CONCLUDING REPORT

on

OPERATION OF AN MGD POWER GENERATOR

for the period

June 1, 1967 to November 30, 1967

prepared for

Spacecraft Technology Division
Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio

under the terms of
Grant NGR 52-026-012

submitted by

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SUMMARY

Several years of constructing a large, inert-gas, blowdown, magnetogasdynamic power generation facility are coming to a successful conclusion. A facility has been created to produce a large volume - and mass-flow-rate of seeded argon or helium plasma and to dispose safely of the high temperature, corrosive plasma after testing. The facility is versatile enough to apply this plasma to a wide variety of channel geometries with minimal changes in reconfiguration. As shown in Table 1, this installation will provide a research facility second to none in scope, size and versatility. It is the largest facility in any university in the world; it exceeds in size those in the national laboratories of the U.K., U.S.S.R., France, Italy, Japan and Germany. It is equalled in many aspects only by the NASA Lewis continuously operating facility.

With the completion of the installation and satisfactory testing of all components but the seeding and seed-removal systems, an increased effort is being placed on analytical and diagnostic studies of the plasma. In order to evaluate the most fruitful operating regimes for the U.T.I.A.S. generator, a series of calculations has been performed for a uniform flow of current through an infinite, argon/NaK-90 plasma, when the driving electric field is $\underline{U} \times \underline{B}$. A later study extended this to a solution of Laplace's Equation in the channel where the boundary conditions are prescribed by a combination of electrodes, insulators and the free stream in the channel. Further modifications have been introduced in this latter study to allow for strong gradients in electron temperature and pressure.

Studies have been started in a number of other areas - spectroscopic and photographic diagnostics, relaxation processes in a flowing plasma, diagnostics by multi-mode electrode configurations, and probe diagnostics.

Preparations are currently under way for a first experimental run on October 29 or 31, 1968. Hot and cold boundary layer tests are now being run (October 24) prior to a hot, seeded MGD run.

1. INTRODUCTION

This semi-annual report is the concluding report written under Grant NGR 52-026-012. It covers the period from June 1, 1967 to November 30, 1967; it also includes work performed since the completion of the grant from the period December 1, 1967 to October 24, 1968.

This grant is supervised under the guidance of Dr. L. Nichols, Lewis Research Center, National Aeronautics and Space Administration. The grant is for the investigation of the operation of a large, inert gas, magnetogasdynamic power generator with emphasis on low pressure operation.

This research is co-sponsored with NASA. All equipment costs and part of the operating costs of the facility have been borne by the University of Toronto, the Defence Research Board, the National Research Council, and the Ontario Department of University Affairs.

2. SCIENTIFIC PERSONNEL

S.J. Townsend, Associate Professor and Assistant to the Director, Institute for Aerospace Studies
C.H. Hersom, Research Assistant, Ph.D. candidate
C.S. Kim, Research Assistant, Ph.D. candidate
C.Z.L. Yeh, Research Assistant, Ph.D. candidate
Marion Ferguson, Research Assistant, M.A.Sc. candidate
J.A.F. Manning, Research Assistant, M.A.Sc. candidate
V. Marello, Summer Student
W. Roger, Summer Student
A. Rosen, Summer Student
D. Tong, Summer Student

3. THREE-MEGAWATT MAGNETOGASDYNAMIC POWER GENERATION FACILITY

Appendix 4 contains a recent description of the facility.

3.1 Inert-Gas Graphite Heater- (C. Hersom)

The graphite work was completed with the construction of the first nozzle of the stagnation chamber. The subsonic nozzle was fashioned out of 2.5 cm (1 in.)-thick graphite plates glued together and contoured internally in order to reduce the 16 cm (6 1/4 in.) diameter outlet pipe from the heater to the 5 cm x 10 cm (2 in. x 4 in.) rectangular channel. Provisions have been made so that vertical expansion of the whole inner graphite assembly from room to operating temperature will bring the exit pipe into alignment with the entrance nozzle.

The problems with the lampblack thermal insulation were overcome by replacing it with three inches of graphite felt and five inches of Fiberfrax alumina blanket. The heater has been taken up to 1750°K over a ten-hour period with no problems whatever. Since the core temperature was still climbing at 200°K per hour, it can be inferred that the thermal insulation is probably adequate for about 2200°K. With more graphite felt insulation, 2500°K is probably achievable.

An emergency re-circulation cooling system capable of dissipating 145 kW (500,000 BTU/hr.) was constructed and tested satisfactorily. This will allow safe cooling of the heater in the event of an unexpected break in water or electrical services.

The argon supply piping was completed, using 15 cm (6 in.) pipe running from the heater to the low-pressure side of the argon regulator system. The regulator system [illegible] (Fig. 2.1, Appendix 3) was completed with the high-pressure manifold, high- and low-pressure regulators and mass flow meter in place. Mass flows sufficient to give slightly sub-atmospheric static pressures (0.7 atmospheres, Fig. 1, Appendix 2) in the MGD channel are possible. The only limitation at the moment is the mass flow meter which can be easily replaced with a larger unit when necessary.

Hot nitrogen flows of approximately 15 sec. duration have been run through a dummy channel at $T_0 = 1750°K$ with no problems in the heater or the downstream heat exchanger.

3.2 Seeding Mechanism - (C. Yeh, V. Marello)

A seed injection system that can cover the argon mass flow rate from 0 - 3 kg/sec has been designed and constructed (Fig. 2 & 3, Appendix 2). Any of K, NaK or Cs vapour can be injected into the argon flow from a positive displacement bellows feeding a seed boiler. A complete description of the system is given in Reference 3.

The boiler has been heated up to 1130°K under vacuum. In preliminary tests with water boiling, it was indicated that a high-temperature stainless steel valve would be needed between the NaK boiler and the argon heater. The NaK pressure would be allowed to build up before the two systems would be connected. This valve has now been installed. The complete seeding line, 2.5 cm (1 in.) diameter SS pipe, has been covered with a heating element and sufficient thermal insulation to guarantee that the alkali seed does not condense on its way to the argon heater.

The first trials for NaK vapourization are planned for October 29-31, 1968.

3.3 Seed Removal Facility - (C. Yeh, W. Roger, J. Manning)

The seed scrubbing system has been completely installed and awaits testing after a run. It consists of an American Air Filter Astrocell filter, guaranteed to stop 99.97% of particles down to 0.3 micron size. The filter can be bathed with an ethanol mixture to form potassium and sodium ethoxide with any seed that has not condensed in the heat exchanger. The ethoxides can then be dissolved with a water spray and flushed away.

An alcohol and water boiler has been designed, constructed and tested to produce vapour to clean the MGD channel, and the downstream heat exchanger. This vapour system complements the liquid washdown system.

3.4 Power Generation Channel - (C. Hersom)

The first MGD channel has been assembled from stainless steel plate, welded into box sections each 30 cm (12 in.) in length with channel dimensions of 5 cm x 10 cm (2 in. x 4 in.) (Section 4, Appendix 3). Six sections of channel have been completed to the alumina-plate insulating stage. Only one channel section has had electrodes installed. This 30 cm channel is presently awaiting an MGD test. Cold boundary layer tests are now being run (October 24, 1968) and will be followed shortly by hot gas runs and a full-scale MGD run on October 29-31.

3.5 Electromagnet Facility - (B. Grace, J. Manning)

The construction of the magnet was completed (Section 5, Appendix 3). Initial testing was done at 50% of design maximum power in order to check field uniformity. Field strength readings were taken along the 1.25 m long gap under the channel along the centerline. Uniformity was constant to better than 1% up to 15 cm (6 in.) or one gap width in from the ends. A field strength of 129% of the central field was found at the end of the pole face. The peak was sharp, extending inward about 7.5 cm (3 in.) and outward about 1.27 cm (0.5 in.). The peak is probably due to the inward curve of the rectangular, racetrack coil at the junction of the end and side conductors. No allowance could be made for this since the computer program available was a two-dimensional one and not a three-dimensional one.

The temperature rise in the uncooled coils at 0.7 Tesla was 5.5^{o}C/min, well within tolerable limits. The water cooling system was not operated since there is sufficient thermal capacity in the coils to run for 2-3 minutes at 1.7 Tesla. The cooling system would be used on longer duration runs at channel pressures much below atmospheric.

3.6 Control System - (D. Tong)

An interlocking safety system to control heat up, magnet activation, seed injection etc. was designed, constructed and tested satisfactorily.

4. CONDUCTIVITY CALCULATIONS FOR A UNIFORM NON-EQUILIBRIUM NaK-90/ARGON PLASMA - (C. Hersom)

A parametric study of an idealized power generation channel simulating the real channel was undertaken (Reference 1). Channel static pressure, static gas temperature, magnetic field strength, seeding ratio and Mach number were taken as the independent variables. The study was conducted for a spatially uniform argon plasma seeded with NaK-90. This particular plasma was chosen as the first one for study in the UTIAS blowdown generator.

A numerical technique was used because of the iterative nature of the problem that arises when electron heating occurs, raising the electron temperature above the gas temperature. With careful design of the program, the solution for electron temperature converged in about ten iterations. Each time a new electron temperature was calculated from the quantities (β_e, ν_e, Q_{ei}, Q_{ea}, etc.) based on the old electron temperature it was found that the new temperature could not be substituted directly back into the iteration procedure without the solution diverging. By invoking a mixing rule - 82.5% of the old Te plus 17.5% of the new Te - to get the next value of Te to begin the iteration over again, convergence was quickly attained. This mixing rule held good over all ranges of the physical parameters studied. Figure D-2.1, D-2.2 and D-2.3 display some of the results. (The vertical scale on the power density is too high by a factor of ten.)

	Westinghouse (USA)	Allison Division General Motors (USA)	Avco-Everett (USA)	Avco-Everett (USA)	MIT (USA)
Gas	He	He	A	A	He
Seeding	Cs	Cs	Cs	Cs	Cs
Conversion duct cross-section (cm)	5.5 × 7	2 × 3	Disc	Disc (tailored) interface shock tube)	(10 - 15) × 3.8
Conversion duct length (cm)	40	45	-	-	46
Gas temperature (°K)	1840	1700	1800 -2000	1500-4000	2000
Gas operating pressure (atm abs.)	1	1	-	0.5-1	5
Mass flow rate (g/sec)	15	17.5 (He)	-	10 000	400
Gas velocity (m/sec)	130	1045	--	1300	3500
Mach number	0.1	0.51 - 0.57	-	2	2 - 2.5
Seed concentration	0.1%	0.3 -1 %	0.1%	0.1 - 0.3%	0.2%
Magnetic field (T)	1.7	2	-	3	1.4
Impurities (ppm)	-	-	-	~ 10	-
Plasma conductivity (mho/m)	1.1	1.1 -3.5	-	1-100	> 5
Output power (W)	3.4 (continuous)	14 (continuous)	5	up to 700 000 (3 ms)	-

	General Electric Space Sciences Laboratory (USA)	General Electric Space Sciences Laboratory (USA)	General Electric Space Sciences Laboratory (USA)	International Research and Development (Mk. II) (UK)	Atomic Energy Research Establishment (UK)
Gas	A	A	Ne, He or A	He	A or He
Seeding	-	Cs	Cs	Cs	K or Cs
Conversion duct cross-section (cm)	5 × 5	1.25 - 1.84 × 5	16 × 10 (diverging)	1.5 × 6	3 × 1.5
Conversion duct length (cm)	28	25	100	55	20
Gas temperature (°K)	5100	1500	1500 - 2000	1300-2200	1500
Gas operating pressure (atm abs.)	0.4	1	4 - 20	0.3-1	1-6
Mass flow rate (g/sec)	146	100	$10^3 - 5 \times 10^4$	6-12	A: ≥ 300 He: ≥ 30
Gas velocity (m/sec)	-	400	1000 - 2000	200 - 1800	-
Mach number	1.28	0.6	~ 1.5 (entrance)	< 0.1-0.8	0.8
Seed concentration	0%	0.02%	0 - 0.1%	0.01 - 1.8%	0.1 - 1%
Magnetic field (T)	2.6	2.25	2	2.2	1.6
Impurities (ppm)	< 100	< 12	< 5	< 10	-
Plasma conductivity (mho/m)	~ 6 (eq.) ~ 1000 (n. eq.)	0.1 (eq.) 10 (n. eq.)	-	≤ 60	10⁻
Output power (W)	62 000 (0.5 msec)	3W/el. pair	-	< 100 (continuous)	0.1 (5-min. bursts)

FIG. D-1.1 CLOSED CYCLE MHD INSTALLATIONS

	Commissariat à l'Energie Atomique (France)	Japan Atomic Energy Research Institute (Japan)	CNEN Frascati (Italy)	Institut für Plasmaphysik Garching (Fed. Rep. Germany)	Kernforschungsanlage Jülich (Fed. Rep. Germany)	I.A.E. Kurchatov Moscow (USSR)	NASA LEWIS RESEARCH CENTER (USA)	INSTITUTE FOR AEROSPACE STUDIES, Univ. of Toronto (Canada)
Gas	He	A	He	A	A	A	A	A
Seeding	Cs	K	Cs	K	Cs	Cs	Cs	N_aK-90, K or Cs
Conversion duct cross-section (cm)	⌀ 5.5	1.5×8	5 × 3	2 × 2.5	5 × 10	Disc R_{min} = 22	6.3 x 19	5 x 10
Conversion duct length (cm)	42	22.5	22	20.5	50	R_{max} = 60	69	120
Gas temperature (°K)	1800	1900-2200	2000	2000	1800	1300	2200°K	1800°K-2500°K
Gas operating pressure (atm. abs.)	< 2.5	1	6	0.3 - 0.5	1 - 8	< 10	4.8	0.01-8 (1000m^3 Vacuum Sphere)
Mass flow rate (g/sec)	150	53 - 33	400	100	4000	< 1000	1300	0-4000
Gas velocity (m/sec)	1600	150 - 130	-	650	-	-	3	650
Mach number	0.3 - 2	0.19 - 0.15	0.6	0.7	0.9	1.8 - 3	0.03-0.3%	0.8-0.9
Seed concentration	< 1%	1%		0.04-2.3%	-	0.01-0.1%	0.03-0.3%	0.3%
Magnetic field (T)	2	2	4	< 3.5	1.8	4	2.0	1.7 0.25% uniformity
Impurities (ppm)	< 10	-	-	< 10	-	-	-	-
Plasma conductivity (mho/m)	-	4 - 35	-	5 - 25	-	370	-	-
Output power (W)	-(0.2-sec bursts)	2.4 - 11 (3 h)	(bursts)	~ 15 (continuous)	- (continuous)	- burst	- continuous	- 1-2 min at max. ṁ

Other installations: MIT United States (argon flow of 10 g/s through a 10 kW reheater); NASA Lewis Research Centre, United States; University of Sydney, Australia and USSR.

FIG. D-1.1 CLOSED CYCLE MHD INSTALLATIONS
ref. Nuclear Fusion 7, p. 267 (1967)

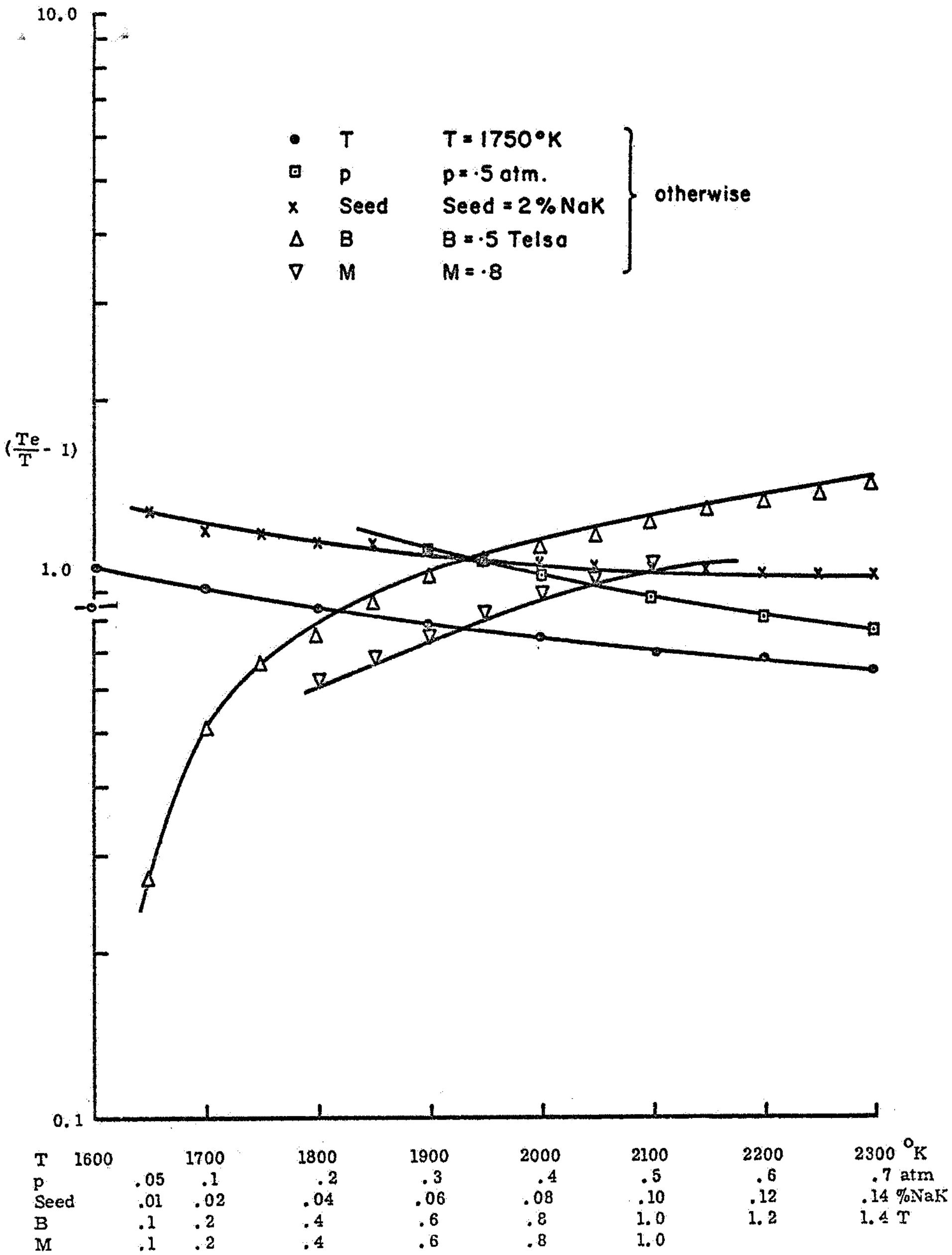

FIG. D-2.1 FUNCTIONAL DEPENDENCE OF ELECTRON TEMPERATURE RISE

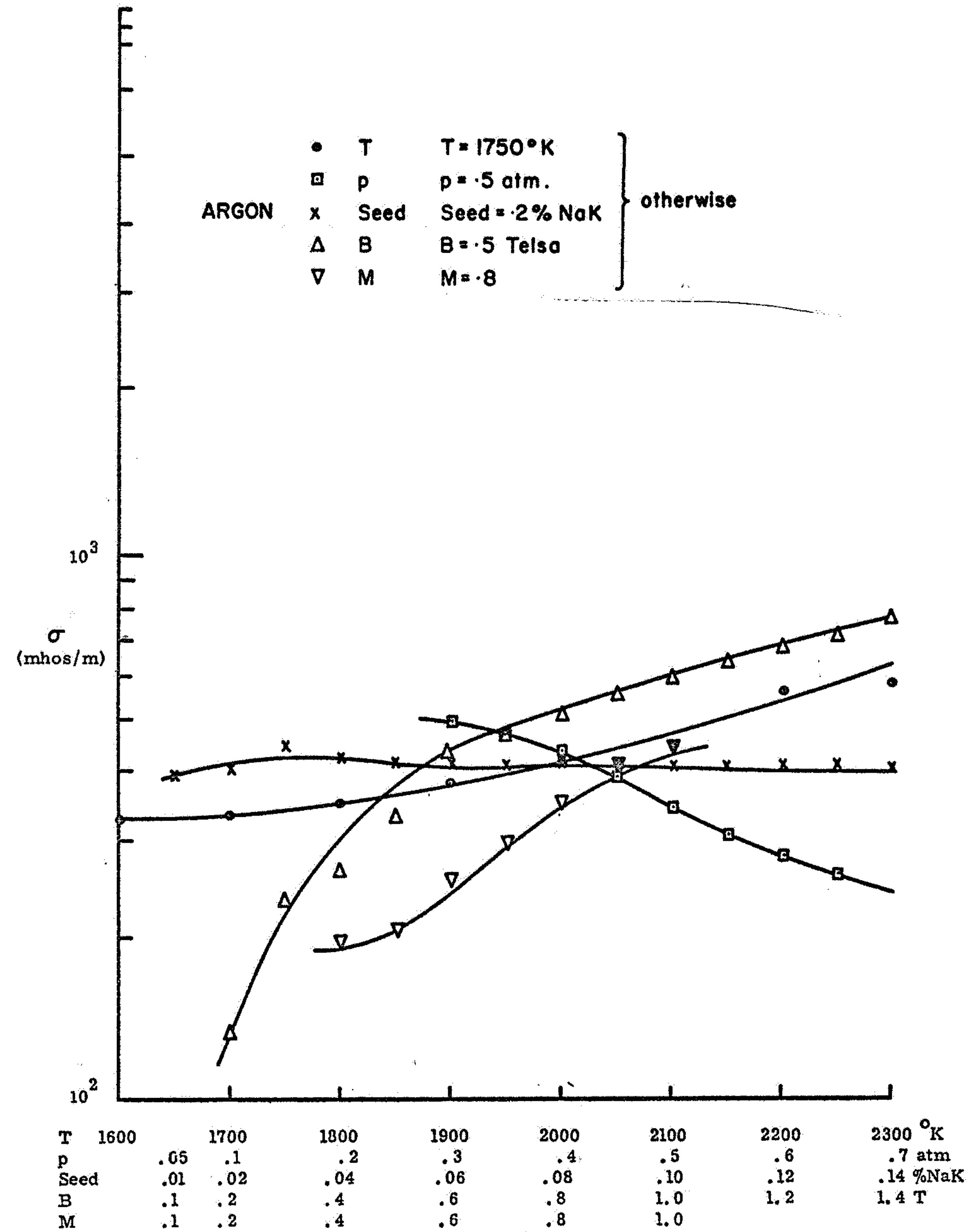

FIG. D-2.2 FUNCTIONAL DEPENDENCE OF PLASMA CONDUCTIVITY

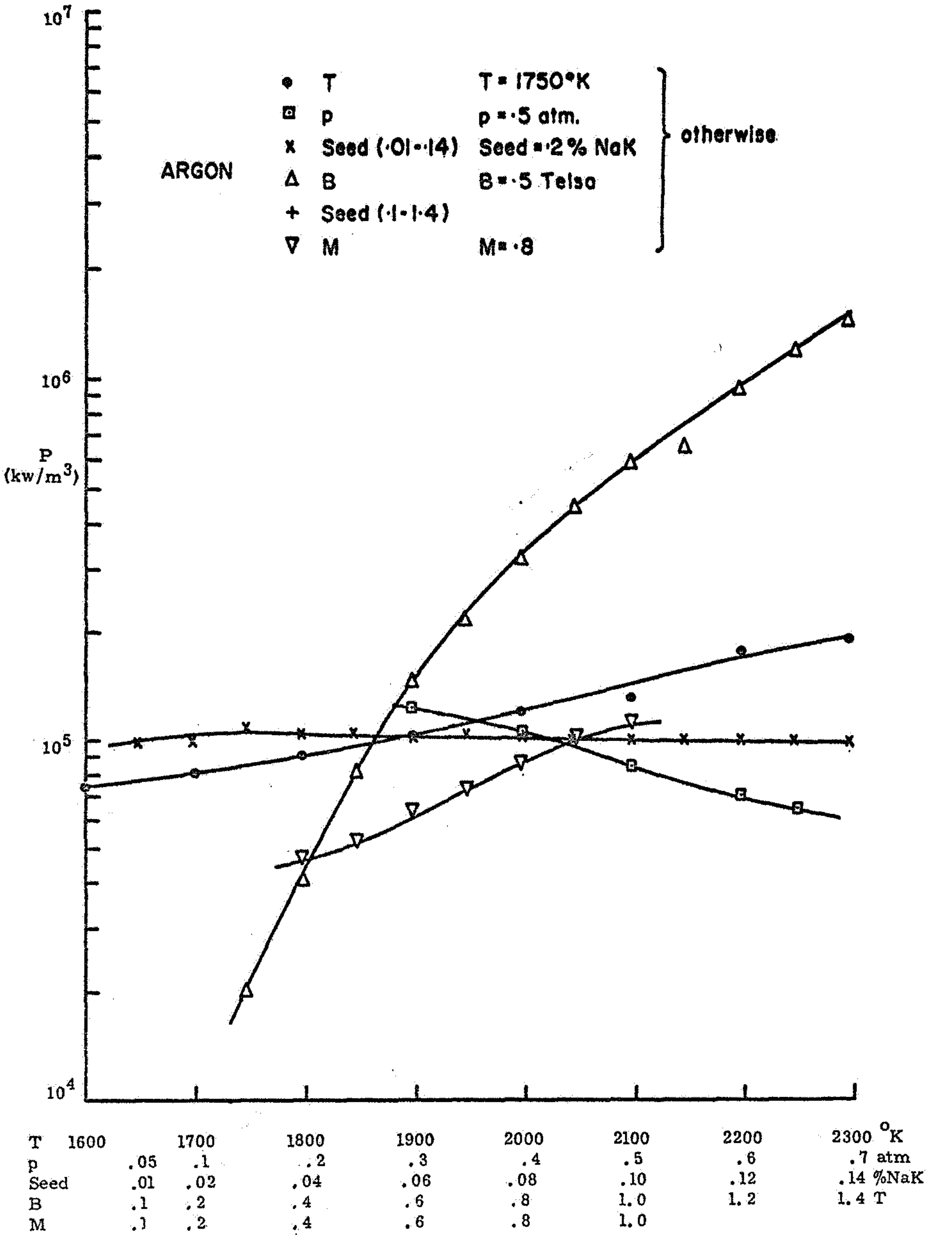

FIG. D-2.3 FUNCTIONAL DEPENDENCE OF POWER DENSITY

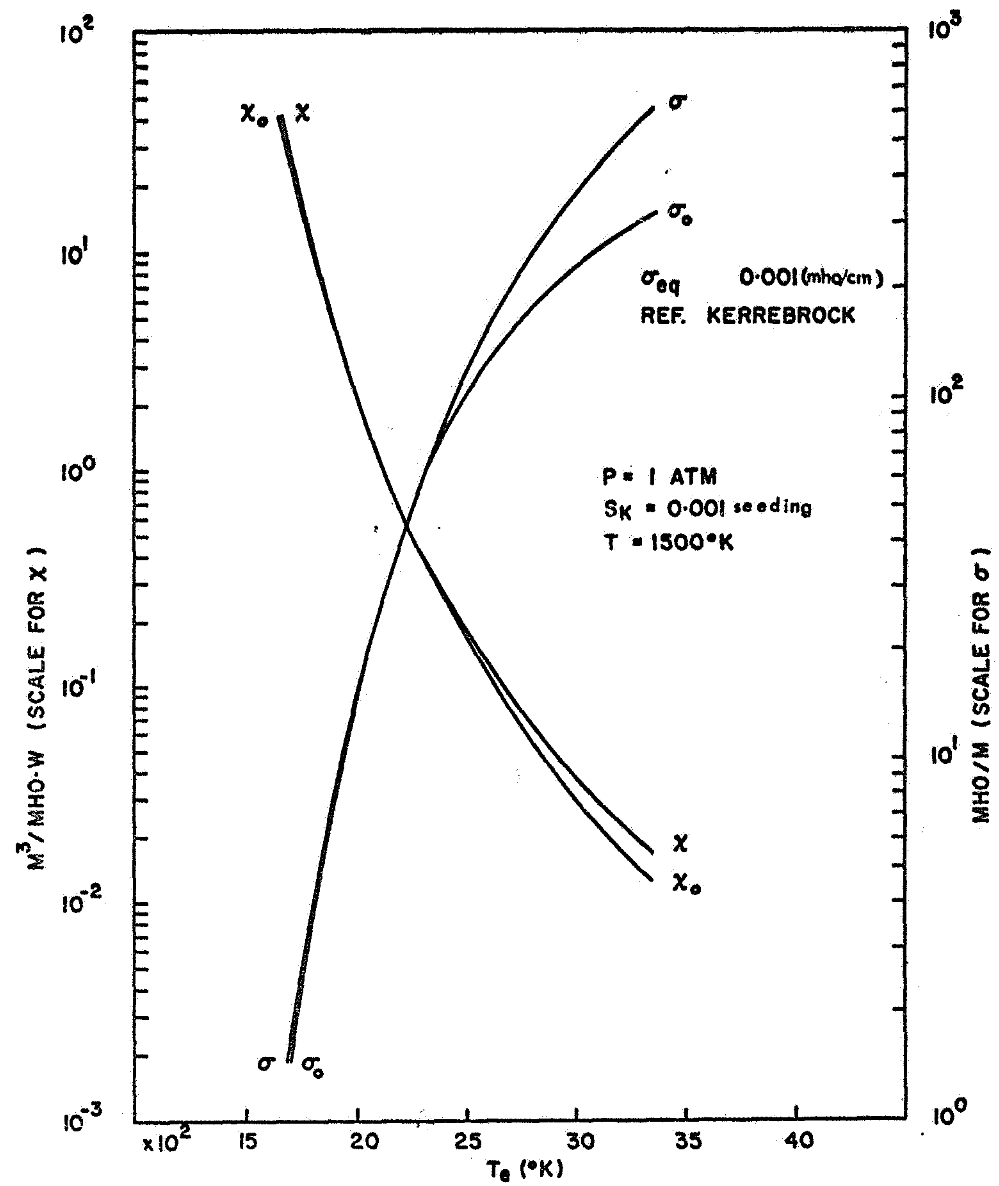

FIG. D-3.1 CALCULATION OF CONDUCTIVITY AND HALL COEFFICIENT

5. STUDY OF A NON-UNIFORM PLASMA FLOWING IN A CHANNEL - (C.S. Kim)

The problem involved is to study the flow of current in a plasma flowing down a channel. Consideration is given to the non-uniformities that arise between a pair of opposing segmented electrodes in the actual channel of an MGD generator. A generalized Ohm's law involving the gradients of temperature and of electron pressure has been developed. Using the results for the calculations of momentum transfer collisional integrals and of electron heat flux given by Zhdanov and Demetriades (5, 6), Ohm's law is given as:

$$E' = \frac{1}{\sigma} J + \chi (J \times B) + \varepsilon (J \times B) \times B$$

The electric field E' is given as

$$E' = E* + \frac{1}{en_e} \nabla P_e + \frac{5}{2} \frac{k}{e} \nu_o \tau_e*$$

and is the actual field affecting the current flow, J, when the non-uniformity is considered.

Expressions for scalar conductivity, Hall parameter and ion slip coefficient are given in this "second-approximation" Ohm's law by

$$\frac{1}{\sigma} = \frac{4}{3} \frac{M_e}{N_e} \frac{\nu_t}{e^2} - \frac{5}{2} \frac{M_e}{N_e e^2} \nu_o^2 \tau_{e*}$$

$$\chi = \frac{1}{N_e e} + \frac{5}{2} \frac{\nu_o^2}{N_e e} \frac{\tau_{e*}^2}{1 + \omega_e \tau_{e*}^2}$$

$$\varepsilon = \frac{-5}{2} \frac{\nu_o^2}{M_e N_e} \frac{\tau_{e*}^3}{1 + \omega_e^2 \tau_{e*}^2}$$

where m_e, n_e, ν_t, τ_e^*, ω_e are electron number density, electron charge, total electron collision frequency, higher-moment electron collision frequency, higher moment electron mean free time and the cyclotron frequency (5, 6). Here, the ion slip coefficient, ε , has been obtained while neglecting the ion concentration.

With the aid of available theoretical arguments (7, 8) of various collision cross sections, all those parameters mentioned previously for an argon plasma seeded with potassium have been studied and calculated as functions of electron temperature (Fig. D-3.1). Comparison with the experimental work of Kerrebrock, and Cool and Zukoski suggested the use of these parameters for the formulation of the current-governing equation. The current-governing equation in terms of the stream function, is

$$\nabla^2\psi + M(x,y)\frac{\partial\psi}{\partial x} + N(x,y)\frac{\partial\psi}{\partial y} = P(x,y)$$

where M(x, y) and N(x, y) are respectively functions of the gradients of conductivity and of Hall parameters; P(x, y) is a functional type of the velocity and of electron pressure gradient and of temperature gradient.

All the calculations have been carried out while neglecting the ion slip coefficient and its gradient.

The Liebmann method for Laplace's equation is used (9).

At present, simple numerical solutions for the current equation are being attempted for the segmented Faraday generator (Fig. D-3.2). Some results for cases of uniform conductivity and Hall parameter, particularly when the Hall parameter is not greater than one, are now available. Figure D-3.3 depicts the flush-electrode geometry on which the program was tried. Figures D-3.4 to D-3.9 show some of the preliminary results obtained when ignoring the fluid forcing function terms in ∇P_e and ∇T_e on the right hand side of the current stream function equation. Hopefully this numerical procedure can be extended to the general case, namely, where the plasma is nonuniform with a Hall parameter greater than one.

This work will attempt to modify the wall boundary conditions by the presence of the intervening boundary layer.

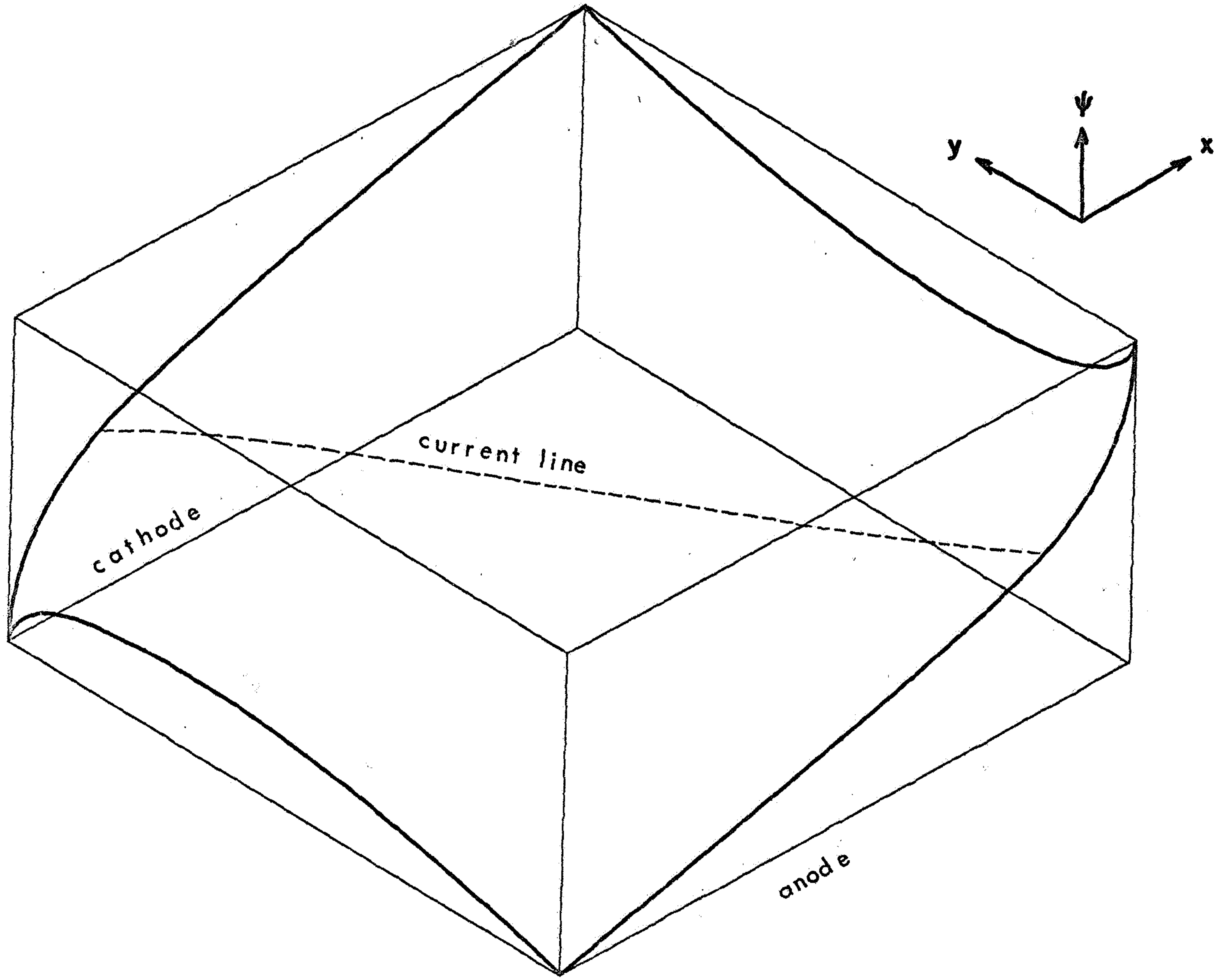

FIG. D-3.2 SURFACE OF THE STREAM FUNCTION BETWEEN A PAIR OF SEGMENTED ELECTRODES IN CASE OF UNIFORM PLASMA AT HALL PARAMETER = 1

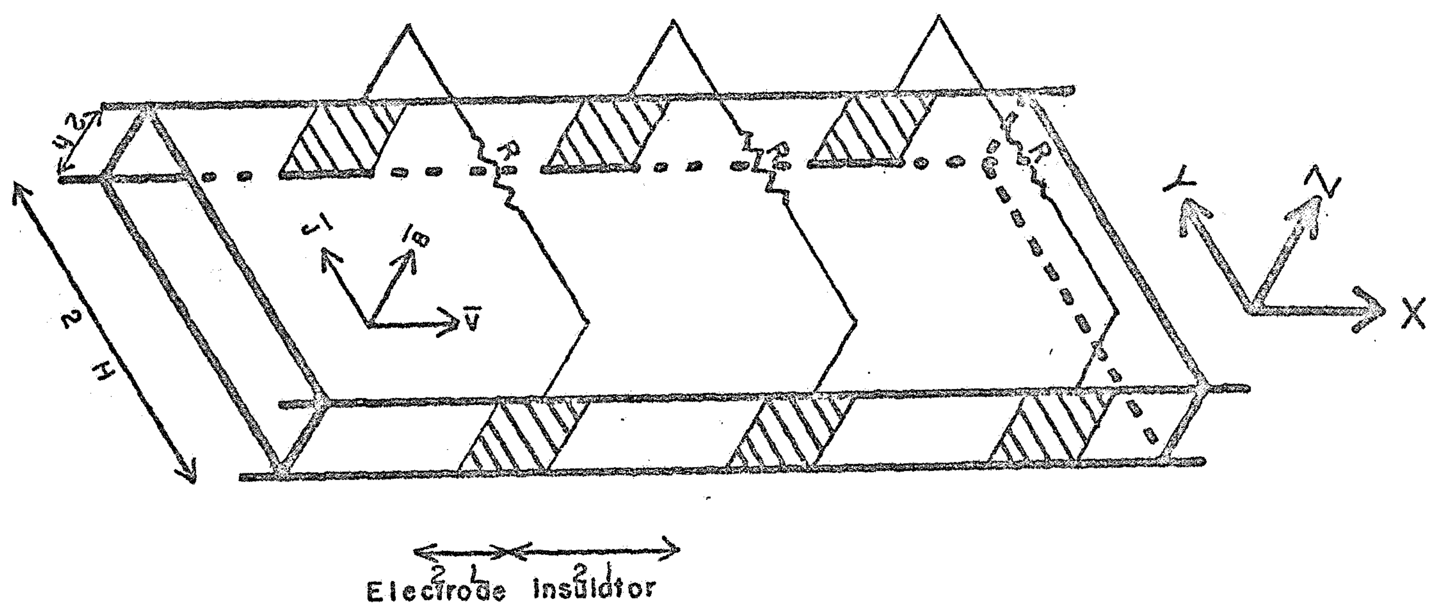

Fig. 8 Faraday Generator Channel Configuration Showing ;

a) Applied Field Direction
b) Current Flow Direction
c) Plasma Flow Direction
d) Channel Dimensionalized Geometry and Single Load Resistance Connections

MASS FLOW VARIATION WITH $\dot{M}$. & P. IN A 5CM. X 10 CM. CHANNEL

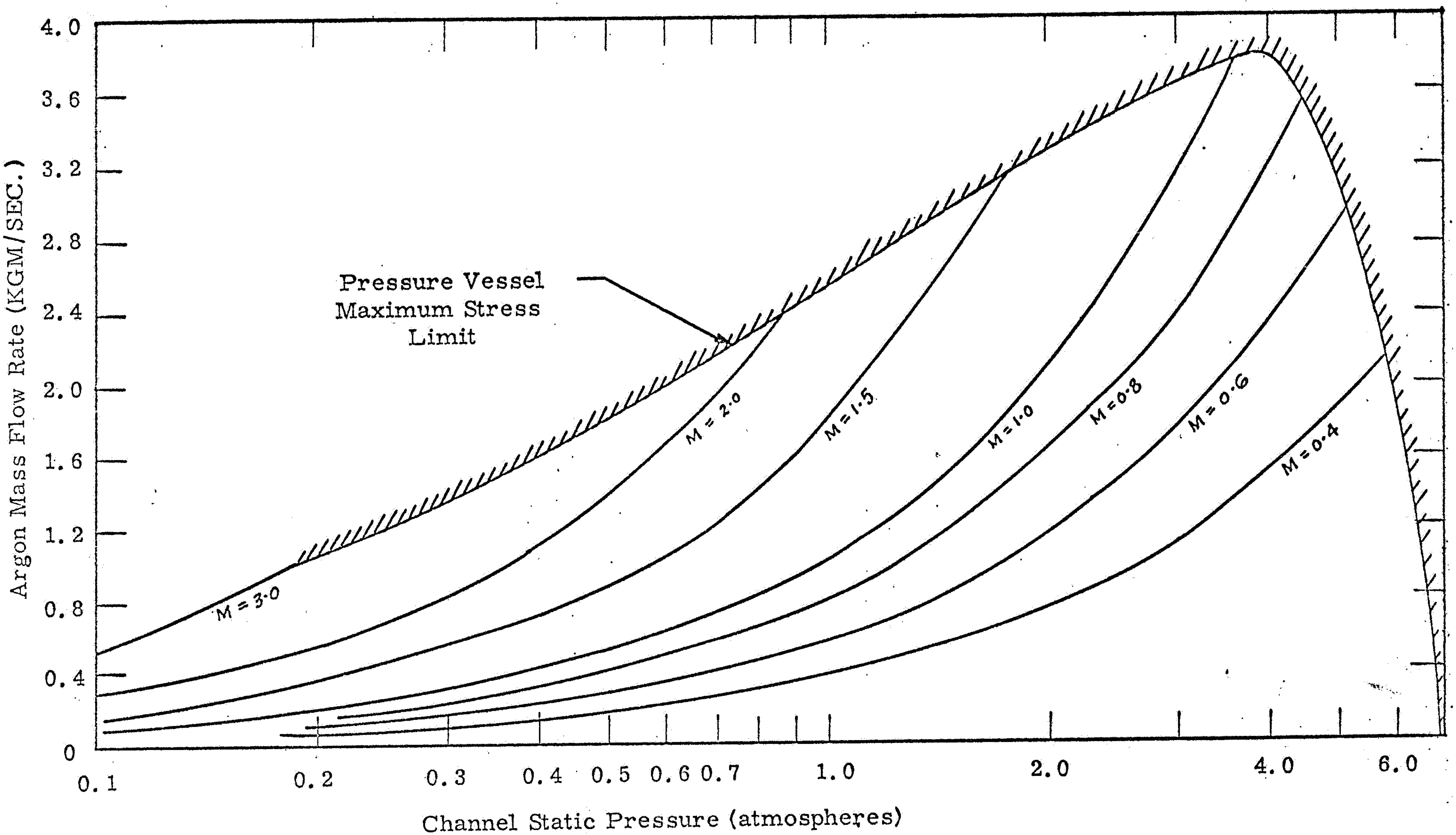

FIGURE 9. Mass Flow Variation With Static Pressure in MGD Channel for Operating Conditions Permitted By Stagnation Pressure Limitation

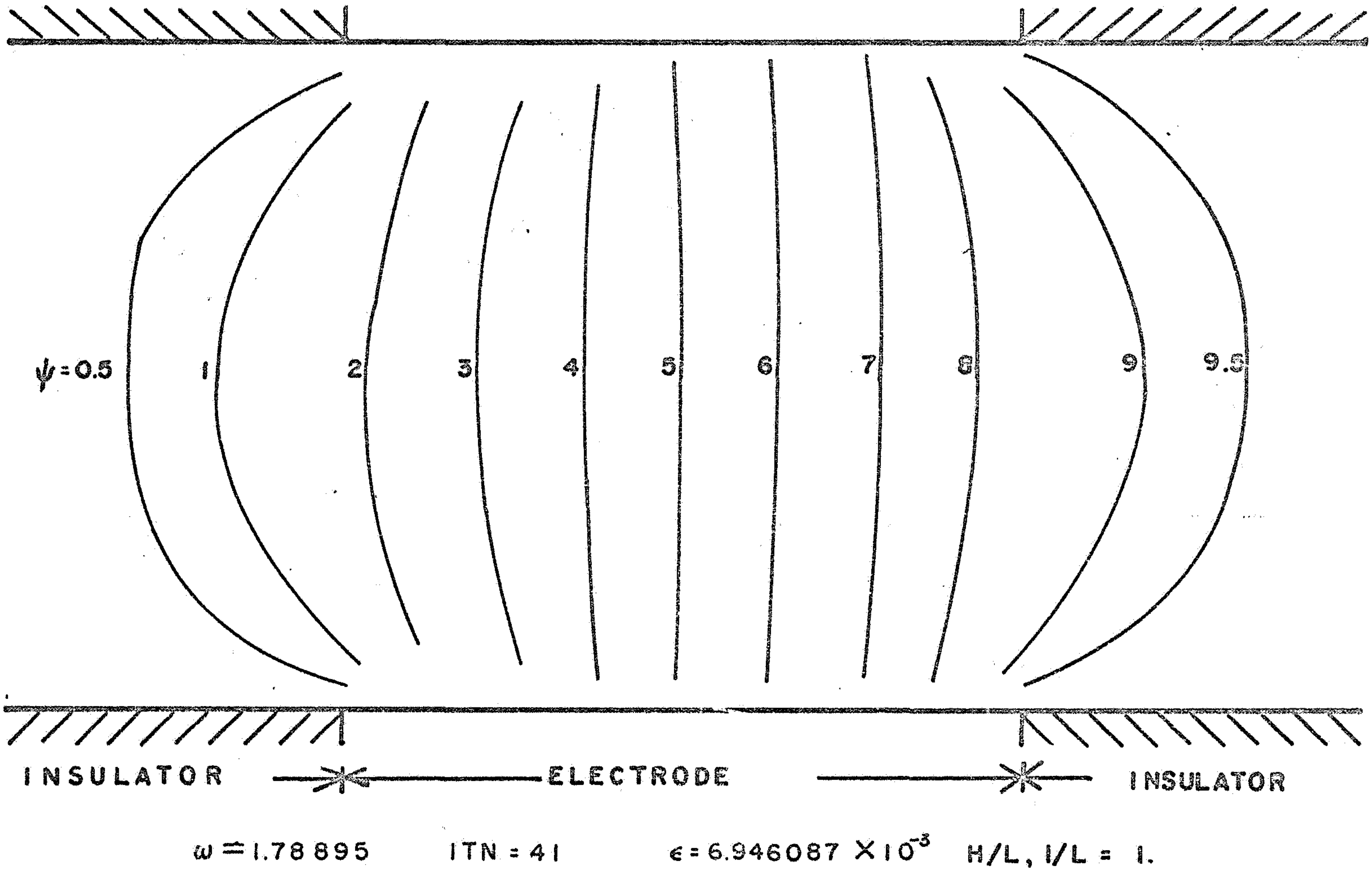

Fig. 10 Current Distribution in the Uniform Plasma Flow in the Faraday Channel at $\beta = 0.0$

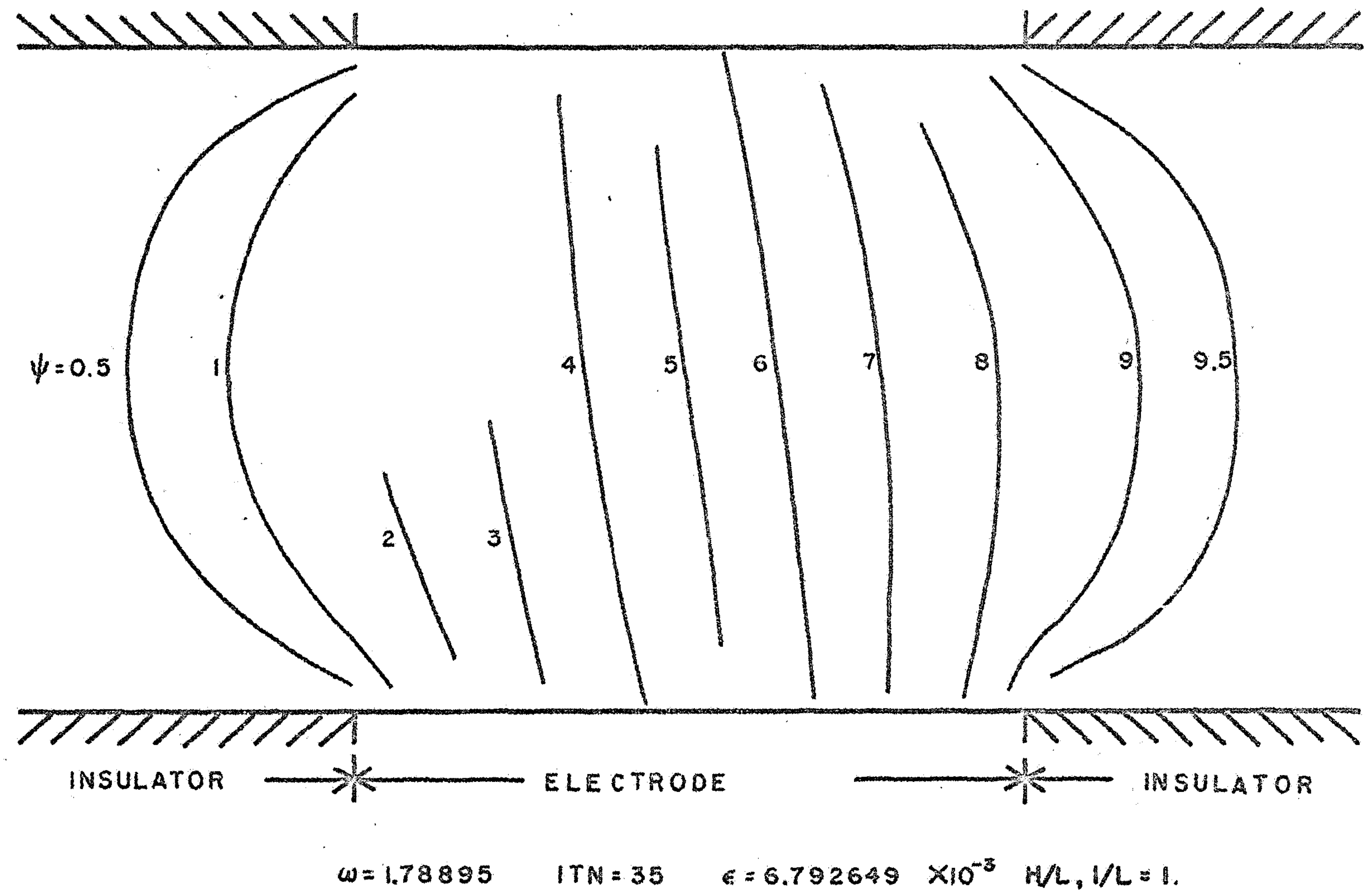

Fig. 11 Current Distribution in the Uniform Plasma Flow in the Faraday Channel at $\beta = 0.2$

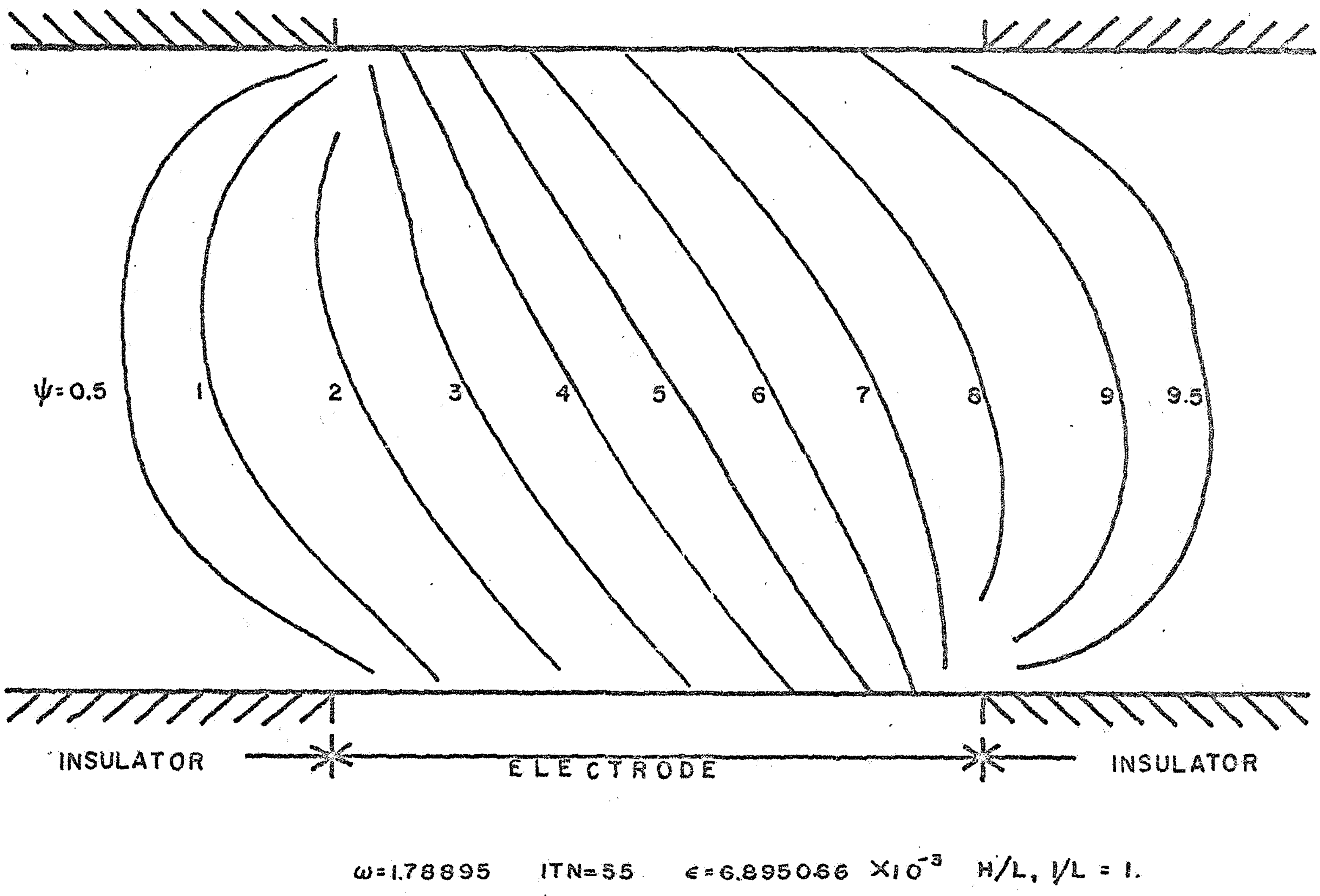

Fig. 12 Current Distribution in the Uniform Plasma Flow in the Faraday Channel at β = 1.0

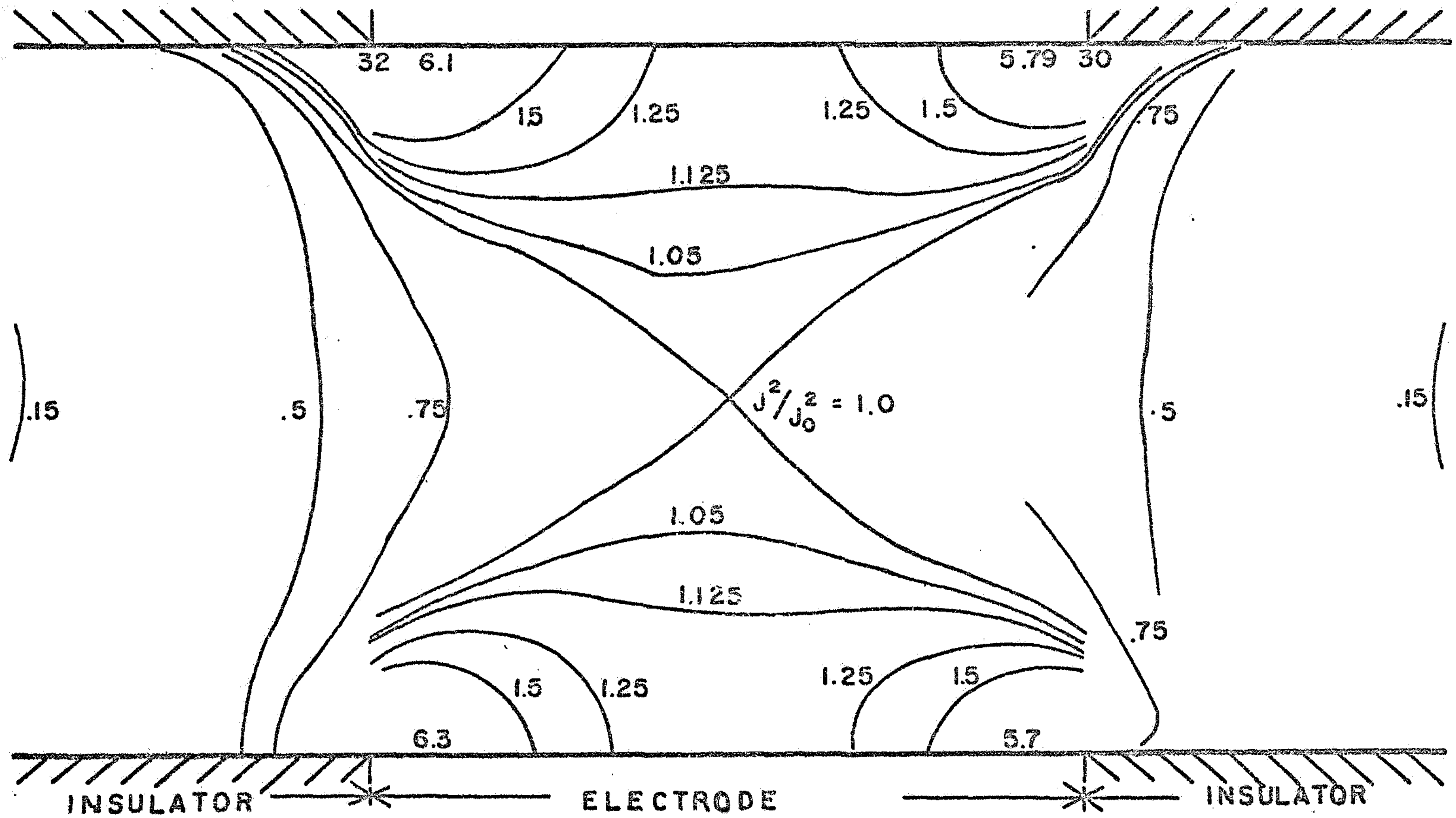

Fig. 13 Calculation of Electron Temperature Distribution by Using Simple Energy Balance Equation and the Obtained Current Distribution at $\beta = 0.0$, Showing Normalized Values of j^2 in Reference to the Value at the Center of the Channel.

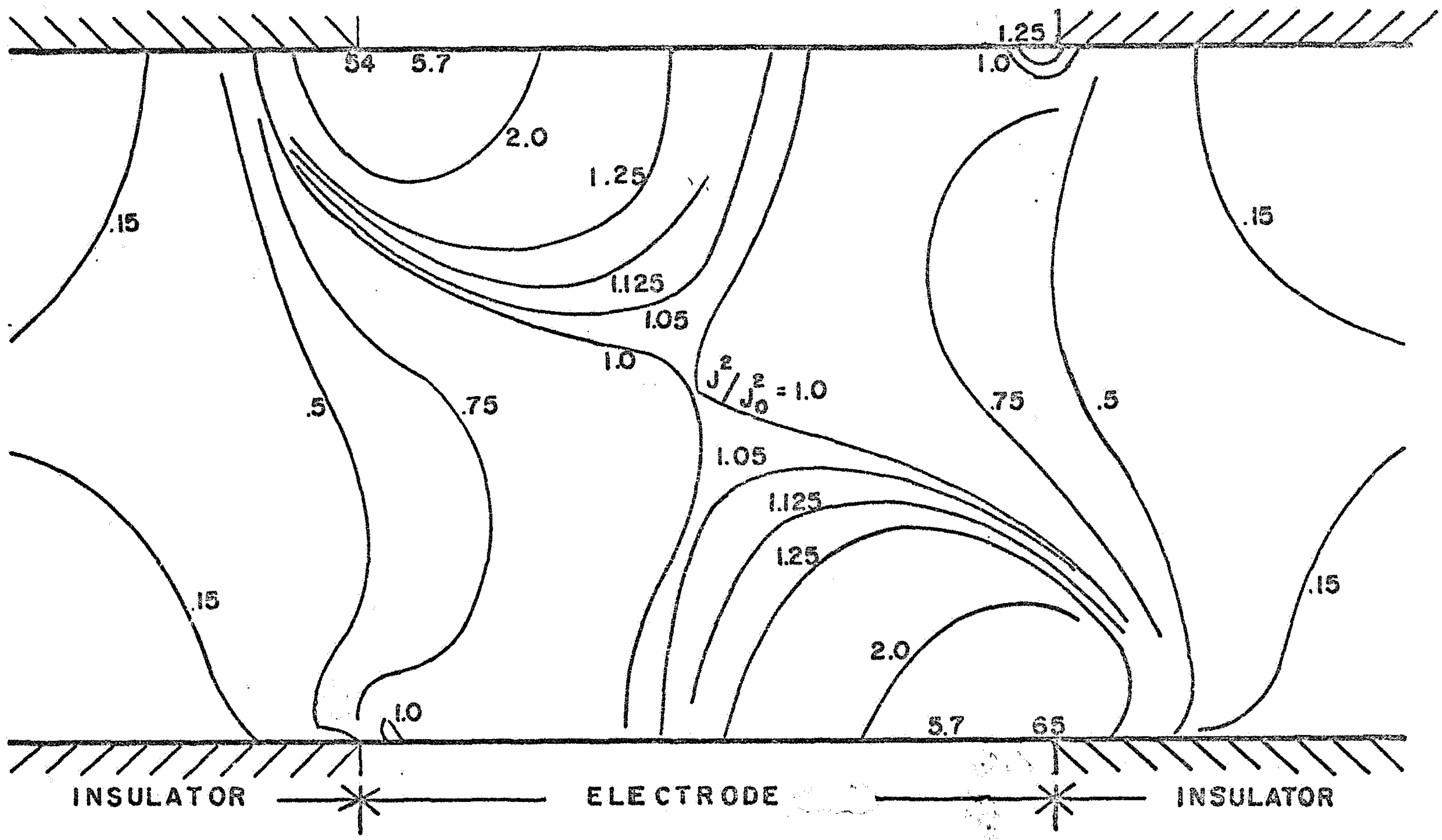

Fig. 14 Calculation of Electron Temperature Distribution by Using Simple Energy Balance Equation and the Obtained Current Distribution at $\beta = 1.0$.

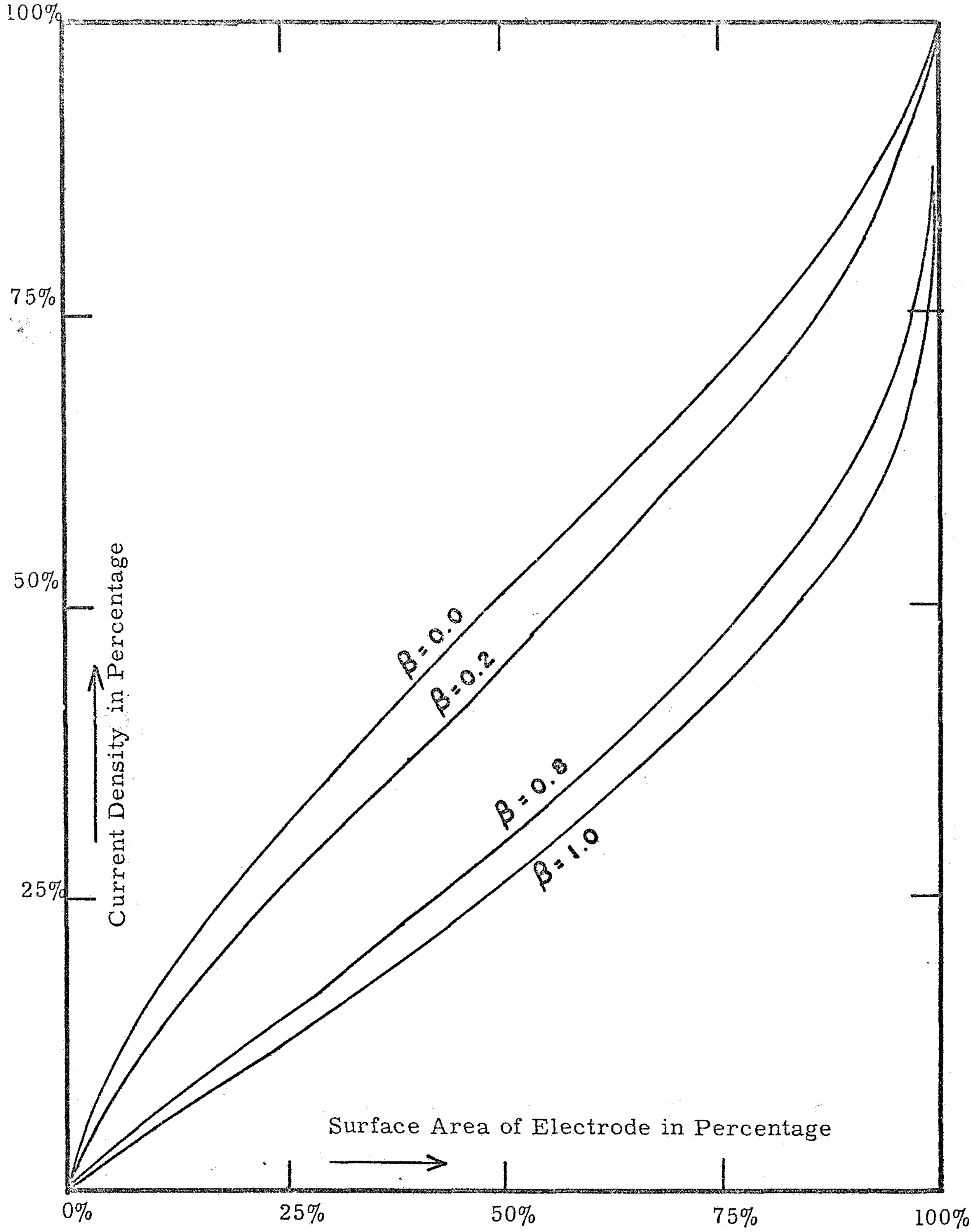

Fig. 15 Current Distribution Along the Electrode Surface

6. RELAXATION PROCESSES IN A FLOWING PLASMA - (C. Yeh and J.A.F. Manning)

Preliminary studies are under way in order to decide upon the several configurations of discharges and arcs to be used in the pre-ionizer section of the channel. A theoretical and experimental study has been started into the factors involved in the relaxation of the plasma to the two-temperature state with and without pre-ionizer operation.

7. CHANNEL PERFORMANCE DIAGNOSTICS BY MULTI-ELECTRODE CONFIGURATIONS - (J.A.F. Manning)

A program of test runs using the existing electrodes connected in a variety of configurations is being set up. These will include connection in the Hall mode with shorting and near shorting of the Faraday current and connection in the Hall mode with all electrode pairs connected in series with each other so all Faraday currents are identical.

8. SPECTROSCOPIC AND PHOTOGRAPHIC DIAGNOSTICS - (C. Hersom and A. Rosen)

Preliminary calculations have been performed on line strengths expected in the plasma. The design of an optical scanning system is under way for a spectrometer/spectrograph.

9. PROBE DIAGNOSTICS AND ELECTRODE INSTRUMENTATION - (Miss M. Ferguson)

A voltage and current recording system for the electrodes was designed and partially constructed (Section 6, Appendix 3). Construction was completed and the system has been tested satisfactorily. Further work has centered on an experimental study of probes which is about to begin.

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APPENDIX 1

FIRST SEMI-ANNUAL PROGRESS REPORT ON

OPERATION OF THE

UTIAS MGD POWER GENERATOR

Dec. 1, 1965 to May 30, 1966

APPENDIX 2

SECOND SEMI-ANNUAL PROGRESS REPORT ON

OPERATION OF THE

UTIAS MGD POWER GENERATOR

June 1, 1965 to Nov. 30, 1966

APPENDIX 3

THIRD SEMI-ANNUAL PROGRESS REPORT ON

OPERATION OF THE

UTIAS MGD POWER GENERATOR

Dec. 1, 1965 to May 30, 1967

APPENDIX 4

TEXT OF A PRESENTATION TO THE
SUPERSONIC TUNNEL ASSOCIATION,
29TH SEMI-ANNUAL MEETING
U.S. NAVAL ORDNANCE LABORATORY
WHITE OAK, MARYLAND

ASPECTS OF A BLOWDOWN SUBSONIC PLASMA TUNNEL

by

Stanley J. Townsend
Assistant Professor
Institute for Aerospace Studies
University of Toronto

ABSTRACT

The design features of a 3-MW, blow-down plasma facility are described. The primary aim has been to construct a facility having a large interaction channel to emphasize volume rather than surface effects. Independent control of flow velocity, static pressure, static gas temperature and magnetic field in the channel can be achieved over a wide range of operating conditions. Static pressures are achievable from a few Torr to over seven atmospheres, stagnation temperatures up to 2200-2500°K and magnetic fields up to 1.7 Tesla. Provision has been made for the addition of radial or vortex-flow channels on a separate outlet of the main heater at a later date.

Instrumentation of a constant-area channel, 5 cm x 10 cm x 120 cm, to measure the voltage and current characteristics of up to fifty electrode pairs has been completed. First runs are expected in the summer of 1968.

INTRODUCTION

With the advent on the Canadian scene of nuclear power reactors producing electricity at costs below those of coal-burning stations, advanced power conversion schemes for nuclear reactors are worthy of increased attention. With the added incentive of the likely demand for large amounts of electrical power in space, particularly for propulsion purposes, it was decided to initiate a research program into magnetohydrodynamic (MHD) power generation. The present study involves the simulation of a portion of a closed cycle system involving a high-temperature, gas-cooled reactor. More properly, then, we should call it magnetogasdynamic (MGD) power generation.

A large number of the earlier experiments in MGD power generation were performed in small scale devices dominated by surface effects such as boundary layers filling most of the channel and radiation losses to the walls from the hot plasma. Accordingly, it was decided to construct a facility which would simulate a small scale nuclear reactor at the megawatt level. This power level is adequate to study the behaviour of a dense, seeded flowing plasma in a rather large interaction channel; surface effects no longer predominate over volume effects. Hence, some rather basic studies can be performed on the plasma.

The use of nuclear reactors as heat sources will involve the use of non-equilibrium ionization to keep the plasma conductivity high. An elevated electron temperature must be maintained while keeping the carrier gas temeperature low to minimize heat transfer to the walls. Thus, a two-temperature plasma is involved. The relatively weak coupling of the electron gas to the atomic species can give rise to electrothermal instabilities, with large scale fluctuations in electron number density.

Of particular interest is the gross behaviour of the plasma in a magnetic field when electrical power is either being extracted in the power generator mode or is being fed in during the accelerator mode.

MAGNETOGASDYNAMIC FACILITY

Figure 1 is a schematic layout of the MGD facility. A blow-down system was chosen in order to provide a plasma flow through a channel having a large cross sectional area. Length of operating time was sacrificed in the interests of a larger power flow. Even so, one to two minutes of plasma flow gives ample time for almost all experimental procedures of interest to be performed. This is particularly true if one preheats the channel and electrodes to near operating temperature before the plasma flow starts.

The pressure gradient between the upstream heater and downstream vacuum sphere is used to accelerate the plasma to the desired Mach number.

The Mach number can be set subsonically by controlling the ratio of stagnation to static pressure. Supersonically, individual isentropic nozzles and proper diffuser recovery techniques must be employed. By choosing a particular value of stagnation pressure in the heater, which can be set independently by a regulator, any desired value of static pressure in the channel can be achieved. By choosing a particular value of the stagnation temperature in the heater, which can be set independently by a pyrometer, any desired value of static temperature in the channel can be achieved. Thus, in the gasdynamic sense, there is independent control of velocity, pressure, temperature and hence density, over a very wide range of operating parameters. Figure 2 shows the upper limit of mass flow rate and static pressure through the 50 cm^2 initial channel. The calculations were done for $T_o = 2500^oK$. The lower limit of static pressure is well below 76 Torr, since the vacuum sphere can be evacuated to at least 2 Torr. The possibility then exists for studies of ion slip at low pressures.

The MGD channel is situated between the pole faces of a large iron C-magnet that can be operated at any value of magnetic field from 0 to 1.7 Tesla.

The plasma exits from the interaction channel, enters a diffuser, and subsequently is cooled down in a pebblebed heat exchanger. The gas flow is then scrubbed of the alkali seed without any attempt at recovery. The cool, scrubbed gas is then discharged to the vacuum sphere. The sphere has a capacity of slightly less than 1000 m^3.

Figure 3 shows a close-up view of the experimental region.

INERT GAS HEATER

The inert gas heater was designed on the heat-sink principle, using a core of graphite. Figure 4 is a diagram of the stagnation heater. The outer steel shell, water-cooled, is 1.37 m in diameter and 2.74 m in height and is designed to operate at a rated pressure differential of 100 psig, just under 8 atmospheres absolute. Within the steel shell there is 12.7 cm layer of alumina fibre insulation, surrounding another layer of 7.5 cm of graphite felt. These two layers of high-temperature insulation sheath the graphite core of the heater.

The core was machined from a solid rod of graphite 0.9 m in diameter and 1.8 m long. This graphite assembly contains an outer annulus in which three radiant-heating graphite electrodes are situated at 120^{o} intervals. They radiate upon the inner core which is a pebble bed 0.45 m in diameter and 0.85 m high. 3-Phase, AC power is supplied to the three electrodes in a Y-connection; the power dissipation is about 150 kW. The heater has been tested to $1700^{o}K$ so far. Since the temperature was climbing at $200^{o}K$ per hour, it can be inferred that the thermal insulation is probably adequate for about $2200^{o}K$. With more graphite felt insulation, $2500^{o}K$ is probably achievable.

The inner core houses a bed of pebbles made out of 1.9 cm diameter rod cut into right cylindrical chunks. The cost of this bed was about 1/20 that for spherical pebbles with no significant sacrifice in heat transfer ability.

The gas flow enters at the top and proceeds down the outer annulus, in through two 10 cm holes in the side of the bottom heater, up through a slotted grate, through the pebbles, into the top plenum chamber where it is mixed with the alkali seed and then accelerated to the desired Mach number in a nozzle.

Temperature control of the heater is accomplished by a two-temperature, infrared pyrometer viewing the bottom current-ring. This ring is the "unipotential" junction connecting the three heater elements.

An emergency water recirculation cooling system capable of dissipating 145 kW has been constructed. It will allow safe cooling of the heater in the event of an unexpected interruption in water or electrical service to the laboratory.

A second outlet hole has been bored into the top plenum chamber to allow the addition of a second outlet pipe. A radial-flow or vortex-flow MGD channel could be installed on this outlet at a later date after a superconducting magnet is acquired.

SEED INJECTION AND REMOVAL SYSTEM

Figure 5 shows a schematic diagram of the seed injection system. The alkali seed is drawn into a stainless steel bellows from which it is driven by positive-displacement into a boiler. The flow of liquid NaK is metered by controlling the speed of a variable-speed motor. The boiler is maintained at 1100-1200°K. The seed vapour is passed through a 2.5 cm stainless steel pipe into the plenum chamber of the inert gas heater. Care is taken that no seed condensation occurs in this line.

The seed injection system can use any of Cs, K, or NaK-90. The seeding ratio can be varied from zero to over 1 mole per cent for up to a 3 kg / sec argon flow. The operating time would be about one minute at this high rate and longer at lower rates.

Seed removal is accomplished by washing down the cold gas flow emerging from the downstream heat exchanger with alcohol (ethanol or preferably amyl alcohol for its low heat release) to form a harmless potassium compound. This compound is then flushed away with water to a settling tank. Because of the low cost of NaK-90 (90% potassium - 10% sodium liquid metal) no attempt is made to recover the seed. The primary interest lies in preventing embrittlement of the steel in the downstream piping and vacuum sphere.

ELECTROMAGNET

Figure 3 is a photograph of the electromagnet and the MGD channel. A C-lamination was used in order to provide ease of access for spectroscopy experiments and for electrode and probe connections. The dimensions of the gap were set at 15 cm x 25 cm in a plane normal to the plasma flow. This accommodated the first channel of 5 cm x 10 cm inner dimensions. The length of the magnet was chosen to be 1.25 m, of which 1.0 m gives a uniform field region. The magnetic field of 1.7 T is uniform to $\pm$ 0.25% over the channel area and to $\pm$ 0.1% over the one meter length. A long, uniform interaction region was desired to permit relaxation studies of non-equilibrium ionization.

The magnet body consists of a stack of twenty-five 10 cm mild steel plates flame cut to the desired cross section. The 10 cm thick pole faces are of machined, annealed mild steel and are removable. They can be replaced by thinner and/or tapered pole faces to allow for a larger channel.

The coils were wound from extruded aluminum conductor, 1.15 cm square with a 0.63 cm I.D. hole for water cooling. Electrical power requirements are 137 volts per coil at 834 amperes from a bank of heavy-duty truck batteries. The rate of collapse of the magnetic field is controlled by crowbarring with a large diode (IN4054R).

INITIAL CHANNEL

Figure 6 shows a pictorial view of one of six sections of the MGD channel. Inner dimensions are 5 cm in the B-field direction and 10 cm in the $\underline{U} \times \underline{B}$ direction. A simple constant-area channel was chosen to be constructed first. Data gathered on boundary layer growth will be used to design a constant Mach number channel. Each section of channel is 30 cm long. Upstream and downstream sections are being instrumented for velocity profiles. One upstream section is being modified to operate as a pre-ionizer. One section of channel has been fitted with four voltage-sensing proves to measure Faraday and Hall voltage gradients.

INSTRUMENTATION

An electrical recording system has been constructed to record automatically voltages from up to fifty pairs of electrodes. A switching circuit can scan all the electrodes over a period that can be varied from one to ten seconds. The output voltages are fed into a 100k buffer amplifier and are then recorded on a high-speed, oscillograph. During a 60 to 120 second run, there is ample time to achieve steady state conditions, perform all D. C. measurements, change load resistors or electrode configuration by relays and then to proceed with further measurements.

In conjunction with the experimental work being performed, theoretical calculations of the electrical conductivity in the channel are being carried out. Calculations of electron number density and temperature elevation above gas temperature for the bulk plasma are also being done. In addition, a detailed study of the variation of these quantities throughout the volume of the ~~MGF~~ CHANNEL is proceeding.

Preliminary testing of most of the components has been carried out. The heater has been tested to 1700°K and has performed flawlessly. The magnet has been checked for proper crowbarring action. A preliminary field survey was performed at low field levels and the uniformity appears to be somewhat better than computer calculations predicted. The NaK boiler burned out its first graphite cloth heating element due to oxidation; it has now been replaced with Nichrome elements. It will be taken up to temperature shortly and tested out. The seed removal system is the only major sub-system yet to be tested.

It is expected that the last of the preliminary testing can be done in May-June, 1968. The first MGD runs are expected in July, 1968.

ACKNOWLEDGEMENT

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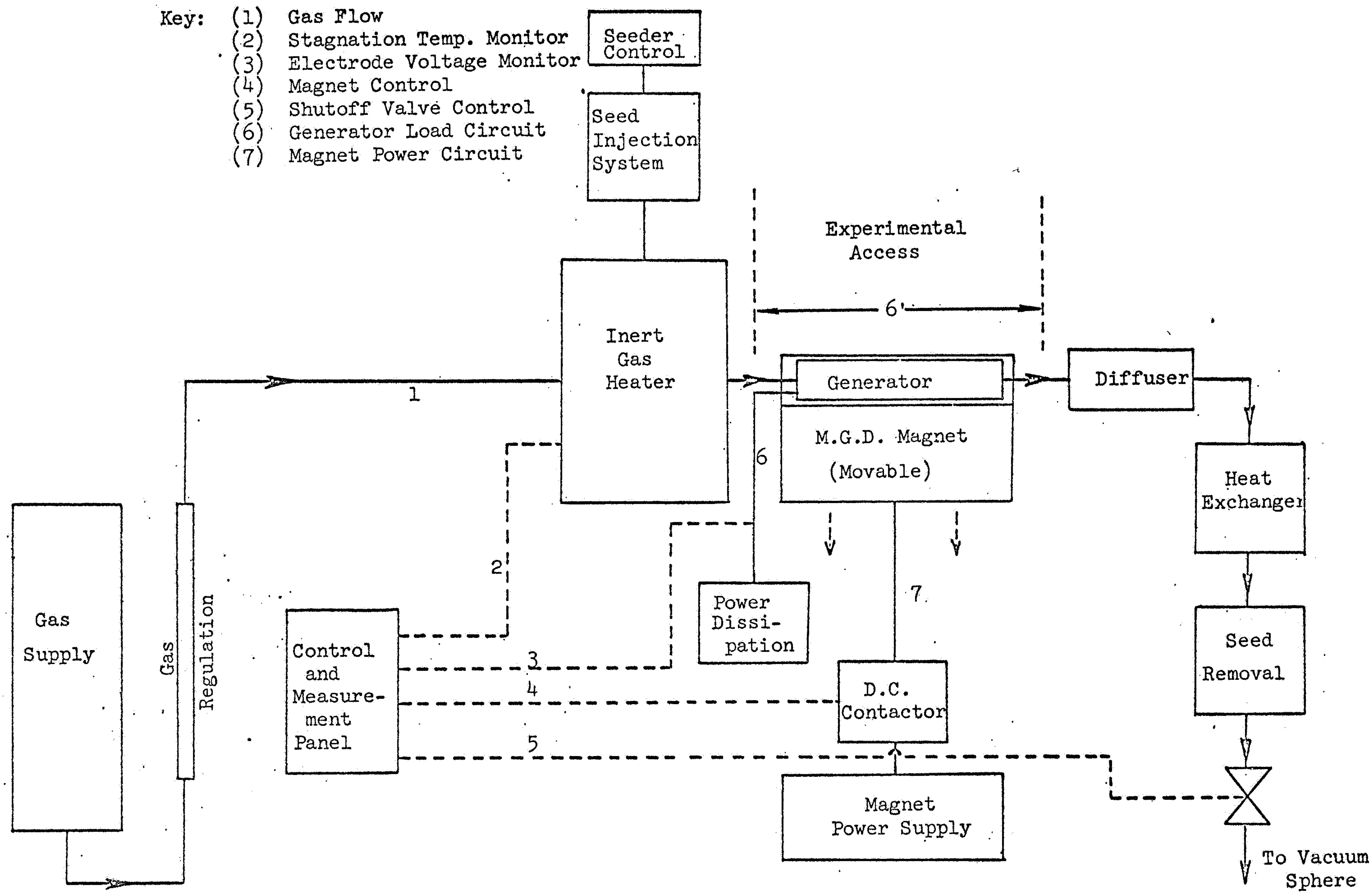

FIG. 1. LAYOUT SCHEMATIC OF M.G.D. GENERATOR FACILITY

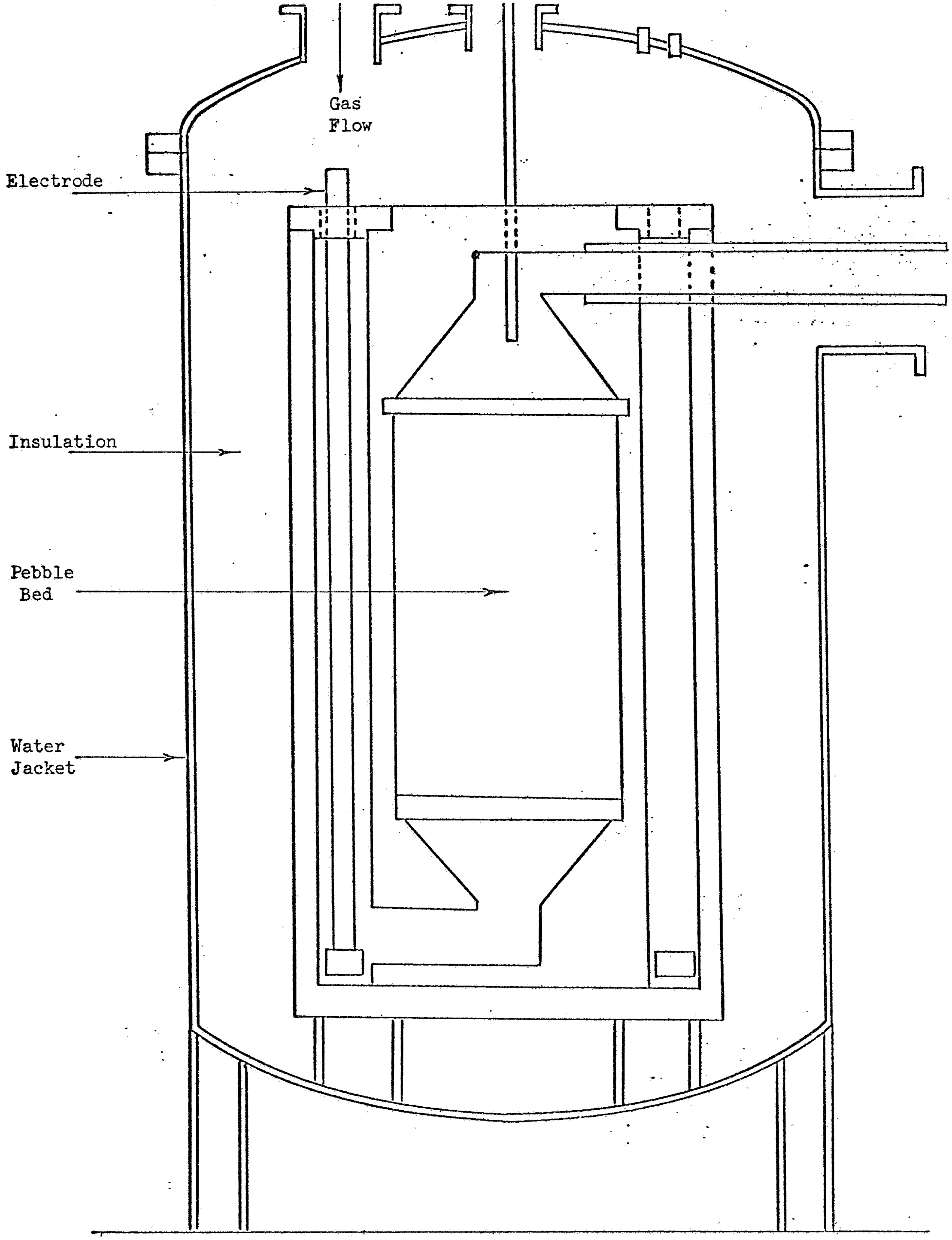

FIG. 3 CROSS-SECTIONAL VIEW OF THE INERT GAS STAGNATION HEATER

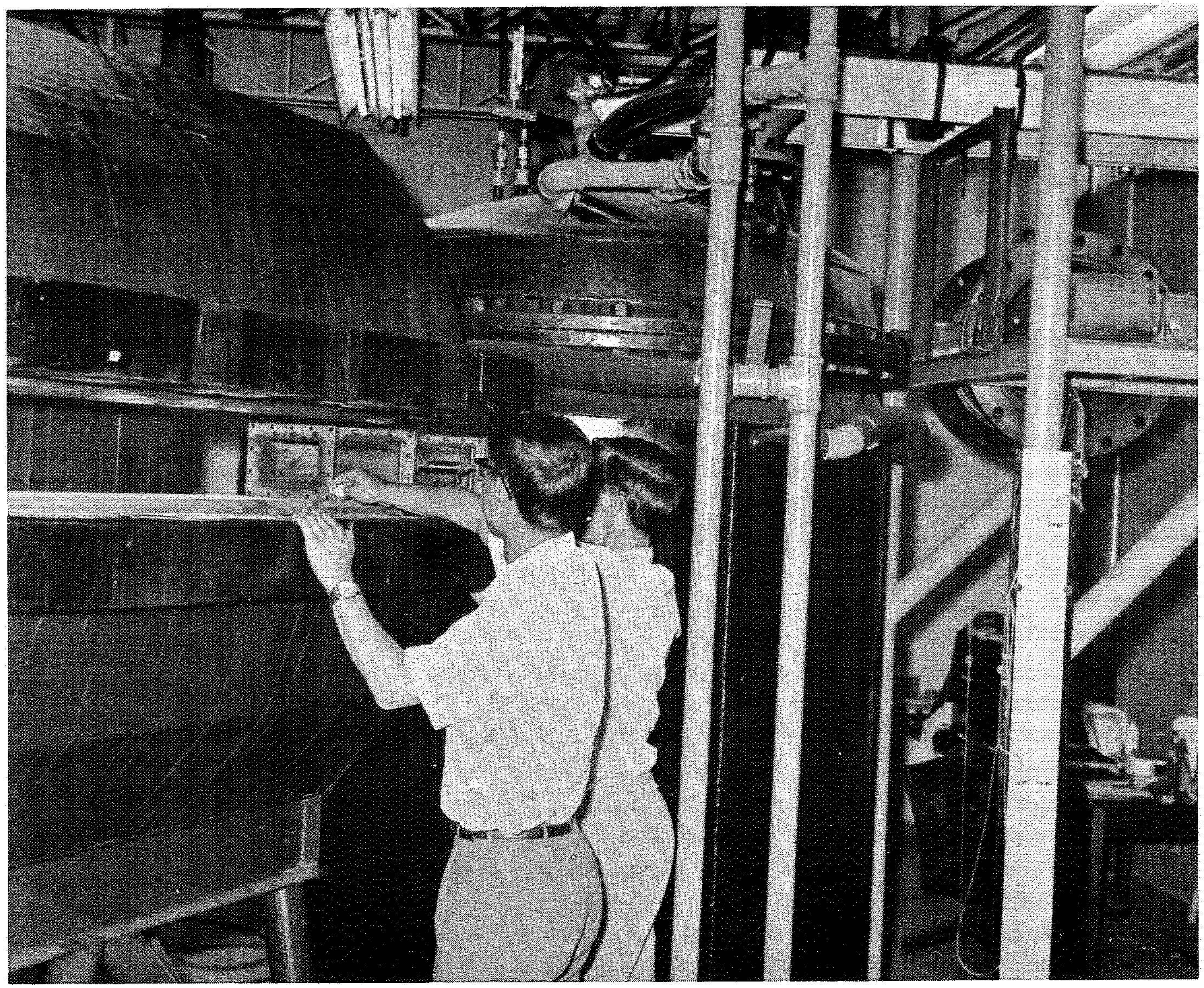

FIG. 3 a OVERALL VIEW OF MAGNET, MHD CHANNEL, HEATER AND SEEDING UNIT.

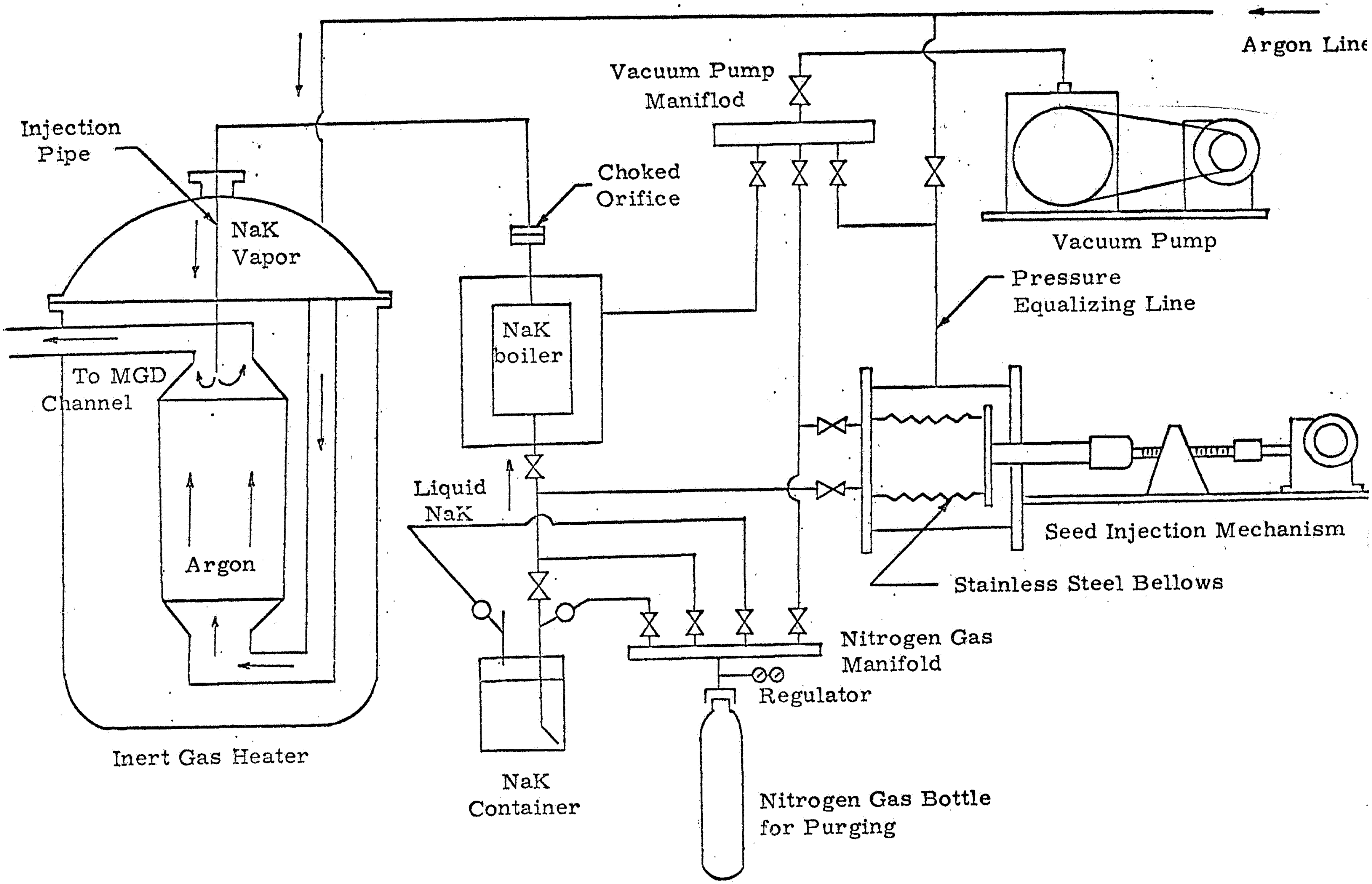

FIGURE 15. SEED INJECTION SYSTEM.

FIG. 5 INITIAL CHANNEL DESIGN: SEGMENTED ELECTRODE FARADAY GENERATOR

(Composite View of One of Six Identical Sections)