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A SURVEY OF MAGNETOHYDRODYNAMIC ELECTRICAL POWER GENERATORS

TECHNICAL REPORT
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INTRODUCTION

This technical report has been prepared as part of a contract on Energy Transfer Problems in Superconductors and Flowing Plasmas. The report presents a survey of magnetohydrodynamic power generators in this country and abroad.

The work was supported by the Army Missile Command (Huntsville) under contract DA-01-021-AMC-12820 (Z).

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1. GENERAL INFORMATION

1.10 Introduction

The generation of electrical power by magnetohydrodynamic methods can be achieved by the interaction of electromagnetic fields with flowing electrically conducting fluids. The basic principles of induction, on which this process of direct conversion of thermal energy to electrical energy is based, were established by Faraday in the 19th century. At the time of his formulation of the laws of electromagnetic induction, Faraday proposed the use of the River Thames as a source of electrical power.[1] He lowered a pair of electrodes from Waterloo Bridge, London, into the river in an attempt to measure the induced voltage that would arise from the flow of the river through the earth's magnetic field. The experiments were inconclusive due to insufficient magnetic field strength, insufficient fluid velocity and fluid electrical conductivity, and ineffective electrodes.

The first reported attempt to actually develop an MHD generator seems to have been by B. Karlowitz and his associates at the Research Laboratories of Westinghouse from 1939 to 1947.[2,3] In order to investigate the possibilities of an MHD generator, Karlowitz and his associates designed and constructed a generator with combustion products as a working medium and carried out several experiments. Because of the low temperature and low conductivity of the gases, the currents drawn from the generator were exceedingly small, even though electron beams and other devices were used to improve the ionization. These early attempts by Karlowitz showed that MHD generation was not practical at that time.

Later, in the 1950's, as a result of plasma studies in controlled fusion and missile re-entry work, a greater understanding of high temperature gases was achieved and this led to renewed efforts to achieve electrical generation by gas MHD methods. Similar advances in conducting liquid studies stimulated new work in liquid MHD generation. By 1959, Sporn and Kantrowitz published a paper presenting a design study for a 500 MW power station.[4] Estimates were made of the total investment and running costs, and a variety of technical problems were discussed. As a result of the increased interest in MHD power generation, a DC gas MHD generator was designed and built by R. F. Rosa, in 1960, at AVCO-Everett Research Corporation.[5,6,7] Experiments were run to investigate some of the basic principles of operation, the aspects of seeding, and the Hall effects. The generator produced 10 KW of power with an operating time of 10 seconds and the results indicated that for the most part the theoretical considerations were correct.

Since then, the number of investigations of magnetohydrodynamic power generation has increased very rapidly and several extensive studies involving both theoretical and experimental considerations have been completed. Aside from the considerable amount of work reported in scientific journals, several symposiums on magnetohydrodynamic power generation have been held in the United States,[8-13,124] and in other countries. For example, international symposiums have been held in England[14] and in France.[15]

In this survey, emphasis has been given to the description and reporting of work concerned with the various types of MHD generators rather than to the advances of materials study for the generators or the integration of the generator into the overall power plant scheme. These associated studies have been mentioned only briefly.

The survey is presented in two sections: the first deals with DC and the second with AC MHD generators. The basic principles of operation

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together with some of the performance data are given for the generators discussed. The present operating status is presented together with the predicted developments.

2. DC MAGNETOHYDRODYNAMIC POWER GENERATORS

2.10 Introduction

The fundamental DC MHD generator, shown in Figure 1, is constructed around a duct, through which the conducting fluid flows. A steady magnetic field is placed orthogonally to the flow direction and also orthogonally to the electrodes. As the fluid moves through the magnetic field, the basic generator interaction takes place and a potential difference develops at the electrodes.

The generator shown in Figures 1-3 are channel direct current generators, the simplest and most widely investigated of the various types of MHD generators. At present DC MHD generators seem to be the most promising type for the large scale generation of commercial power. When combined with conventional steam generating plant, the MHD-steam turbine combination could theoretically increase the overall conversion efficiency to approximately 50% compared to an upper limit of approximately 45% that may eventually be realized with steam plant alone. Several MHD-steam turbine plants have been designed and reported in the literature.[9-15]

Another possible use of MHD generators is generation of large amounts of power for short periods of time, e.g., a few microseconds up to several minutes. Generators specifically for this use have been designed or constructed which operate with combustion gases or the detonation of a seeded explosive product.

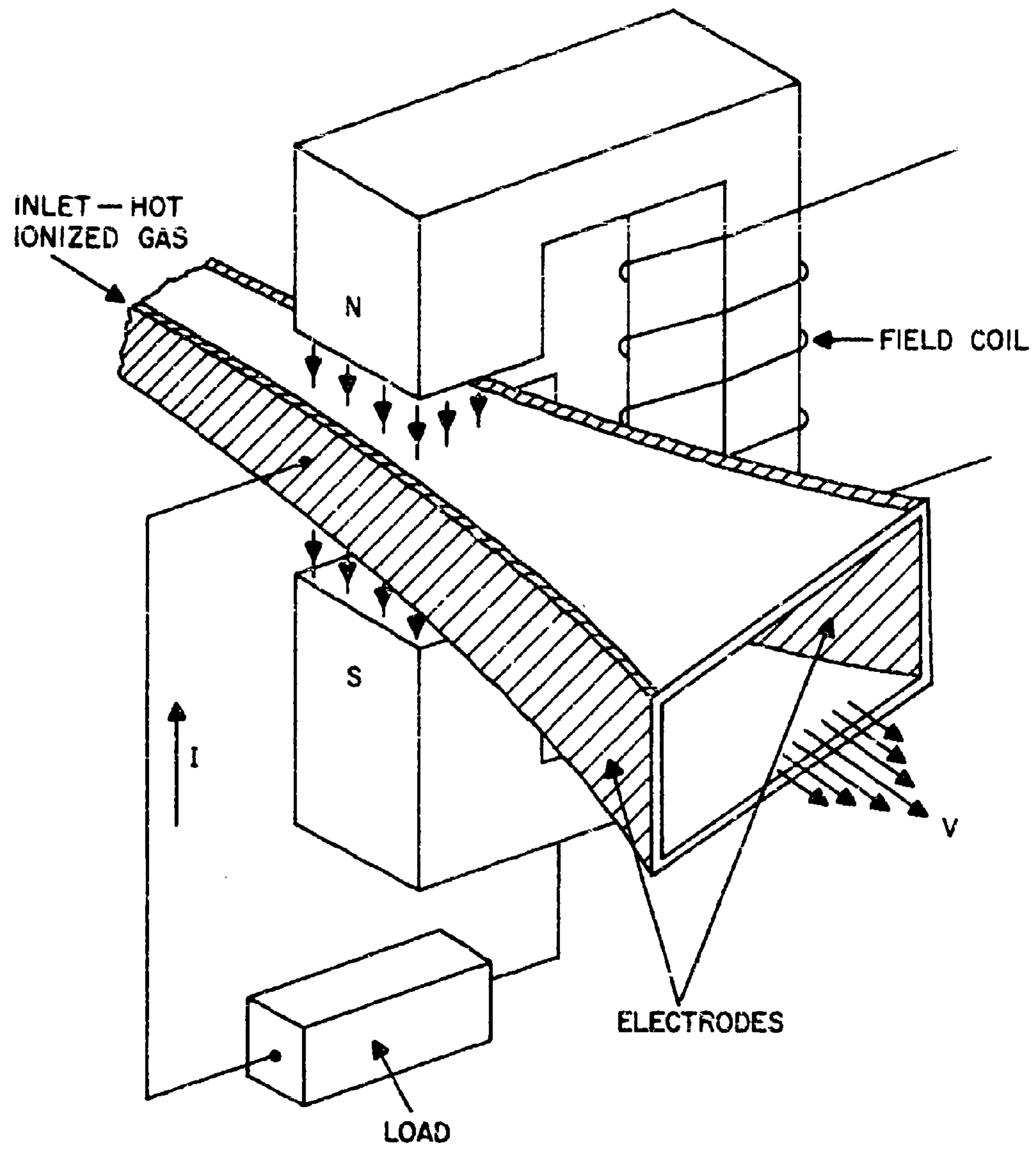

FIGURE I. D-C Channel MHD Generator — Continuous Electrodes

2.20 Linear DC MHD Generators

There are two basic variations of linear DC MHD generators (shown in Figures 1-3) which are distinguished by the mode of operation. These generators either operate as Faraday (conduction current) generators or they operate as Hall (Hall current) generators.

2.21 Continuous Electrode Generator

With the continuous electrode generator of Figure 1, the Hall coefficient $\omega\tau$ must be in the range $\omega\tau < 1$ (where ω = electron gyrofrequency and τ is the mean free time between collisions for an electron). Under these circumstances the net electron current is perpendicular to the gas flow and a voltage is developed across the electrodes. For $\omega\tau > 1$, the electron current is no longer perpendicular to the gas flow and a component of current exists along the flow because of the Hall effect. With the continuous electrode geometry these currents cause additional losses in the electrodes.

2.22 Segmented Electrode Generator

For the range $1 < \omega\tau < 10$, the segmented electrode configuration of Figure 2 avoids the losses which would result from the additional currents if continuous electrodes were used. The axial current flow is supressed by segmenting the electrodes, and pairs of segments are connected through separate external loads. Cross connection of some of the electrodes has also been suggested by Dzung,[16] and series connections have been discussed by de Montardy.[17] The segmented electrode configuration seems to be the most feasible generator within present technology, although it does have the disadvantage of the distributed loads.

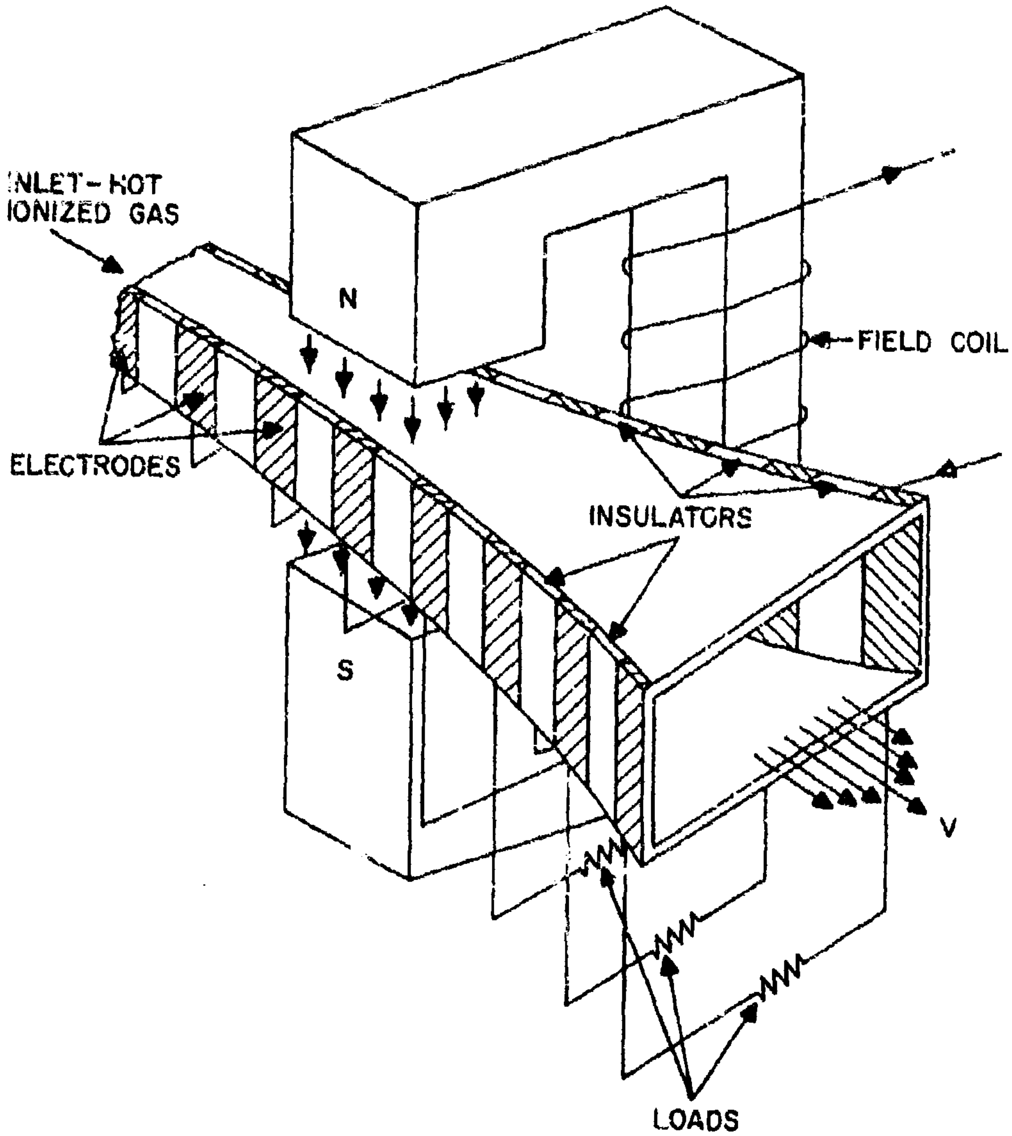

FIGURE 2. D-C Channel MHD Generator — Segmented Electrodes

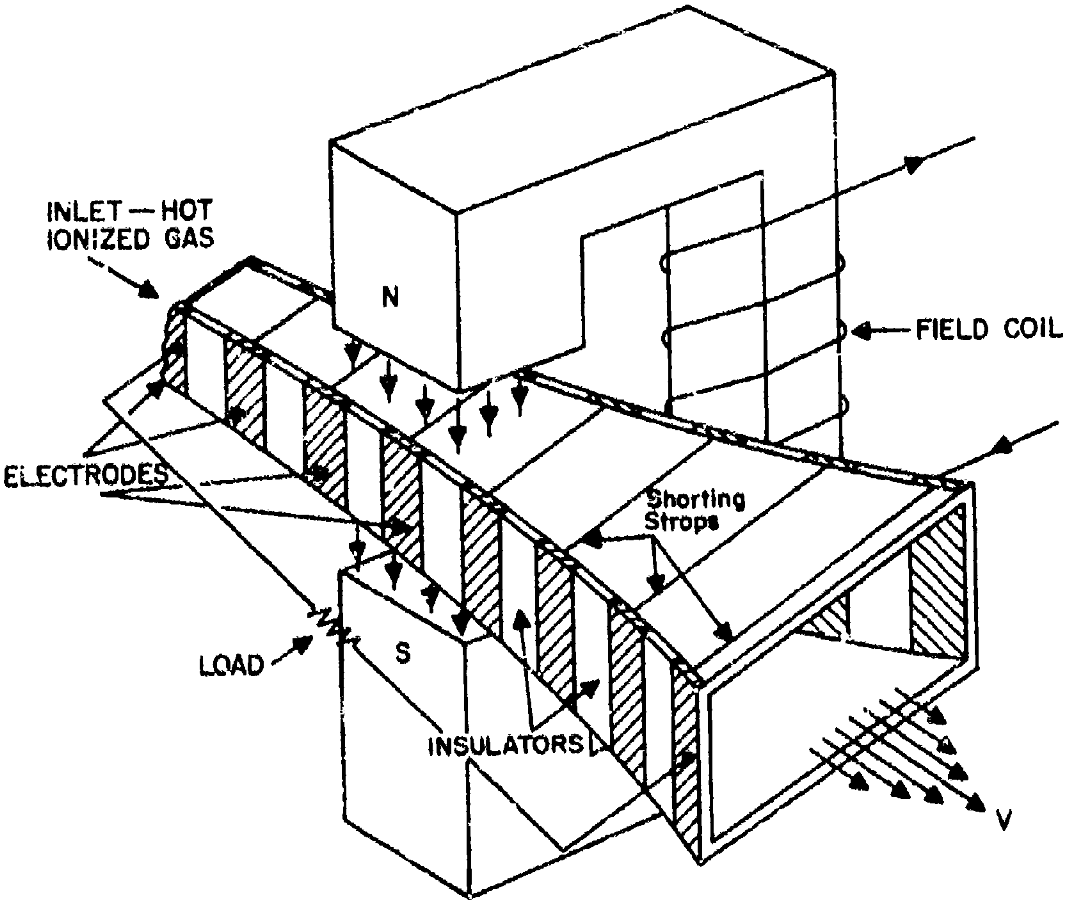

FIGURE 3. D-C Channel MHD Generator — Hall Type

2.23 Hall Generator

If $\omega\tau > 10$, the net electron current is almost entirely in the flow direction and a potential difference is established between the ends of the duct as shown in Figure 3. This type of generator is called a Hall generator since, unlike the preceding two, it relies entirely on the Hall current for its operation. In the construction of the generator, the electrodes are also segmented but each pair is short circuited except for the pairs nearest the inlet and outlet.

2.24 Performance Characteristics of Linear MHD Generators

The various performance characteristics of the three types of linear MHD generators have been discussed by Sutton,[18] Croitoru,[19] Lindley,[20] Kowbasiuk et al,[21] Harris and Cobine,[22] Celinski,[23] Coombe,[112] Sutton and Sherman,[113] and others. Idealized theoretical expressions for the power density, open circuit electric field, short circuit current density, and local efficiency for the above three ideal cases have been summarized in Table I for each of the three configurations. The quantities in this table were derived under simplified conditions assuming conductivity, density, velocity, Hall parameter, etc. constant, and neglecting such effects as thermal boundary layers, viscosity, electrode losses, etc. More information about the calculations and assumptions is given in references cited above.

Figures 4-6 also indicate the power density and efficiency for each case for several values of the Hall coefficient $\omega\tau$.

In addition to the electrode configurations several flow possibilities have been considered, e.g., constant velocity, constant temperature, etc., some of which have been investigated by Neuringer,[24,25,26] Way,[27,28] Ralph,[29] Swift-Hook,[30] etc.

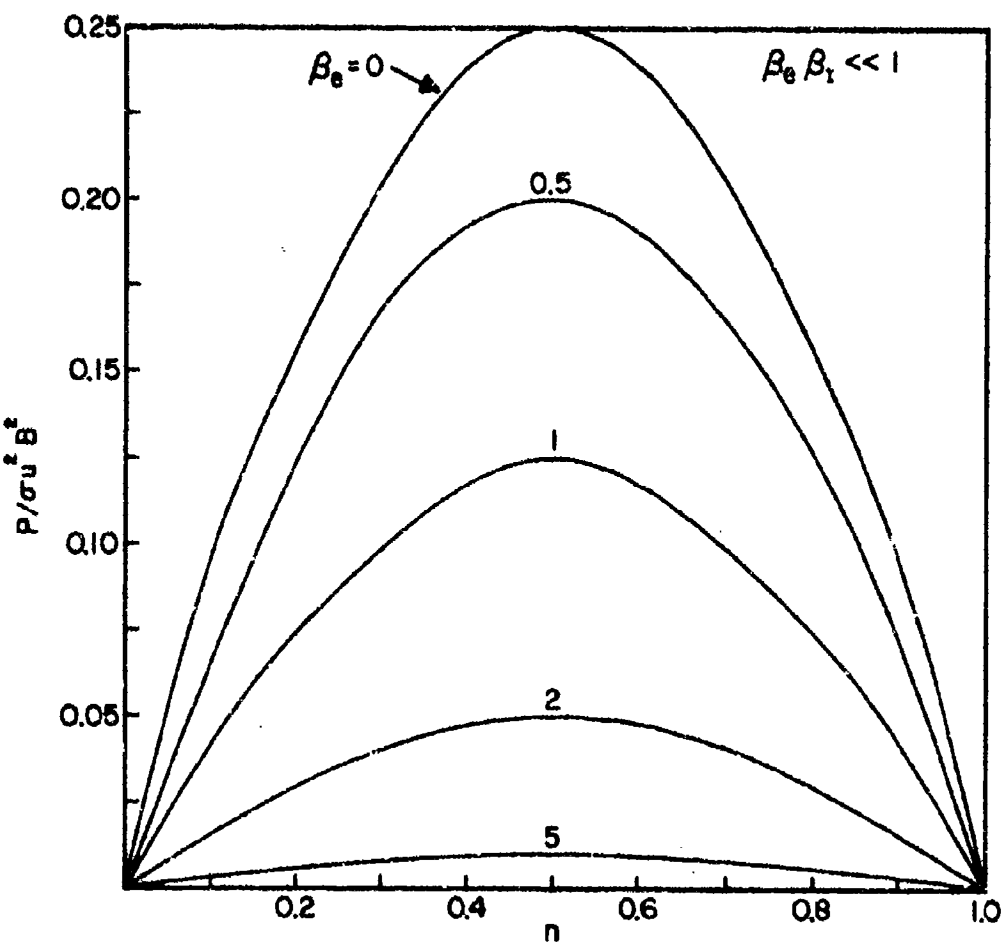

FIGURE 4.
Power and Efficiency for Continuous Electrode Generator

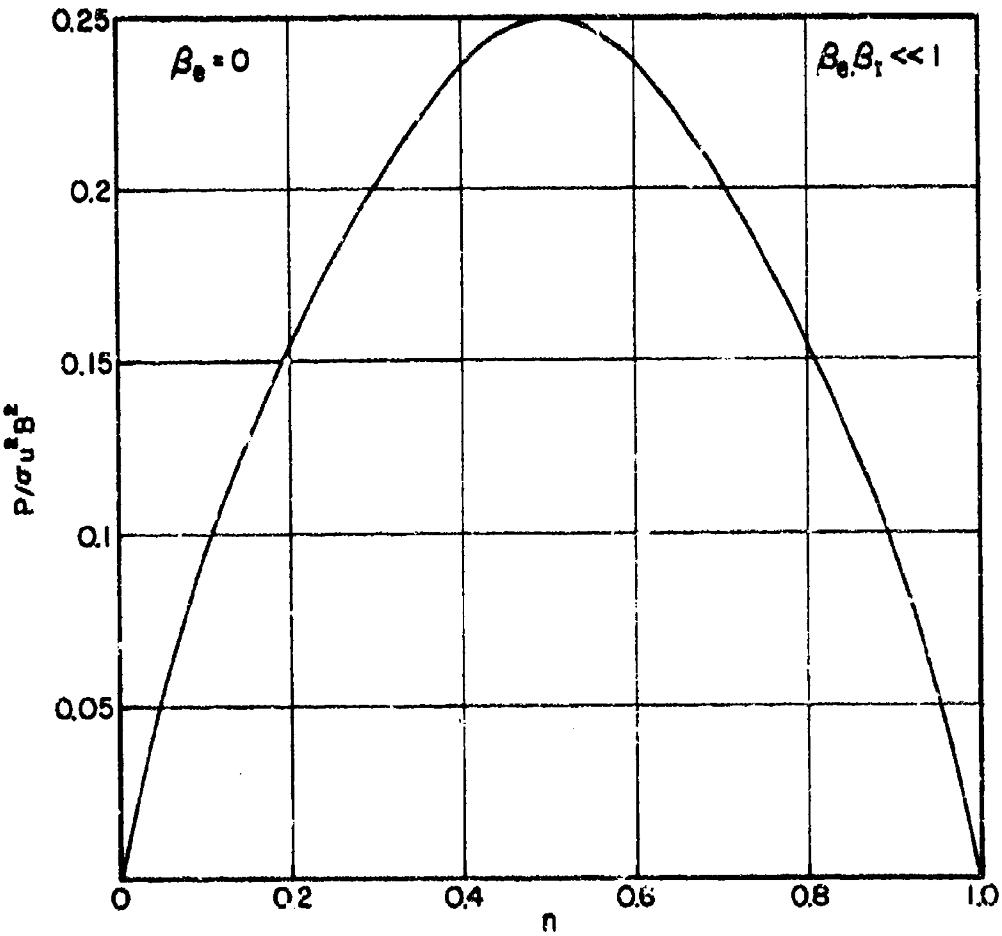

FIGURE 5.
Power and Efficiency for Segmented Electrode Generator

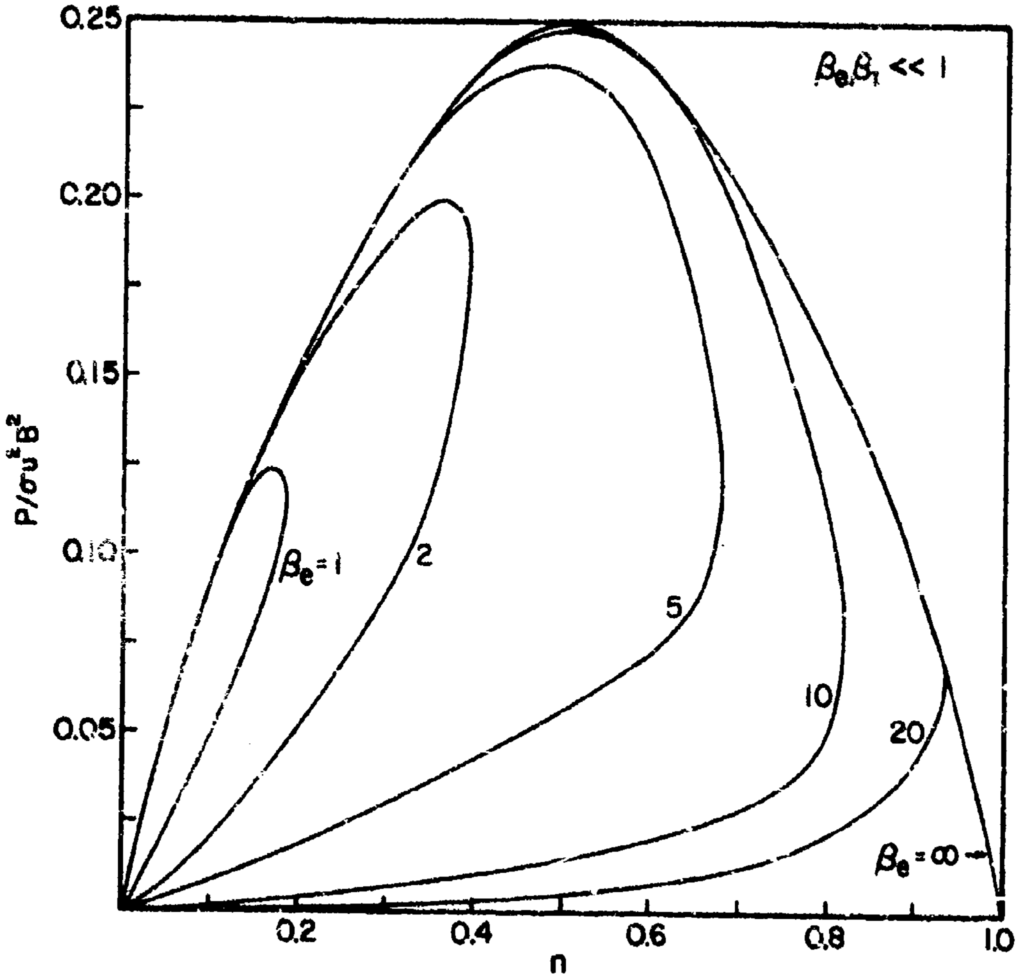

FIGURE 6.
Power and Efficiency for Hall Generator

Table I*

Parameters	Units	Generator Type: Continuous	Segmented	Hall
Open Circuit Field	Volt/m	UB	UB	$\frac{\beta_e}{1+\beta_i\beta_e}\, UB$
Short Circuit Current Dens.	Amp/m^2	$\frac{1+\beta_i\beta_e}{1+\beta_e^2}\,\sigma UB$	$\frac{\sigma UB}{1+\beta_i\beta_e}$	$\frac{\beta_e\,\sigma UB}{1+\beta_e^2}$
Power Dens.	$Watts/m^2$	$\frac{(1+\beta_i\beta_e)\sigma U^2B^2K(1-K)}{1+\beta_e^2}$	$\frac{\sigma U^2B^2K(1-K)}{1+\beta_i\beta_e}$	$\frac{\beta_e^2\,\sigma U^2B^2K(1-K)}{(1+\beta_e)^2(1+\beta_i\beta_e)}$
Local Conv. Efficiency	--	K	K	$\frac{\beta_e^2\,(1-K)}{1+K\beta_e^2}$

Where: U = gas velocity; B = magnetic field; σ = electrical conductivity; β_i = Hall coefficient for ions $= \omega_i\tau_i$; β_e = Hall Coefficient for electrons $= \omega_e\tau_e$; K = loading factor $= \frac{E_{transverse}}{UB}$.

*References 18-23.

2.30 Geometrical Considerations

In addition to the linear type of geometry with its variations, there are geometrical variations such as the coaxial generator[5] of Figure 7. This geometry was employed in the early experiments of Karlowitz.[2] As shown in the figure, the coaxial geometry requires operation as a Hall generator, and if the Hall coefficient $\omega\tau$ is not much greater than one, performance in this type of configuration will suffer.

Another variation is the vortex type of generator shown in Figure 8. A conducting medium is made to spiral outward or inward between two concentric cylinders which are located in a magnetic field. The resultant $\vec{V} \times \vec{B}$ force causes a current to flow between the two electrodes and into an external load. The analysis of this type of generator is complicated but a few investigations have been carried out.[31-35] It has received more attention lately as a possibility for a liquid metal MHD generator.[36]

The vortex generator operates on a conduction basis, that is, the interaction between the tangential velocity and the magnetic field produces a radial electric field and current flow. The generator can be modified so that the flow of gas is essentially radially outward as shown in Figure 9 and the current flow induced by the magnetic field is everywhere circumferential. With a strong enough magnetic field, Hall currents will be present in the gas flow direction and the generator can be operated as a Hall generator. This configuration has been considered for use as a non-equilibrium MHD generator,[37] using the fact that the strong induced currents will create joule dissipation in the gas and raise the electron temperature well above the mean temperature of the gas.

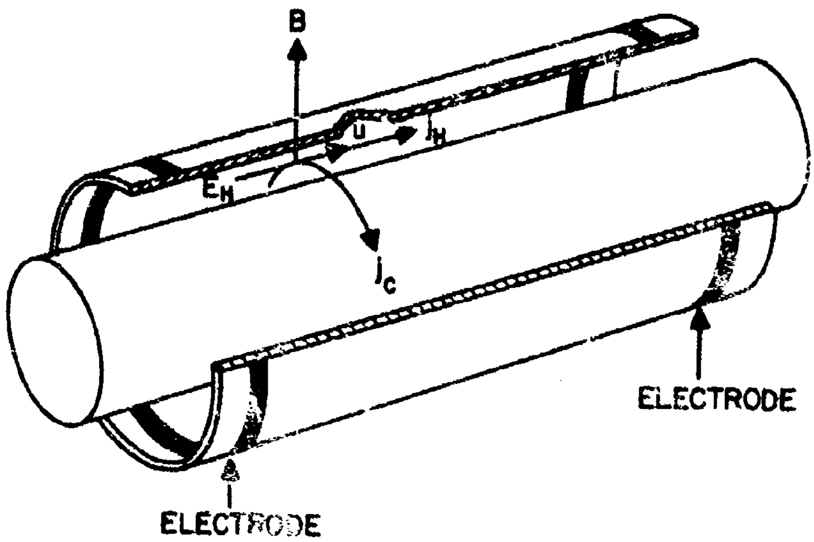

FIGURE 7. Coaxial MHD Generator

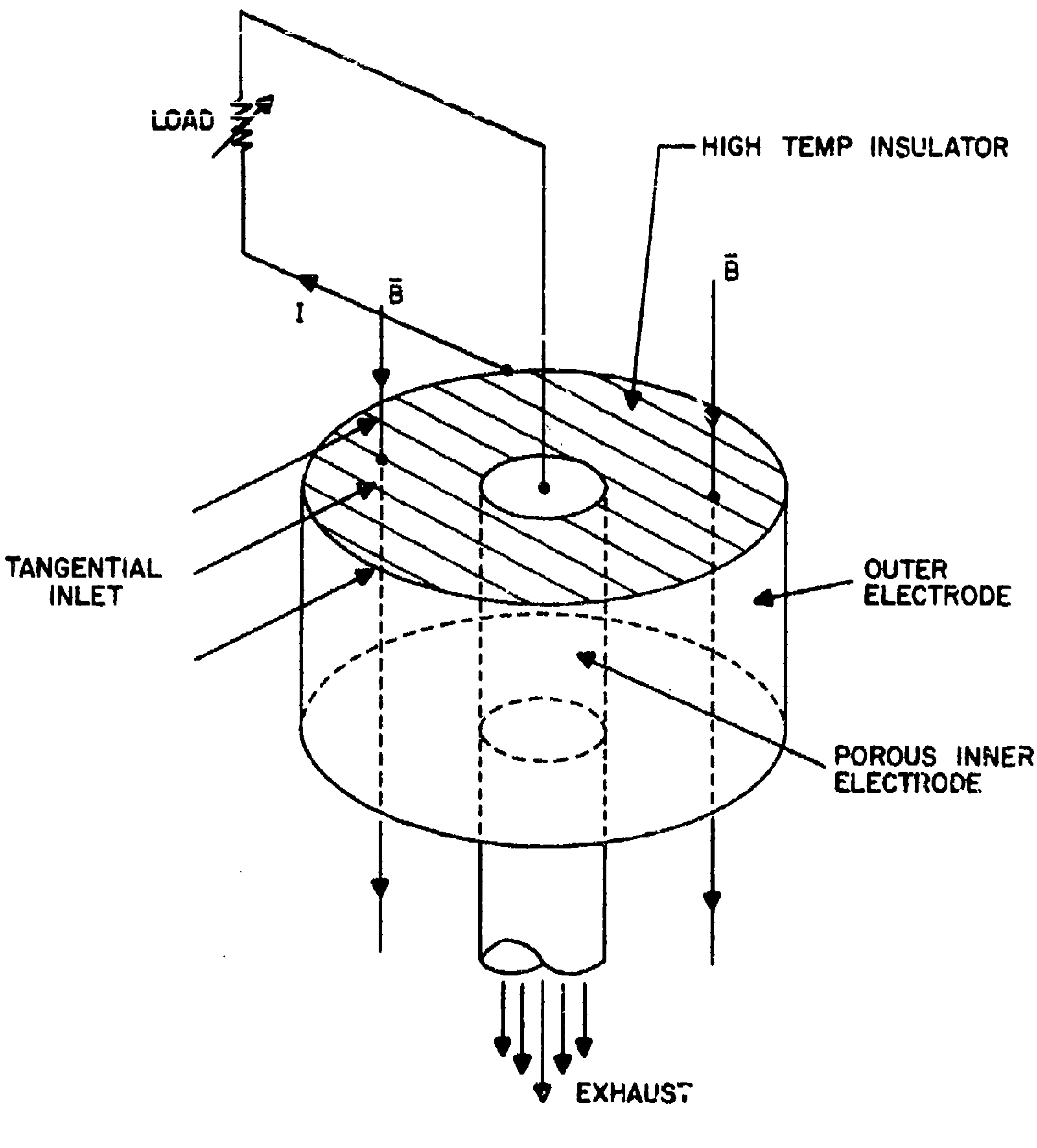

FIGURE 8. Vortex MHD Generator

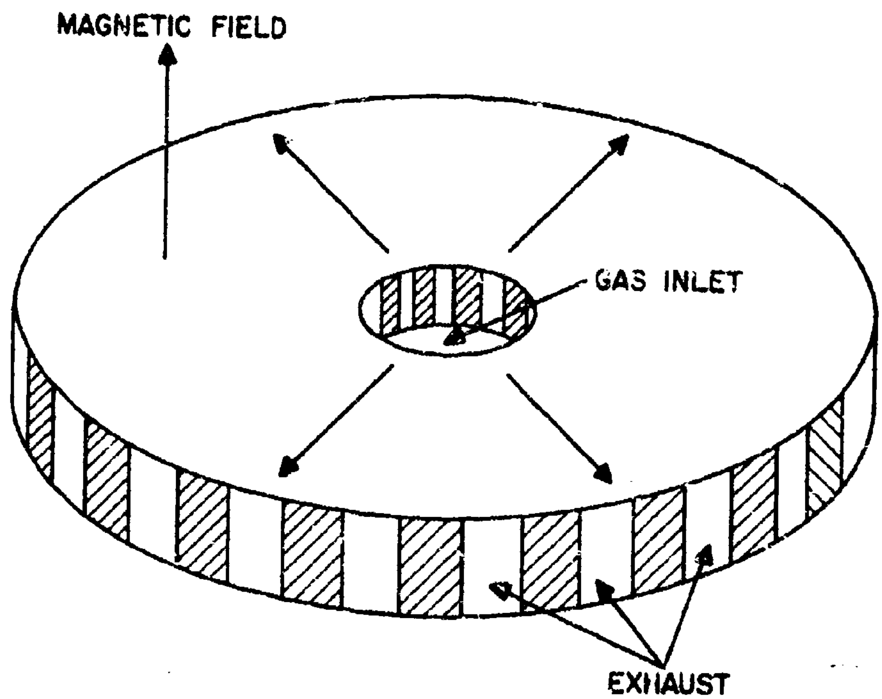

FIGURE 9. Radial Out-flow MHD Generator

The disk geometries, e.g. radial outflow (or inflow) and vortex types, appear to be well suited for magnetic field considerations whereas the coaxial geometry is probably the most difficult. In addition the coaxial geometry is the most disadvantageous from the point of view of heat transfer and viscous losses. The results of one study[111] also indicate that the disk geometry is inferior in performance to the linear generator.

For the most part, the linear geometry has been the most popular geometry for investigations. Not only does it have the advantage of its simplicity but also it has the ability to operate as either a Hall or conduction type depending on the Hall coefficient. In addition, the geometry permits an easier analysis when considering the aspects of variable velocity, temperature, etc.

2.40 <u>MHD Generator Experiments</u>

The first MHD generator experiments were those carried out by Karlowitz and Halasz[2] at Westinghouse up to approximately 1946. Because of a lack of knowledge of gas properties at that time the experiment failed to produce sufficient amounts of power, even though electron beams were used to enhance ionization.

The next experiments, perfomed in the late 1950's and early 60's utilized plasma jets as a thermal source, since the higher temperatures needed were not available from combustion flames. Way,[38] et al, performed the first combustion experiments in which over 10 KW of power was generated. Since then several experiments have been carried out utilizing combustion gases, the largest of which is the AVCO Mark V which has already delivered a gross power of 32 MW. The Mark V has been designed for short duration use and will produce approximately 40 MW from a thermal input of approximately 300 MW.[39] Other MHD experiments have also been carried out in England, France, Poland, Japan, and in the USSR.

2.41 Experiments in the United States

As mentioned above, several experiments with MHD generators have been successfully performed in the United States, and designs have been carried out for large and small MHD generators. For example, a preliminary design of 1000 and 250 MW generators for short duration use has been carried out by Pratt and Whitney Aircraft.[40] The generators have been designed to produced power for durations up to thirty minutes, with a total operating time of twenty-four hours. Although construction and operation of the generators has not been carried out, extensive experimental studies of materials, plasma, systems analysis, etc. have been conducted. Some of the design data for the 1000 MW generator has been summarized in Table II below.

Table II*

Fluid	JP-4 + 0.1% K + O_2
Inlet Dimensions of Channel	Height, 9.48 ft.; [illegible]th, 5.98 ft.; Length, 13.31 ft.
Mach No.	Inlet 3; Exit 1.52
Magnet Field Strength	3 wb/m^2
Cross Stream Voltage at Load	14,595 V
Axial (Hall) Voltage at Load	40,800 V
Gross Power	1300 MW
Net Power	1000 MW
Total Mass Flow Rate	1,649 lb/sec.
Energy Source	Combustion Chamber

*Reference 40.

Some of the experiments performed in the U. S. have been summarized in Table III along with some of the pertinent data cited in the references. The first successful unit was built by AVCO and reported by Rosa.[6] The generator was the segmented type driven by a 2.4 MW Argon plasma jet, with neither the jet nor the generator cooled to allow easy modification of the equipment. Although the operating life of the generator was limited, the experiments demonstrated that significant power could be generated from a moving plasma and, for the most part, that theoretical considerations were correct.

Similar experiments were carried out at the G. E. Space Science Laboratories by Foshag and Were[41] and by Sutton and Robben.[42] In the experiments of Sutton and Robben, the plasma source was a 2500 KW plasma jet with nitrogen as a working fluid. The results are shown in Table III.

At Westinghouse, Way,[38,43-45] et al., developed a combustion fired generator with an output of approximately 8 KW. Extensive studies of gas conductivities, materials problems, etc. have been carried out. Values for two experimental runs are also given in Table III.

A small MHD generator using continuous electrodes has been reported by Mullaney and Dibelius.[46] The generator was powered by a propane-oxygen burner and measurements of voltage-current data were obtained. It was found that the power output varied as the square root of the seed concentration.

Successful combustion experiments were also carried out by Blackman,[47] et al., at MHD Research Inc. with emphasis on the gas dynamic aspects of the duct. A segmented electrode configuration was used and voltage-current characteristics were obtained from five pairs of electrodes and losses from leakage currents, boundary layers, etc., were analyzed theoretically.

Table III*

Company	AVCO Mark I	AVCO Mark II
Generator Type	Segmented Electrodes	Segmented Electrodes
Dimensions	1x3x20 inches	3x9' 3x13 out 60" long
Gas and Seed	Argon + 1% K_2CO_3	Methylcyclohexane Ethyl Alcohol + KOH
Velocity	Mach 0.7	Mach 1
Temperature	2800°K	3000°K
Electrode Material	Tungsten non-cooled	Graphite
Insulator Material	Transite	Non-ablating
Magnetic Field	14 Kgauss	33 Kgauss
Pressure	13-20 psig	3 atm. abs.
Mass Flow	300 gm/sec.	3-6.5 lb/sec.
Voltage Generated	55 volts	Up to 1400 volts
Current Generated	Up to 800 amps	Up to 4500 amps
Power Generated	11.6 KW	1.5 MW (Peak)
Power Density	20 watts/cm^3	--
Test Duration	10 sec.	10 sec.
Elec. Conductivity	80-150 mhos/m	10 mhos/m
Efficiency	0.1 Heat → Elec.	3-7% heat; 80% local
Energy Source	Plasma Jet 2.4 MW max. input	Combustion Chamber 20 MW input

*References 5-7, 49-53.

Table III* (Continued)

Company	MHD Research	Westinghouse
Generator Type	Segmented Electrodes	Segmented - 3 pairs
Dimensions	2x1/2x24 inches	1.62x4.87x16 inches
Gas and Seed	Kerosene, Alcohol + O_2, N_2 and KOH	Diesel Oil, butyl cellulose & potassium 2-ethyl hexoate + nitrogen
Velocity	Mach 0.7 to 0.8	800 m/sec
Temperature	$3400^{\circ}K$	$\sim 3000^{\circ}K$
Electrode Material	Refractory Metal	Test I, Tungsten Test II, Graphite
Insulator Material	MgO	Magnesia
Magnetic Field	20 Kgauss	3-14 Kgauss
Pressure	--	1 atmosphere
Mass Flow	2.58 lb/min kerosene 0.85 lb/min alcohol	0.5 kgm/sec
Voltage Generated	50-100 volts	Test I, 85 v (O.C.) Test II, 100 v (O.C.)
Current Generated	6 amps (one electrode)	Test I, 180 amp (S.C.) Test II, 280 amp (S.C.)
Power Generated	1.03 KW	Test I, 3.6 KW max. Test II, 8 KW max.
Power Density	--	--
Test Duration	30 min.	10 min.
Elec. Conductivity	1-10 mhos/cm	18-20 mhos/meter
Efficiency	0.2 Heat	--
Energy Source	Combustion Chamber 1 MW peak	Combustion Chamber

*References 47, 115.

Table III* (Continued)

Company	G. E. Research Lab	G. E. Research Lab
Generator Type	Hall - Faraday	Continuous
Dimensions	2x4x24 inches	2.8x2.9x4.9 cm
Gas and Seed	Air, H_2, KOH	Propane + O_2 + K_2CO_3 (1-6% by weight)
Velocity	720-740 m/sec	56.8 m/sec
Temperature	2100°K	2300°K
Electrode Material	SiC	Graphite
Insulator Material	MgO	MgO
Magnetic Field	3-12 Kgauss	4250 gauss
Pressure	11 psig	--
Mass Flow	1.35 lbs/sec air, 0.0044 lb/sec H_2, 0.034 lb/sec. KOH	--
Voltage Generated	90v - 90 v	0.7 volts
Current Generated	1 amp - 9 amp	0.237 amp (S.C.)
Power Generated	15 W - 20 W	0.02 watts
Power Density	≤ 0.13 w/cm^3	--
Test Duration	5 min.	5 min.
Elec. Conductivity	~ 1-2 mhos/m	10 mhos/m
Efficiency	--	--
Energy Source	Combustion Chamber	Combustion Chamber

*References 48, 41.

Table III* (Continued)

Company	G. E. Space Science Lab
Generator Type	Segmented - 4 electrodes
Dimensions	5/8 x 4 x 24 inches
Gas and Seed	$N_2 + K_2CO_3$
Velocity	Mach 1
Temperature	3200°K
Electrode Material	Graphite
Insulator Material	Refractory Material
Magnetic Field	11 Kgauss
Pressure	1.2 atm.
Mass Flow Rate	0.55 lb/sec.
Voltage Generated	78 volts (O.C.)
Current Generated	70 amps
Power Generated	6 KW (Max.)
Power Density	--
Test Duration	10 sec.
Elec. Conductivity	25-200 mhos/m
Efficiency	0.2 Heat → Elec.
Energy Source	2500 KW Plasma Jet

*Reference 42.

Problems of electrode erosion, materials problems, and noise level studies were also carried out. The results indicated that MHD generators could be constructed which operate for periods of several minutes.

Harris and Moore[48] have reported the successful operation of a generator as a Faraday and Hall generator. The generator was also the segmented type operating with air as a fuel seeded with KOH. The results of the experiments are also shown in Table III.

As a result of previously conducted experiments and a study by Kantrowitz and Sporn,[4] AVCO began an investigation of the feasibility of MHD power generation. One of the areas of interest was in MHD generator fluid mechanics. The Mark II generator was built as a facility for detailed studies of the electrical and fluid mechanical problems associated with practical, large sized generators.[49-53] It has produced up to 1.5 Megawatts of power for 10 second runs and the results of some of the studies are shown in Table III. The generator is also the segmented electrode type operating from combustion gases.

In addition to the Mark II, a long duration test facility has been built for long-duration tests of generator components which are exposed to the hot ionized gas stream. Several other authors have presented studies of similar systems and material studies.[54,133]

Recently,[121,122] some results have been reported on the successful operation of the AVCO Mark V MHD generator. The Mark V is the first MHD generator designed for self excited operation and has well demonstrated the feasibility of the MHD concept.

The generator is a rocket driven d-c channel MHD generator designed for a net power output of 20,000 KW. Some of the design parameters of the generator are summarized in Table IV.

Table IV*

Combustion Source	Rocket engine operating with a mixture of ethyl alcohol and methyl cyclohexane combusted with oxygen
Mass Flow	60 kg/sec.
Fuel Flow	19.1 kg/sec.
Oxidizer Flow	39.8 kg/sec.
Seed	1% KOH by volume
Seed Flow	1.1 kg/sec.
Combustion Pressure	8 atm. abs.
Exit Static Pressure	0.9 atm. abs.
Magnetic Field	Inlet 35 KG, out 30 KG
Channel	Inlet Section 0.126 m^2 area, 1.12 m long
	Excitation Section - 0.126 m^2 -0.253 m^2, 1.32 m long.
Electrode System	Excitation Section - Continuous pair
	Power Section - Segmented 50 pairs (0.4 MW each)
Net Output Power	20 MW
Gross Power Output	40 MW

*References 121, 122.

Fifty-six power generation tests were carried out to determine operating and self-excitation conditions for the generator. A maximum net power output of 23.6 MW was produced at only 87% of the design flow rate, with a gross power output of only 32 MW. The transverse voltage for one test varied from approximately 500-1000 volts over the length of the power section. Details of the design, construction and experiments can be found in the references.

2.42 Developments in MHD Generators Abroad

The following summary deals with some of the experimental work carried out in England, France, Poland and Japan.

(a) England

The Central Electricity Generating Board in England has been interested in an MHD generator as a topper in a conventional steam turbine plant.[55,56] Most of the work to date has been in the areas of electrodes, duct walls, magnet, etc. The various experimental facilities available to them include an oil-burning rig, a plasma jet electrically induced, an electromagnetically driven shock tube and a mercury closed-cycle apparatus. The generator with which most of the work has been done is of the segmented electrode type using fuel oil seeded with 1% potassium. Due to the availability of coal in England, it is hoped that this material will show promise as a fuel in the future.

In the area of duct walls, most success has been obtained with water-cooled metal tubing with an insulating material such as alumina sandwiched between the tubes. The tubes are angled so that they lie along equipotentials in the gas and operations of many hours have been obtained with no appreciable deterioration of duct walls. Carbon electrodes inserted directly into the flame survived for less than a minute, and conductivities of only 0.3 mho/m were obtained when using water-cooled copper as electrodes.

Lindley, et al[57-60] has found that overall steam turbine-MHD generator efficiencies of 50% should be obtainable in 10 or 12 years with a future prospect of 60%. His experimental facilities are located at the International Research and Development Company, Ltd., at Newcastle-upon-Tyne, U. K. Some of the specifications of his work include:

Table V*

Type of Generator	Closed-loop
Electrode Configuration	Segmented
Gas	Helium
Seed	Cesium up to 3%
He. Mass Flow	1-10 gm/s
Exp. Nozzle Inlet Temp.	1500-2500°K
Exp. Nozzle Inlet Press.	0.2-1.2 atm.
Exp. Press. Ratio	20
Mach. No. at Gen. Inlet	2.3
Velocity at Inlet	3400-4000 m/s
Duct Cross Section	0.5 x 1.5 inches
Duct Length (Mag. Field Region)	5 inches
Mag. Field	0-12 wb/m^2
Duct Material	Alumina
Electrode Material	Tantalum

*References 57-60.

The work is closely associated with the possibility of utilizing a high temperature nuclear reactor heat source in conjunction with an MHD generator and steam cycle, the overall efficiency of such a system being estimated as up to 60%.

Future plans at IRD include modification of the present duct to allow for other electrode configurations and the building of a Bitter-Type 30 K gauss water-cooled copper electromagnet. Technology gained from this is hoped to be used in building a 50 K gauss superconducting Helmholtz pair magnet, which is already commissioned to be built.

Pain and Smy[56] have extracted electrical power of 0.32 MW for a duration of 100 microseconds from a shock-ionized argon. The experiments consisted basically of exploding a 10% oxygen-90% hydrogen mixture to drive argon (the O_2 - H_2 mixture and the argon were separated by a thin copper diaphragm, which burst upon ignition). Shock front velocities of the order of 4×10^5 cm per sec. were obtained and could be adjusted from Mach 8 to Mach 23 by adjusting the pressures on both sides of the diaphragm. Temperatures of 12,000°K, degrees of ionization of about 20%, and conductivities of about 10^3 mho/meter were observed as the shock front was passed through a pulsed transverse magnetic field of 10,000 G.

The pulsing of the field was accomplished by discharging a 900 μf, 5 KV capacitor bank through a pair of coils arranged as a Hemholtz pair. Since the period of discharge was approximately 1 msec, the plasma saw an essentially constant magnetic field. Proper timing of the capacitor discharge and O_2 - H_2 ignition produced the maximum field as the plasma passed through.

Both a small and a large electrode system were designed. The small system consisted of a pair of copper electrodes 2 cm long and of 1 cm cross-section. The arrangement was such that the electrodes were perpendicular to the plane formed by the plasma and the magnetic field. The larger system consisted of two brass electrodes 7 cm long with a 4 cm arc.

At maximum loading, the energy withdrawn represented approximately 30% of the total energy available in the plasma.

(b) France[61]

The Electricité de France is conducting present work with an arc jet generator facility to gain experience in measuring the plasma parameters under high temperature conditions. Future plans include several open-cycle MHD generators and studies of high temperature combustion processes.

The Commissariat a l'Energié Atomique in coordination with the Institut Francais du Pétrole is involved with open-cycle generators in an extensive program of combustion plasma diagnostics. Electrical conductivities are measured using graphite electrodes in an annular cell. Seeding has been investigated, using kerosene seeded with potassium hydroxide in alcohol and burned with oxygen enriched air. An arc of 100 V p-p, 50 c/s, was used to obtain the voltage and current characteristics. Evidence of the formation of unipolar and cathode spots was observed, the effect probably depending on temperature, thermoemission density, cathode space charge, and the extent of the resulting magnetic field. Some of the results of their experiments are shown in Table VI.

(c) Poland[62,79]

The majority of work in Poland is being conducted at the Institute of Nuclear Research, Swierk, Warsaw, and is concerned with the open-cycle DC type of MHD generator. The project was begun in 1960 with small power

Table VI*

Cross-Section	2.1 x 5 cm
Length	20 cm
Insulating Walls	Magnesia
Electrodes	Graphite
Magnetic Field	1 wb/m^2
Inlet Pressure	1.4 atm.
Inlet Velocity	Mach 0.8
Thermal Input	
$O_2 + 2N_2$	480 KW
$O_2 + N_2$	690 KW
Specific Power	0.1 MW/m^2

*References 61,79.

generators and experimental results obtained during 1961 and 1962. In 1963 a larger device was designed and is at present being tested.

The work to date has been in the area of materials and instrumentation. The search for non-ablating electrodes using pure graphite, graphite coated pyrolytically with silicon carbide, pure silicon carbide, and silicon carbide with silicon nitride has yielded no satisfactory results. A research program was begun in 1964 to study zirconium oxide and some metal borides in this application but no results were available as of the Paris Symposium in July, 1964.

A small rig has been constructed in order to test materials suitable for wall insulation in the conditions similar to those taking place in MHD generators. Refractory bricks of MgO, ZrO_2, Al_2O_3, Refrax, Carbofrax, etc., have been tested with heat fluxes of 14 w/cm^2 for SiC and 50% Al_2O_3 and 71 w/cm^2 for Refrax representing the two extremes.

The present electromagnet capabilities extend to 20,000 gauss and future plans include testing of a 1 MW thermal input system, on which construction was begun in 1963. Some results of some of the experiments are shown below.

Table VII*

Generator Segmented Electrode				
Fuel	Acetylene			
Oxidant	Oxygen			
Seed	$K_2 CO_3$			
Channel Dimensions	6.2 cm x 1.4 cm with 0.9 cm electrode spacing			
Electrodes	Graphite			
Duct Walls	Transparent quart tube			
Velocity	m/s	40	60	80
Duct Wall Temperature	°C	--	--	1900
Duration of Run	min	3	3	3
Magnetic Field	wb/m^2	0.57	0.68	0.57
Maximum Power	mW	0.01	0.03	3
S. C. Current	mA	0.2	0.4	30
O. C. Voltage	V	0.2	0.3	0.4
Power Density	W/m^2	1.3	3.9	390
Gas Conductivity	mho/m	0.01	0.014	0.78

*References 62,79.

(d) Japan

Japan's progress in the MHD field was well presented at the Paris International symposium and it is evident that their effort is planned to be far more substantial in the future. Ito,[63] *et al*, reported some results on an MHD generator driven by a plasma jet. The measurements performed on the MHD duct included spectroscopic measurements of temperature and electron density as well as the usual measurements of velocity, flow rate, etc. Some investigations of space charge effects also were presented. The experimental results of the measurements were compared with the theoretical values from a one dimensional treatment and the discrepancies were discussed. Some of the results are shown in Table VIII.

Table VIII*

Energy Source	Plasma Jet
Fuel	Air seeded with 1% volume of K
Dimensions	Area 36 cm^2, Length 90 cm
Mass Flow Rate	200-300 g/sec.
Electrodes	Segmented (20)
Magnetic Field	20,000 gauss
Temperature	4000-5000°K
Power Generated	Up to 10 KW

*Reference 63.

Fushimi and Mori[64] have reported some results of an experiment on a gas fired MHD generator using propane and oxygen seeded with KOH. Segmented graphite electrodes were used in a rectangular channel with dimensions 2 x 6 cm by 19 cm long. The plasma velocity in the experiments was approximately 700 m/sec with a temperature of 2800°K, and a magnetic field of 17,000 gauss. The power output was approximately 1 KW max. from a thermal input of 1 MW.

Some results on a 10 KW Oil Fired MHD generator have also been reported by Yamamoto and Saito[65] and some of the details are given below:

Table IX*

Fuel	Oil and oxygen seeded with K
Generator Dimensions	50 x 120 x 1000 mm
Electrodes	Carbon segmented
Magnetic Field	15,000 Gauss
Mass Flow Rate	700 gm/sec.

*Reference 65.

More recent results have also been reported by Yamamoto,[125] et al. and are as follows: Heat Input 7 MW; fuel and seed, light oil and K soap dissolved in the fuel and combusted with oxygen; combustion flow rate, 800 g/sec; max. elec. output, 20 KW and operation time 5 minutes. The combustor is designed as a reaction motor, and the generator channel is constructed of MgO side wall bricks with 20 pairs of graphite electrodes. The experiments were carried out with the gas flow varied from 300-800 g/s; at the maximum flow rate the no-load generator voltage exceeded 100 v. The generator is being mofified for ten times the present output.

3. AC MAGNETOHYDRODYNAMIC POWER GENERATORS

3.10 Introduction

Direct current magnetohydrodynamic generators have several design inherent disadvantages. For the temperatures required for reasonable conductivities, the direct contact of the electrodes with the gas introduces problems of electrode erosion and pitting, in addition to anode and cathode voltage losses. If the electrodes are cooled there are large heat transfer problems and cool boundary layers form on the electrodes which decrease the temperature and conductivity of the gas. Another disadvantage of the DC generator is the problem of inverting the DC to AC for use in conventional power systems.

Because of these difficulties, several investigations have been carried out to investigate the possibilities of direct AC MHD generators. Most of the generators which have been proposed are analagous in some manner to conventional AC machinery, e.g., induction and synchronous generators, with the rigid metal conductors of the conventional generator replaced by a conducting ionized gas or liquid metal.

In comparison with the vast amount of material published on DC generators, a relatively small amount of work has been carried out on the development of AC MHD generators. This is probably because of the lower coupling available between the gas and the magnetic field in an AC MHD generator when compared to a DC one, and also because of the large reactive power requirements in comparison with the amount of power generated within the system.

Recent developments, however, have indicated that liquid metals with their higher conductivities are suitable for use in AC MHD generators and several other ideas have been suggested and investigated which make the outlook for AC generation more promising.

Several basic methods have been suggested for AC MHD generators. The magnetic field through which the fluid flows can be varied at the desired frequency, the flow of fluid can be pulsed to give the desired variation, or a spatially distributed magnetic field can be used which can be stationary or traveling.

In addition, there are the usual geometrical considerations which have been considered, e.g., a linear, cylindrical, or vortex geometry. A large volume of AC MHD work so far has been carried out with the cylindrical geometry which is easily available in shock tubes.

An MHD generator with an AC magnetic field could be similar to the ordinary channel DC MHD generator with any type of alternating field. However, this approach does not reduce the problem of retaining the electrodes. Another method which might be used is the induction type shown in Figure 10 which has been suggested by Harris[66] and reported by Lindley.[66] An applied radial alternating magnetic field produces an alternating electron current in the plasma which acts as a primary transformer current coupled to the secondary coil which provides the electrical output.

Clark, Swift-Hook, and Wright[67,68] have conducted a study of the various types of AC MHD generators, and two of those reported were: (a) Generators similar to the DC type with a time varying magnetic field, and (b) Generators in which the fluid is used to amplify a traveling wave. It was concluded that these two types were not economic for uses with combustion gases because of the large reactive energy storage required for the AC magnetic field. Some of the results of this

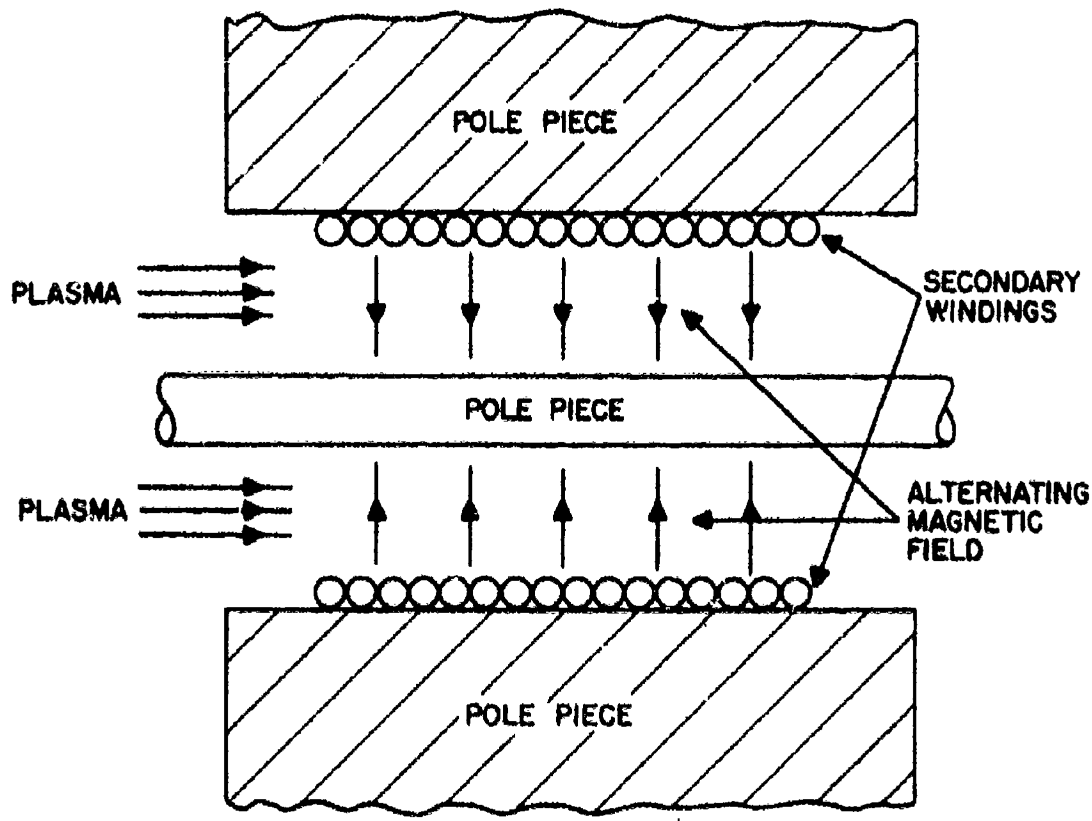

FIGURE 10. Induction Generator with Alternating Field

study are presented below for fuel oil combustion products seeded with one per cent potassium with an applied magnetic field of 10,000 gauss.

Table X*

Gas Temperature	2000°K	2500°K	3000°K
Elec. Conductivity (mhos/m)	0.8	10	80
Velocity (m/sec)	690	770	840
Max. Power Density (MW/m^3)	0.1	1.5	14
Magnetic Reynolds No./meter	2×10^{-4}	3×10^{-3}	3×10^{-2}
Q of circuit for damping losses in field equal to generated power	2,625	169	17.7
Capital Cost of Field driving/KW of generated power	$22,100	$1,430	$147

*References 67,68.

For pulsed gas streams, several generators have been suggested and investigated. Techniques for pulsing gas streams have been investigated mostly in England and France. Basically the methods proposed consist of passing alternate high and low temperature regions of gas through a generator as shown in Figure 11.

Thring[69] has proposed an idea of using two fluids for pulsed generation. By injecting a short pulse of fuel and pure oxygen into a nozzle, allowing combustion to continue as the gas passes through the nozzle, a high temperature zone of gas with good electrical conductivity is sandwiched between layers of a thermodynamic working fluid, allowing operation with a better thermodynamic cycle (Figure 11).

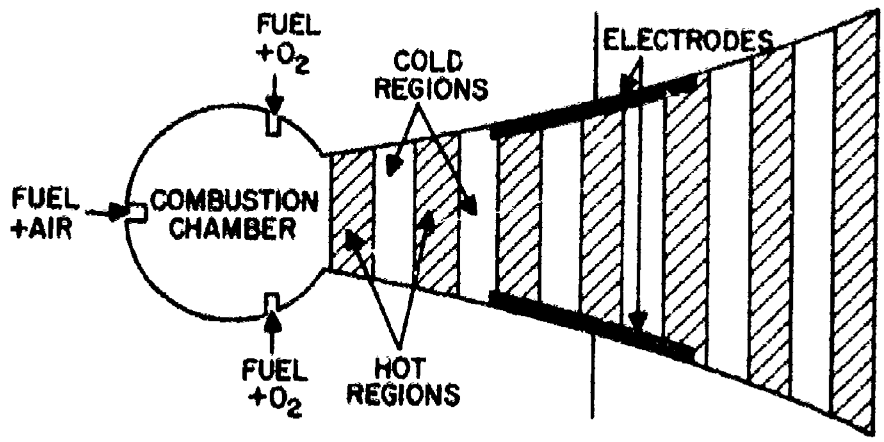
FUEL
+O2
COLD
REGIONS
ELECTRODES
FUEL
+AIR
COMBUSTION
CHAMBER
FUEL
+O2
HOT
REGIONS

FIGURE 11.

Riceteau and Zettwoog[70] have published calculations for a DC installation operating with a modulation of the gas. Some of the results of their calculations are summarized below:

Table XI*

	Cycle	
	Closed	Open
Fuel	Helium	Kerosene
Entrance Conditions		
Velocity	2160 m/sec.	1000 m/sec.
Cold-Regions Temp.	1650°K	2500°K
Mean Temp.	1815°K	2750°K
Exit Conditions		
Velocity	706 m/sec.	500 m/sec.
Cold Region Temp.	1025°K	1600°K
Mean Temp.	1305°K	2230°K
Performance		
Overall Specific Power**	2.35 MW/m³	Entrance Specific Power 4.8 MW/m³ Exit Specific Power 1.5 MW/m³
Overall Efficiency***	36%	15%
Magnetic Field	1 W/m²	1 W/m²

*Reference 70.

**$\frac{\text{Total Power to External Circuit}}{\text{Total Volume of MHD Nozzle}}$

***$\frac{\text{Energy Supplied to External Circuit}}{\text{Energy given by hot source}}$

The authors concluded that a modulation of the gas, if stable from entrance to exit would be a considerable improvement over the ordinary MHD generator.

Experimental investigation of striated flows have been carried out by Devime, et al,[71] and also by Marchal and Servanty.[72]

In the work by Devime, et al, the temperature was modulated by electric power produced across an electrode channel through which flowed a mixture of air, oxygen burned with kerosene and seeded with 0.8% potassium. The device consisted of two stages, a modulation stage and a second stage consisting of an amplifier which delivered power proportional to the conductivity. Luminosity modulations were observed using a stroboscope and camera with the first stage operating at 50 Hz. The temperatures were 2,700°K for the hot zones and 2,100°K for the cold zones with a velocity of 310 m/sec., and a thermal input of 150 KW. Luminosity modulation was also observed at 1000 Hz. Marchal and Servanty,[72] have also reported on an experimental attempt to produce striated flows, using a burner in an acoustic resonance chamber to produce a wave system with modulations in temperature. The first stage has been operated for as long as 40 minutes at frequencies of 400 and 670 Hz without frequency irregularities or combustion abnormalities. Other work in France has been reported by Karr,[73] in a paper which suggested the mixing of two different gases. The two mixtures will be fed alternately into a combustion chamber with a rotating disc acting as a regulating valve.

Fraidernaich,[74,75] et. al., have also investigated the possibilities of striated layer MHD Generation. They investigated effects of some of the Raleigh Taylor instabilities and concluded that there is a growing rate of the instability which causes the characteristic time of the disturbance to be less than the transit time through the duct. Fraidernaich,[116] has also investigated the case of a finite conducting fluid bound by a non-conducting one when a uniform horizontal magnetic field and vertical electric field are applied. He concluded that for the deceleration occurring in the impulse - type striated layer MHD generator, a range of wavelengths exists for which the disturbance is fast enough to destroy the equilibrium configuration.

In one experiment reported,[76] AC power was generated using a pulse jet source with a steady magnetic field. The combustion source was a small pulsed jet operating on gasoline and seeded with one-half to one per cent potassium by weight. Both inductive coupling and electrodes were used to extract the energy from the gas. Some of the results of the experiment are summarized in Table XII below:

Table XII*

Gas	Petroleum seeded with potassium ethyl hexoate
Source	Pulsed gas jet
Magnetic Field	500 gauss
Velocity	400 m/sec.
Frequency	400 Hz
Width of Gas Stream Perpendicular to Flow and Magnetic Field - 0.025m	
Output Voltage	Carbon electrodes - 0.5 Volts 400 turn coil - 20-40 millivolts

*Reference 76.

It was concluded that although it is possible to generate AC power by induction methods, the power levels obtainable are small compared to the case where electrodes are used.

A shock wave AC MHD generator to be used in conjunction with a nuclear reactor has been suggested by Brocker and Chevalley.[117] The basic generator consists of two shock tubes which contain electrodes which are presumably located in an applied external field, and a distributor which allows a preheated driver gas to be introduced into the tubes. The procedure for operation is as follows. The driven gas fills the volume of the tubes initially. When the distributor rotates to the appropriate position, the heated driven gas is introduced creating a shock wave which travels down the tube and into the MHD generator. Here the gas is decelerated as energy is removed, and when it reaches the diffuser, it is further decelerated and its kinetic energy transformed into pressure. The re-opening of the tube by the distributor allows the driver gas to be evacuated until its backward motion is stopped by the closing of the tube, and the cycle will start again. Two tubes are used, each tube giving power over a half cycle only. The design of a 500 MW power plant for 50 Hz power was also considered.

Assuming that continuous and pulsed gas streams are available, several generator configurations have been proposed and investigated. These are classified in general as parametric, induction, synchronous induction, and traveling wave magnetohydrodynamic generators.

3.20 Induction and Synchronous MHD Generators

The induction MHD generator has been suggested by Lewis[77] in an M. I. T. thesis supervised by Akhurst. His method was also suggested later by Harris.[78] The basic configuration of the generator is shown in Figures 12 and 13. It consists of a cylindrical non-conducting channel with a concentric coil. Slugs of conducting material move

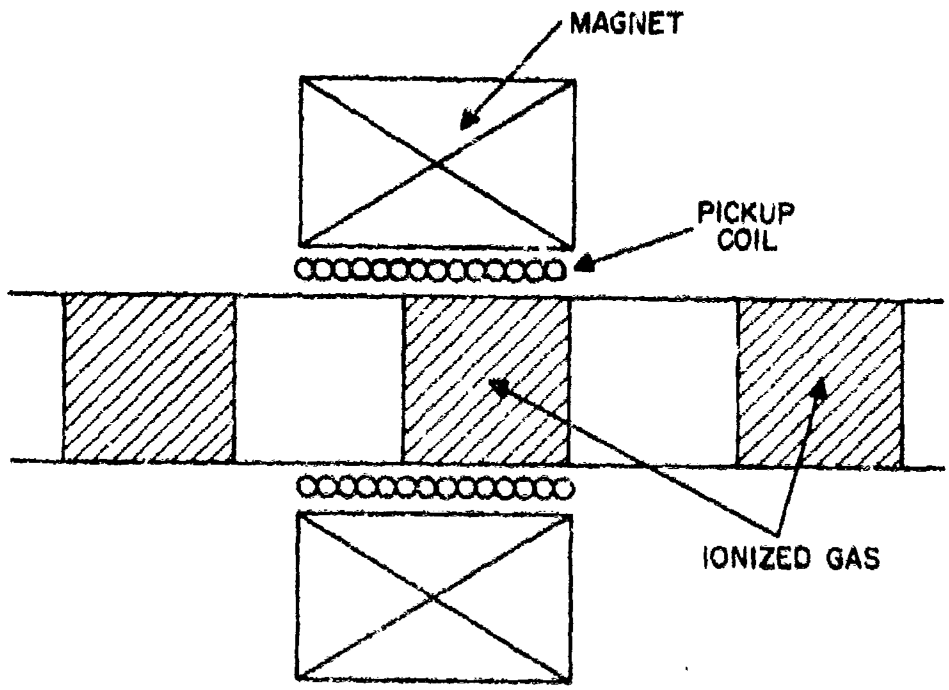

FIGURE 12. Induction-Synchronous MHD Generator

periodically through the coil and interact with the magnetic field to produce electrical energy. Such a system has the advantages of no electrode problems, higher working temperatures of the gas, and the possibility of AC production.

Two methods of extracting the electrical energy have been proposed. One is to use an auxiliary winding such as the one shown in Figure 13, whereby the circulating currents induced in the moving plasma by the primary field cause a voltage to be induced in the output windings. Generators of this type have been referred to as induction or induction-synchronous MHD generators. The other possibility is to make use of the parametric amplifier principle with an external circuit such as the one shown in Figure 13. A similar method has been mentioned by two other authors[66,79] and the equivalent circuit is shown in Figure 14.

In the configuration of Figure 14, the resistance r is much less than the load resistance R_L, but the inductance L_{∞} is as large as possible so that the DC exciting current flows through r, L_{∞} and the time varying inductance L(t). The variable inductance L(t) is modulated by the ionized gas and an alternating current is produced in the circuit which will flow through the load resistance R_L.

The parametric MHD generator has been investigated extensively by Woodson and Lewis. As shown in Figure 13, slugs of moving plasma are used to excite an LC resonant circuit by causing the inductance of the coil winding to vary at twice the resonant frequency of the circuit. Under certain conditions the system should operate in the steady state with no electrical excitation, e.g., operate as a self excited generator.

In an early investigation, Woodson and Lewis[80] formulated an equivalent circuit to satisfy the assumption that single frequency power was to be

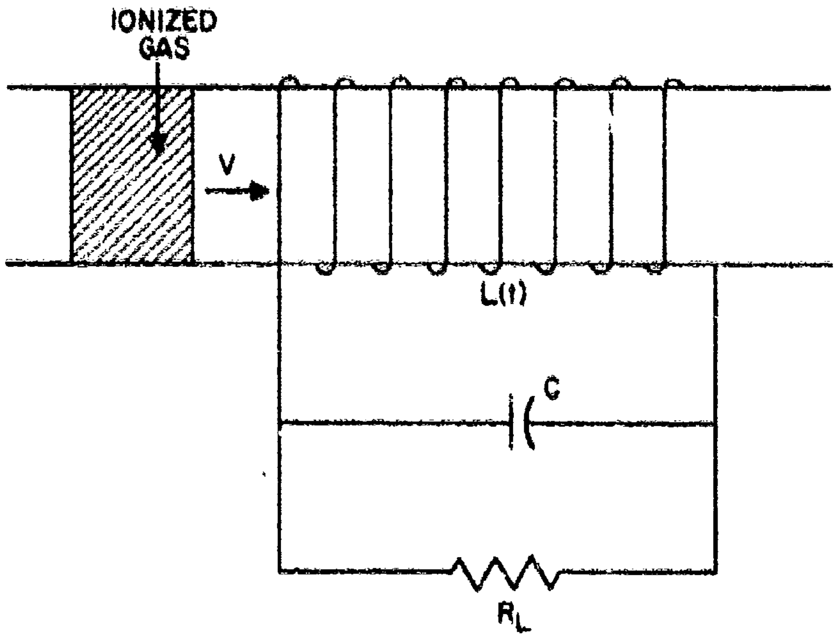

FIGURE 13. Parametric MHD Generator

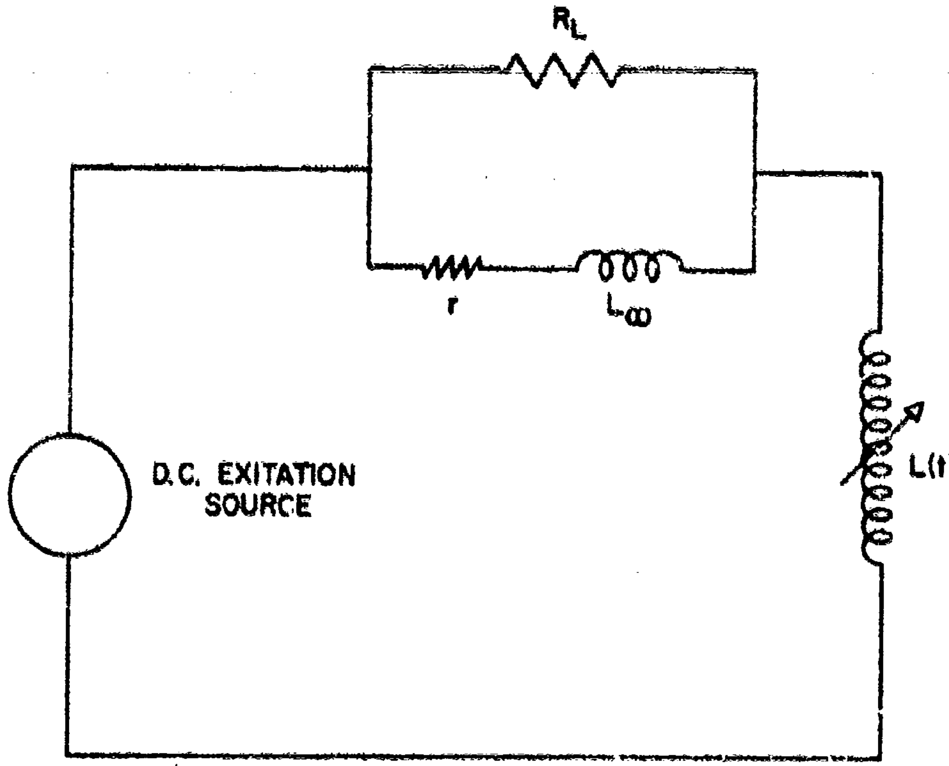

FIGURE 14.

generated. This equivalent circuit was then related to some of the gas properties by using experimental results obtained from an investigation by Lewis with a magnetically driven shock tube. From the analysis and the experiments estimates were made of the magnetic Reynolds number required for efficient generation and it was concluded that magnetic Reynolds numbers in the range $R_m \geq 1000$ were necessary for self excitation and efficient generation. Estimates of the electrical efficiency (ratio of power delivered to the load to the power generated) and ratio of active to reactive power were also considered. For R_m approximately 1000, an electrical efficiency of approximately 33%, and an active to reactive power ratio of approximately 0.3 were presented.

In a more refined analysis[81-83] with a more general equivalent circuit, it was found that approximate values of the parameters for the equivalent circuit could be obtained from small signal measurements in the sinusoidal steady state with a stationary geometry. This procedure allowed the circuit parameters to be related to the magnetic Reynolds number and also allowed the determination of a minimum value of R_m for self excitation without solving the complex time dependent magnetohydrodynamic equations. As in the previous analysis, the plasma compressibility was neglected, and it was also assumed that the magnetic field did not affect the gas flow.

An experiment was performed using a device with copper slugs mounted on a rotating wheel. The slugs were allowed to pass between the poles of a two coil electromagnet, and measurements were taken for various stationary positions of the slugs.

The approximate values obtained from the stationary measurements agreed well with the terminal relations of the coil while the wheel was moving. The results of the experimental and theoretical considerations indicated that the generator would operate in the range of magnetic Reynolds numbers of 50-100. Criterion for self excitation, electrical efficiency, and ratio of active to reactive power, were presented. Table XIII below summarizes some values that were quoted for electrical efficiency, reactive power ratio, and estimated generator radii for operation with combustion gases, based on the small signal analysis.

Table XIII*

Magnetic Reynolds Number	50	100
Electrical Efficiency	25%	50%
Electrical Efficiency for maximum power output	12.5%	25%
Ratio of reactive power to generated power	150	10
Esti[illegible] Generator radius (m[illegible])	50	100

*References 81,83.

[illegible]he small signal analysis gave some of the requirements for efficient operation, but another study[84,85] was conducted in order to extend the analysis to the large signal case for which the magnetic field strongly affects the gas flow. The interaction between the magnetic field and the gas flow was analyzed by using a model which consisted of a nozzle and a leaky piston. Two cases were considered: [illegible] pulsed flow (plasma bunches separated by a vacuum) and continuous flow (regions of high and low conductivity gas). The investigation was carried out in order to determine the overall efficiency, stability, estimates of size, scaling factors of the generator, and also to determine if the magnetic Reynolds number requirements were as strict as those found from the small signal analysis. Experiments were carried out in a shock tube using hydrogen gas in order to examine the generator operation on a half cycle basis. Some of the conclusions of the study were: (1) The velocity and conductivity were not increased significantly for large signal operation, indicating that the magnetic Reynolds number requirements were not increased significantly for large signal operation, (2) For very high R_m, approximately forty per cent of the gas power might be extracted for pulsed flows and approximately 20% for continuous flows, (3) The ratio of reactive power to load power would have to be approximately 10 for efficient operation, (4) A minimum R_m of approximately 100 is required for the generator. The minimum generator diameter for combustion gases is approximately 16 meters, with an efficiency of approximately 3% for continuous flow and 7% for pulsed flows. For this generator the optimum Mach number would be M = 1.5 with a power output of 2000-4000 megawatts and a stagnation pressure of one atmosphere.

An inductive MHD generator which utilizes an auxiliary winding has been investigated by Cormack.[86] The generator consisted of a shock tube with the excitation and output coils constructed and mounted in much the same manner as in the experiments performed by Lin, et al,[87] and Lewis.[88] (See Figure 12). Theoretical expressions for the output voltage and power were calculated on an electrodynamic basis and experimental measurements of the output voltage and power closely agreed with the theoretical considerations. The maximum power generated was approximately 10 watts for a period of a few microseconds, and voltages in excess of 6 volts were generated for approximately the same length of time.

K. Koyama and T. Sekiguchi[89] have carried out a theoretical and experimental study of a similar type of induction generator, using a device similar to the one shown in Figure 15. In this configuration a train of periodically produced plasma rings are projected through two coaxial non-conducting cylinders in an axially symmetric radial magnetic field which varies sinusoidally in the axial direction with wavelength λ as shown. A solenoid is wound around the outer cylinder to provide an electrical output circuit. Formulae were derived for the output voltage, current, internal impedance, power output, and conversion efficiency and compared with the experimental results using a shock tube as a driving mechanism. Two different cases were considered, one with and the other without a magnetic material in the inner cylinder. The results of the experiment are summarized in Table XIV below.

Table XIV*

Gas - Neon
Pressure - 0.01 - 1 mm Hg
Velocity - Mach 10-30
Length of Output Coil - 2 cm (20 turns)
Open Circuit Voltage - 40 volts
Short Circuit Current - 10 amps
Maximum Power - 100 watts
Magnetic Field - 3,000 Gauss
Outer Cylinder - 50 mm
Inner Cylinder - 20 mm
Electrical Conductivity - 10^3 mhos/m
Time - several microseconds

*Reference 89.

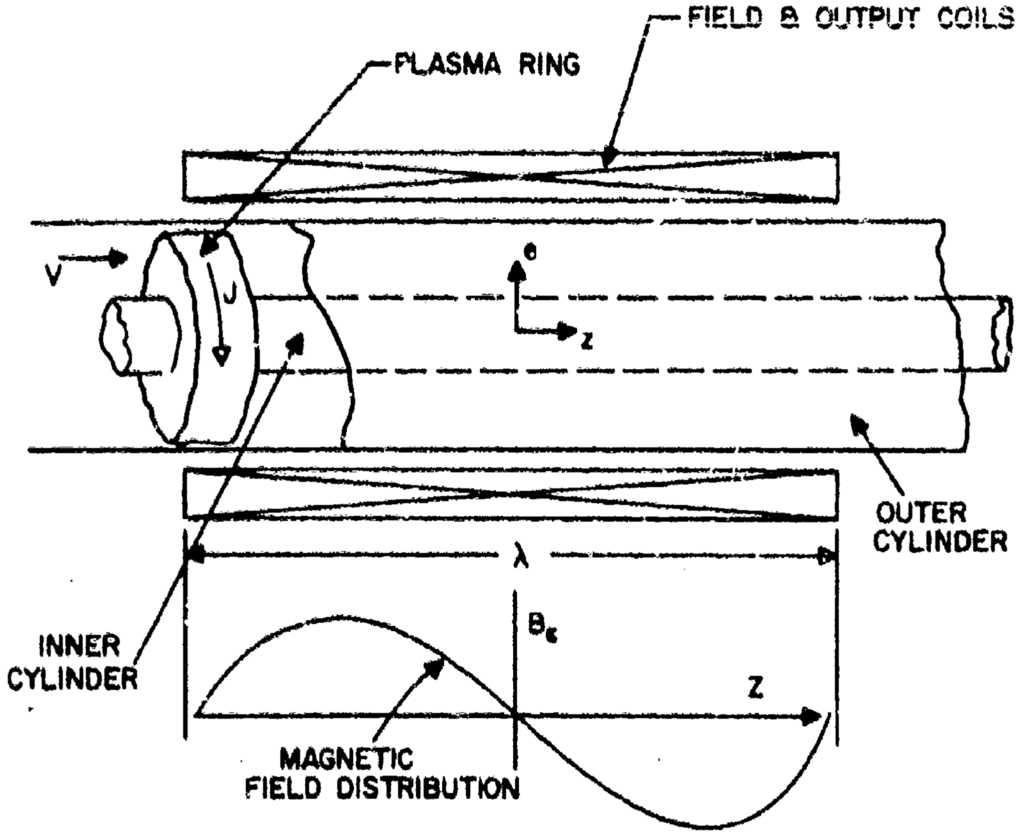

FIGURE 15. A-C MHD Generator

In addition to the results mentioned above, a comparison was made between the amount of power generated per unit volume in this configuration with that of a DC generator with segmented electrodes operating under similar conditions. The ratio of P_{ac}/P_{dc} was found to be ≤ 0.3, indicating that higher magnetic fields, velocities, and conductivities are necessary for competition with DC generators. An investigation of another type of AC MHD Generator has been carried out by Milewski.[90]

3.30 Traveling Wave MHD Generators

An electrodeless MHD generator which operates in much the same manner as a squirrel cage induction machine has been proposed by Bernstein, et. al.,[91] and other investigations of this type of machine have been carried out.[92-96]

The basic machine is shown in Figure 16. In this device a sinusoidal magnetic field is produced in the plasma by a multiphase winding. The magnetic field moves in the flow direction with a velocity less than the flow velocity and power is transferred from the gas to the field in the same manner as in a conventional induction generator, removing the need for electrodes in contact with the gas.

In an analysis based on a simplified model Bernstein,[91] et al. derived expressions for the complex impedance, power, and efficiency of the generator. An example was given for typical channel dimensions with the magnetic field produced by copper coils 5 cm thick on the top and bottom faces. The data is shown in Table XV.

For these values, the frequency of the generated power would be 666 Hz with a reactive to active power ratio of approximately 30. The power factor could be improved somewhat by increasing the temperature and velocity.

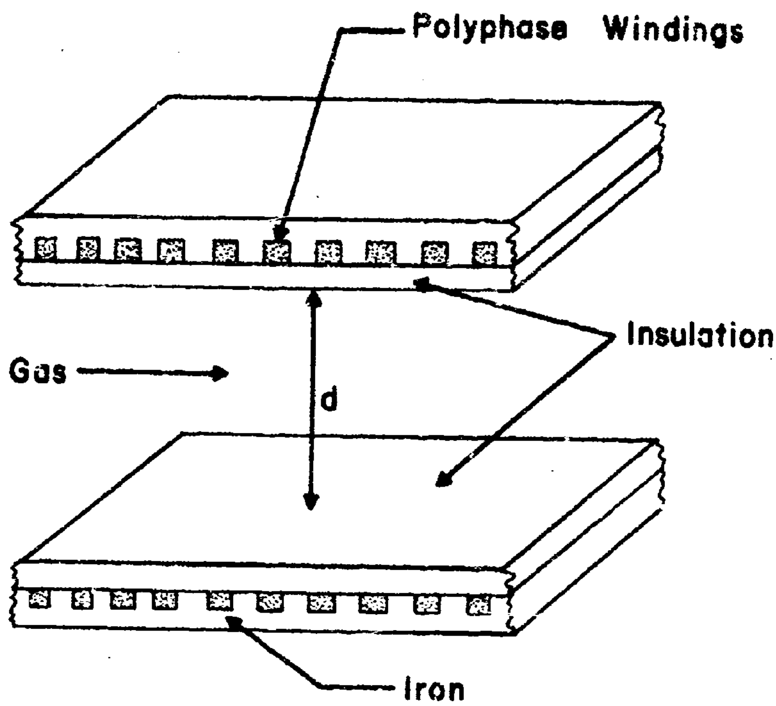

Figure 16 Electrodeless MHD Generator

Table XV*

Permeability = 1.26×10^{-6} km/coul^2
Electrical Conductivity = 1000 mhos/m
Velocity of Gas = 2000 m/sec
Wavelength = 1 m
Area = 1 m^2

*Reference 91.

In Bernstein's analysis, the plates of the generator were assumed to be infinite in two dimensions in order to simplify the analysis. Later work by Fanucci, et al.[94] and Sudan,[96] extended the analysis to account for fringing effects caused by finite lengths. Sudan gave expressions for the magnetic field, current density, power developed, power output and joule losses for the generator, and described a method to eliminate the electromagnetic end effects by a distribution of the exciting current in the polyphase windings. The possibility of using fractional wavelength generators for 60 Hz was also mentioned. A similar investigation has been carried out by Peschka,[97] et al.

Peschka,[118] et al. have also considered the problem of excitation of the generator using capacitors. Some investigations into the effects of a finite width[119] and boundary layer effects have also been reported.[120] The possibility of using conducting walls has been investigated by Porter and Jackson[126] and mentioned by Yakovlev.[127] Yakovlev has also qualitatively described a synchronous generator[128] which requires passing currents through the moving fluid. The moving magnetic fluid created in this way induces an emf in a set of windings.

There are also geometric variations of this type of generator. Yantovskiy and Tolmach[129] have investigated the solution of the MHD equations for a helical induction generator, and the impedance of an annular MHD generator[130] has been reported. There are also several papers which consider the theory and application of induction pumps for liquid metals.[131,132]

Lengyel and Ostrach[98] have theoretically investigated an AC vortex MHD generator and presented calculations for the generated power, effective power ohmic losses, and the electrical efficiency. Perturbation techniques were used to obtain the velocity, field, and current distributions. A coaxial AC non-equilibrium induction generator has also been proposed.[99]

In an effort to increase the efficiency of a traveling wave MHD generator, Tanner[100] has proposed a configuration in which a steady field and a traveling field are applied. The generator would be the conventional DC MHD generator with the addition of the traveling wave field as shown in Figure 17. As the gas moves down the duct, the traveling magnetic field excites a wave of temperature, which gives large periodic increases in the conductivity along the duct. The effective conductivity is increased without increasing the mean temperature of the gas, enabling more work to be extracted from the gas by the electrodes than in the DC case.

Calculations were presented for the increase in conductivity due to the resonance in the duct. It was found that the effective conductivity was increased five times without raising the mean temperature of the gas, and the only additional requirement was the addition of the traveling flux wave which was 10-50% of the DC field strength.

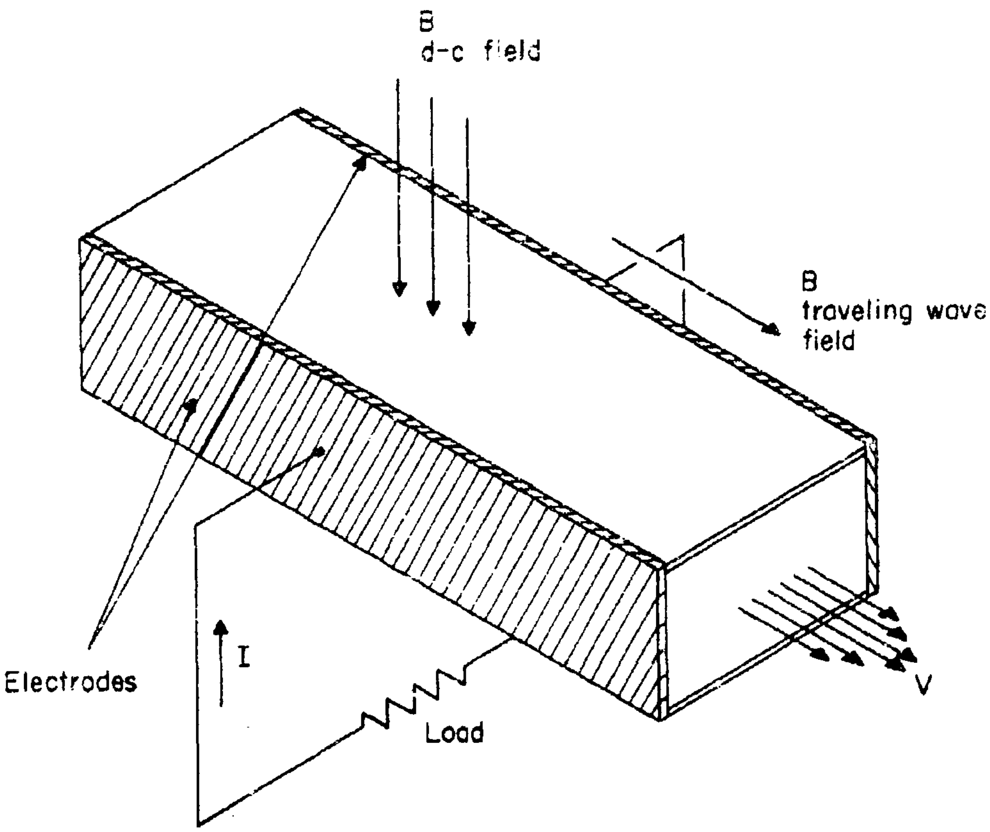

FIGURE 17. DC MHD Generator with Superimposed Travelling Wave Field

Haus[101] reported a one dimensional analysis of an AC MHD generator in which hydromagnetic waves, in an infinitely conducting fluid flowing at supersonic velocity, couple with an electrical circuit to obtain amplification of signals in the circuit. With the proper feedback, oscillation will occur and the device will generate electric power. This idea has been extended by Woodson[102] to the case when gas losses are considered. It was found that the generator lengths required for use with combustion gases were too excessive, but that for gases such as hydrogen and argon laboratory experiments could be carried out.

Woodson[103] has also proposed a conduction AC MHD power generator with all reactive power handled by inductive energy storage.

The system is shown in Figure 18 for solid electrodes. The basic generator consists of a constant cross section channel with a constant velocity conducting fluid flowing as shown. The two pairs of electrodes feed through the two sets of coils and the load resistors. The machine could consist of several of such phases. Preliminary calculations based on an incompressible fluid have indicated that the machine might be promising for gaseous as well as liquid metal MHD systems. The criterion that it operate as a self-excited AC machine is that the machine be suitable for self-excitation as a DC machine. A preliminary investigation of the machine with continuous and segmented electrodes was carried out.

Jackson, Pierson, and Porter[104] have considered the induction generator for use with liquid metals. The use of the liquid metal instead of an ionized gas allows the generator to be operated with a more acceptable power factor. The effects of magnetic core permeability, field, and velocity profiles on machine impedance were obtained and compared with the corresponding results of a one dimensional analysis. Some measurements of

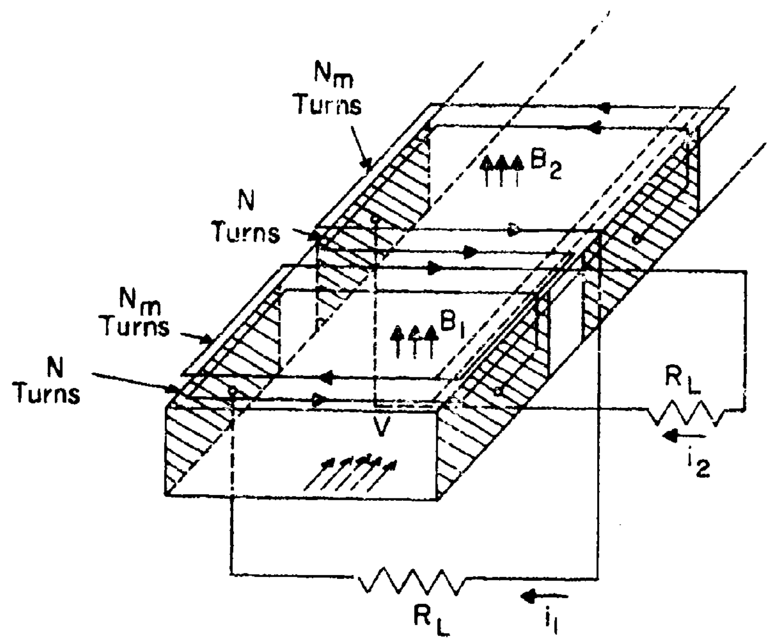

FIGURE 18. MHD Conduction Machine

fluid velocity, pressure drop, and power flow on a sodium potassium closed loop facility were also discussed.

A preliminary design of a 300 KW power generator was also presented. Some of the data is summarized below.

Table XVI*

Power Source	SNAP 50 Nuclear Reactor
Working Fluid	Cesium
Liquid Temperature	$1200^{\circ}K$
Electrical Conductivity	1.46×10^{6} mhos/m
Fluid Velocity	14.1 m/sec.
Frequency	75 Hz.
Field Losses	46 KW
Friction Losses	4700 watts
Overall Efficiency**	67%
Power Factor	0.12

*Reference 104.

**The efficiency of the machine has been defined as:

$$\eta_q = \frac{\text{Power delivered to coils by gas by gas - Joule losses in Core}}{\text{Friction Losses + Mechanical Power Input}}$$

Patrick and Lee have also reported some preliminary measurements on a NaK, NaK - N_2 liquid metal generator.

Wang, and Dudzinsky[115] have reported some theoretical and experimental results on an induction traveling wave MHD generator. Their theoretical analysis treated the flow as quasi-one dimensional and accounted for the attenuation of the wave in the channel due to an insulation layer. The analysis accounted for real machine effects, and expressions based on classical machine theory were presented for the required exciting current generated voltage, net power output and electrical efficiency.

An experimental generator, rated at 2 to 4 KW at 200-400 Hz, 220v and 50 amp. was designed and built on the basis of the analysis.

In an experiment using NaK as a working fluid, the maximum power output has been 1.84 KW with a power factor of 0.11 lagging and a net electrical efficiency of 36%.

Some of the experimental results are presented below.

Table XVII*

Inlet Pressure	786 psig
Exit Pressure	57 psig
NaK Flow Rate	19.2 lb/sec.
Flow Velocity (calculated)	161.6 ft/sec.
Synchronous Velocity	125.2 ft/sec.
Slip	-0.29
Frequency	350 Hz
Terminal Voltage	126 volts
Line Current	46 amps
Total Power Generated	1840 watts

*Reference 115.

4. EXPLOSIVE DRIVEN MHD GENERATORS

One of the most attractive features of an MHD power generator is the potential for achieving high specific power outputs from small devices for short periods of time. To date several generators have been designed specifically for high power, limited duration running. Systems which might use power at these high levels are high power radar systems, sonar, X-ray, emergency communication systems, laser pumping, etc.

For large power outputs from relatively small lightweight devices, the possibility of using explosive driven MHD generators has been proposed and some investigations into this type of system have been carried out.

At MHD Research, Inc.,[106-108] experimental and theoretical work has been performed to determine the basic physical processes occurring in the explosive driven generator and to obtain the necessary data for scaling to larger units. A wide range of experiments have been conducted to investigate factors such as the choice of explosives, geometry, pressure, initial composition of gases, seeding, optimum load conditions, etc. The major emphasis has been placed upon determining the effect of these variables and others such as velocity, conductivity, magnetic field, on the performance of the generator.

Recent experiments[107,108] were conducted in two different sized channels under a variety of initial conditions. Some of the results for one of the channels are presented in Table XVIII.

Burnham and Marshall[109] have considered the possibility of using an inductively coupled explosive MHD generator. Measurements of conductivity and velocity of seeded detonatation charges have indicated that magnetic

Table XVIII*

Maximum Power Density	2×10^{10} watts
Peak Power	23 MW
Output Current	30,000 amp
Voltage	770 volts
Load Resistance	25.8 ohms
Dimensions of MHD Channel	1 x 4 x 8 inches long
Pulse Length	60 µsec.
Magnetic Field	23,500 gauss
Conversion Efficiency (chem. to elec.)	1 per cent

*References 107,108. More detailed information is given in the references.

Reynolds numbers greater than 20 have been achieved. In a recent paper, electrodeless and electrode type generation equipment was discussed briefly together with some theoretical considerations. Some of the major advantages of the electrodeless generator over the electrode type were pointed out and also some experimental results of both configurations were reported. The electrode generator, which is the ordinary DC channel MHD generator has problems of electrode sheaths, low internal impedance (which requires low impedance loads for matching), output limitations because of electrode current density considerations, etc.

On the other hand, the electrodeless MHD generator, operating under similar conditions, with explosive driving, seems to be ideally suited for this type of operation. The electrodeless generator would be an inductively coupled device similar to the one investigated by Cormack.[86]

Experiments were performed with both the electrode and electrodeless type generator and it was reported that a generator based on the electrodeless concept had shown a small load output of approximately four times that of the electrode type. It was concluded that pulsed MHD generation using conventional explosives will occur most efficiently through the use of the electrodeless model.

The possibility of using an explosive driven MHD generator for laser pumping has been reported.[123] The generator was used to pump a neodymium doped crown glass laser, which was preionized by an external power supply. The experimental generator was operated with a magnetic field of 2.8 web/m^2. The denotation of a one pound charge of high-explosive C-4 was initiated by a plane wave generator to create a plane wave front of plasma with an initial velocity of 11 km/sec. The generator channel had an electrode separation of 0.15 m, a width of 0.2 m and was 1 m long. With an open circuit voltage of 3.2 KV and a peak current of 430 KA for a pulse length of 200 microseconds, the generator fired a low impedance, coaxial flash lamp filled with argon at 150 mm Hg. Laser threshold, which was substianted by damage produced on an external target, was achieved 60 microseconds after the start of the current pulse. Peak power in the flash lamp was 70 MW and the current pulse lasted 165 microseconds, giving an energy dissipation in the flash lamp of 6,000 joules.

The efficiency of the explosive driven generator is approximately 25%, mechanical to electrical; and approximately 1%, chemical to electrical. Pulse lengths up to one or two milliseconds appear to be feasible. Brogan and Mattson[110] have investigated the possibility of using rocket engines as a source of large amounts of power for short amounts of time. Estimates were made of the power output available from conventional rocket systems such as the Titan, Saturn, etc, and the design of a 20 MW prototype generator was presented. The results for a Titan rocket driven MHD generator, for example, have been reproduced below:

Table XIX*

Thrust	260,000 lbs.
Mass flow	1040 lbs/sec.
Output	1500 MW
Estimated Equipment Cost	$6/Kw output
Efficiency	0.28
Range of Available Output Voltage	4-25 Kw

*Reference 110.

The results for several other rockets were presented including those for a Nova Cluster.

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