{\text{eff}}$  with potassium seeded helium, (b) conduct generation experiments with higher pressures and higher magnetic fields, and (c) compare the disk generator with the linear generator.

In regard to the second item, we have conducted generation experiments with a supersonic helium-potassium linear generator. We have observed  $\sigma_{\text{eff}}$  and  $\beta_{\text{eff}}$  under the effect of ionization instability and found that  $\sigma_{\text{eff}}$  obeys the semiempirical formula observed in the simulated MHD channel. Furthermore, we have observed the effects of Lorentz force on the boundary layer and the flow field. We want to know more precisely how the boundary layer development is connected with flow separation and finally with shock formation. Other losses in the linear MHD channel, such as the nonuniform current conduction, the voltage drop near electrodes, the current inclination, and the finite segmentation effect, are also being investigated.

In order to investigate the third item, we have completed an arc heated wind tunnel (thermal input, 200 kW) which can give both subsonic and supersonic flows. The preliminary experiments on the effect of the gas flow on the discharge are now in progress.

Finally, in regard to the fourth item, heat sources for closed-cycle MHD, we are convinced that it is most important, particularly in our country, to combine the closed-cycle MHD with nuclear energy. For this reason, we are investigating this possibility with special interest.

# RESEARCH ON MHD POWER GENERATION AT HOKKAIDO UNIVERSITY

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## EXPERIMENTAL FACILITY

The main characteristics of the arc-heated inert-gas MHD experimental facility are as follows:

### Plasma source, continuous operation

|   |                    |
|---|--------------------|
| Plasma jet electric power input, kW . . . . . | 0-200              |
| Thermal power input (MHD), kw . . . . .       | 0-150              |
| Potassium seed fraction by weight . . . . .   | 0-10 <sup>-3</sup> |

### Magnetic system, continuous operation

|                                    |            |
|------------------------------------|------------|
| Magnetic flux density, T . . . . . | 0-2.5      |
| Pole surface area, mm . . . . .    | 200 by 800 |
| Pole gap distance, mm . . . . .    | 100 by 70  |

### MHD channel

|                                    |                             |
|------------------------------------|-----------------------------|
| Inlet cross section, mm . . . . .  | 15 by 50                    |
| Outlet cross section, mm . . . . . | 15 by 80                    |
| Length (usual), mm . . . . .       | 600                         |
| Electrode . . . . .                | segmented Faraday electrode |

Small fractions of some kinds of molecular gasses such as CO<sub>2</sub> and N<sub>2</sub> can also be added to the plasma in order to realize the equilibrium plasma properties.

## EXPERIMENTAL WORK

Experimental research is now under way to investigate the nonequilibrium MHD channel characteristics under hot electrode conditions. Thin tungsten and tantalum

\*The staff working on the MHD project at the Laboratory for Energy Conversion Processes, Department of Nuclear Engineering and Science, includes Y. Ozawa, Y. Aoki, T. Enoto, H. Kitagawa, and five graduate students.

electrodes immersed in the wall free plasma stream are used in order to investigate the nonequilibrium plasma characteristics. The effects of gasdynamic boundary layer could be eliminated by this method, and various data are being collected.

## THEORETICAL WORK

As reported at the 6th MHD Conference in Washington, D. C. , the main subject of our theoretical work is the dependence of the power output performance on the configuration of the magnetic flux density (refs. 1 and 2). Based on plane wave theory for non-uniform MHD electrical conduction processes (ref. 3), it has been verified that there does exist an optimal field strength for each section of the channel and also that the current concentration at the edges of the electrodes can be defused completely if the magnetic field distribution in the transverse direction is properly arranged.

The optimal field strength ranges from 5 to 12 T for the expected commercial size open-cycle MHD generator, depending on electron mobility, electrode surface temperature, boundary layer thickness, and segmentation pitch.

The optimal field configuration, under which the local Hall current could completely vanish, should satisfy the following condition:

$$\frac{\partial}{\partial y} \left[ \frac{B(y)}{N_e(y)} \right] = 0$$

where  $y$  is the transverse coordinate and  $N_e$  the local electron number density. Under these magnetic fields the power output could be improved by a factor of 3 and become comparable with the power output under the uniform magnetic field distribution.

## FUTURE PLANS

Further efforts will be made to investigate theoretically the optimal configurations of the magnetic field for nonequilibrium MHD power generation.

The previously mentioned results and of our theoretical work will be tested experimentally in the very near future. For this purpose, an equilibrium plasma with relatively large electron mobility should be produced by adding a small amount of  $\text{CO}_2$  to the argon arc-jet plasma. The experiments will be carried out with a strongly cooled electrode in order to obtain the optimal field strength in the range 1.0 to 2.5 T.

In parallel with these plans MHD experiments with a fully ionized pulsed plasma will also be made by using our small size Theta-Pinch plasma facility, which has an 18.0-kJ energy storage capacitor bank.

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## NONEQUILIBRIUM MHD POWER GENERATION STUDIES AT KEIO UNIVERSITY

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Yokohama, Japan

In the laboratory at Keio University experimental work has been done on nonequilibrium MHD power generation by using a shock tunnel generator. This shock tunnel was explained in the paper presented at the 13th Symposium on Engineering Aspects of MHD (ref. 1).

### NONEQUILIBRIUM MHD POWER GENERATION EXPERIMENTS WITH STRONG INTERACTIONS

We used argon gas without seed as a working fluid to study the performance of the nonequilibrium MHD generator with strong interactions. The stagnation temperature was 5600 to 12 000 K, and the stagnation electron density was  $3 \times 10^{15}/\text{cm}^3$ . The behavior of plasma in the generator agreed with the two temperature theory, with Coulomb collisions, electrode voltage drops, and  $J \times B$  force effects being considered.

In our experiments, the interaction parameter  $S = J \times BL / \rho u^2$ , where  $J$  is current density,  $B$  is magnetic field,  $\rho$  is density of the gas,  $u$  is flow velocity, and  $L$  is the duct length, reached values up to 5 in the generator. We observed a reflected shock wave in the interaction region. The structure exerted a strong effect on the current density distribution in the generator. The value of Hall parameter  $\beta$  also was influenced by the  $J \times B$  force, as already shown by Zauderer (ref. 2). The electrothermal instability was not observed because of Coulomb collision effects; theoretically,  $\beta_{cr} = 10$ . We obtained  $\beta_{eff} = 8$ . The output power density reached  $3 \text{ MW/m}^3$ , and enthalpy extraction efficiency, values up to 4 percent. We showed that  $J \times B$  force effects become predominant when the enthalpy extraction efficiency exceeds 1 percent.

In the future experiments we will diagnose the detailed structure of the interaction processes.

## NONEQUILIBRIUM MHD POWER GENERATION USING DISSOCIATED HYDROGEN

We think that hydrogen must be utilized as the working gas in the nonequilibrium MHD power generator if it is to use energy from a fusion reactor. We used dissociated hydrogen as a working gas in our shock tunnel generator. Because it was difficult to compress and heat hydrogen to full dissociation in our shock tube, we used a mixture of hydrogen and argon. The mole fraction of hydrogen was 0.1 or 0.3 in the mixture. Hydrogen was fully dissociated at the entrance of the generator and expanded in the generator channel. The stagnation temperature was 5000 K, and the static temperature was 3700 K when the mole ratio was 0.1.

The performance of the generator was calculated and compared with that in the experiments. The Hall parameter nearly equaled the calculated value, but the conductivity was considerably smaller than the calculated value. Evidence of electrothermal instability was observed in the data.

The research is still in the early stages and it is difficult to show firm conclusions, but this work would offer a new method of using hydrogen in energy conversion.

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## MHD RESEARCH AT KYOTO UNIVERSITY

K. Yoshikawa

Corpuscular Engineering Laboratory  
Institute of Atomic Energy  
Kyoto University  
Kyoto, Japan

In the Corpuscular Engineering Laboratory at Kyoto University investigations have been conducted on the following three subjects:

(1) Plasma diagnostics

(a) Electron temperature measurement by the line-reversal technique. The influence of temperature distribution and measuring configuration on line-reversal temperature was studied for a potassium seeded argon gas plasma at atmospheric pressure. The experimental results showed that the line-reversal temperature obtained is a strong function of the optical thickness and that the temperature is higher when the optical thickness is smaller, which agreed fairly well with the theoretical results.

(b) Spectroscopic measurement of the seed fraction. For the wavelength with a very small optical thickness, the light intensity is proportional to the optical thickness, and since in the MHD plasma collision broadening is predominant, the light intensity is proportional also to the seed fraction. According to the experimental results at the wavelength  $\lambda = 7630 \text{ \AA}$ , the relation between light intensity and seed fraction is sufficiently linear to provide a very simple method of determining seed fractions if only one seed fraction could be accurately calibrated.

(2) Relaxation of the current concentration on the electrode edge by a resistive electrode

(a) Resistive segmented electrode with a lead wire at the extreme edge of the electrode. If a lead wire is connected at the extreme edge of the resistive electrode opposite the edge where the current usually concentrates, the generated electric field whose direction is opposite to that of the Hall field can offset the effects of the Hall field in the vicinity of the electrode surface; consequently, the current concentration as well as the high Hall field at the border of the electrode and insulator can be greatly reduced. The two-dimensional numerical analyses showed that the increase of the internal resistance due to resistive electrodes is not so large for larger Hall parameters. The fraction of the power dissipated in the resistive electrodes cannot exceed 20 percent of the total

power dissipated in the load, plasma, and resistive electrodes for  $\beta = 5$  and a load factor of 0.75. Other additional favorable effects may be expected, such as heating of the cold gases in the boundary layer by the power dissipated within the resistive electrodes, reduction of the electrode voltage drop in the boundary layer, and reduction of the heat flux toward the outer casing.

(b) Electrode coated with resistive materials. The electrode coated with resistive materials also has the effect of smoothing current concentrations. The optimized shape of the resistive electrode was studied by solving the two Laplacian problem of two dimensions in order to obtain the minimum power loss in the resistive electrodes. Experimental investigations are now being conducted with  $ZrO_2$  and  $LaCrO_3$ .

(3) Performance of a nonequilibrium MHD generator including ionization instabilities

(a) Numerical calculations using the effective electrical conductivity relation  $\sigma_{\text{eff}}/\sigma = \beta_{\text{cr}}/\beta$  gave the result that the power density for a seed fraction of  $10^{-3}$  where the plasma is supposed to be subject to the ionization instability is higher than that for a seed fraction of  $10^{-5}$  where the seed atoms are perfectly ionized.

(b) With increasing pressure, the influence of the ionization instability decreases because of the more frequent collisions, that is, the stronger relaxation effects of the energy; this effect will be very favorable for practical nonequilibrium MHD power generation.

(c) With respect to the influence of the impurity, the effective collision loss parameter  $\delta_{\text{eff}} (\propto \sum \delta_j \nu_j / m_j)$  should be less than 10 in order to obtain a power density of  $50 \text{ MW/m}^3$  under the conditions  $Ar + 10^{-3} \text{ K}$ ,  $T_g = 1500 \text{ K}$ ,  $P_0 = 10 \text{ atm}$ ,  $B = 5 \text{ T}$ , and  $u = 1000 \text{ m/sec}$ .

SUMMARY OF CLOSED-CYCLE MHD RESEARCH AT  
EINDHOVEN UNIVERSITY OF TECHNOLOGY

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Eindhoven, The Netherlands

Recent results of our work on MHD were reported during the sixth MHD symposium in Washington in two papers:

- (1) A paper on our shock tunnel facility with, as a major result, a 24-percent enthalpy extraction and a  $140\text{-MW/m}^3$  electric power density at a stagnation temperature of 3200 K
- (2) A paper giving detailed calculations that we performed in collaboration with the National Aerospace Laboratory in Amsterdam on boundary layers along the insulators of an MHD channel

Our future shock tunnel work will include, first, enthalpy extraction experiments with a channel designed for a stagnation temperature of 2000 K with the shock tunnel in a tailored interface condition at that temperature. The shock tunnel program will include enthalpy extraction experiments with an argon plasma seeded with cesium and additives of impurities such as N, CO, and CO<sub>2</sub>.

Second, boundary layer calculations will be performed at the electrode walls, and boundary layer experiments will be performed in the shock tunnel generator. Dr. Merck gives further details on the program in the next paper.

Third, part of the program at Eindhoven University is directed to plasma turbulence: ionization and magnetoacoustic instabilities are studied. Two kinds of experimental apparatus are available for this work: the plasma oven and the shock tunnel. No clear results are available yet. However, both experiments are in progress, and results can be expected before the end of this year.

A new 5-MW<sub>th</sub> blowdown mixed cycle facility has been proposed. Our results in the shock tunnel interested the Dutch industry de Verenigde Machinefabrieken N. V. at Amsterdam, and a contract between VMF and Eindhoven University is in effect. As part of this contract our group is designing the 5-MW<sub>th</sub> blowdown facility. VMF is working on a feasibility study of a 25-MW power generator. The total costs of the blowdown facility will be about \$4.5 million. This amount includes housing, salaries, and overhead during a period of 5 years. The university is able to contribute 30 percent to this amount. We

have not yet applied to the government for the additional money. However, one of the committees in our country that advises the government on energy research has already given a positive advisement. Decisions on this project are expected to be made at the end of this year.

THE UNIVERSITY OF TEXAS AT AUSTIN

DEPARTMENT OF CHEMISTRY

1970

Department of Chemistry

Austin, Texas

Dear Sirs: I am pleased to hear that you are interested in the work of the Department of Chemistry at the University of Texas at Austin.

The Department of Chemistry at the University of Texas at Austin is a large and active department with a strong emphasis on research in the areas of physical, organic, and inorganic chemistry. We have a number of excellent faculty members and a well-equipped laboratory.

Our research interests include the study of the properties of matter, the synthesis of new compounds, and the development of new materials. We are particularly interested in the study of the structure and properties of molecules and the reaction rates of chemical reactions.

We have a number of excellent graduate students and postdoctoral fellows who are working on a variety of projects. We are particularly interested in the study of the properties of matter and the synthesis of new compounds.

If you are interested in the work of the Department of Chemistry at the University of Texas at Austin, please contact me at the address given below. I would be pleased to discuss the work of the Department and the opportunities available to you.

Very truly yours,  
Dr. M. J. Cantow, Jr.  
Department of Chemistry  
The University of Texas at Austin  
Austin, Texas 78712

I am sure that you will find the work of the Department of Chemistry at the University of Texas at Austin to be of great interest and value. I would be pleased to discuss the work of the Department and the opportunities available to you.

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Department of Chemistry  
The University of Texas at Austin  
Austin, Texas 78712

## MHD BOUNDARY LAYER STUDIES AT EINDHOVEN UNIVERSITY OF TECHNOLOGY

W. Merck

Eindhoven University of Technology

Eindhoven, The Netherlands

The study of boundary layer development in MHD generators is performed within our group at Eindhoven University of Technology along two lines:

(1) Solution of the full set of turbulent gasdynamic and electronic equations. This work is performed in cooperation with the National Aerospace Laboratory, and a part of it was presented at the 6th International Conference on MHD Electric Power Generation (ref. 1). In that paper the solution was presented for the turbulent insulator wall boundary layer and related to former experiments of one of the authors. At the time that paper was prepared the full solution of the electronic equations was not yet available and it was replaced by an overall calculation of Brederlow (ref. 2). In our work special attention is given to the exact solution of  $dp/dx$  and to the wall conditions on the velocity component  $v$  perpendicular to the wall, where singularity problems arise.

(2) Calculation of boundary layer separation phenomena, using Patankar's calculation method. This work is performed within our group mainly by Dr. C. Pian, on a Visiting Scientist Fellowship to Eindhoven University of Technology (ref. 3). It is a more general approach to obtain insight into the physical quantities that are of importance to the phenomenon of boundary layer separation. Figures 1 to 4 give the influence of magnetic induction  $B$ , ohmic heating  $\sigma_{eff}$ , wall temperature  $T_w$ , and wall heat flux  $q_w$  on the friction coefficient  $C_f$  along the electrode wall for the laminar boundary layer. The sharp dips in  $C_f$  occur at the downstream edges of the electrodes, where high current concentrations exist. The choice of very high mean current densities leads to the somewhat exaggerated pictures but does not violate the physical meaning. Calculations of the turbulent boundary layer in the shock tube MHD-generator for the case of 1.4-MW enthalpy extraction will be performed soon. These calculations will be followed by a series of hot-wire anemometer experiments to measure the eventual separation of the boundary layer.

In the near future the calculation methods mentioned under item (1) will be extended by the two-dimensional current potential distribution calculations, which are already available. Both systems of equations will be coupled and solved iteratively.



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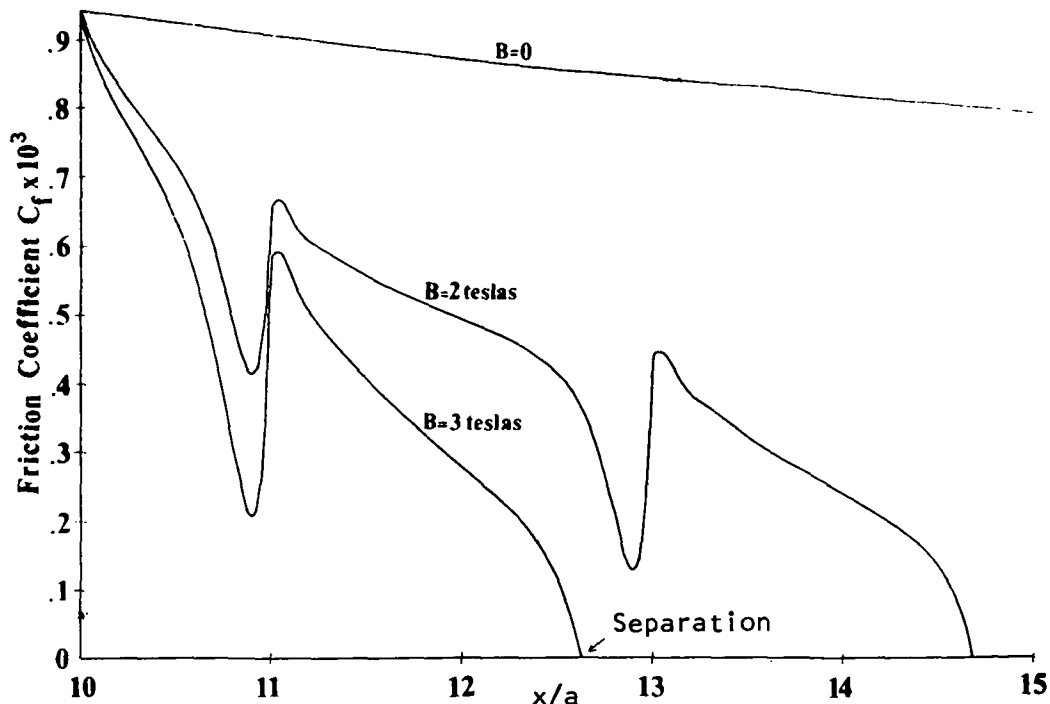


Figure 1. - Variation in friction coefficients and separation points as function of  $B$  for constant area.  $u_{\infty i}$ , 1000 m/sec;  $T_{\infty i}$ , 2000 K;  $M_{\infty i}$ , 1.31;  $P_{\infty i}$ ,  $1.5 \times 10^5$  N/m<sup>2</sup>;  $J_{y \infty}$ , 12.6 A/cm<sup>2</sup>;  $\sigma_{eff}$ , 60 mho/m.

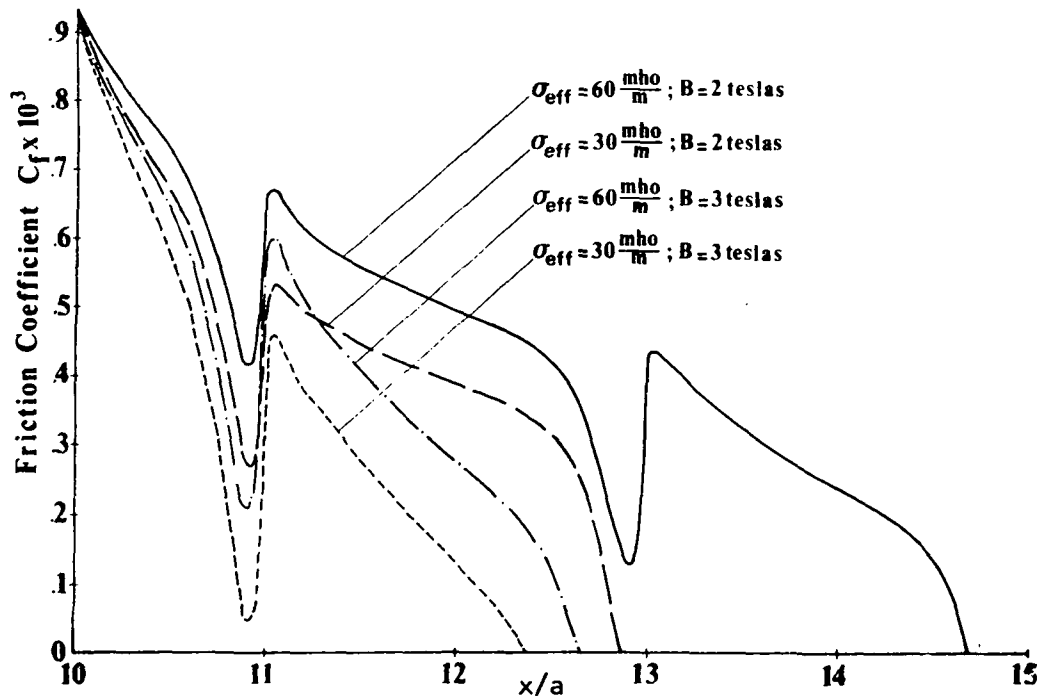


Figure 2. - Variation in friction coefficients and separation points for different values of  $\sigma_{eff}$ .  $J_{y \infty}$ , 12.6 A/cm<sup>2</sup>; inlet conditions as in figure 1.

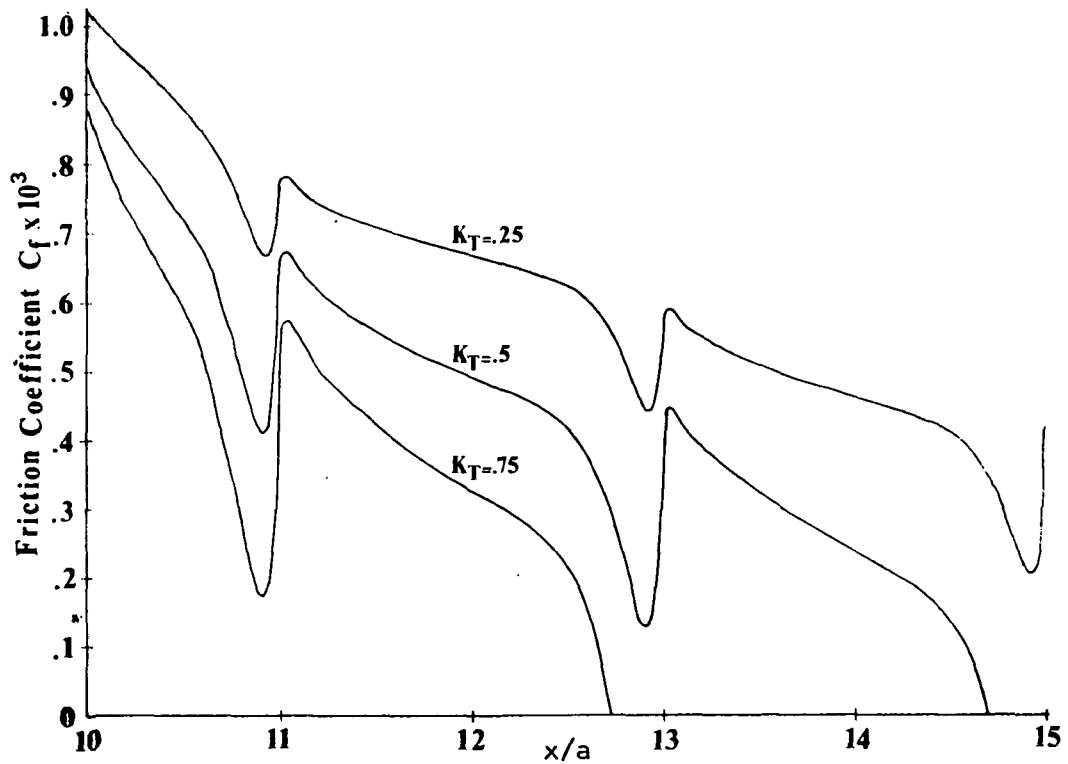


Figure 3. - Effects of wall temperature upon friction coefficient and separation points.  $J_{y_{\infty}}, 12.6 \text{ A/cm}^2$ ;  $B, 2T$ ;  $\sigma_{\text{eff}}, 60 \text{ mho/m}$ ; initial conditions as in figure 1;  $K_T, T_{\text{wall}}/T_{\infty i}$ .

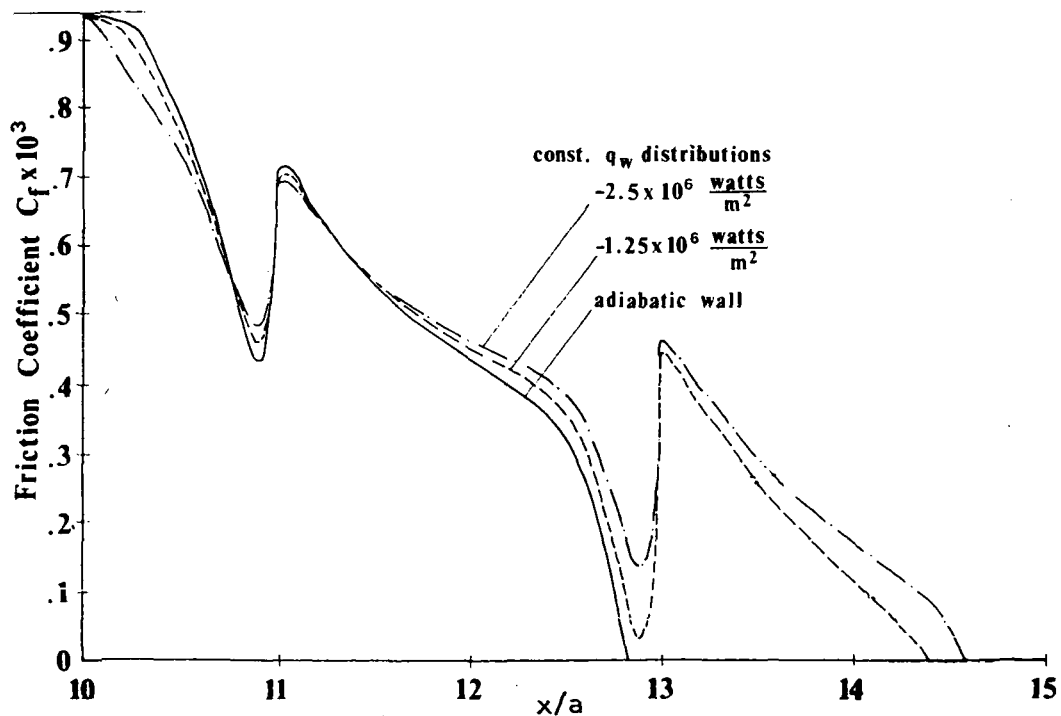


Figure 4. - Variation in friction coefficients and separation points for different values of heat flux  $q_w$ .  $J_{y_{\infty}}, 12.6 \text{ A/cm}^2$ .

## 1975 STATUS OF SWEDISH MHD PROGRAM

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For many years Swedish MHD activities have been focused on the investigation of *afterglow MHD generators*, since it was originally thought that the plasma could be pre-ionized by nuclear reactions. This concept was abandoned because of technical problems connected with the integration of the MHD generator into the reactor. Instead, electrical ionization of a noble gas plasma, especially He and He-Xe, at the generator entrance was considered an alternative preionization method. Experimental studies were made of the lifetime of the preionized plasma and the power to be invested in a diffusive discharge maintained with resistive ceramic electrodes. It was shown that a He-Xe plasma at supersonic velocities would live long enough to allow for appreciable power production in the first part of the MHD channel, and in the second part this plasma at lower pressure would be sufficiently ionized by nonequilibrium ionization to make a closed-cycle MHD generator without metallic seed feasible even at moderate inlet temperatures (1800 K). Because of lack of adequate gas-cooled reactors, this closed-cycle program was reduced during 1973 in favor of two programs dealing with the study of open-cycle peaking power systems.

The first program was an economical evaluation of natural-gas-fired MHD generators eventually combined with an air turbine for topping power. This work was performed in cooperation with KFA-Jülich (FRG). The main conclusion drawn from that study was that combined MHD-generator - air-turbine systems offer only marginal economic advantages for the Swedish power system, and therefore their usefulness is limited to special applications (emergencies).

The second program was devoted to investigation of a plant combining an MHD generator with a coal gasifier of the suspension type for intermediate load. Preliminary studies of such a process using pure oxygen as the oxidizer exhibited interesting economic aspects for operation times between 1000 and 2000 hr/yr.

However, as a consequence of the energy crisis all Swedish R&D activities were subjected to an extensive stocktaking which resulted in a new R&D policy and assigned new priorities to the several fields within energy research. Because of these priorities all Swedish MHD activities will be stopped in July 1975. The reason is a completely new orientation of the Swedish energy policy:

- (1) Expected responsible planned energy consumption growth rate, 2 percent
- (2) Additional base load supplied by additional nuclear reactors
- (3) Peaking power increasingly supplied by hydroelectric powerplants presently used for base load
- (4) No remarkable extension of fossil powerplants (neither for base load nor for peaking power)

The Swedish closed-cycle research could perhaps have had a chance to survive according to the new energy policy if high-temperature gas-cooled reactors had been expected to be available within the period covered by the energy forecast. As the situation is now, Sweden will be out of the MHD business from now on if no way can be found to reenter through a viable liquid metal MHD concept applicable to nuclear reactors.

HELIUM TESTS WITH RADIOFREQUENCY PREIONIZATION IN  
UNIVERSITY OF MARYLAND CLOSED-LOOP MHD FACILITY

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University of Maryland  
College Park, Maryland

During the 1974 MHD Closed-Cycle Specialists Meeting a brief report highlighting the main features and status of the University of Maryland closed-loop MHD facility was presented. It was also mentioned that the design features of that facility were checked during 10 long duration hot noble gas test runs totaling 634 hr and ranging in continuous time for each run from 36 to 133 hr. These runs were conducted mostly at temperatures around 1100 K (1500<sup>o</sup> F) but with the temperature of the metal tubes of the main heat exchanger remaining continuously at 1370 K (~2000<sup>o</sup> F) for nearly 60 hr during one test run. These hot test runs demonstrated that, with the exception of the compressor system, the facility (a) was to a high degree leaktight, (b) could withstand thermal cycling without developing leaks, (c) could be operated at a high level of noble gas purity, and (d) achieved heat transfer temperature differences in the heat exchangers as low as 120 K and in the coolers as low as 35 K.

Numerous troubles were encountered with two reasonably priced rotary compressor systems of standard industrial design which were tried with the facility. These troubles forced us to defer injecting cesium seed into the University of Maryland loop until a compressor system of the more reliable diaphragm type could be acquired.

However, the facility was operated for many relatively short duration runs of 2 to 8 hr to conduct preionization and discharge tests with unseeded noble gases moving at high velocity. This paper briefly reports on these tests.

During most of these runs the noble gases were slightly preionized by establishing a 10-megacycle electrodeless radiofrequency discharge in the high velocity noble gases within a short preionization region located upstream of the electrode section of the test duct. This rf discharge was repeatedly realized in pure helium and in helium plus 0.2 argon at Mach numbers in the range 0.3 to 0.5 and at temperatures in the range 500 to 550 K by using test sections which were made of quartz glass and fitted with tungsten or molybdenum electrodes. The 500 to 550 K temperature was dictated by the temperature limit on the uncooled viton O-ring seals in the fittings joining the quartz glass test duct

to the rest of the loop. With rf preionization maintained upstream of the electrode region, two types of dc measurements were made.

In one type of measurement the current through the magnet coil was varied, and the magnetically induced open-circuit voltages between opposite electrode pairs, downstream of the preionization region, were observed by using vacuum tube voltmeters having very high internal impedances. Figure 1 gives a typical plot of the open-circuit voltage as a function of applied magnetic flux density obtained with pure helium gas. Good agreement is shown between the measured open-circuit voltages and the calculated values.

In the second type of measurement an external dc voltage was applied between opposite electrodes located downstream of the radiofrequency preionization region in a direction aiding the magnetically induced voltage, and the resulting current was measured. These tests were conducted with and without an applied magnetic field. The applied magnetic field was oriented so as to have a component along the direction of the electric field between opposite electrode pairs. Figure 2 shows plots of the typical experimental voltage-current-characteristic curves obtained with an applied magnetic field of about 1.9 T. The upper curve was obtained as the applied voltage was increased from zero, and the lower curve was obtained as the applied voltage was reduced back to zero. Similar voltage-current-characteristic curves were obtained when the applied magnetic field was zero.

Two interesting observations were also made during these current-voltage-characteristic test runs:

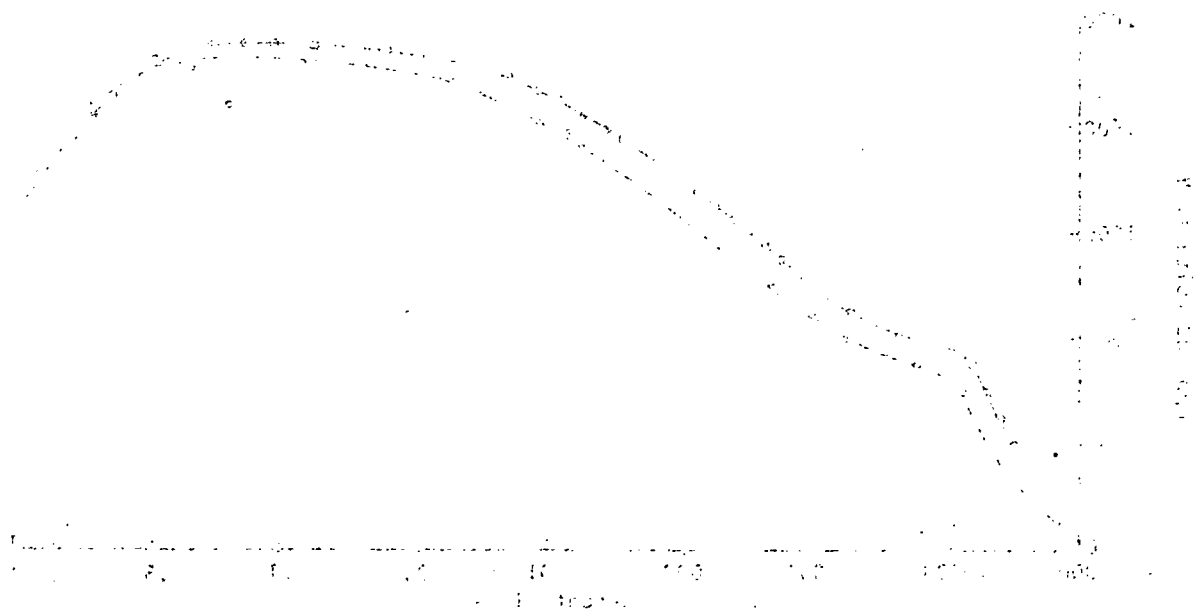
(1) When the applied magnetic field was zero, the discharges observed were characterized by two flame torchlike portions extending downstream (by about 1 to 1.75 in.) from the two opposite electrode tips near the boundary layers. The voltage measured across the adjacent electrode pairs, downstream from the electrode pair across which the dc discharge was established, was unsteady and indicated that a large portion of the applied dc voltage appeared across the adjacent downstream electrode pair (see fig. 3).

(2) With an applied magnetic field of about 2 T and with the field oriented so as to have a component along the direction of the applied electric field between opposite electrode pairs, the flamelike torches of the discharge were driven away from the boundaries toward the center of the duct, and the voltage detected across the adjacent electrode pair downstream was low and steady (see fig. 4).

The current-voltage-characteristic curves at high velocities differ from those that would be observed under static conditions by the contribution to the voltage due to the motion of the gas. It is therefore of interest to determine, for each current value, the components of the voltage due to the resistivity of the plasma in the free stream region, due to the sheath potential drop at the electrodes, and due to the motion of the gas. From a plot of the electron temperature against the current density in helium gas at the same gas pressure, temperature, and velocity as the data of figure 2, one can determine the voltage drop due to the resistivity of the plasma in the free stream region for each

current value. Subtracting that voltage from the total voltage of figure 2 would yield the sum of the voltage drop due to the electrode-plasma sheaths and the voltage drop due to the gas velocity (see fig. 5). To determine the voltage drop due to the electrode-plasma sheaths a static discharge test was made at the same gas density as that of figure 2. For example, at a current between an electrode pair of 0.435 A the measured static voltage was 320 V at the same gas density as that of figure 2, and with a voltage drop due to the pure helium plasma resistivity of 206 V, the sheath potential was 114 V. This means a voltage drop due to the motion of the gas of 1420 V at the current value of 0.435 A. The subject of separating the various contributions to the voltage drop across the plasma at high velocities deserves continued study.

The test results just discussed were obtained with high purity helium gas. Similar results were also obtained with a mixture of helium and 20 percent argon. It would be interesting to examine other mixtures containing neon, krypton, and xenon while using also electrode surfaces yielding high thermionic emissions at surface temperatures of the order of 1000 K or more.





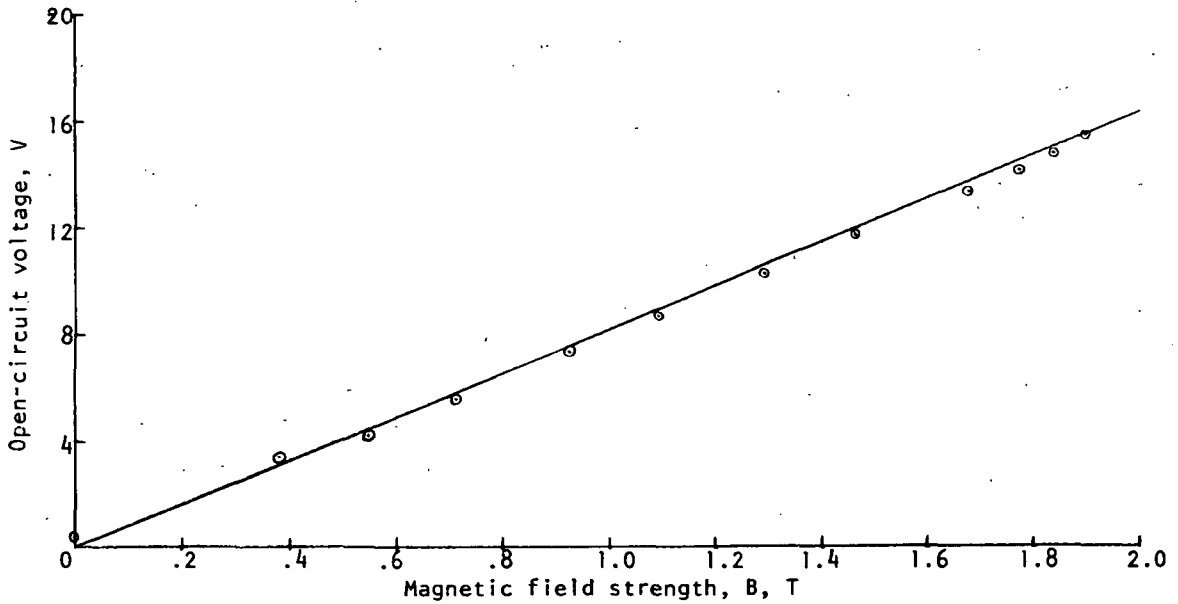


Figure 1. - Open-circuit voltage as function of magnetic field strength. 10-MHz rf preionization;  $I_G$ , 0.06 A;  $I_p$ , 0.3 A;  $V_p$ , 2.46 kV;  $p$ , 0.567 atm;  $T$ , 511 K;  $D$ , 1.587 cm;  $\theta_E$ ,  $69^\circ$ ;  $\dot{m}$ , 11.35 g/sec.

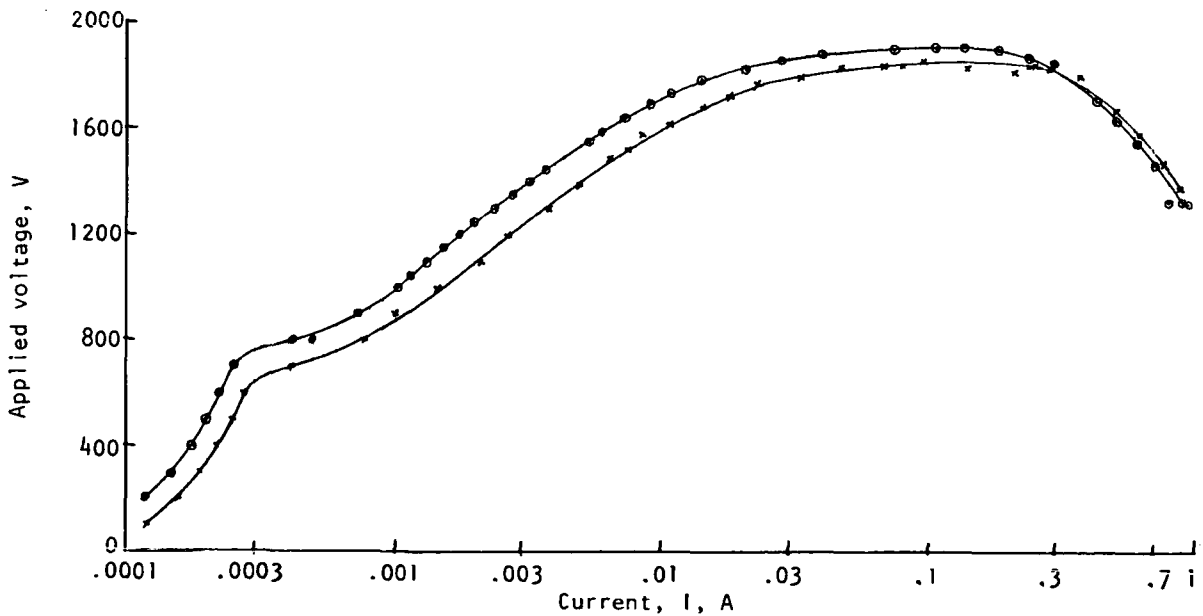


Figure 2. - Applied voltage as function of current. 10-MHz rf preionization;  $I_G$ , 60 mA;  $I_p$ , 300 mA;  $V_p$ , 2.45 kV;  $p$ , 0.573 atm;  $T$ , 511 K;  $\dot{m}$ , 11.45 g/sec;  $D$ , 1.587 cm;  $B$ , 1.895 T;  $\theta_E$ ,  $69^\circ$ .

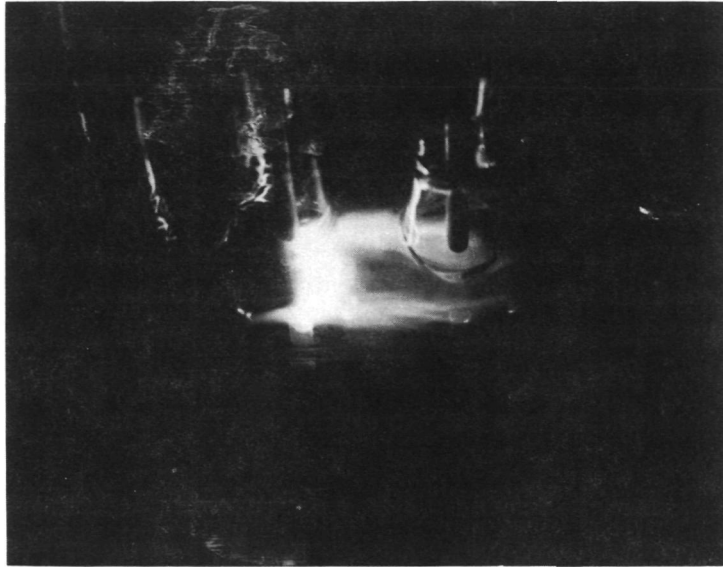


Figure 3. - Discharge in helium with zero magnetic field. Note torchlike portions extending downstream from opposite electrode tips near boundary layers. Current, 105 mA; gas velocity, 320 m/sec.

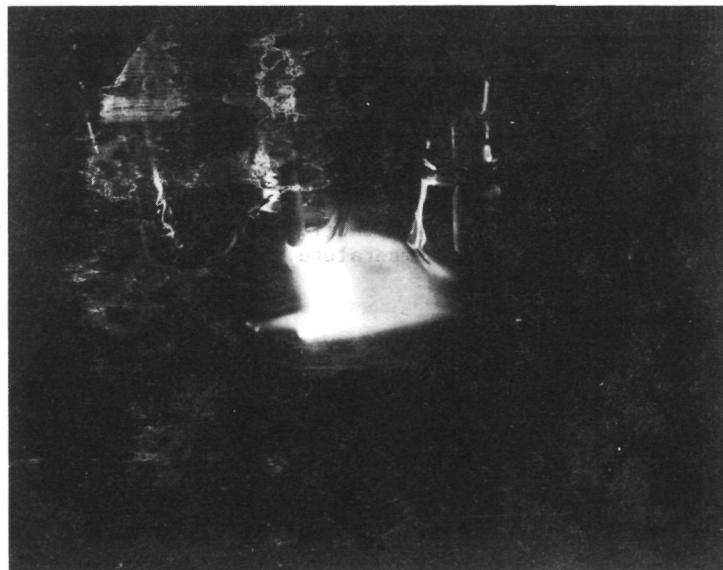


Figure 4. - Discharge in helium with applied magnetic field of about 2 T oriented at angle of  $63^\circ$  with centerline of electrodes. Note that torchlike portions are driven away from walls and appear merged together. Current, 120 mA; gas velocity, 320 m/sec.

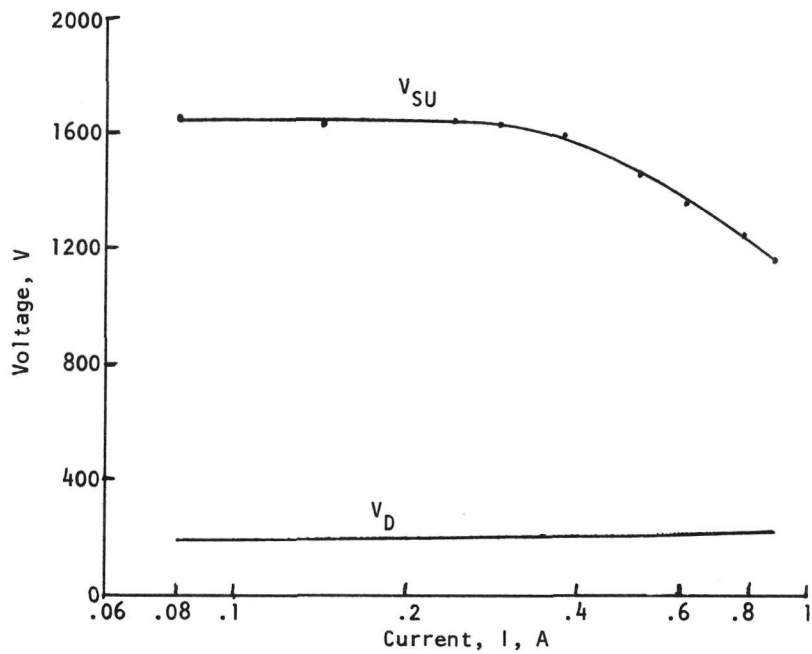


Figure 5. - Voltage as function of current. Helium; pressure, 0.573 atm; temperature, 511 K; velocity, 551 m/sec; Mach number, 0.413.

## MHD RESEARCH AT MONTANA STATE UNIVERSITY

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Montana State University

Bozeman, Montana

The present Montana State University program on MHD is a study of an open-cycle system. However, we have applied to ERDA, in conjunction with General Electric, for additional funding for research and sonic design work on closed cycles.

It is planned to expand present open-cycle research in the areas of heat exchanger design, slag flow, systems instrumentation, data acquisition and control, NOX chemical kinetics, superconducting magnet design, and diffuser design.

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## MHD MAGNET WORK AT MAGNETIC ENGINEERING ASSOCIATES, INC.

R. D. Hay

Magnetic Engineering Associates, Inc.  
Cambridge, Massachusetts

Magnetic Engineering Associates, Inc., is currently providing the detailed design and engineering support for the fabrication and construction of the up-graded LORHO MHD magnet at Arnold Engineering Development Corporation. The coil contains 90 tons of copper and after precooling to 80 K will produce a field pulse of over 6 T for about 30 sec with 27-MW input in a volume of approximately 1 by 1 by 6.5 m. A rigid aluminum alloy frame has been designed to contain the very large  $J \times B$  forces at a peak field near 6.8 T. Extensive use has been made of the existing iron pole system, which (with some additions) contributes 1.2 T to the central field. This results in considerable saving in power compared with generating all the field without iron and improves the transverse field uniformity as well. There is the added complication of thermal insulation and the consequent loss of aperture with cryogenic operation, but the reduction of power input by a factor of 4 may be the only way to obtain the highest pulse fields at reasonable cost. (Superconducting magnets potentially may be expected to provide continuous high fields but at present are three times as expensive and represent an extension of the state of the art, as no large dipoles have yet been constructed.)

The same coil can also be cooled with water, and when energized with 27 MW, the magnet will provide 3.7 T continuously. Construction of this magnet is now under way.

MEA is also in the midst of designing a cryogenic pulse magnet for the closed-cycle blowdown facility planned at General Electric. A field pulse peaking at 3.8 T and remaining greater than 3.5 T for 10 sec has been the basis for the coil design. An interesting arrangement of the conductors has been devised to provide the required field profile along the channel axis. In addition to coil taper in both the transverse directions, some conductors cross over short of the downstream end, thus reducing the ampere turns at that end. Careful use of iron results in achieving the necessary peak field and correct uniformity of the field along the channel.

This magnet can also be run with water cooling at room temperature; however, the continuous field of 2 T is limited by the 10-MW power supply.

We are also involved with design and developmental engineering of several superconducting dipoles for MHD. Large size moderate field solenoids have been successfully

built and operated. Large scale, high field dipoles present very different mechanical and structural problems. The low critical temperature of NbTi superconductors presents significant limitations on incidental energy dissipation which bring about short term temperature increases. New Nb<sub>3</sub>Sn filamentary materials offer enticing improvements in this regard. Support for this very important subject is very meager, with the exception of the magnet being designed for the U. S. A.-U. S. S. R. cooperative program. There is a great need to get started on a full scale MHD superconducting magnet engineering design so that, when one is justified, final design and construction can start immediately.

# EVALUATION OF CLOSED-CYCLE INERT-GAS MHD GENERATOR FOR CENTRAL STATION APPLICATION

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Westinghouse recently completed Task I (parametric analysis) of a government contract, "Study of Advanced Energy Conversion Techniques for Utility Applications Using Coal or Coal Derived Fuels." One of the conversion techniques studied is a combined powerplant incorporating a closed-cycle, inert-gas MHD generator (fig. 1). Our major effort in Task I was to search out that combination of operating parameters which would yield the highest efficiency and at the same time produce a generator configuration conducive to low cost. For this purpose we developed a special computer program capable of calculating nonequilibrium plasma properties, designing the MHD generator, and making the overall heat balance. After making more than 900 computer runs, we found that for an inlet stagnation temperature of  $3800^{\circ}$  F, the best system employs argon gas seeded with 0.001 mole fraction of cesium, an inlet stagnation pressure of 9.27 atm, a generator coefficient of 0.75, a Mach number varying from 0.90 at the generator inlet to 0.87 at the exit, and a magnetic flux density varying from 5.0 T at the generator inlet to 2.3 T at the exit. The generator duct is 18 m long and has an inlet area of  $2.0 \text{ m}^2$  and an exit area of  $12.6 \text{ m}^2$ . The total plant output is  $1000 \text{ MW}_e$ . The thermodynamic efficiency (plant electric output divided by heat input to argon gas) is 59.3 percent.

We are convinced this is the highest possible efficiency because any deviation, either upward or downward, of any parameter from its optimum value causes the efficiency to drop. This is illustrated in figure 2, which shows the effect of deviation from optimum of a few of the parameters.

When losses in the external heating system (gasifier losses, stack losses, etc.) are taken into account, the cycle efficiency is reduced from 59.3 to 47.2 percent. After the necessary auxiliary power is deducted from the plant output, this efficiency is decreased further to the net plant efficiency of 46.4 percent. The capital cost is estimated to be \$1750/kW. The cost of electricity, estimated to be 67 mills/kWh, is distressingly high.

However, it should be pointed out that 90 percent of the cost of electricity is due to capital investment, and 70 percent of the total capital cost is due to the external heating system. The following conclusions and recommendations resulted from this study:



1. The nonequilibrium MHD generator operating on cesium seeded argon is capable of high power density, large enthalpy extraction, and good isentropic efficiency at a moderately high inlet temperature ( $3800^{\circ}\text{F}$ ) and a moderately high magnetic flux density (5 T). There are no significant materials problems. Its continued development is recommended.

2. When combined with a 3500-psia  $1000^{\circ}\text{F}/1000^{\circ}\text{F}$  steam plant, the MHD generator is capable of a thermodynamic efficiency of 59.3 percent. However, this efficiency drops to 47.2 percent if the argon gas has to be heated externally with gasified coal through a periodic, refractory heat exchanger, which is very expensive.

3. For the short range, it is recommended that the external heating system be given further design study with the aim of making it less costly and more compact. Several other high-cost items should also be studied further.

4. For the long range, it is proposed that the external heating system be replaced with an internal one, namely, a high-temperature, gas-cooled, nuclear reactor. Such a substitution will not only restore the thermodynamic efficiency to 59.3 percent, but also in all probability will reduce the capital cost.

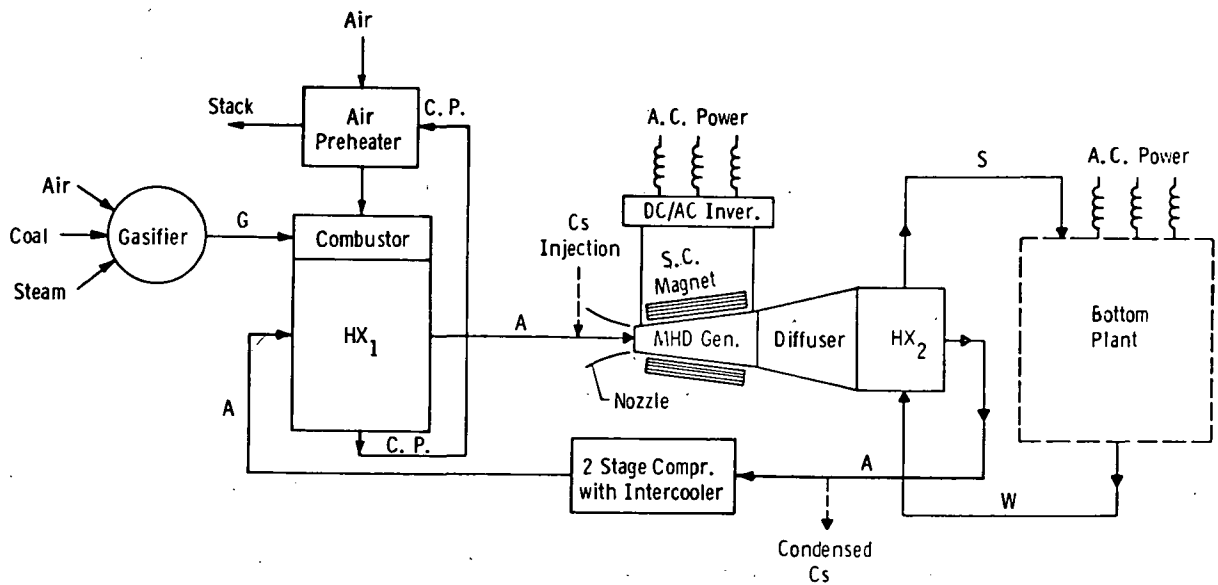


Figure 1. - Closed-cycle, inert gas, MHD generator combined powerplant.

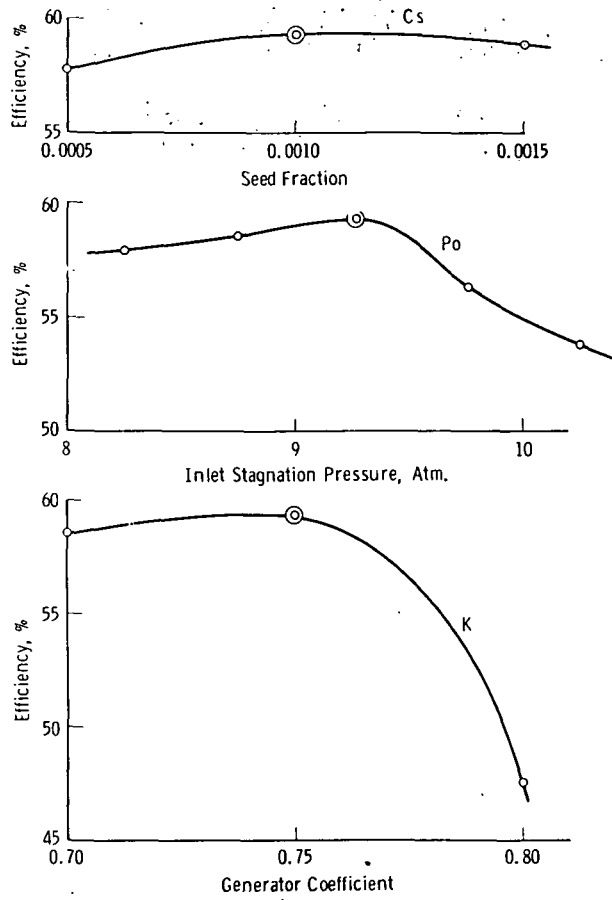


Figure 2. - Parametric point no. 1 deviations from optimum.

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HIGH-PRESSURE PLASMA LABORATORY AT  
GEORGIA INSTITUTE OF TECHNOLOGY

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INTRODUCTION

The measurement of the properties of high-density plasma in the temperature range 5000 to 20 000 K at pressures between 1 and 1000 atm is of considerable scientific and engineering interest. These data are needed in the design of devices such as high-power switches and wind tunnel arc heaters, they are needed to provide an understanding of the basic physics of high-pressure gases at high temperatures, they are necessary for calculating the effects of atmospheric reentry or nuclear fireballs on the propagation of electromagnetic waves, and they are important for evaluating the performance of high-power MHD devices. In order to determine the transport properties of such high-pressure plasmas, a unique high-pressure arc plasma laboratory was developed in 1970 and 1971 by the Air Force at the Thermomechanics Research Laboratory of the Aerospace Research Laboratories, located at the Wright Patterson Air Force Base. In 1972 this laboratory was transferred from the Air Force to the Georgia Institute of Technology, where it has become one of the major research laboratories of Georgia Tech. Work currently under way is concerned with the development of new arc plasma devices, the improvement of plasma diagnostic techniques, and the measurement of the thermal and electrical conductivity of air and argon at temperatures from 5000 to 12 000 K at pressures to several hundred atmospheres.

DESCRIPTION OF LABORATORY

Most of the work at present is being carried out by using wall-stabilized electric arcs. An unrestrained arc between two electrodes is usually very unstable because of the interaction of the electric arc with its environment. Such an unstable arc, because of its wild gyrations and rapidly fluctuating characteristics, is of little use for the determination of arc plasma properties. One method of stabilizing such an arc is to

physically restrain it in a water-cooled channel, as illustrated in figure 1. This device is called a cascade arc; the arc is confined in a circular channel in the center of a stack of copper water-cooled cascade plates, which are insulated from each other and at floating potential so as not to short out the arc. A properly designed cascade arc will operate stably over a certain range of currents and pressures. The wall-stabilized electric arc can usually be examined by looking between the separated cascade plates. Since non-equilibrium ionization effects are unimportant over the pressure range of interest, this wall-stabilized arc is an extremely useful device for measuring the thermal and electrical transport properties of gases at elevated pressures and temperatures.

The cascade arc configuration in figure 1 is an example of one that has been used to measure the transport properties of a reactive gas (air) while the electrodes are shrouded with argon to retard electrode deterioration. The electrodes degrade very rapidly if a reactive gas such as air is allowed to come into contact with them while the arc is operating. The walls of the cascade are kept cool and carry no current, so they are not degraded. One of the important milestones of a current contract was reached when this cascade arc was operated stably at pressures to 30 atmospheres with pure air in the central portion of the cascade while the electrodes were surrounded by argon.

Air purity is determined spectrographically; when air is introduced into the cascade, the argon spectral line intensities drop to approximately 1 percent of their previous value while strong oxygen and nitrogen lines appear. Once the flow conditions are established which result in stable arc operation with a pure test gas in the central portion of the cascade and pure argon around the electrodes, measurements of the transport properties of the test gas can be made. This technique can be used to determine the properties of almost any type of gas at temperatures from 5000 to 20 000 K at pressures of 1 to hundreds of atmospheres.

The cascade arc assembly is operated within a high-pressure vessel containing quartz or sapphire windows for viewing the arc from opposite sides, connections for the water and gas flows, and electrical connectors for powering the arc and measuring its electrical parameters. The laboratory contains four of these pressure vessels, two for operation at pressures to 200 atm and two for operation at pressures to 1000 atm. These pressure vessels have been tested to 1.5 times the maximum working pressure, and calculated burst pressures are in excess of 5 times the maximum working pressure. One of the 1000-atm pressure vessels is of SA-286 stainless nickel steel alloy, which has a very low magnetic permeability, and thus is useful for studies of magnetic interactions with plasma arcs.

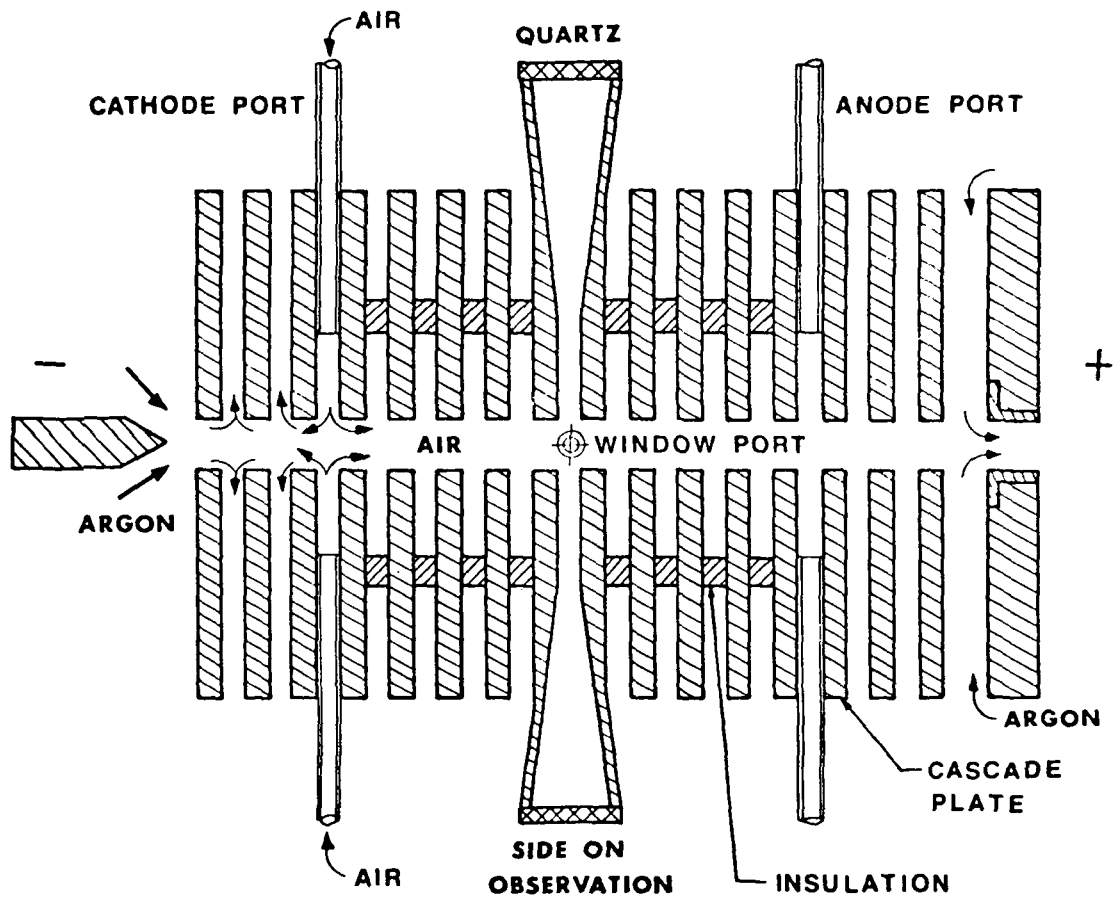


Figure 1. - Schematic diagram of arc apparatus.

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## CLOSED-CYCLE MHD RESEARCH AT GENERAL ELECTRIC COMPANY

C. H. Marston

General Electric Company  
Valley Forge, Pennsylvania

Three major programs on closed-cycle MHD power generation are currently in progress at General Electric. These involve work on the shock tunnel MHD generator, the 2.7-MW<sub>th</sub> ceramic regenerative heat exchanger, and the 50-MW<sub>th</sub> blowdown facility.

Papers reporting the current status of the shock tunnel and heat exchanger programs were presented at the 1975 International MHD Symposium. The ST-40 shock tunnel generator has delivered 19.3-percent enthalpy extraction (1.82-MW net output power) with electron temperatures well in excess of the local static temperature. The working fluid was neon and 1 percent cesium with  $T_{stg} = 3520$  K,  $P_{stg} = 5.39$  atm, and  $B_{max} = 2.7$  T. Enthalpy extractions in the range 9 to 16 percent were measured with stagnation temperatures between 2150 and 2600 K in spite of lower induced voltages and consequently more severe electrode losses.

The heat exchanger, which became operational in May 1975, was constructed for the purpose of monitoring thermal performance and measuring combustion gas and particulate entrainment at the operating conditions of a closed-cycle MHD generator. The design operating point is a 3000° F (~2000 K) argon temperature at 10 atm, decreasing about 100° F (~56 K) during the 60-sec blowdown, with a mass flow rate of 2.5 kg/sec. Diagnostic tools include a He-Ne laser particulate light scattering apparatus and a water-cooled gas sampling probe. Thus far, the maximum operating temperature has been 1730° F (~1200 K), which was the result of a staged 8-hr reheat from room temperature. The light scattering apparatus was not operating, but gas samples during a 20-sec blowdown with nitrogen showed a rapid decrease in CO and CO<sub>2</sub> concentration, which indicated impurity levels consistent with closed-cycle MHD generator operation.

A design study for a 50-MW<sub>th</sub> blowdown facility is nearing completion. It will be of sufficient size and the nominal 1-min run time will be sufficiently long to demonstrate adequate generator performance, 25-percent enthalpy extraction at 70-percent isentropic efficiency under near steady-state conditions. Design operating conditions are  $T = 2000$  K,  $P_{stg} = 10$  atm, argon and 0.1 percent cesium, and  $\dot{m} = 48$  kg/sec. The Faraday mode MHD channel will operate supersonically and have a 6 to 1 area ratio (will be geometrically similar to the ST-40 shock tunnel channel). Ceramic brick channel



walls will be preheated to  $\sim 1300$  K by electrically heated argon. Thermal power will be supplied by a clean gas fired ceramic regenerative heat exchanger, and the 4-T magnetic field by a liquid nitrogen precooled copper coil magnet.

Figure 1 is a diagram of the facility showing the gas supply heater, channel, magnet preheat loop, diffuser, and exhaust system.

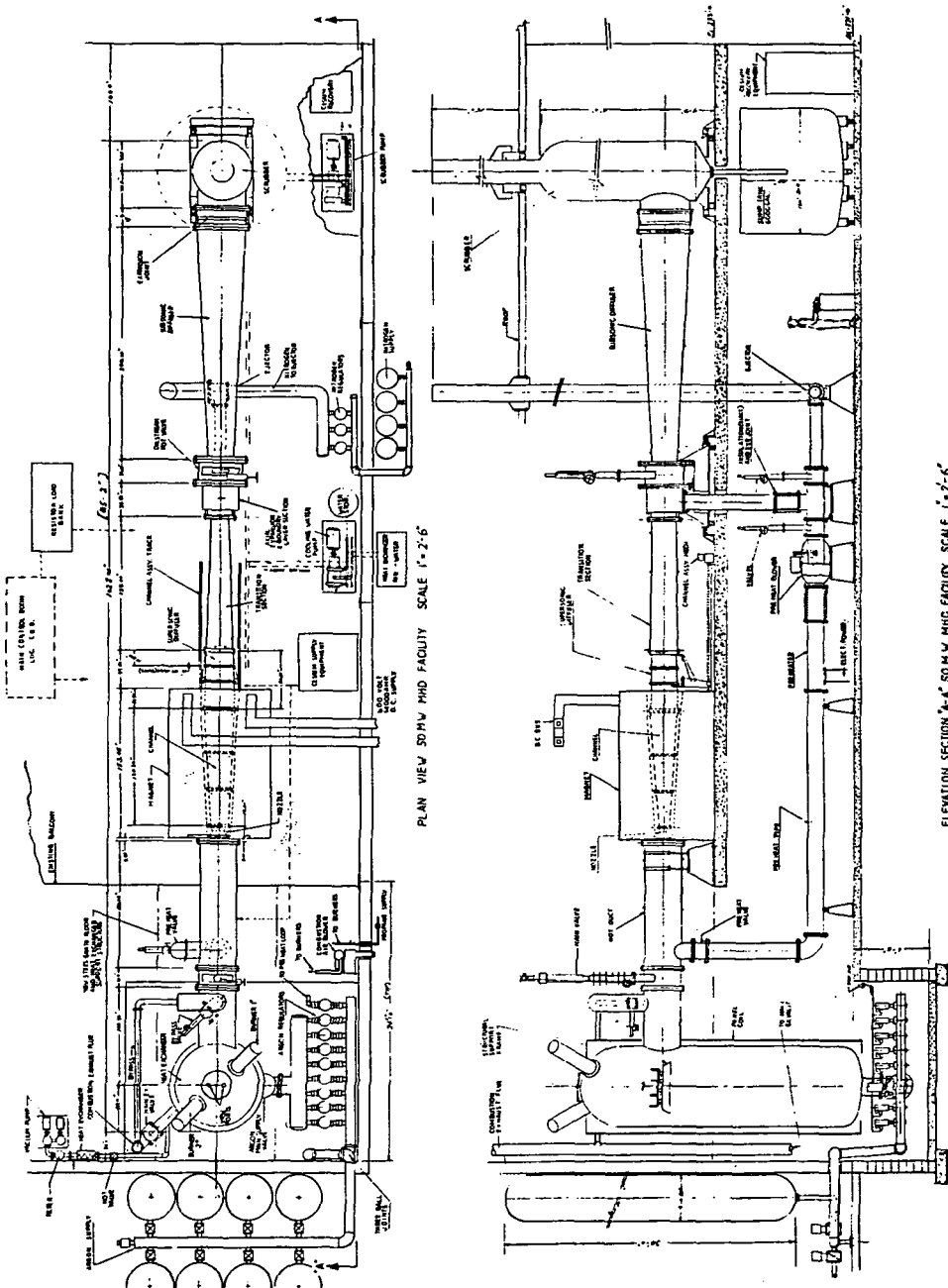


Figure 1.

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## CLOSED-CYCLE MHD PROGRAM AT NASA LEWIS RESEARCH CENTER

R. J. Sovie

NASA Lewis Research Center  
Cleveland, Ohio

The goal of the NASA Lewis MHD program is to demonstrate nonequilibrium performance at temperatures of  $\sim 2000$  K and power densities of  $\sim 1$  MW/m<sup>3</sup> for short-duration tests or continuous (steady state) operation. The closed-loop facility is operated continuously with hot generator walls ( $\sim 1900$  K) to simulate better the conditions under which a real generator must perform.

The achievement of our goal requires that we not only solve the basic plasma physics problems associated with obtaining good MHD generator performance, but also address and overcome problems associated with design and construction techniques for good generator performance and lifetime, materials lifetime and compatibility, systems component compatibility, electrode effects, Hall shorting phenomena, cesium seed system behavior, and general overall system integrity. Although the progress toward obtaining good MHD generator performance has been slow, we have reached the point of overall system integrity that allows us to direct our main effort toward the plasma physics problems.

In the present mode of operation, the inert gas loop operates in the steady state. When the system is at the operating temperature (1900 to 2100 K), cesium injection tests of duration between 10 seconds and a few minutes are made.

Since last year's meeting, the MHD channel, which was operated for over 500 hours, 10 thermal cycles, and over 200 cesium seed injection tests, was removed from the facility and redesigned. The cross sectional dimensions of the channel were reduced to 5 by 16.5 cm to allow operation over a variety of conditions. The redesigned channel has now been in operation for 7 thermal cycles and about 300 hours with no problems. The ability to run under a variety of conditions coupled with improvements in Hall voltage isolation and seed vaporization techniques have increased our understanding of the generator phenomena and resulted in significant improvements in performance. Experiments have been run at temperatures of 1900 to 2100 K at Mach numbers of 0.3 to 0.55 in argon and  $\sim 0.2$  in helium. The best results have been obtained in helium at the conditions  $M = 0.194$ ,  $\mu = 500$  m/sec,  $T = 1950$  to  $2000$  K,  $uh = 87$  V/T, and  $\dot{m}_{\text{He}} = 0.33$  lb/sec. Faraday open-circuit voltages are above 90 percent of ideal for  $B$  up to 1.8 T.

With 17 electrodes, a power output of 1200 W, or  $P/V$  of  $0.35 \text{ MW/m}^3$ , has been measured. This represents a factor of 10 improvement over the previous results. For the 17-electrode tests, a Hall voltage of 360 V, or 870 V/m, was obtained.

## SUMMARY OF WORKSHOP SESSION

R. J. Sovie

NASA Lewis Research Center  
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The workshop session began with presentations on the applications, efficiency, advantages, and future potential of closed-cycle MHD systems by Bert Zauderer of the General Electric Company and George R. Seikel of the NASA Lewis Research Center. The attendees then participated in discussions of these presentations, problem areas, and future research and development needs. The following sections summarize these discussions.

### APPLICATIONS OF CLOSED-CYCLE MHD SYSTEMS

The potential attractiveness of high-temperature nuclear-heated closed-cycle MHD systems for lightweight multimegawatt space power systems and for high-efficiency terrestrial powerplants has been recognized for years. If an appropriate high-temperature reactor (2000 to 2500 K) is developed, these nuclear MHD systems could provide space power systems with weights of 10 lb/kW<sub>e</sub> or less and terrestrial powerplants of 60-percent efficiency. Although it is not likely that such reactors will be developed in the near future, the successful demonstration of steady-state nonequilibrium MHD performance could supply the impetus for their development.

The near-term application for closed-cycle MHD systems lies in fossil-fired binary MHD-steam powerplants. Initial analyses in the NASA-Lewis-managed Energy Conversion Alternatives Study (ECAS) indicate that overall efficiencies in the range 40 to 50 percent are obtainable for fossil-fired inert-gas MHD-steam powerplants. The realization of these plants requires the development of regenerative refractory heat exchangers that can operate on the combustion products of coal or coal-derived clean fuels supplied by an integrated gasifier. These heat exchangers will be similar to those required for the high-temperature air preheater in open-cycle MHD-steam powerplants.

## RELATIVE MERITS OF CLOSED-CYCLE MHD SYSTEMS

The excellent long-range potential (post-2000) of nuclear-MHD systems is clearly recognized. However, a realistic appraisal of fossil-fuel-fired closed-cycle MHD-steam powerplants indicates that such systems face competition from other advanced energy conversion systems. Gas-turbine - steam-turbine combined cycles offer the potential of relatively high efficiencies at low capital costs. Open-cycle MHD-steam powerplants also offer the potential of very high system efficiencies.

The inherent advantages of both MHD systems over the combined turbine cycles lie in their potential for very high system efficiencies (~50 percent). The realization of these efficiencies could more than offset the lower capital costs of the turbine systems, particularly in this era of rapidly rising fuel costs. The MHD systems also avoid the need for high-temperature rotating components. Open- and closed-cycle MHD systems have much in common. Both require high-temperature refractory regenerative heat exchangers, large superconducting magnets, and compressors. This is advantageous, since both systems can benefit from a common research and technology program for development of these major components.

If one compares open- and closed-cycle fossil-fired MHD systems, one sees that there are advantages to each concept that must be fully explored in an advanced research and development program. Among the advantages of the closed-cycle inert-gas system are the following:

- (1) Because of nonequilibrium, ionization systems can be run at inlet stagnation temperatures ranging from 1800 to 2500 K.
- (2) The high electrical conductivity associated with the nonequilibrium ionization allows for a feasibility demonstration in a small system (~15 MW<sub>e</sub>).
- (3) The inert-gas working fluid allows the use of conventional thermionic electrodes and offers the potential of long lifetime MHD channels.
- (4) The economic and performance penalties associated with seed reprocessing are avoided.
- (5) The steam boiler corrosion problem is alleviated.

Among the disadvantages associated with fossil-fired closed-cycle MHD-steam power systems are the following:

- (1) The compressor power required is higher.
- (2) A regenerative refractory heat exchanger system with low impurity carryover and an inert-gas purification system are required.
- (3) The refractory heat exchanger must operate at higher temperatures than the open-cycle air preheater in order to produce the same system efficiency.

The closed-cycle MHD specialists feel, of course, that the potential advantages of their system outweigh the disadvantages. It is also recognized that, although such discussions of the relative merits of various energy conversion systems are instructive,

they are inconclusive. However, the discussions did supply the perspective for formulating the key elements of the future research and development program for closed-cycle MHD systems.

## CLOSED-CYCLE MHD RESEARCH AND DEVELOPMENT PROGRAM

In order to provide an accurate technological assessment of the feasibility and potential benefits of closed-cycle MHD systems and to build upon the basic knowledge and performance generated in almost a decade of research, it is strongly felt that the next phase of research and development of these systems must begin immediately. It is recommended that the research and development program contain the following items:

(1) A high priority is set on the need to demonstrate enthalpy extraction and isentropic efficiency at stagnation temperatures of 2000 K during a blowdown process of about 1 minute. Demonstration of 25-percent enthalpy extraction and 70-percent isentropic efficiency in such a system is a logical extension of the excellent results obtained in shock tube experiments and would prove the feasibility of efficient closed-cycle MHD powerplants.

(2) Fossil-fuel-fired combustors and regenerative heat exchanger combinations must be developed that will operate reliably at temperatures of at least 2000 K. The combustor and heat exchanger should be developed as one unit with optimum performance and economics. The heat exchanger development should be independent of development of the blowdown facility.

(3) System studies must be performed to optimize the performance and economics of fossil-fired closed-cycle MHD power systems and identify components requiring future research and development. The results obtained in the ECAS Task 1 study are considered to be an enlightening first pass at evaluating these systems, but in no way to represent the best case to be presented. It is imperative that follow-on studies be made to optimize these systems.

(4) Steady-state closed-loop experiments should proceed at kilowatt power levels to supply an information base on component design and compatibility, electrode and materials performance, Hall voltage isolation problems, and basic plasma phenomena in a hot-walled steady-state environment.

(5) Research on electrodes and electrode processes should continue at an accelerated pace to determine the optimum materials and configuration for long lifetime thermionic emitting electrode performance. The effects of the expected impurity carry-over on electrode lifetime and performance should be investigated in this program.



(6) Such problems as electrode losses, boundary layer and segmentation effects, end effects, plasma instability limitations and suppression, and ionization relaxation require further work. These studies will supply the research and technology base for obtaining optimum generator performance.

(7) If the studies just listed show favorable results, a fossil-fired closed-cycle MHD pilot plant should be constructed. The pilot plant will operate at approximately the same thermal power level as the blowdown experiment, which will be sufficient for 50-percent efficiency operation, but the plant will be relatively economical to build. The plant will provide the necessary engineering and economic data for construction of much larger plants.

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