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Magnetohydrodynamic Power Generation

James Lee Smith

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Magnetohydrodynamic Power Generation

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NASA

National Aeronautics
and Space Administration

Scientific and Technical
Information Branch

TABLE OF CONTENTS

	Page
I. INTRODUCTION	1
II. HISTORY	1
A. Theory	1
B. Research	2
C. Geography	2
III. BASIC CONCEPTS	2
A. Theory	2
B. Structure	3
C. Engineering Problems	3
D. Energy Conversion	4
IV. MULTI-SYSTEM UNITS	5
A. Design	5
B. Pros and Cons	6
C. Reynolds Metals Project	6
V. OTHER TYPES OF MHD	6
A. Liquid-Metal MHD	6
B. Nuclear MHD	7
VI. SUMMARY AND CONCLUSION	7
A. Summary	7
B. Conclusions	7
REFERENCES	31

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LIST OF ILLUSTRATIONS

Figure	Title	Page
1.	MHD coordinate system	9
2.	Field flow patterns	10
3.	Power-magnet mass graph	11
4.	Electrode and generations figures	12
5.	Arnold burner	13
6.	Arnold flow train	14
7.	Arnold flow train and magnet	15
8.	Arnold schematic	16
9.	Hall and Faraday comparisons	17
10.	Output comparisons	18
11.	Electrode placement diagrams	19
12.	Engineering limits graph	20
13.	Brayton cycles	21
14.	Brayton cycle efficiencies	22
15.	Voltage graph	23
16.	Faraday graphs	24
17.	Operation parameters	25
18.	Magnetic field distribution	26
19.	Enthalpy versus power graph	27
20.	Enthalpy percent graph	28
21.	Coal-fired MHD schematic	29
22.	Steam and air MHD systems	30

TECHNICAL PAPER

MAGNETOHYDRODYNAMIC POWER GENERATION

I. INTRODUCTION

Magnetohydrodynamics (MHD) is the study of using ionized gas or plasma to perturb a magnetic field thus producing a current flow if a load (resistance) is applied. There are three types of MHD: (1) ionized gas, (2) liquid metal, and (3) nuclear. All three types use the same theoretical principles. Since the ionized gas is the most widely used, and the most promising, only it will be discussed in detail in this paper.

A plasma is any state of matter which contains enough free charged particles for its dynamic behavior to be dominated by electromagnetic forces. Very low degrees of ionization are sufficient for a gas to demonstrate electromagnetic forces. About 1/10 percent ionization of a gas achieves over one half its possible maximum electrical conductivity. A 1 percent ionization conductivity is nearly that of completely ionized gas. With the exception of the Earth, the majority of the matter in the universe is plasma. The natural occurrence of plasma on the Earth's surface is non-existent [1:1].*

The purpose of this paper is to explore the area of MHD in an attempt to give a brief, but thorough, overall view of MHD structure and energy conversion, its applications, and its developmental history.

II. HISTORY

A. Theory

"When Faraday discovered the principle of electromagnetic induction, he understood that it applied to conducting fluids as well as to solids. In his time the heat engine was also in use, even though the principles of thermodynamics and gas dynamics had yet to be formulated. The primary ingredient that Faraday lacked was a knowledge of the electrical properties of gases. This knowledge, which necessarily encompasses the science of atomic and molecular physics, began to be acquired through the study of gas discharges in the late nineteenth and early twentieth centuries. These empirical studies were accompanied by the development of the kinetic theory, statistical mechanics, and the quantum theory, all of which were in large part efforts to explain what was observed in discharges," [2:4-5].

The first patents dealing with MHD power generation began to appear in 1910. These patents were very vague about the method of ionization and the resulting electrical properties of the working fluid or plasma.

Magnetohydrodynamics first became a distinct science because of the efforts of scientists (specifically astronomers) who were trying to understand certain astrophysical phenomena. During and after World War II the pursuit of controlled nuclear fusion created additional quests for plasma knowledge [2:5].

*Number following colon indicates page number.

B. Research

In the 1940's a large, sophisticated MHD generator was built at Westinghouse Electric; it failed because sufficient knowledge of the properties of ionized gases was still not available.

In 1959, an experimental MHD generator was built at AVCO that produced 11.5 kW of power and obtained a sufficiently strong interaction between the gases and the magnetic field to cause an appreciable pressure drop. The plasma was argon at a temperature of 3000°K [2:5].

Calculations in the 1950's and 1960's indicated quick success. An ambitious, large scale program was undertaken in America. Although progress was made, these large scale programs were not successful. Scientists turned to small experimental setups in which many problems were solved [3:1].

In 1964 work began on a generator to supply power for a high-enthalpy wind tunnel at the Arnold Engineering Development Center in Tullahoma, Tennessee. This project is still operating [2:8].

The MHD generator for the wind tunnel at Arnold Engineering is known as LORHO. It was designed to produce 20 MW peak, and actually achieved 18 MW for ten seconds [3:4].

In 1963, Avco-Everett Research Laboratory designed, built, and put into operation the first large MHD generator that worked. It produced 32 MW for a few seconds. It was called the Avco Mark V [3:4].

A new project is in progress at Arnold Engineering. It will be discussed later.

C. Geography

World development of MHD has been on a relatively intense basis during the last fifteen years, though less than that for nuclear reactors. The major countries that are doing MHD research are Great Britain, France, Germany, Poland, Japan, the United States, and the Soviet Union. America and Russia are doing most of the development.

National fuel situations have led to different types of development in various countries. In Russia natural gas MHD is being developed. While the USA is working with coal and Japan is working with oil [3:2-3].

III. BASIC CONCEPTS

A. Theory

Consider the coordinate system in Figure 1. The plasma is moving in the $x+$ direction with velocity u , and a scalar conductivity σ . Let B denote the magnetic field. Using the right hand rule, $u \times B$ is in the positive y direction. $u \times B$ is the induced electromotive force or the potential. Therefore the current $j = \sigma (u \times B - E)$ is defined as the Faraday Current where E is the electric field. $j \times B$ produces F in the negative x direction. Define $F = j \times B$ as the Hall Current. The Hall Current is due to the Hall Effect which is caused when charged particles drift randomly in the magnetic field producing F . The basis of MHD is the utilization of j and F to produce power. Power is defined as $P = j \cdot E$. MHD

power is a direct extraction of enthalpy from the ionized gases. An MHD generator that utilizes Faraday Current is called a Faraday Generator; one that uses Hall Current is called a Hall Generator [2:10]. Figure 2 shows the flow field patterns for potential and current between electrodes in an MHD generator.

B. Structure

The MHD generator consists of a very large magnet that fits around the combustion channel. This magnet is called a saddle coil. Magnet mass is directly proportional to power production (Fig. 3). At the beginning of the combustion channel is the burner where fuel and oxidizer are mixed and combusted. Within the walls of the channel are electrodes (Fig. 4, top) which are attached to loads which receive the current generated. Also in the channel are probes which measure temperature, pressure, velocity (as a function of distance and time), and enthalpy (to be discussed later). At the end of the channel, according to the system, there may be a diffusor and seed recovery apparatus, or there may be an additional mode of power generation. All dimensions of the above apparatus depend on the amount of power desired, the type of fuel to be used, and the type of MHD generator to be used [2].

Figure 5 is a schematic for the Arnold Engineering MHD project in Tullahoma, Tennessee. Figures 6 and 7 are schematics of the entire system, while Figure 8 shows the flow and field alignments [4].

C. Engineering Problems

In choosing the type of MHD generator to use, one must consider the following: (1) hall generators produce high voltage and low current, solid electrodes are needed to receive Hall current (Fig. 9); (2) Faraday generators produce low voltage and high current, segmented electrodes are needed to receive Faraday current (Fig. 9).

However, there is an alternative. Build a generator that uses the point of intersection of the figure (Fig. 10). This can be accomplished by using segmented electrodes to receive the high amount of Faraday current and by diagonalizing these electrodes to increase the voltage. The result is a happy median or the best of both generators. (Figure 11 shows the three types of generators: (1) Hall, (2) Faraday, and (3) Diagonalized [2].)

Also the channel and especially the electrodes are subject to erosion and heat damage. Erosion is due to the velocity of the plasma and from slagging effects. Also the 3000°K temperature damages the electrodes. Materials are the number one concern in designing an MHD generator [5].

Much heat is lost through the channel walls at such high temperatures. Most channel walls are water cooled, composite (layered), metal. Electrodes are made of steel, zirconia, and other metals. Carbon has been used but does not hold up. The Russians have developed metal water cooled electrodes that are able to run 24 hours per day and year round. Their sacrifice is lower efficiency, about 10 percent.

Ion slip, due to the atoms deionizing and reionizing is minute at high pressure, and thus is not too much of a problem [2].

After materials, heat loss and excessive magnet cost are the two main design concerns. Along with low pressure ion slip, these three form an operations envelope (Fig. 12). This envelope controls the interaction length [2:148].

MHD generators produce direct current. Direct current-alternating current inverters are expensive. However, many industries, especially metallurgical industries, need direct current anyway.

The final problem is due to the high temperatures of ionization. The heat of ionization, when expressed in electron volts, is called the ionization potential. Most common gases, such as air, carbon monoxide, carbon dioxide, and the noble gases, which are used in MHD, have high ionization potentials. This problem is overcome by adding one of the alkali metals, which have low ionization potentials, to the gas in small amounts. The common gases mentioned above ionize around 4000°K, while the alkali metals ionize around 2000°K. One or less parts alkali metal per one hundred parts gas is sufficient to lower the ionization temperature to 3000°K. This process is called seeding. The seeding process results in temperatures low enough to be withstood by some solid materials [2:17].

There are many other very small problems to be diagnosed and solved in the future that cut the resulting efficiency.

D. Energy Conversion

The MHD generator transforms the internal energy of a gas into electric power in much the same way as a turbine generator. In the turbine generator the energy of a gas is converted into the motion of a solid conductor by the means of the turbine blades and a connecting mechanical linkage. But the MHD generator uses the gas itself as a conductor and by expanding through a nozzle, the gas moves. In both cases the motion of a conductor through a magnetic field produces an electromotive force and a current flow. The conventional turbine generator carries current to an external load through brushes. This same process is carried out in MHD by the electrodes [2:1-2].

A generator producing the equivalent of ten large power plants is possible for MHD, that is approximately 10^7 KW. Applications for which MHD is well-suited are those calling for high power and high temperature. This includes many public and military requirements. "Today an output of 1000 MW from a single plant is not uncommon; and the steam cycle uses only a small fraction of the available temperature from fossil fuels." Higher efficiencies are obtainable with MHD topping of the steam cycle [2:3].

An MHD generator uses a Brayton cycle. (Figure 4 gives MHD-Turbine comparison.) (Figure 13 shows T-S diagrams of the Brayton cycle. The pseudo-Brayton cycle does not use a compressor, while the Brayton cycle utilizes a compressor [2:3-4].) (Figure 14 gives a comparison of closed Brayton cycles with and without steam bottoming.) (Figures 15 through 18 give magnetic field strength, voltage, current, burner pressure, flame temperature, fuel and seed flow, etc., for the Arnold Engineering MHD Generator. These figures will give one a feel for the parameters involved in MHD power production [2:4,4,6].

The power production efficiency is defined as follows:

$$\eta = \frac{h_i - h_f \text{ (actual)}}{h_i - h_f \text{ (isentropic)}} = \frac{\Delta h \text{ (actual)}}{\Delta h \text{ (reversible, adiabatic)}}$$

where η = efficiency, h_i = enthalpy (initial), and h_f = enthalpy (final).

Efficiency can be calculated by computer utilizing a component composition analysis program. All modern MHD generators are computer monitored and controlled. An enthalpy probe has been designed that measures Δh (actual) by measuring (velocity) time, and temperature difference. After being calibrated for the system, it is fairly accurate [5].

The highest Russian (Moscow Project) efficiency obtained to date is 10 percent. The highest efficiency obtained in the world is 12 percent at the Arnold Engineering Development Center. It is believed that the highest achievable is 15 percent, while the theoretical efficiency is 20 percent. Cost per kilowatt hour is estimated at \$10 to \$20. (Figs. 19 and 20 give Arnold Engineering enthalpy charts.)

IV. MULTI-SYSTEM UNITS

A. Design

The steam generator required for an MHD binary system is of somewhat different design than that for conventional power plants because of the high temperature of the MHD exhaust, the presence of ash, seed, and slag in the combustion products. Another important component required by an MHD system is an inverter to convert direct current to alternating current. Much inverter progress has been made in Russia [3:9-10].

The MHD steam unit (Fig. 21 and the top of Fig. 22) consists of a coal or natural gas fired MHD channel. Attached at the end of the channel is a steam generator (somewhat like a boiler) which produces steam to drive turbines. Beyond the steam generator is a seed recovery system which sends seed back to the combustor. Next we have attached a nitrogen and sulfur remover (sulfur is the number 1 drawback in coal combustion) which removes nitrogen and sulfur in the forms of acid. Both of these acids are in demand in industry. Only clean gas goes out of the plant [3:9].

Binary system efficiency is defined as the following:

$$\eta_{\text{total}} = \eta_{\text{MHD}} + \eta_{\text{other system}}$$

Most steam plants have efficiencies of 30 to 35 percent. Therefore a binary efficiency of 40 to 50 percent is obtained with 60 percent a good possibility [5].

A similar setup uses air instead of steam (Fig. 22, bottom). This system is basically the same, but uses air instead of steam turbines. It is not quite as efficient [3:9].

Most MHD applications use a Brayton (gas) cycle rather than a Rankine (vapor) cycle. Working fluids suitable for use in high temperature Rankine cycles tend to be highly corrosive. Most of these fluids are metals and not gases. On the other hand, gases seeded with metals are less corrosive and do not present as much materials problems. This favors binary systems. The products of fossil fuel combustion are gases and therefore result in a Brayton cycle and binary possibilities [2:164-165].

An MHD-steam cycle utilizes the waste heat (Q_{out}) from the Brayton cycle to produce steam and run turbines. Most proposals for commercial fossil-fueled power plants have included steam bottoming [2:170].

B. Pros and Cons

The strong points of MHD binary systems seem to outweigh the weaker points. Over a period of time initial costs would be absorbed by lower power production costs (a result of higher efficiency.) A factor of increasing concern is pollution control. A coal fired power plant produces three types of pollution: (1) thermal, (2) particulate, and (3) chemical. An MHD steam plant rejects only half of the heat of conventional steam plants. MHD has an advantage of 3 to 1 in heat loss as compared to nuclear. The process of seed recovery removes most of the particulate pollution. Chemical pollution from power plants consist of NO and SO₂. These are removed in the forms of acids in the MHD system. The initial costs for MHD are greater than steam, but comparable to nuclear. In summation it appears that MHD has something to offer from an economic as well as ecological viewpoint [2:174-175].

C. Reynolds Metals Project

Consider the Reynolds Multisystem MHD plant project. This system is not a true binary system, but its efficiency and usage warrant its mention in this section. The following project was researched in the seventies.

Reynolds Metals, an aluminum producer, needed a means to combat rising electricity costs. Aluminum production needs large amounts of direct current. High temperatures are needed for smelting. Much hot water is needed for processing. A pilot project at Listerhill, Alabama, was conducted by Ed Scannell, Ph.D. Dr. Scannell claimed an overall efficiency (total energy, not electricity) of 80 percent with the following explanation:

- 1) Direct current was generated and used in processing.
- 2) The generator was a water cooled system. Instead of the plant heating water as usual, cool water was used to cool the generator yielding hot water as a by product which in turn was used in processing.
- 3) The plasma at the end of the generator could be used directly in the furnace to melt the ore.
- 4) Hot air from No. 3 above could be used in the processing also.

As one can see, MHD is perfectly suited for the metalurgical industry. This project ended two years ago when Billy Reynolds (who supported it) died.

V. OTHER TYPES OF MHD

A. Liquid-Metal MHD

Liquid-metal MHD uses a flowing melted metal instead of an ionized gas to produce current. The metal is very corrosive and electrodes do not last long. Most research has used coal for heat and sodium as the metal. This can be coupled with steam turbines in a Rankine cycle. Liquid-metal does not look as promising as ionized gas MHD.

B. Nuclear MHD

In nuclear MHD, nuclear fission takes place and the nuclear plasma is allowed to flow through the MHD channel in a closed system. Steam bottoming would also be used. It is feared that in nuclear MHD radioactive material would be allowed to leak from the system because of the high temperatures. Nuclear MHD requires a temperature of 2500°K , while nuclear reactors operate at 1000°K .

Because of the absence of hot, highly stressed, moving parts, both in the generator and in the rest of the cycle, it is possible that nuclear MHD would require little maintenance. The expensive part of the generator is the field coil, and it is outside of the channel. If the channel became contaminated, it could be discarded and the magnet saved. Theoretically the nuclear MHD system would be more efficient than the standard nuclear reactor. Costs would be approximately the same [2:178-179].

VI. SUMMARY AND CONCLUSION

A. Summary

MHD generators produce current by passing a high velocity conducting fluid through a very strong magnetic field. The conducting fluid is an ionized gas, or plasma, or a liquid metal. The simplest MHD system is an open system, in it an alkali metal is used to seed the combustion products.

The other system is a closed system, in which a very pure inert gas is heated in a heat exchanger and seeded with an alkali metal. The inert gas is recycled.

In a liquid-metal MHD system, a mixture of metal and gas is heated to a high temperature and expanded in the channel as a foamlike substance. This foam is used as the working fluid.

Open cycles have higher efficiencies than closed cycles. For this reason, MHD power systems are being considered for advanced power plants.

The MHD working fluid exits the MHD channel at high temperatures. To design high performance power plants, this exit heat must be utilized. This is generally done by using steam bottoming. Heat exchangers are normally used to produce the steam.

The disadvantages of MHD are their complexity compared to standard steam plants, construction time is longer, costs are higher, direct current must be converted to alternating current, and all the drawbacks are not yet known.

The advantages are high potential for high efficiency and low cost per unit power, and cleaner emissions.

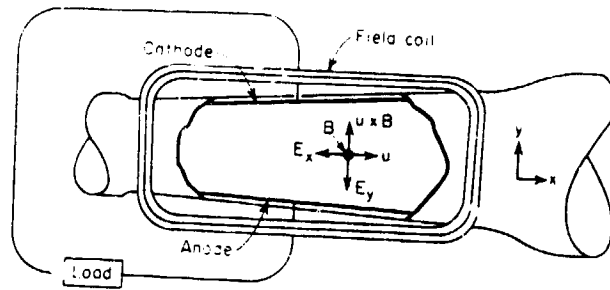
B. Conclusions

The author believes that much additional research is warranted. Although the costs of MHD are high, the good points override the weak points. With the coal reserves of America and the antipollution setups of MHD, MHD generation seems to be one of the best ways to utilize the resource of coal. One

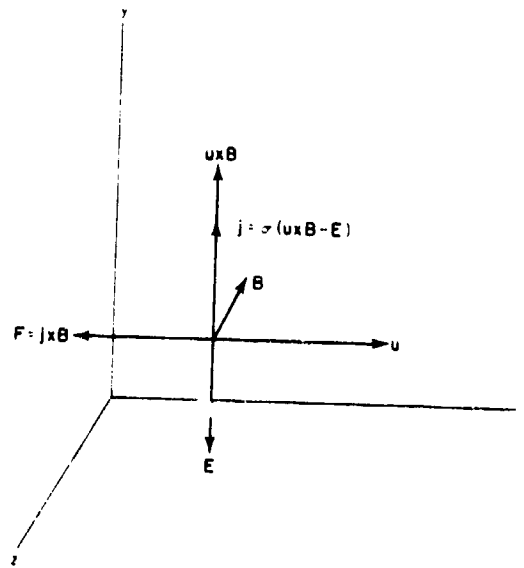
of the best areas for research in the near future is MHD. In due time the efficiencies will be raised as problems are solved and discoveries are made.

Magnetohydrodynamics does have a future in power production for America and the world.

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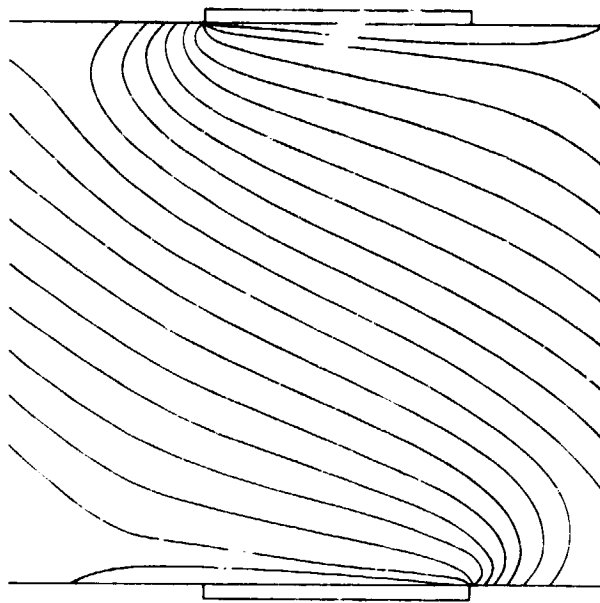
Schematic diagram of a dc magnetohydrodynamic generator. [2:3]



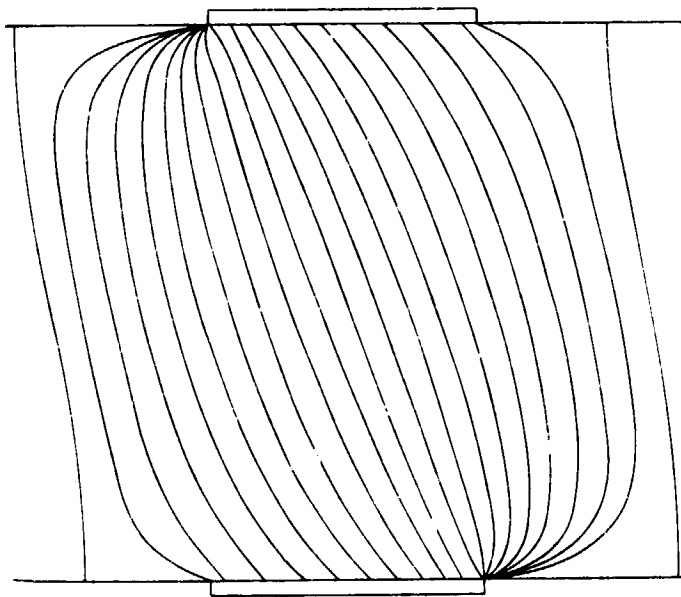
Coordinate system. [2:10]

Figure 1. MHD coordinate system.

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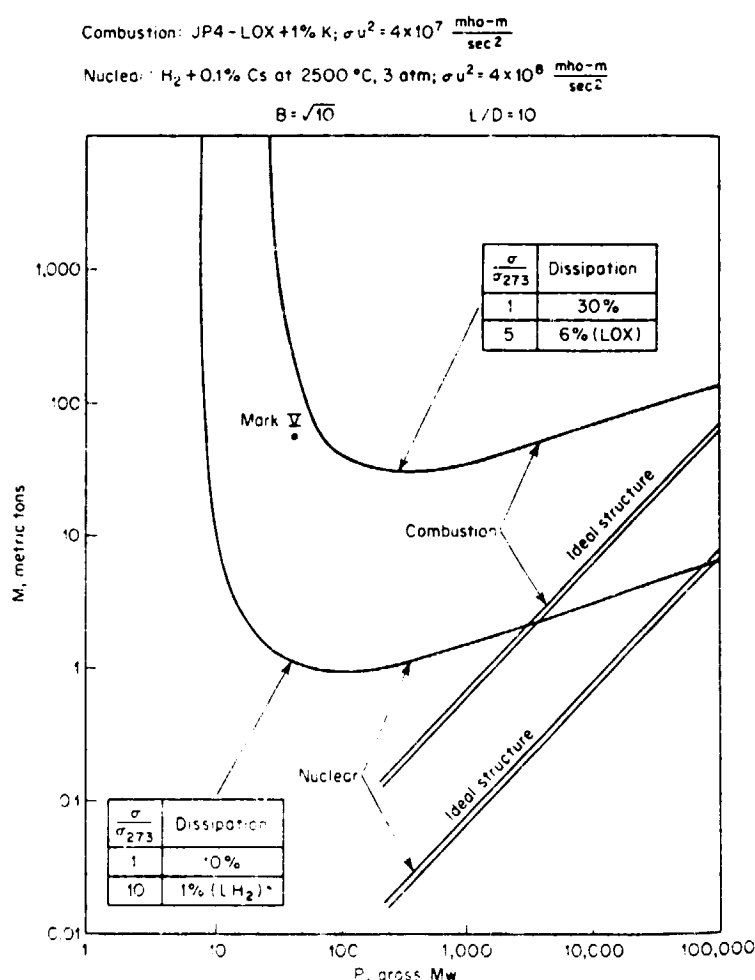
MHD potential flow field lines. [2:69]



MHD current flow field lines. [2:68]

Figure 2. Field flow patterns.

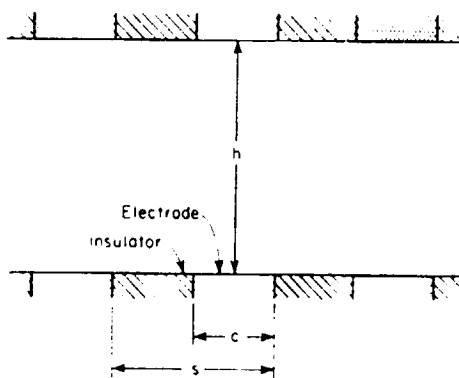
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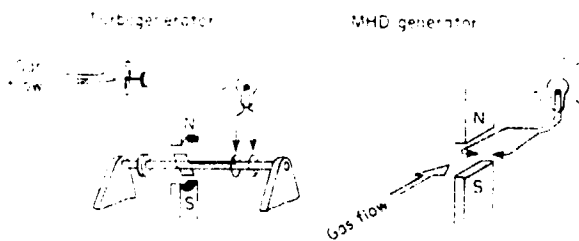
Coil mass versus generator power output. [2:128]

Figure 3. Power-magnet mass graph.

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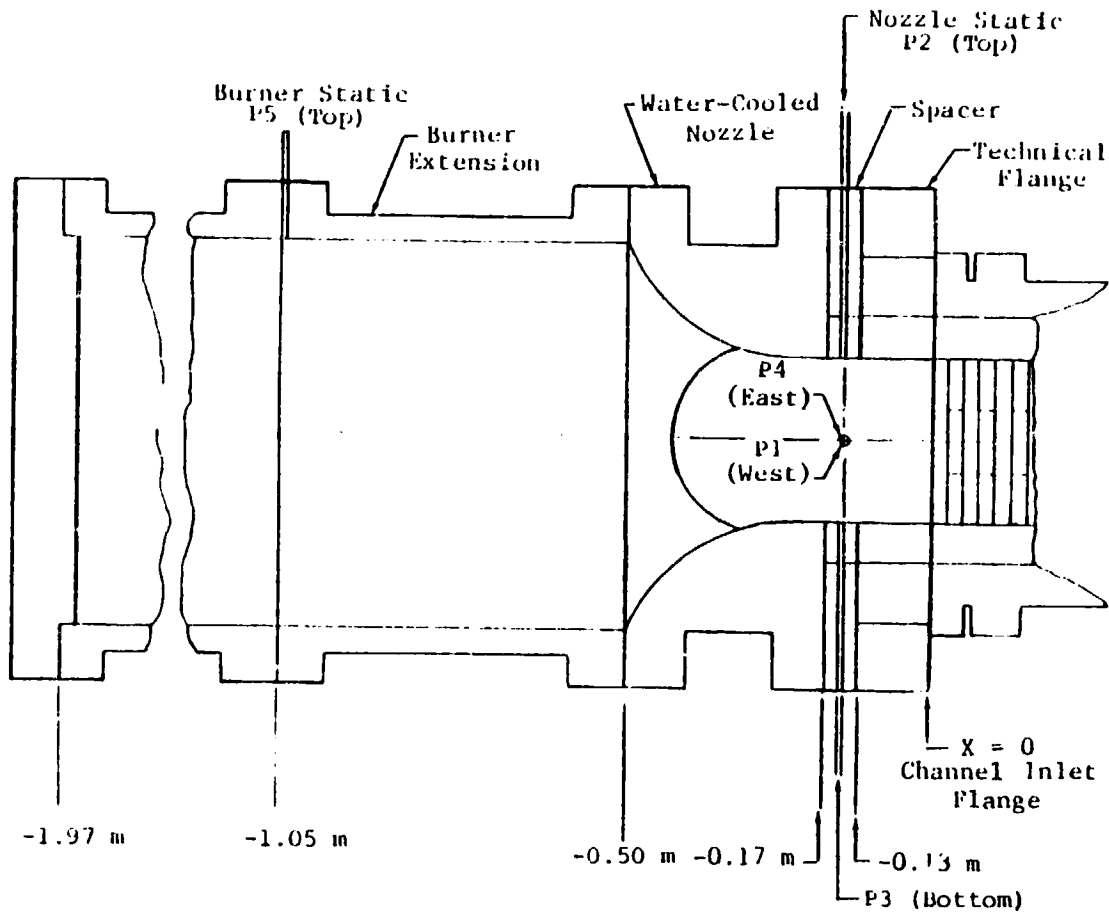
Segmented electrodes. [2:67]



Comparison between the turbogenerator and the magnetohydrodynamic (MHD) generator. [2:2]

Figure 4. Electrode and generations figures.

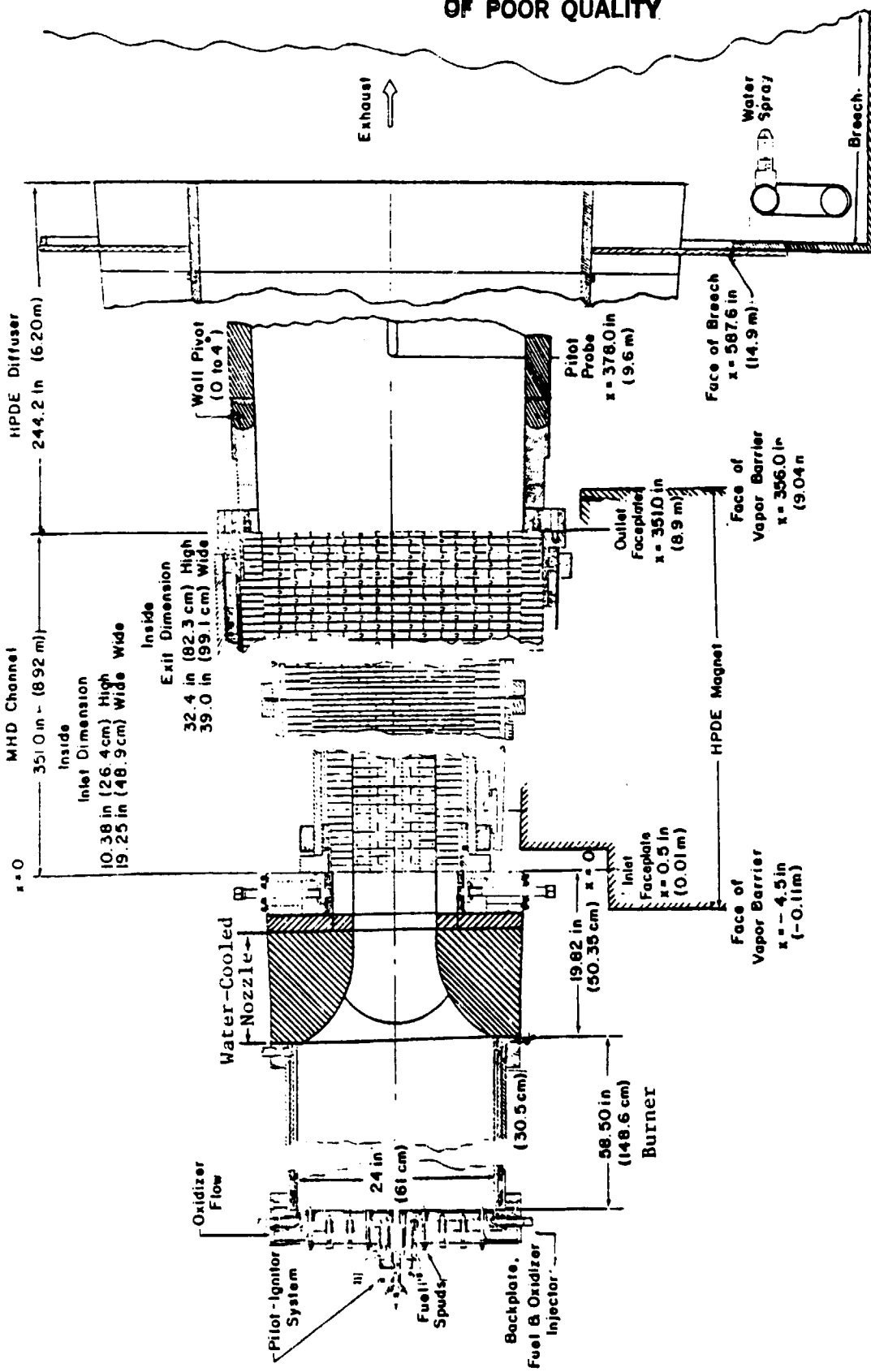
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HPDE burner showing location and designation of pressure instrumentation. [4:A-14]

Figure 5. Arnold burner.

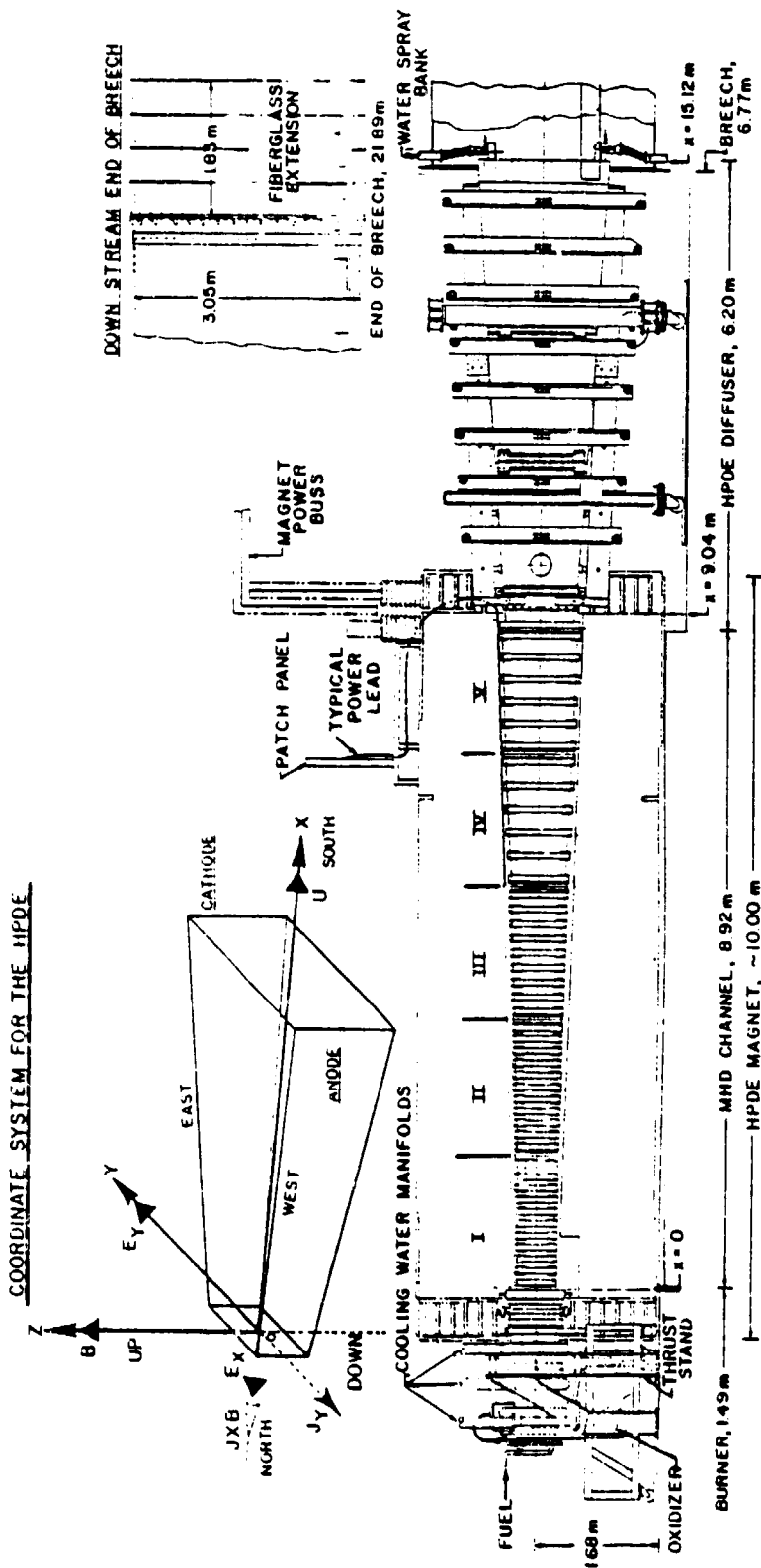
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Elevation of HPDE flow train. [4-a-13]

Figure 6. Arnold flow train.

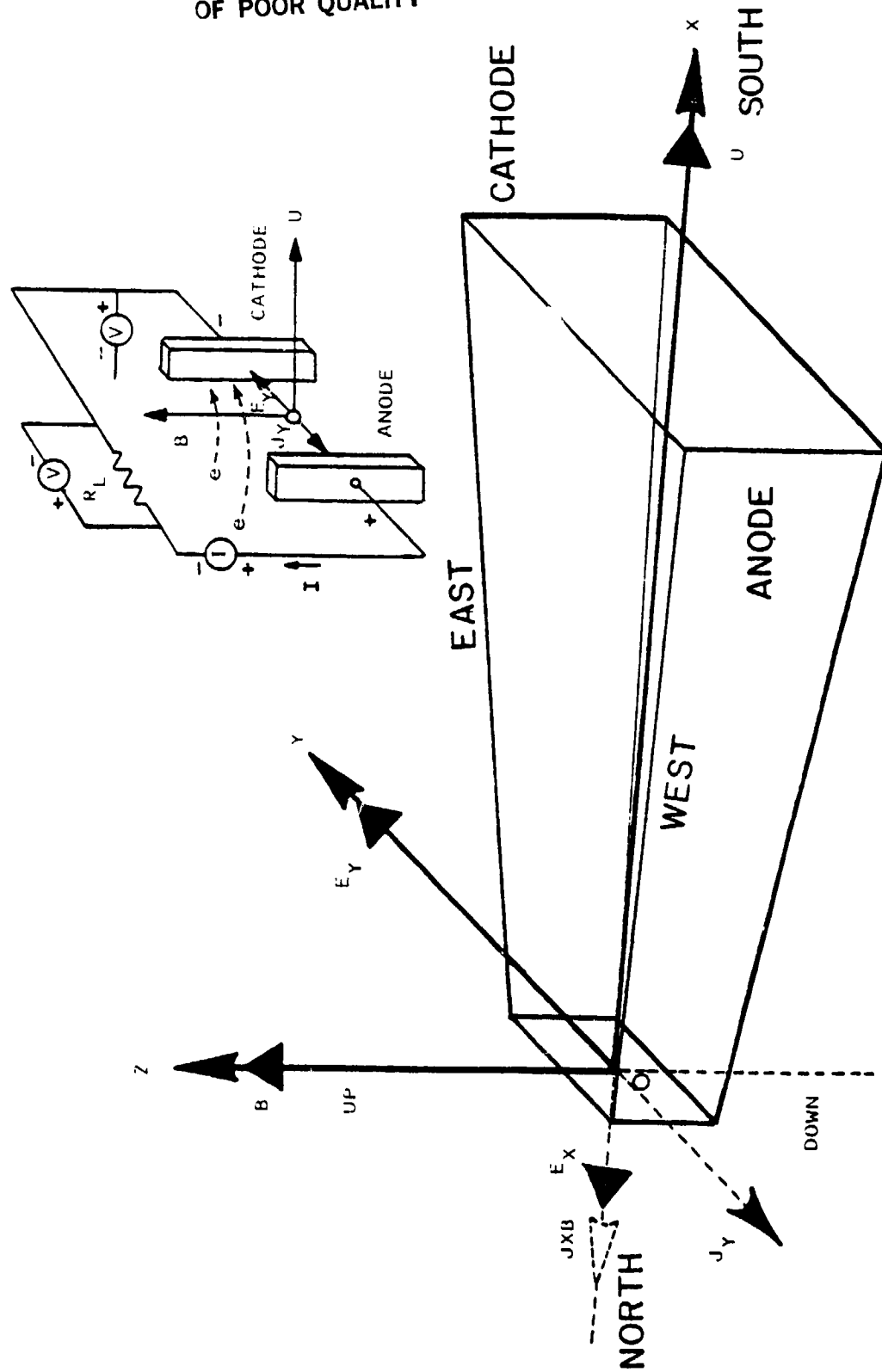
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Elevation of schematic of HPDE flow train and magnet. [4:2]

Figure 7. Arnold flow train and magnet.

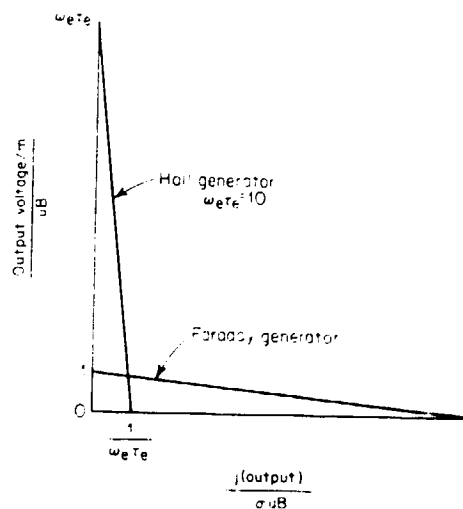
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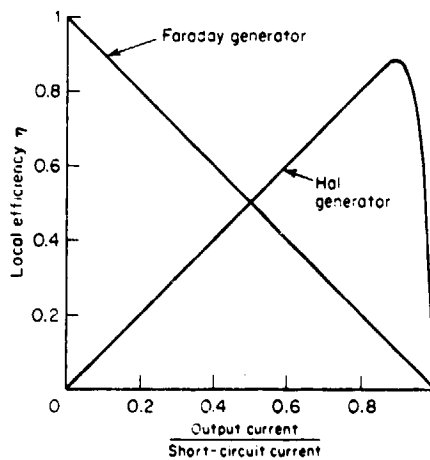
Coordinate system for the HPDE with origin defined as center of the inlet channel flange and geographic orientation in HTL building noted. [4:A-12]

Figure 8. Arnold schematic.

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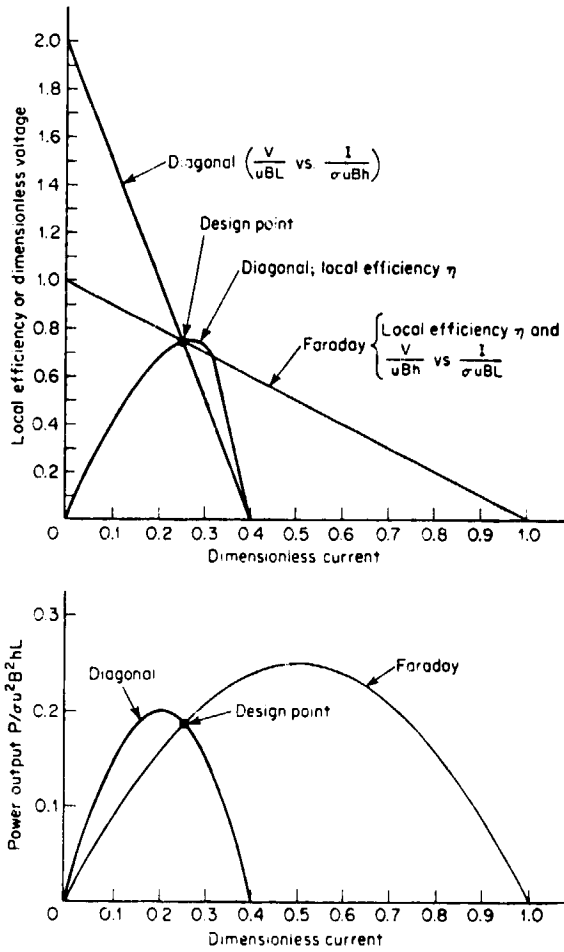
Comparison of the V-I characteristics of Hall and Faraday generators. [2:62]



Comparison of η_c versus I characteristics of Hall and Faraday Generators. [2:63]

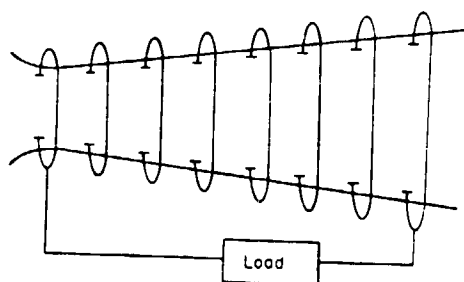
Figure 9. Hall and Faraday comparisons.

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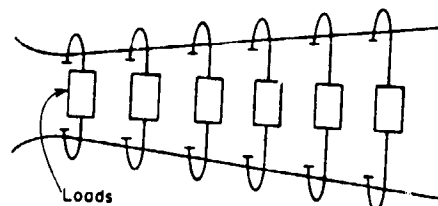


Comparison of the output characteristics of a diagonal and a Faraday generator. [2:66]

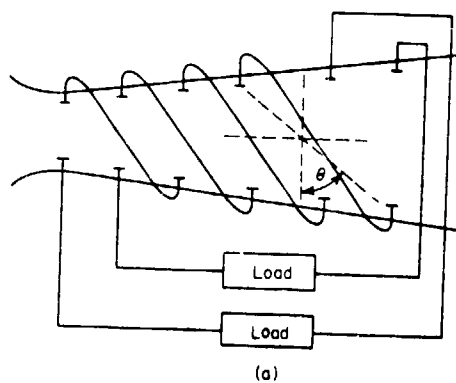
Figure 10. Output comparisons.



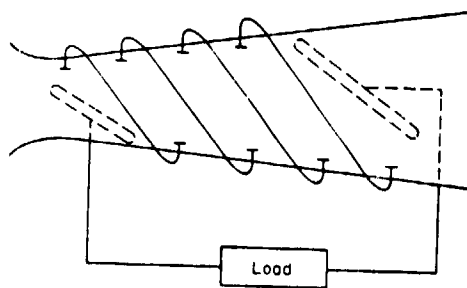
A linear Hall generator [2:61]



A linear Faraday generator with segmented electrodes. [2:60]



(a)

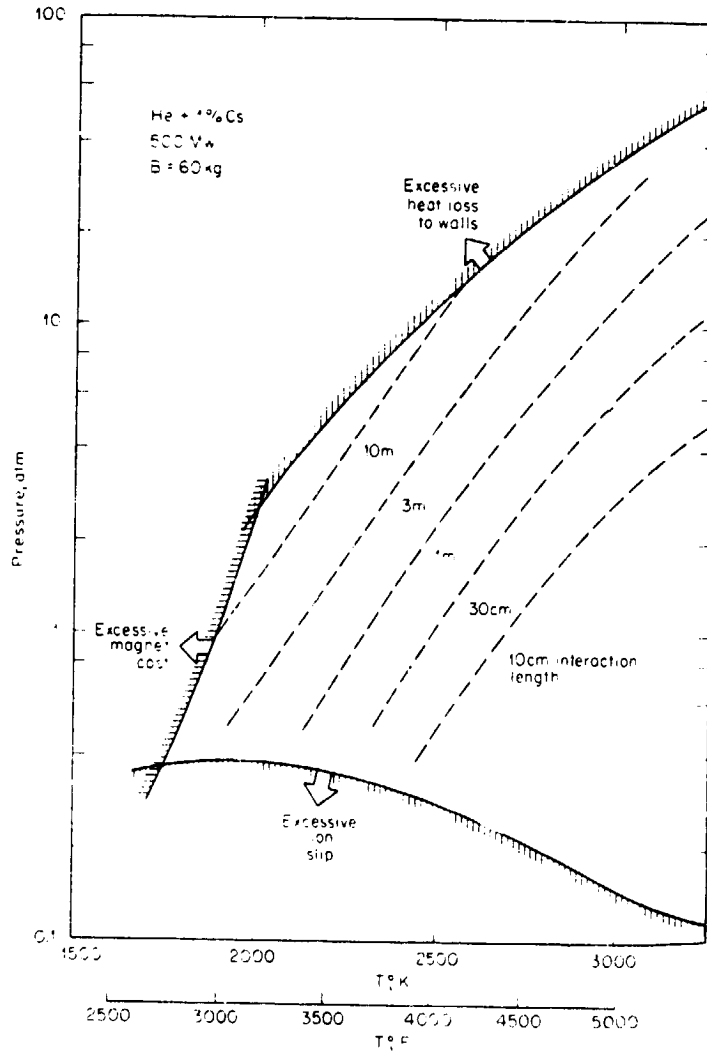


(b)

*(a) A diagonally connected generator;
(b) diagonal-load electrodes. [2:64]*

Figure 11. Electrode placement diagrams.

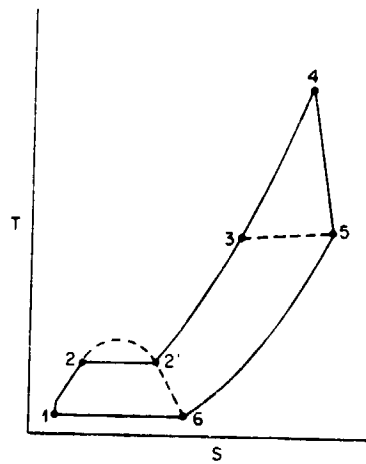
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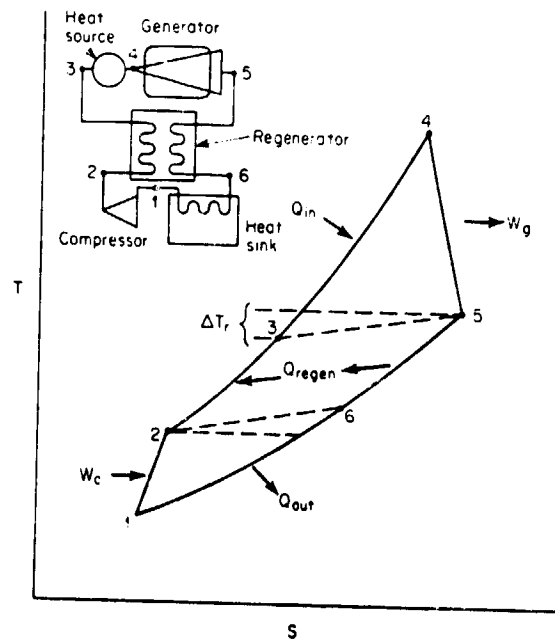
A typical envelope of allowed operating conditions, and the variation of the interaction length within the envelope. [2:146]

Figure 12. Engineering limits graph.

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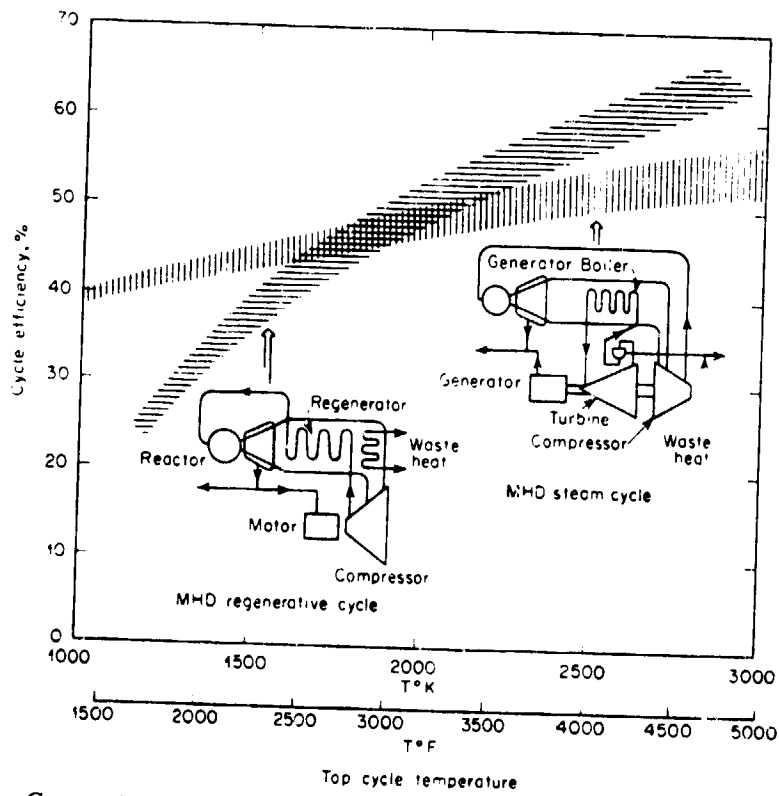
Pseudo-Brayton cycle. [2:169]



Brayton cycle with regeneration. [2:165]

Figure 13. Brayton cycles.

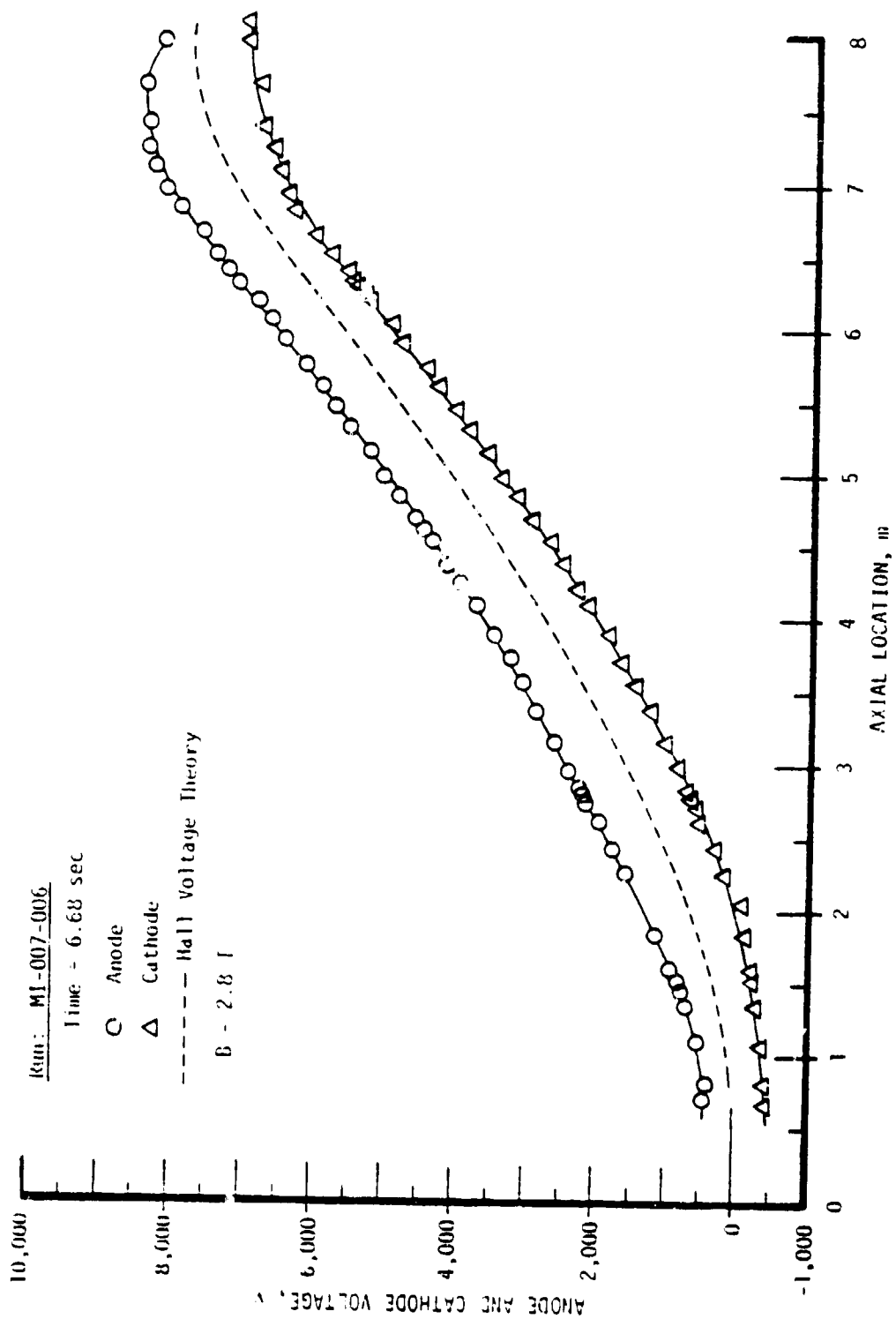
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Comparison of closed Brayton cycles with and without steam bottoming. [2:171]

Figure 14. Brayton cycle efficiencies.

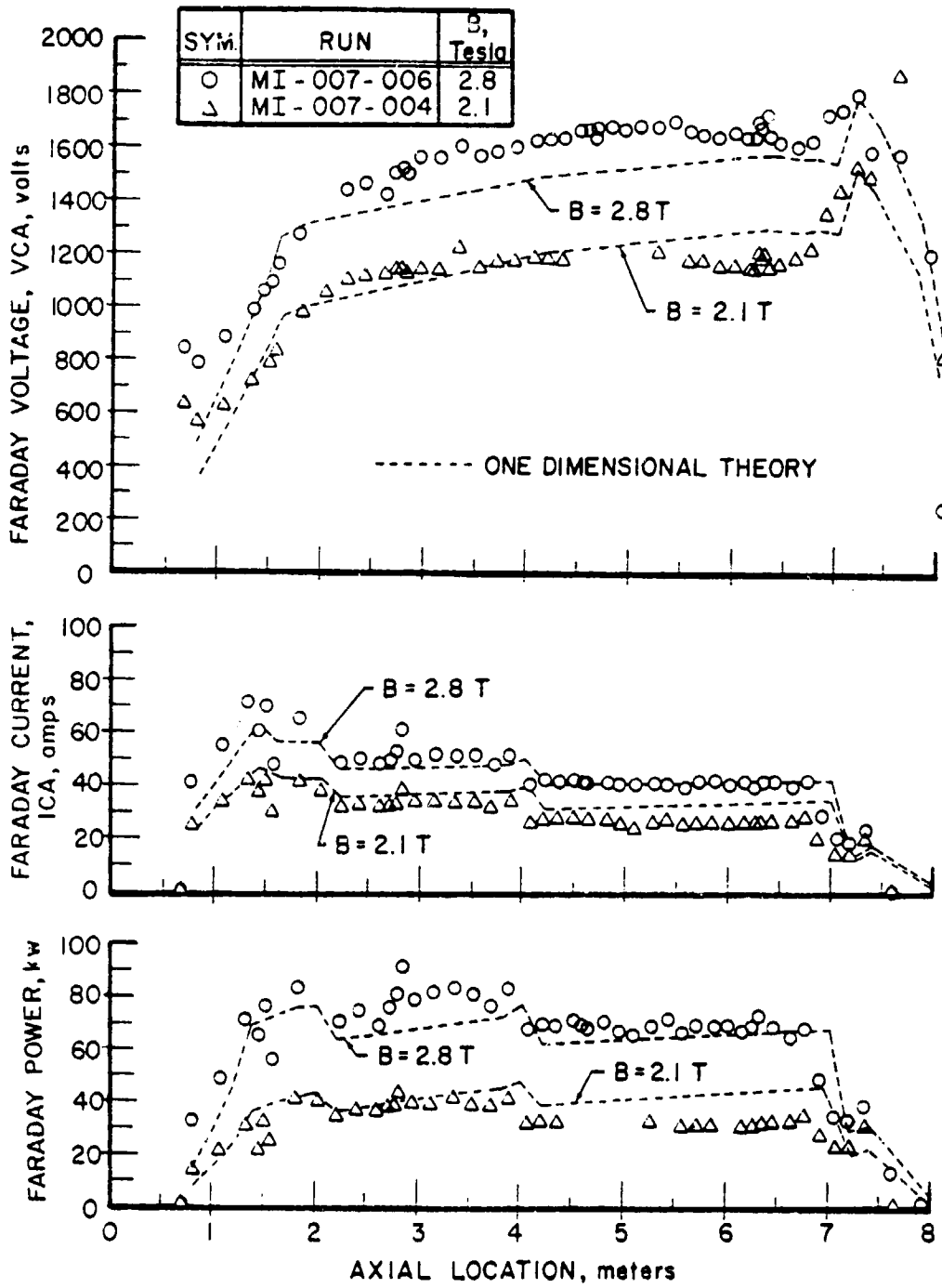
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Development of cathode and anode voltage along the channel walls, $B = 2.8 T$ [4:18]

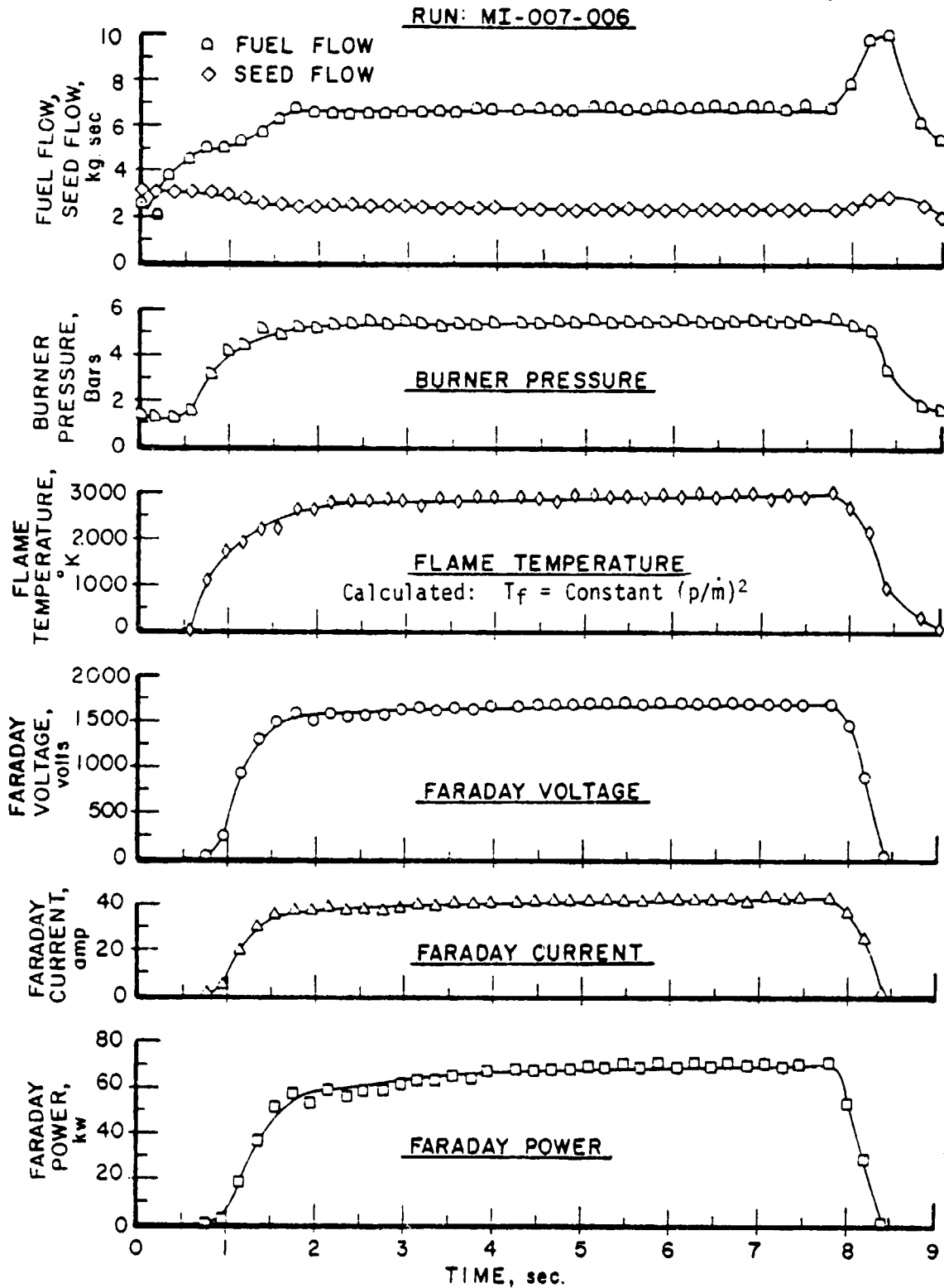
Figure 15. Voltage graph.

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Development of Faraday voltage, current, and power along the channel, $B = 2.1$ and 2.8 T. [4:19]

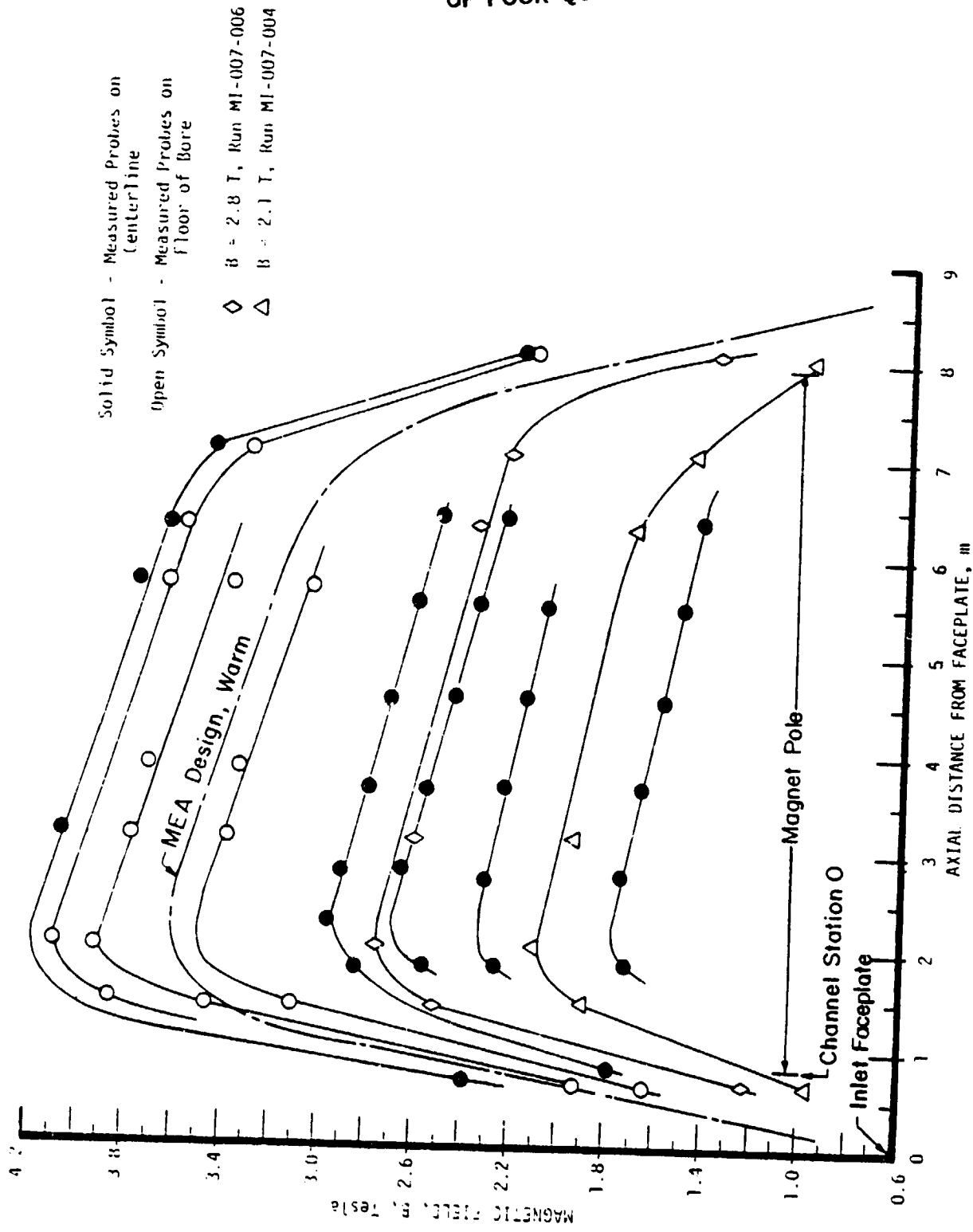
Figure 16. Faraday graphs.



Variation of selected key parameters during HPDE run MI-007-006. [4:13]

Figure 17. Operation parameters.

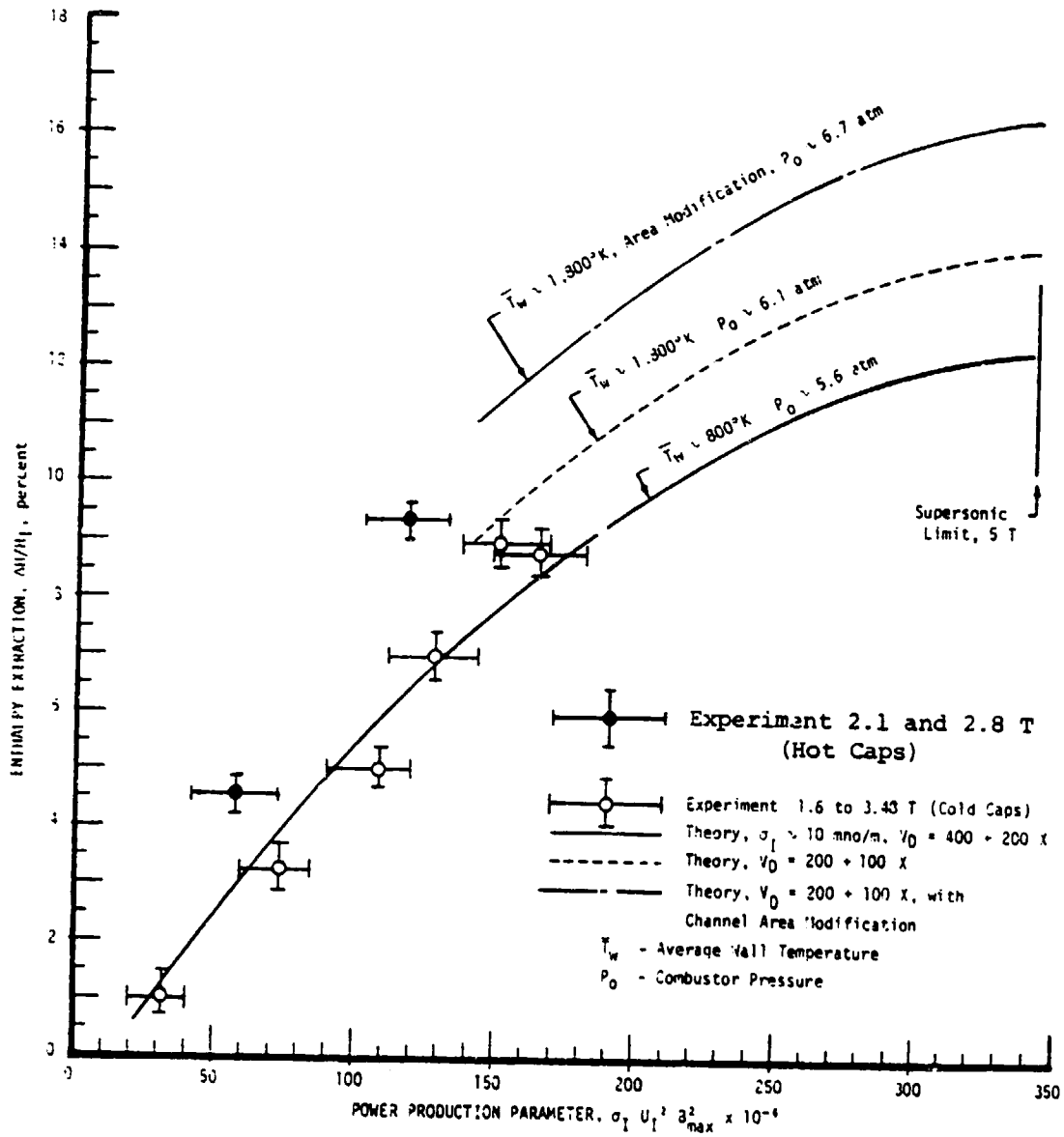
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Magnetic field distribution in HPDE magnet. [4:13]

Figure 18. Magnetic field distribution.

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Enthalpy extraction versus power production parameter, $\sigma U^2 B^2$. [4:20]

Figure 19. Enthalpy versus power graph.

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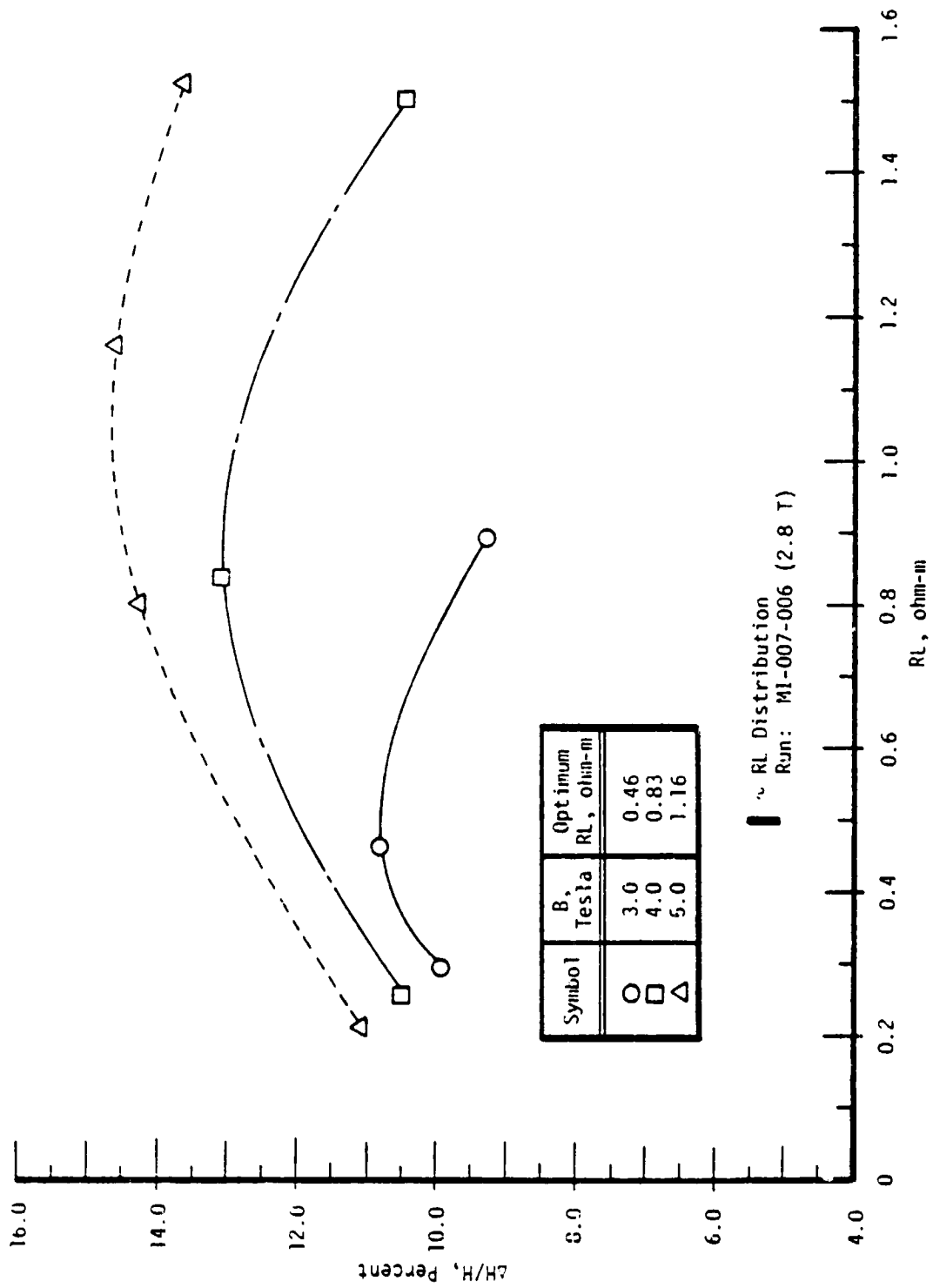
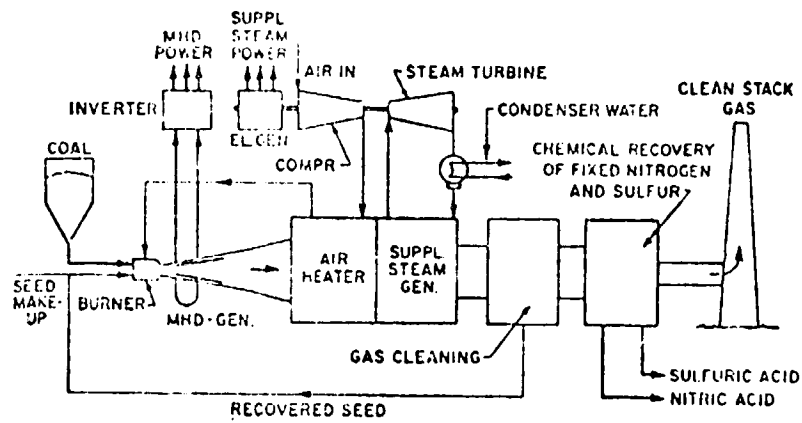
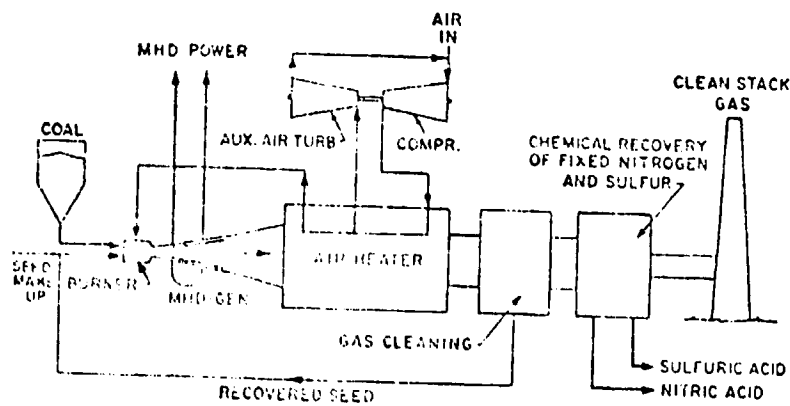


Figure 20. Enthalpy percent graph.

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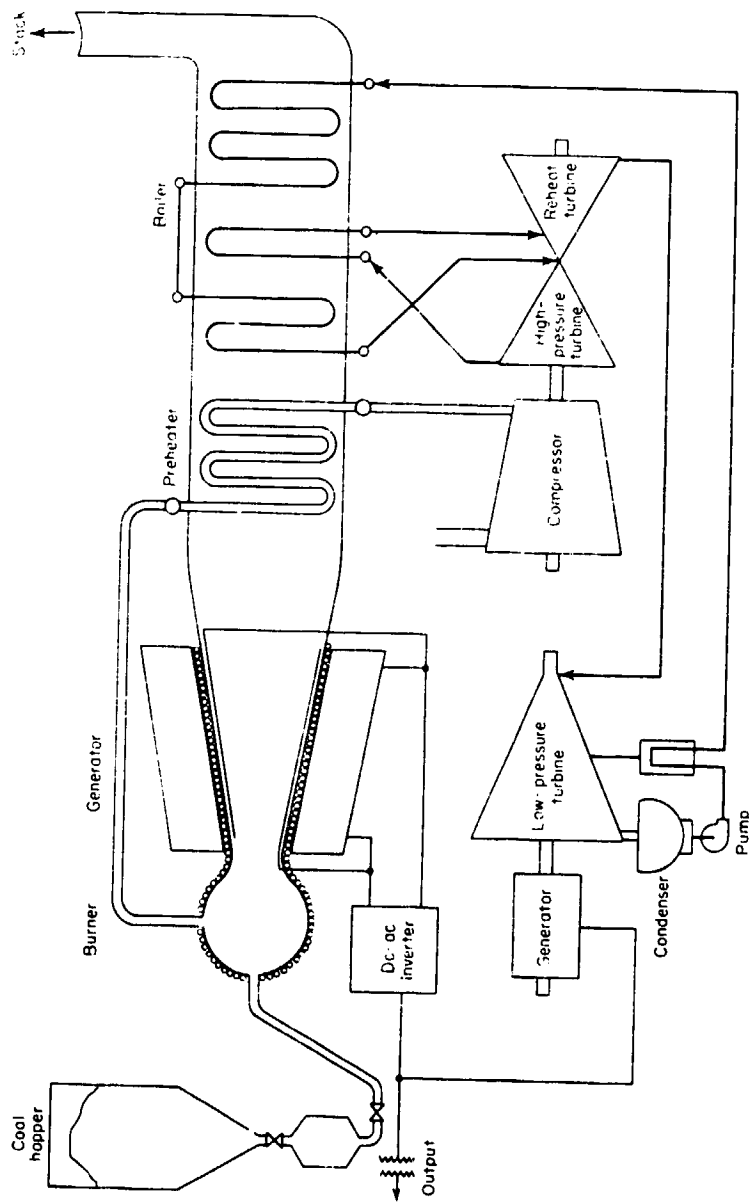


MHD-steam binary power system. [3:9]



MHD-air binary power system. [3:9]

Figure 21. Coal-fired MHD schematic.



Coal-field MHD steam power cycle. [2:173]

Figure 22. Steam and air MHD systems.

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