MHD POWER GENERATION

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Introduction

The MHD Generator is now widely recognized as one of the more promising new methods for large-scale electric power generation. However, the term "generator", although correctly implying that this is a device for producing electric power, is misleading in the sense that it is not truly descriptive of its primary function.

This primary function, in the terminology of thermodynamics, is that of an "expansion engine" like the reciprocating piston engine and the turbine. That is to say, it is a device for converting heat (or more specifically the enthalpy of a gas) into a more useful form of energy. Since expansion engines are the prime movers of modern technological society, the refinement of such engines is potentially of far-reaching importance.

Although premature, it is tempting to suppose that the MHD generator represents the next and perhaps the ultimate step in the refinement of such engines. One might view the development of expansion engines as having proceeded from the piston engine with its multiplicity of valves, cams, and sliding seals, through the turbine, which is little more than a windmill inside of a pipe, to the MHD generator in which the windmill too is removed, the pipe alone remaining--with the aerofoils of the windmill replaced by lines of magnetic force.

The potential advantages of the MHD generator over the turbine are to a degree analogous to the advantages of the turbine over the piston engine. As a result of their conceptual simplicity, turbines outclass piston engines in power handling capacity and reliability. Likewise, the MHD generator, which represents a still further increase in simplicity, also represents a still further increase in intrinsic power handling capacity and potential reliability.

But beyond this, the MHD generator also represents a large step forward in temperature handling capability and thus efficiency. With respect to temperature the turbine is actually a step backwards, whereas the MHD generator, in principle, can handle even the very high temperature that may be produced someday in the plasma of a fusion reactor.

While the bulk of the present MHD development effort is directed toward fossil-fired plants, the advance of reactor technology toward higher temperature could eventually make it possible for nuclear plants to take advantage of MHD also.

The MHD Energy Conversion Process

The magnetohydrodynamic (MHD) generator transforms the internal energy of a gas into electric power in much the same way that a turbogenerator does, and the basic physical phenomena that are employed are the same in both cases. Figure 1 illustrates this point and also illustrates the essential difference. In a turbogenerator, the energy of a gas is converted into the motion of a solid conductor by means of turbine blades and a connecting mechanical linkage. In the MHD generator the gas itself is a conductor and by expanding through a nozzle moves itself. In either case, the motion of a conductor through a magnetic field gives rise to an electromotive force and a flow of current in accordance with Faraday's law of induction. In a conventional generator, the current is carried to the external load circuit through "brushes". In the MHD generator, the same function is performed by "electrodes".

In order to conduct electricity, a gas must of course be partially ionized. So far, only thermal ionization has proven practical for this purpose because instabilities associated with other methods of ionization tend to produce a plasma that is not sufficiently uniform for use in an MHD generator. Most common gases, such as air, CO, CO_2, or the noble gases, do not ionize appreciably until temperatures in excess of 4000°K are reached. However, if a common alkali metal-bearing compound such as potassium carbonate is added to a gas in small amounts (on the order of one part per hundred or less), sufficient thermal ionization can be obtained at temperatures of 2000° to 2500°K. This process, called seeding, thus results in temperatures low enough to be withstood by some solid materials and to be produced in furnaces. Figure 2 shows a curve of conductivity vs. temperature, typical of combustion product gases.

At this point it may be helpful to summarize the major differences between the plasma in a fusion reactor and the plasma in an MHD generator. The latter will consist primarily of neutral particles, only about one in 10^4 being ionized. The energy distributions of all particles will be essentially maxwellian and--under most circumstances--all will have the same mean energy which will correspond to only a few thousand degrees Kelvin. The gas pressure will range from one-half atmosphere to several atmospheres, hence even though magnetic fields of up to 8 tesla are contemplated, the ratio of electron cyclotron frequency to collision frequency ($\omega\tau$) will not exceed four or five. The magnetic Reynolds number ($\mu_0 \sigma u L$) will be less than unity--generally much less. That is to say, the magnetic field distribution will not be appreciably altered by the motion of the plasma.

It will be recognized that these conditions are very much less complex than those in a fusion plasma. Indeed the MHD generator problem is essentially solved by combining the gas-dynamics of wind tunnels with the equations of current flow pertaining to ordinary solid or liquid conductors--with one notable exception, namely that the gas exhibits a much stronger Hall effect than all but a very few solids, i.e., the conductivity is a tensor. This fact does significantly complicate the design of MHD generators, and it does lead to some potential instabilities. These are mild however compared with those with which the fusion researcher wrestles. This rather drab phenomenological picture doubtless accounts for the relatively slight interest that fusion researchers have traditionally exhibited toward MHD. It is worth remarking, however, that this has not been the case in the U.S.S.R. where fusion researchers have made some notable contributions to MHD generator theory.

An MHD generator in its most typical form (Figure 3) consists of a duct down which the gas flows owing to an applied pressure gradient, an arrangement of coils which produce a magnetic field across the duct, and electrodes on either side which carry off the current. Because of the absence of hot, highly stressed moving parts, or of any solid parts at all which are not readily accessible for external cooling, and because there are no close tolerances to be maintained, the device can handle gas conditions which would quickly destroy a conventional turbine. Experimental generators have been built which have withstood gas temperatures of 3000°K and the erosive and corrosive effects of ash for many hours.

Construction

It was concluded at an early stage in MHD development at Avco that it would not be practical to employ thick refractory duct liners operating at the gas temperature, especially if ash-bearing fuels such as residual oil or coal were to be used. This meant that the walls had to be cooled. However, the properties of high thermal conductivity and low electrical conductivity are not found in any single material. Therefore, the composite channel structure illustrated in Figure 3 was developed. In this drawing, the top and bottom walls are electrodes, while the side walls have a voltage gradient along them, and therefore must be insulators. In both cases, the walls are made up of water-cooled metal elements with a thin layer of refractory insulation in between. Such a wall looks to the gas like an electrical insulator so long as the voltage between adjacent elements is less than that required to support an arc (about 50 volts under typical gas conditions).

On the electrode walls an additional feature is present. This is a groove filled with refractory in the face of the metal element. The depth and width of the groove are chosen so that the heat transfer from the gas raises the surface temperature of the refractory to approximately 2000°K. At this temperature, it becomes a good electron emitter and electrical conductor. The refractory most often used for this purpose has been stabilized zirconia. However, there is evidence that many other refractory mixtures, including coal slag, would serve the purpose nearly or equally as well.

The wall structure described above is capable of withstanding the high-temperature combustion gases with ease. That is to say, the handling of high temperature per se is not a problem. The major problem has been rather a gradual degradation of the resistivity of the inter-element ceramic (generally MgO) due to penetration by seed compounds (KOH, K_2SO_4, and K_2CO_3) dissolved in water.

There appear to be several solutions to this problem. These are illustrated in Figure 4. One is to use insulators of pure, dense MgO. A second is to add a small amount of refractory in the combustion chamber along with the fuel. This refractory coats the entire wall and, because its surface temperature is above the dew point of the seed, prevents the seed from condensing and penetrating the insulators. In the case of a direct coal-fired generator the ash contained in the fuel may serve for this purpose.

A third solution, favored in the U.S.S.R., is to allow a coating of seed (presumably K_2CO_3) to form while maintaining a wall temperature cold enough so this layer is solid but hot enough to prevent the layer from absorbing water vapor from the gas. The validity of this solution is open to question if direct coal firing is contemplated. However, it seems adequate if the fuel is gas or light oil.

Machine Efficiency

An MHD generator uses a thermodynamic cycle similar to that used by a turbine, i.e., a Rankine cycle if the working fluid is condensed at some point, or a Brayton cycle if it remains a gas. The efficiency of an MHD generator as a cycle component is defined as the ratio of the energy actually extracted to the energy that would be extracted by a perfectly reversible or isentropic expansion between the same two pressures. This is the same definition as that used for a turbine. The most important dissipative processes are joule dissipation and wall friction, but heat loss to the walls and excitation power consumed by the magnet (if it is not superconducting) can also be important.

All losses tend to become smaller compared with the total output as the device becomes larger, or as the power output per unit volume goes up. The latter requires either increased magnetic field strength and/or increased conductivity resulting from increased flame temperatures. Present practical limits are represented, on the one hand, by a fossil fuel burned with pure oxygen and, on the other hand, a fossil fuel burned with air preheated to 2000°F. In the first case, power density as high as 1000 MW/m^3 and an efficient generator as small as approximately 1 MW is possible. In the second case, power density is on the order of 25 MW/m^3 and a smallest efficient size of several hundred MW results.

Cycles and Cycle Efficiency

As noted above, the MHD generator may be used in either a Brayton or Rankine cycle depending upon whether the working substance is a gas or a vapor. In either case, its thermodynamic role is that of an "expansion engine" like a turbine. For a variety of reasons, primarily greater suitability for high temperature, the Brayton or "gas" cycle is favored. Figure 5a shows the basic Brayton cycle. Figure 5b shows the cycle with embellishments added for maximizing its efficiency. This is the cycle proposed for base-load use. Finally, Figure 5c shows a simplified cycle proposed for emergency, peaking, and military applications. Thermodynamically, it is only a partial cycle since it depends upon an outside source for liquefied (or compressed) oxidizer. It could be called a "rocket cycle". (As might be imagined, there is also a spectrum of cycles lying between the extremes represented by b and c and exhibiting a corresponding spectrum of characteristics. However, these need not be considered here.)

Detailed cycle efficiency calculations performed according to the standards of and with the aid of utility power engineers are summarized in Figure 6 and compared with calculations performed by other U.S. and foreign groups. Efficiency is here plotted against air preheat temperature since it is one of the most important practical parameters controlling top flame temperature and cycle efficiency. A considerable amount of experimental testing, both here and in Russia, indicates that 3000°F preheat is practical in gas or oil fired plants. Much less testing with fuel having a high ash content, i.e., coal, has been done, but the indications are that at least 2000°F is feasible. Schemes for raising this figure have been advanced, but none has yet been tested. In any case, it is now widely accepted that first-generation MHD plants ought to reach 50 percent efficiency and with further development attain an efficiency of 60 percent.

Emergency and Peaking Applications

An MHD plant using the simplified cycle shown in Figure 5c has a number of striking features. These are:

1. A virtually unlimited single unit rating.

2. Extremely rapid start-up (one to five seconds), and even more rapid response to load variation (milliseconds).

3. Low capital cost.

These have led to its consideration for utility applications where the objectives are to replace spinning reserve and to handle the daily and seasonal peaks of the power demand curve. A significant fraction of installed utility capacity must be assigned to meet such needs. Since peaking calls for a relatively simple plant that is used intermittently, it is attractive as an early application for MHD.

Pollution

Thermal

High efficiency means low thermal pollution. The amount of heat rejected by a power plant per kilowatt of useful output is proportional to $(1-\eta)/\eta$ where η is the plant efficiency. This relation is plotted in Figure 7.

Another important consideration is the type of cycle used. The closed Rankine cycle used in conventional steam plants must reject most of the heat through a heat exchanger, and its performance in terms of both cost and efficiency is very dependent upon having the lowest possible heat rejection temperature. Thus, such a plant is always sited on a large body of water, or else must employ large cooling towers to transfer the waste heat to the atmosphere. The open Brayton cycle, on the other hand, intrinsically rejects all heat to the atmosphere. Therefore, an MHD Brayton cycle, if bottomed by a gas turbine Brayton cycle as shown in Figure 5b, eliminates thermal water pollution entirely, and without the expense of cooling towers.

Particulate Emission

A large fraction of the particulate emission from conventional plants is due to unburned fuel. This will be greatly reduced in an MHD plant due to higher combustion chamber temperature and pressure. Furthermore, as an integral part of the process, particulate matter in the effluent gas will be removed by--for example--electrostatic precipitation. This is done because of the economic necessity for recovery of an alkali seed impurity added to enhance the electrical conductivity of the combustion gases. Highly efficient removal of particulate matter (in excess of 99%) is, therefore, ensured with the MHD process, and equipment for this is always part of the plant equipment.

Nitrogen Oxides

While it is easy to show that the use of MHD can reduce particulate pollution and virtually eliminate thermal water pollution, it had long been recognized that the situation was not so obvious with respect to the oxides of nitrogen. Therefore, a considerable experimental and analytical effort was addressed to this problem. Here nature has proven kind, and it has been shown that the same high temperature that promotes rapid formation of NO in the MHD burner also promotes rapid decomposition upon subsequent cooling if the cooling rate and the stoichiometry of the flame are suitably controlled. Detailed calculations of the reaction kinetics and experiments carefully designed to simulate the composition temperature-time history of the gas in an MHD plant have yielded NO concentrations well below the standards set by the Environmental Protection Agency (EPA).

Economic Consideration

With regard to all forms of pollution, the advantages ultimately boil down to a question of economics. Any type of power plant can have a clean exhaust if one is willing to pay for it. And the technical requirements for doing so are sufficiently clear that the cost of doing so can be estimated even now with at least ball-park accuracy. We have attempted to do this, using published data where possible, and the results are summarized in Figure 8. Savings of up to 2.15 mills per kilowatt hour in pollution control cost are projected for MHD relative to conventional plants, and if these are even reasonably accurate, the annual savings in pollution control costs alone would very quickly pay the total development cost of MHD.

Nuclear Applications

MHD conversion combined with a high temperature fission or fusion reactor could prove to be the ultimate power plant of the future in terms of compactness, low maintenance, efficiency, and minimum thermal pollution. Since, at present, only the Nerva rocket reactor produces temperatures high enough to be effective with MHD, one can only speculate what form a commercially acceptable nuclear-MHD plant might take. However, one can list a number of interesting facts suggestive of the future possiblities. They are:

1. Electron beam ionization techniques (developed originally for high power lasers) show promise of leading to an efficient MHD plant using temperatures somewhat higher than the Peach Bottom and Fort St. Virain HTGR's but significantly lower than Nerva.

2. MHD is well adapted to a hot loop. The most expensive part of the generator, the magnet, is completely isolated from the working gas or vapor. The relatively inexpensive MHD duct could be regarded as a throw-away item.

3. A recent study suggests that a gaseous core cavity reactor would have an exceptionally good breeding ratio. Because such a reactor has almost no top temperature limit, it would also be an ideal heat source for MHD.

4. Thermonuclear fusion reactors, by virtue of much different and much less severe requirements for the containment of radioactivity, should have far less difficulty producing high temperature.

Given a commercially acceptable reactor capable of temperatures above 2000°K, there seems little reason to doubt that MHD would be the preferred way of converting the reactor heat to bulk electricity. In a nuclear closed loop, in which an inert gas would be the probable choice of working fluid, materials problems would be minimal and unrivaled efficiency would result.

Status of MHD Technology

The development of MHD technology has spanned a period of almost 15 years. This development was pioneered in the United States but the major effort is now occurring in the U. S. S. R. There the construction of a 75 MW MHD-steam pilot power plant incorporating a 25 MW MHD generator has just been completed.

The development work has naturally centered on the MHD generator itself but major efforts have also involved important plant components such as superconducting magnets, combustion systems, air heaters, seeding and seed recovery systems and methods for pollution control of sulfur and nitrogen oxides.

The study of the MHD generator itself has proceeded along two complementary paths. The first has included construction and operation of relatively large experimental generators designed for short term operation. Parallel to this, studies have been conducted with small scale installations to establish the integrity and performance of electrodes, insulators and channel mechanical design features for continuous long term operation.

In the United States two large experimental MHD generators were built and successfully operated in the middle sixties. These two generators represent perhaps the highlights of generator development in the United States. They were both supported by the Department of Defense, were designed and built by the Avco Everett Research Laboratory, and were intended for special purpose short-duration applications. One of these generators called the MK V was self-excited and produced a gross power output of 32 MW. This generator is pictured in Figure 9. The other generator called the LORHO generator (Figure 10) located at the Arnold Engineering Development Center, Tullahoma, Tennessee, delivered an electrical output of 18 MW. Experience gained with these larger installations has provided a good understanding of the MHD process and an experimental basis for predictions of MHD generator performance.

In addition to these larger short-duration experimental generators considerable work has been conducted with smaller fossil-fueled generators at much lower power levels of a few kilowatts. This work has mainly been carried out at Avco Everett Research Laboratory, University of Tennessee, and Stanford, and has provided design data and information regarding long-term operation of MHD generators under conditions appropriate to commercial power applications. Experimental work has been encouraging and indicates that the electrical performance and integrity of electrodes and insulators can be maintained by using the proper level of axial electrical field and proper operating temperatures of electrodes and insulators. Work presently underway is aimed at extending long term channel operating experience up to power levels of 500 kW in the facility shown in Figure 11.

In parallel with the development of the MHD generator itself, efforts have been devoted to the development of superconducting magnets, combustion systems, high temperature air heaters, seed recovery systems and pollution control systems. The construction and testing of a large 4 Tesla model superconducting coil magnet in the middle sixties was one highlight of this effort.

Present work in the United States is funded both by private industry and government. This includes a number of leading electric utilities,* Edison Electric Institute, American Public Power Association, Avco Corporation, the Office of Coal Research of the Interior Department, and the Department of Defense. The work is being carried out principally at the Avco Everett Research Laboratory, M. I. T., Stanford, and the University of Tennessee. Also involved are Westinghouse, G. E., STD Corporation, the Bureau of Mines, and the Arnold Engineering Development Center.

By far the most impressive MHD effort exists in the Soviet Union with the strong support of the State Committee on Science and Technology and the joint sponsorship of the Academy of Sciences and the Ministry of Electrification. The Soviet program is broadly based and involves many institutes of which the chief ones are the Institute for High Temperatures, the Krzhizhanovsky Power Institute in Moscow and also the Research Institute of the Ukrainian Academy of Sciences in Kiev. The most significant accomplishment to date has been the design, construction and preliminary operation of a natural gas-fired pilot plant with a designed MHD output of 25 megawatts. Pictures of this plant are shown on Figure 12 and Figure 13. The plant is located in the north of Moscow on a power station site adjacent to the Moscow ring road and is a complete pilot plant in every way, including an inverter system for feeding generated power directly into the Moscow grid system. As such, it constitutes the first commercial pilot plant in the world for network service. Basic development for this plant has been carried on, and continues to be undertaken, in the U-02 installation located in the center of Moscow. This experimental installation is shown in Figure 14. It is a unique 5-megawatts (thermal) experimental facility in which all the elements for an MHD system can be tested for endurance. These two installations are the direct responsibility of the Institute for High Temperatures. The Krzhizhanovsky Power Institute operates a generator test facility, the ENIN-II which may later be converted for experiments with coal firing. The fourth major Soviet installation is located at Kiev where an old power station has been converted for long-duration MHD tests. Thus, the U. S. S. R. possesses four facilities which can generate a great amount of experience in all aspects of MHD technology and it is expected that runs of up to 5000 hours will be demonstrated within the next few years. In parallel with this effort, work is progressing on the design of the first commercial demonstration unit, and this has variously been reported to have an MHD generator of between 200 and 600 megawatts electrical output.

The MHD effort in the Soviet Union involves several thousand scientists, engineers and technicians, according to estimates from professional people who have been there in recent years. The cost of the U-25 installation has been estimated in dollar equivalent to be in the 100-150 million dollar range. All of this indicates the determination and vigor of the MHD development program in the U. S. S. R.

For the last 10 years, Japan has also undertaken a very comprehensive program in MHD power generation. All components of the total system are being studied and extensive system and economic evaluations are also being conducted. The general character and scale of the Japanese facilities are in many ways similar to those which have been built and tested in the United States except that there is no equivalent to the Mark V or LORHO. On the other hand, a superconducting magnet has been combined with an MHD generator, and the construction of a larger superconducting magnet for a 1000 kW MHD generator test facility is now almost completed. A small pilot plant has reached an advanced stage of construction and operation is expected during 1973.

*Baltimore Gas and Electric, Boston Edison Co., Consolidated Edison Co. of New York City, Inc., NEGEA Service Corp., New England Power Co., Northeast Utilities Service Corp., TVA.

Within the past three years, efforts have been initiated in the Federal Republic of Germany. The Bergbau-Forschung Institute at Essen and the KFA Nuclear Institute at Julich are cooperating on the testing of a small propane-fired long-duration experimental facility. The Institut fur Plasmaphysik in Garching together with an industrial group (MAN) has built a 1-megawatt short-duration facility. A 3-megawatt thermal natural-gas-fired long-duration installation is being operated by the Nuclear Research Institute at Swierk in Poland.

References

Symposia on the "Engineering Aspects of MHD" are held yearly in the United States and an international symposium on MHD is held every second year. The proceedings of these meetings are a good starting point for those interested in going deeper into the subject. Basic texts include G. W. Sutton and A. Sherman, "Engineering MHD," McGraw-Hill, N. Y., 1965 and R. Rosa, "MHD Energy Conversion," McGraw-Hill, N. Y. 1968. The results of the short-lived but comprehensive British effort in this area are summarized in J. B. Heywood and G. J. Womack, Ed., "Open Cycle MHD Power Generation," Pergamon Press, Oxford, Eng., 1969.

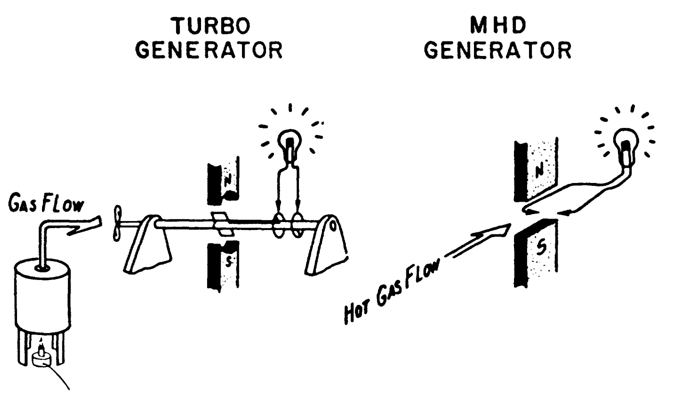

Fig. 1. Comparison of Basic Principles

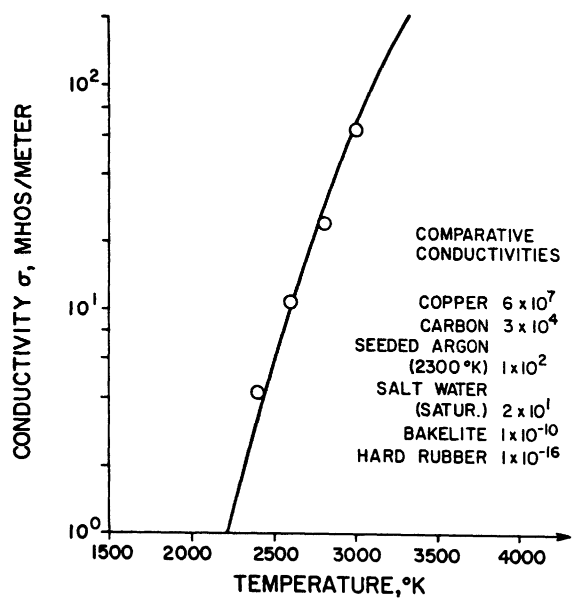

Fig. 2. Conductivity of Seeded Combustion Products

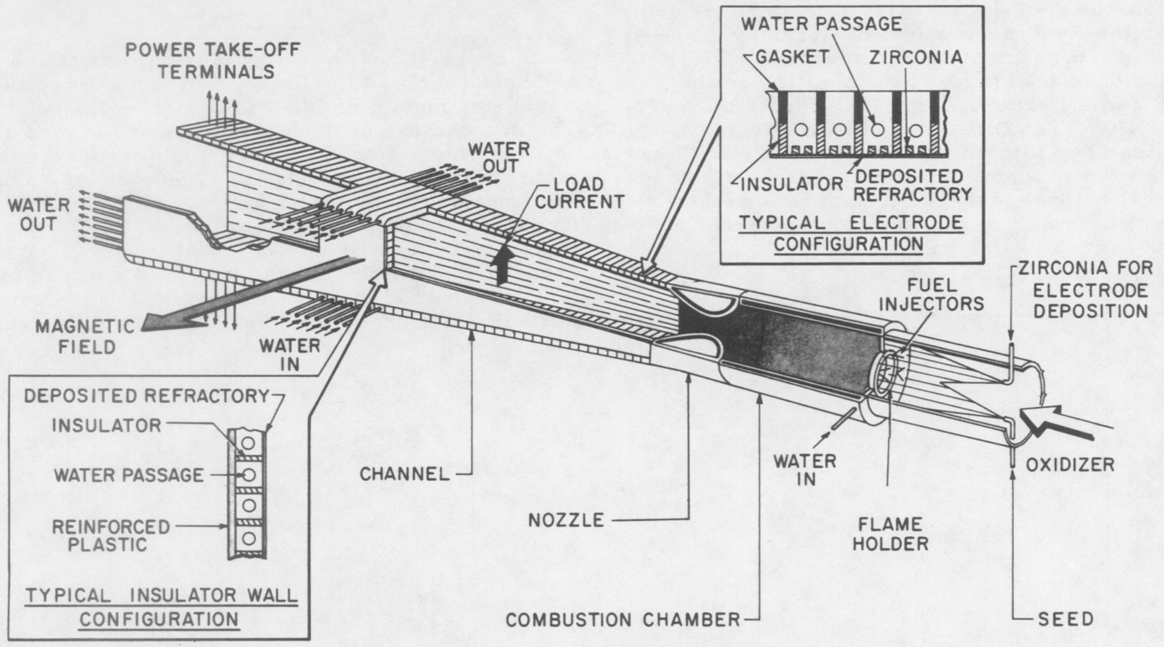

Fig. 3. MHD Generator Construction - Faraday Configuration

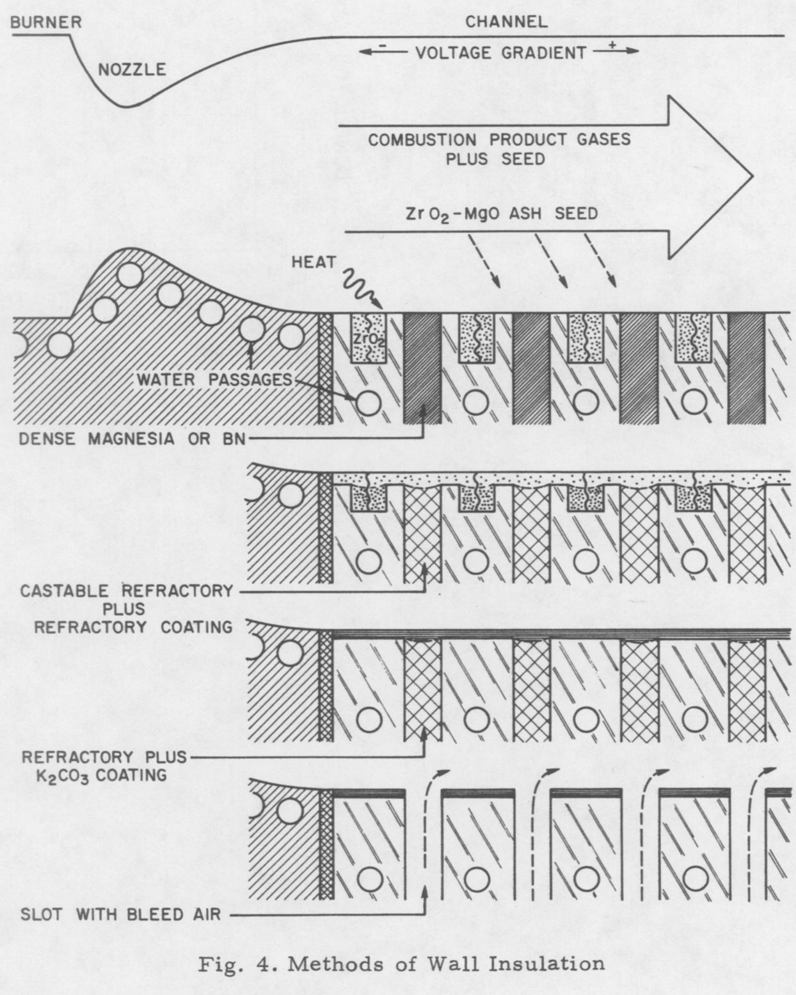

Fig. 4. Methods of Wall Insulation

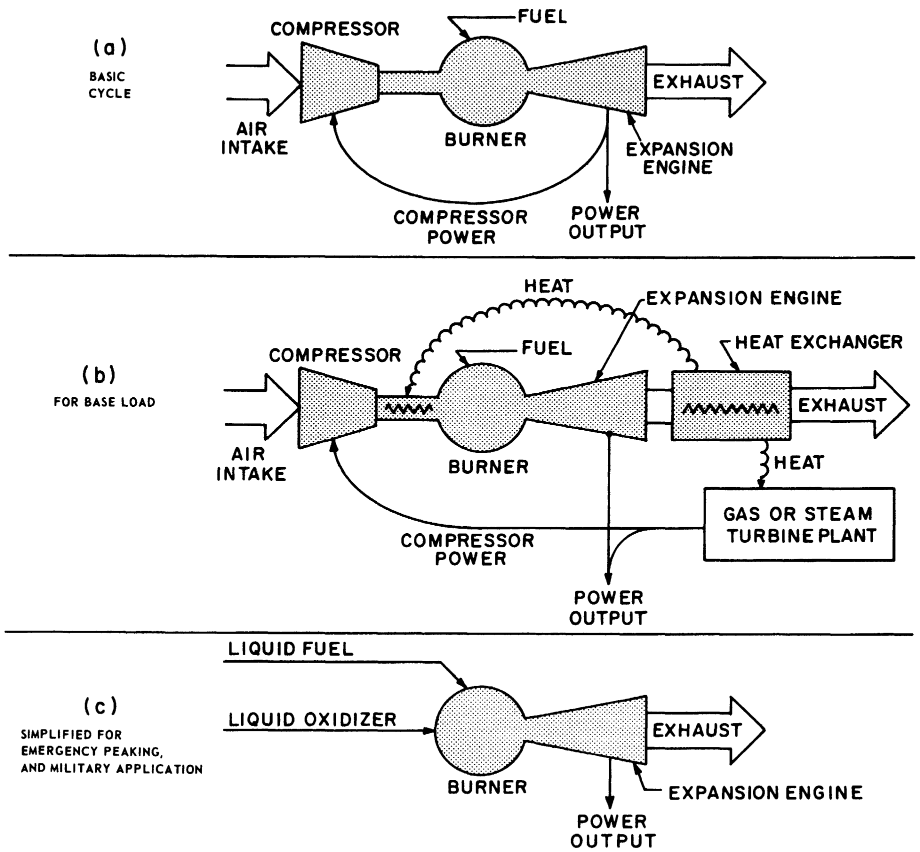

Fig. 5. The Brayton Cycle

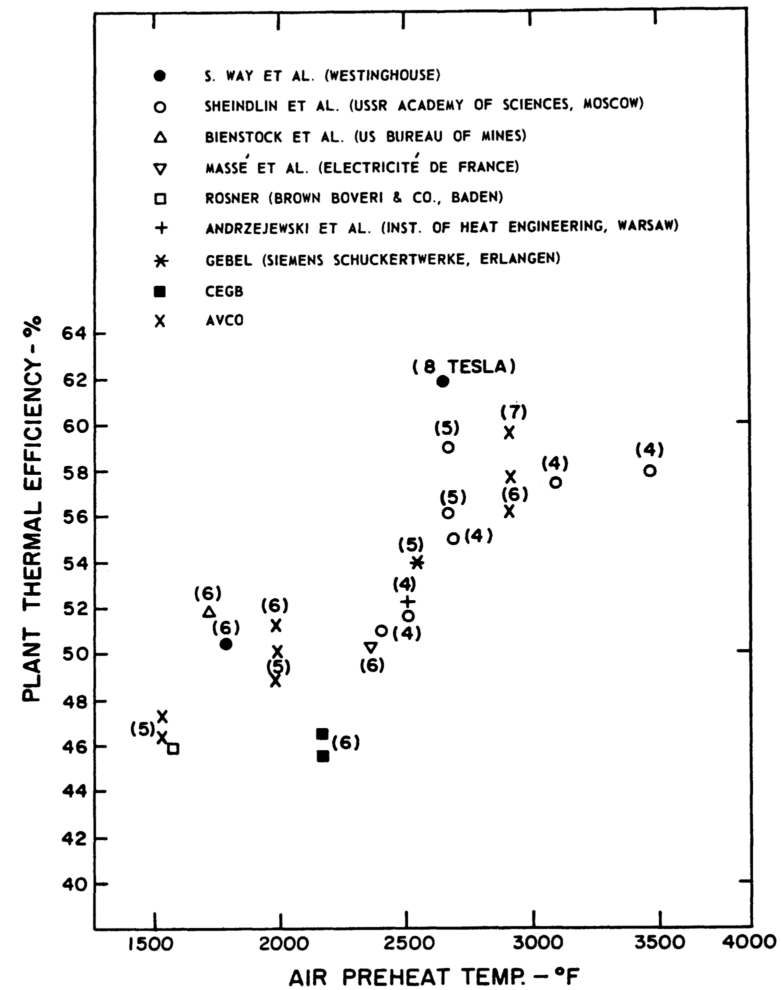

Fig. 6. Baseload MHD Plant Efficiency

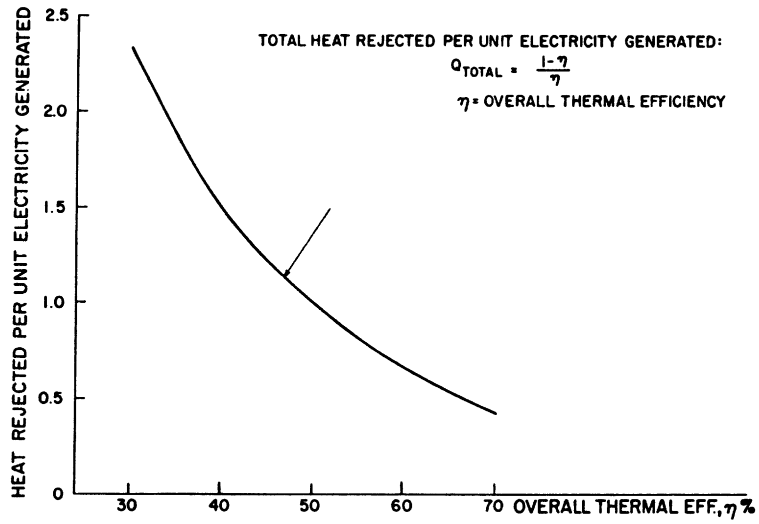

Fig. 7. Heat Rejection vs Cycle Efficiency

COMPARATIVE ESTIMATED COSTS OF COAL BURNING
1000 MW (NOMINAL) POWER PLANTS[0]

	MHD Early	MHD Developed	Conv. Steam	Nuclear Present
Efficiency %	50	60	40	32
Basic Plant Cost $/kW	210	150	225	300
Basic Generation Cost - Mills/kWhr				
Capital Charges[1]	4.65	3.32	4.98	6.62
Fuel[2]	2.05	1.71	2.56	1.70
Operation & Maintenance	0.30	0.30	0.30	0.35
Seed	0.05	0.02		
Basic Generation Cost	7.05	5.35	7.84	8.67
Additional Generation Cost - Mills/kWhr				
Dry Cooling Towers	0.50[3]	None[4]	0.80[5]	1.20
SO_2 - Removal	0	0	0.90[6]	--
Total Add. Generation Cost	0.50	--	1.70	1.20

(0) Basis 1971 U.S. Dollars

(1) 15.5% and 80% Capacity Factor

(2) Coal Cost at 30 cents/10^6 Btu

(3) MHD-Steam Cycle, Cost prop. to Steam Plant

(4) MHD - Gas Turbine Cycle

(5) Office of Science and Technology Report "Considerations Affecting Steam Power Plant Site Selection"

(6) Based on $40/kW

Figure 8

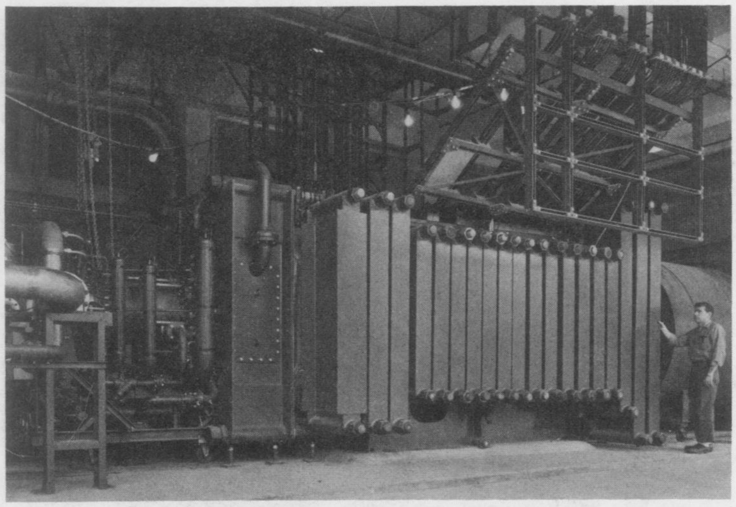

Fig. 9. MK V Self-Excited MHD Generator with
32 MW Gross Electrical Output

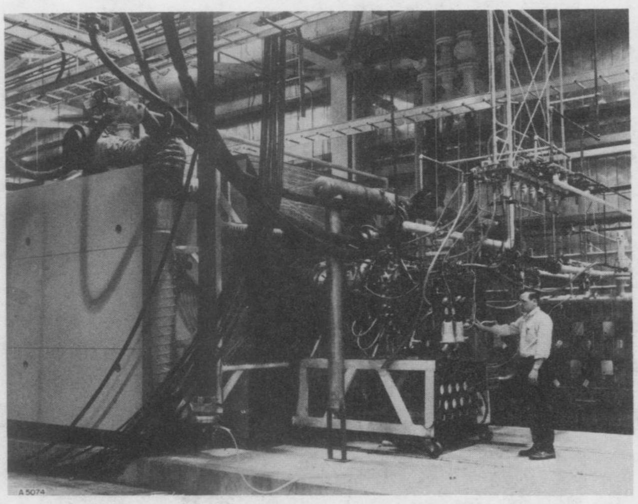

Fig. 10. 18 MW LORHO Pilot MHD Generator

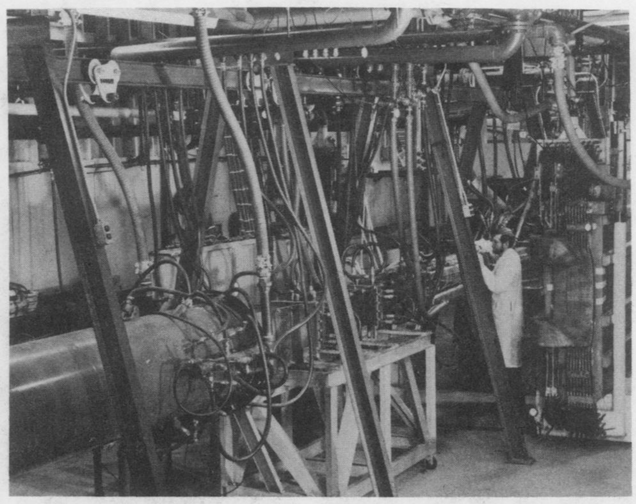

Fig. 11. MK VI Long-Duration Facility

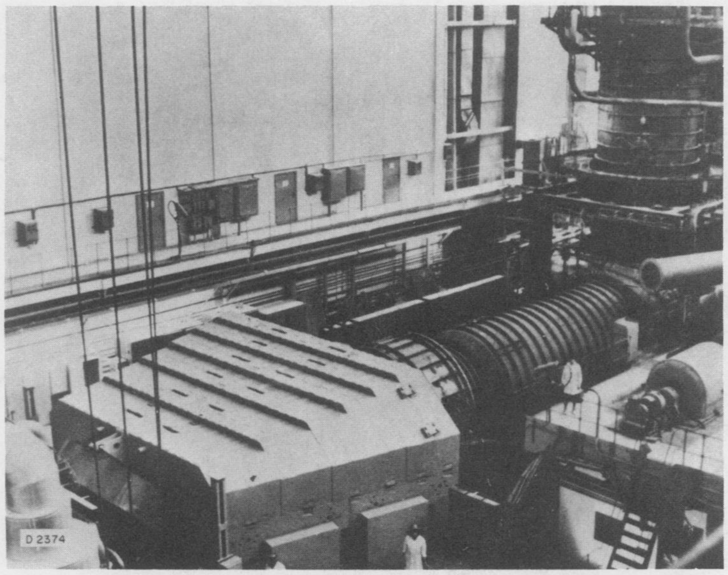

Fig. 12. 25-Megawatt MHD Generator in U-25
Plant

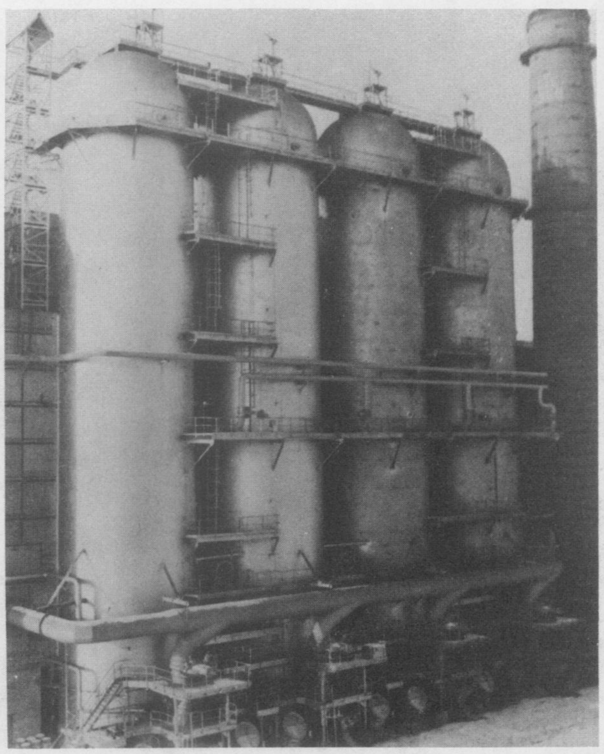

Fig. 13. Air Preheaters for U-25 Installation

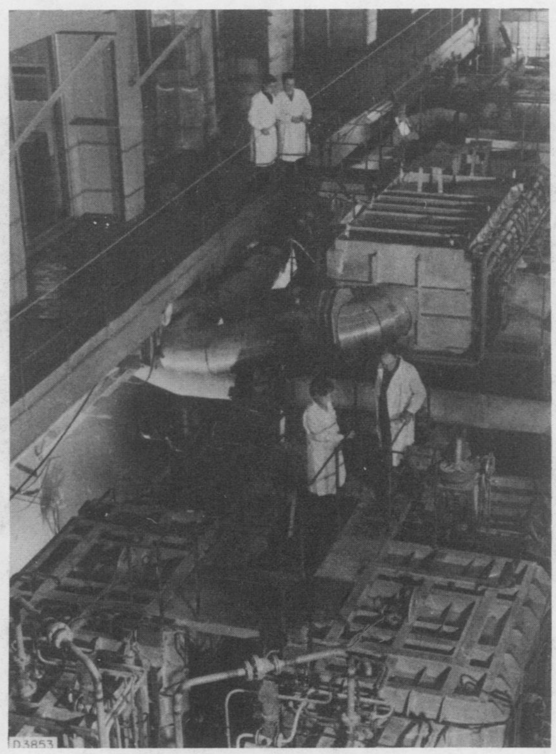

Fig. 14. General View of U-02 Installation Showing Preheater in Foreground