JOURNAL OF PROPULSION AND POWER
Vol. 15, No. 2, March–April 1999

Open-Cycle Magnetohydrodynamic Power Generators

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Current status of open-cycle magnetohydrodynamic generator development is reviewed. Discussions focus primarily on generator channels designed for operation with coal-fired flows. Generator channel durability issues are reviewed. Channel gas-side design features capable of overcoming the lifetime limiting effects are described. Various generator mechanical and thermal designs are also described. Finally, the status of generator development testing is summarized.

I. Introduction

MAGNETOHYDRODYNAMIC (MHD) power generation is a method of generating electric power by the direct interaction of an electrically conducting fluid flowing through a magnetic field. In the simplest form, the MHD generator consists of a duct through which the gas flows, driven by an applied pressure gradient, and a magnet, in which the duct is situated.

In the application of MHD to electric utility power generation, high-temperature coal-combustion gas is used as the working fluid. The MHD is combined with steam power generation, as shown in Fig. 1, with the MHD generator used as a topping unit to the steam bottoming plant. Starting with combustion products at a pressure of 500–1000 kPa, and a temperature sufficiently high (about 3000 K), to produce a working fluid of adequate electrical conductivity when seeded with an easily ionizable salt such as potassium, the hot ionized gases flow through the MHD generator at approximately sonic velocity. The MHD generator channel extracts energy from the gas, and the flow is expanded so that it can maintain its velocity against the decelerating forces resulting from its interaction with the magnetic field. The combination of energy extraction and flow expansion causes the gas temperature to drop. Electrical power is extracted until the gas temperature becomes too low (about 2300 K) to have a useful electrical conductivity. The gases exhausting from the generator still contain significant useful heat energy. This energy is used in the bottoming plant to raise steam to drive a turbine and generate additional electricity in the conventional manner of a steam plant, and also to preheat the combustion air. The highest overall plant efficiencies are obtained by direct preheat of the combustion air with the MHD exhaust gas, but this requires the use of high-temperature refractory heat exchangers, which are not yet available. The required combustion temperatures can also be attained by enriching the combustion air with oxygen and preheating the oxygen-enriched air to more moderate temperatures using conventional metal tubular heat exchangers. The resulting plant efficiencies are not as high as with direct preheat, but are high enough to make this latter method attractive for use in earlier commercial MHD plants.[1] Development and use of high-temperature refractory heat exchangers in future advanced MHD plants would allow the realization of the full efficiency potential of MHD with correspondingly improved fuel utilization and lower CO_2 emission.[2]

The MHD generator channel is the heart of the MHD power generation system. It is the component that produces the MHD power, and its requirements determine the major specifications for other components and subsystems of the MHD powerplant. The basic requirements for channel development are governed by overall powerplant requirements of high plant reliability and availability, high coal pile-to-bus bar efficiency, and low cost of electricity. To satisfy these plant requirements, three major MHD generator channel design criteria can be identified.[1,2] These are 1) duration or operating time between maintenance periods; 2) fraction of thermal energy input extracted from the gas as electric power output (enthalpy extraction ratio); and 3) isentropic efficiency, the ratio of the actual enthalpy change of the gas flowing through the channel to the enthalpy change of an isentropic flow at the same pressure ratio. For early commercial MHD powerplants, the generator goals are operation for several thousand hours between scheduled maintenance, enthalpy extraction of at least 15%, and isentropic efficiency of 60% or more.

The generator channel must provide a secure means of containing the working gas from the combustor and a means of conducting current from the working plasma to the external load, with adequate durability to satisfy overall power system requirements. Issues related to generator durability have dominated the development of channel construction methods, particularly of those electrode and sidewall elements that must face the hot conducting plasma. Durability issues and the resulting gas-side designs for coal-fired channels differ from those for channels fired on clean fuels, e.g., natural gas. The latter channels can use a variety of high-temperature ceramic materials, for both electrode and insulating surfaces, which cannot be used in coal-fired channels because of their incompatibility with molten slag. This allows operation with hotter walls and reduced electrical and thermal losses compared with coal-fired channels, which are typically built with cooled metal-based elements better able to survive the environment. Natural gas-fired MHD channels have been studied extensively at the High Temperature Institute of the Russian Academy of Sciences in Moscow.[3] The most recent work, however, has been on coal-fired MHD systems, both in the U.S. and elsewhere, and so the following discussion will focus on channels designed for operation with coal-fired flows.

Generator channel durability issues are reviewed in the following section. Features of the generator gas-side designs, for electrode and insulator walls, are described in Sec. III. Gen-

Received Nov. 28, 1997; revision received April 14, 1998; accepted for publication April 22, 1998.

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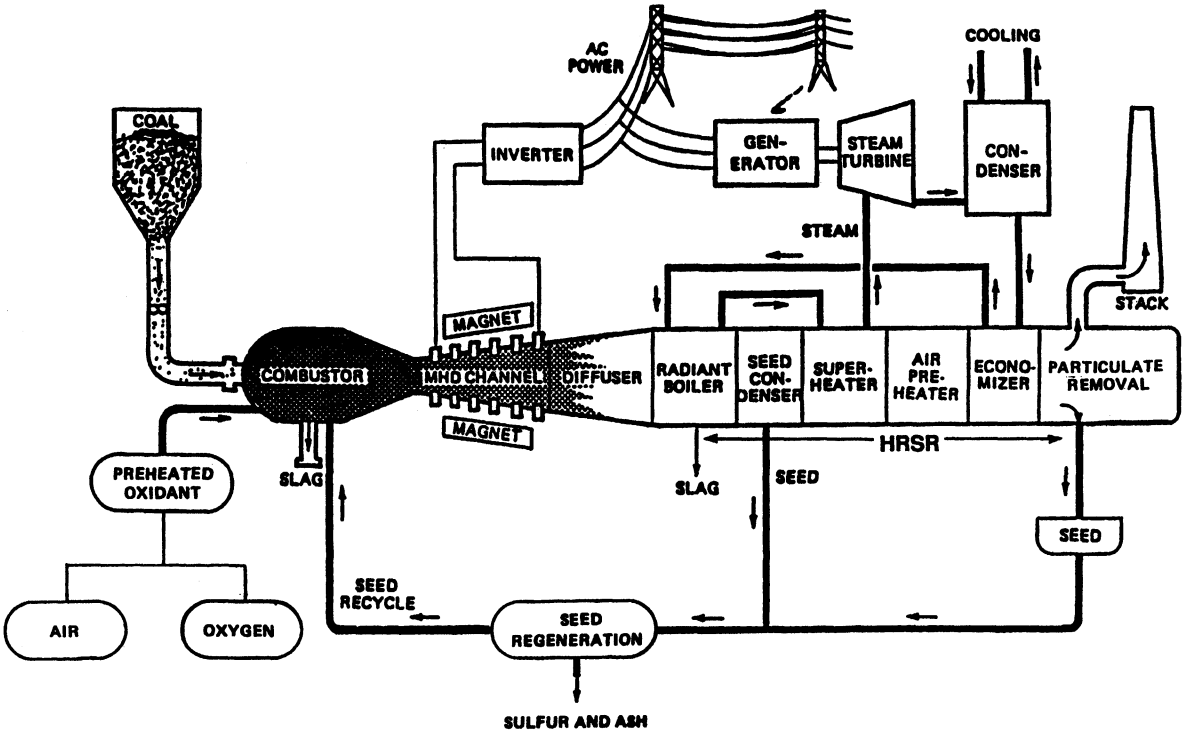


Fig. 1 Schematic diagram of an MHD/steam powerplant.

erator mechanical and thermal designs are discussed in Sec. IV. Finally, the status of generator development testing is reported in Sec. V.

II. Channel Durability Issues

Two major channel lifetime-limiting mechanisms have been identified from long duration generator tests with slagging flows.[4] These are a) electrochemical corrosion of channel gas-side surfaces, which occurs over relatively long periods at normal operating conditions, and b) localized electrical arcs or faults, which can cause serious damage to the channel walls. Channel design features capable of overcoming these lifetime limiting effects have been developed and refined in the various subscale MHD generator test programs conducted over the years.

The mechanisms affecting surface wear differ for anode, cathode, and insulator walls. Anodes are subject to electrochemically induced oxidation and/or attack by sulfur.[5] These effects are illustrated in Fig. 2. The corrosion is caused by sulfur and oxygen anions that are driven to the anode surface by the electric field, or which are chemically bound in the slag and released by transverse arc current transport through the slag layer. Judiciously placed protective caps, using oxidation and sulfidation-resistant materials, are required to mitigate this problem. Cathode walls and insulator walls are less subject to severe electrochemical attack than are anode walls. In the case of the cathode, this is because of the reducing conditions that prevail, and in the case of the insulator wall, because it nominally carries no current.

Localized electrolytic corrosion of the anodic (positive) surfaces can also occur on all four of the channel walls. Anodic wear results from either surface leakage currents between adjacent wall elements or recirculating currents driven by voltage differentials caused by misalignment between the direction of plasma equipotential plane and the orientation of the sidewall bar elements.[6] Surface protection against electrochemical attack is required over these anodic regions.

In addition to gas-side surface corrosion, the other important lifetime-limiting mechanism is the damage caused by interelectrode faults. These axial faults are a result of arcing between adjacent electrodes, which result from complete break-

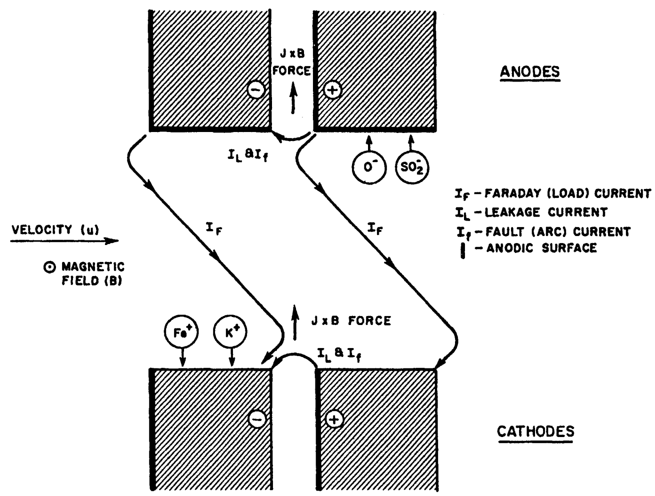


Fig. 2 Conceptual schematic of current and ion flows in the MHD generator channel.

down of the interelectrode insulator gap.[7,8] This sharply increases the wear at the corner edges of the affected electrodes and results in rapid destruction of the interelectrode insulator. Interelectrode arcs are particularly dangerous on anode walls, where they are driven by the Lorentz force into the wall structure and can cause severe damage (see Fig. 2).

The effects of interelectrode faults are minimized, first, by limiting the power that can be coupled into such faults; second, by incorporating design features that will quench these arcs; and finally, by employing wall structures that can withstand the effects of the arcs. Generator design features adopted for fault prevention are described in Sec. III.

For a given channel power density, the value of the fault power (per electrode) in the channel is proportional to the square of the electrode pitch (the distance between the centers of adjacent electrodes) times the electrode length in the magnetic field direction.[9] Hence, the most effective way to limit fault power in the channel is to minimize the electrode pitch. Electrode pitch of about 2 cm is the practical minimum value for large channels, limited by manufacturing constraints. Once the minimum electrode pitch has been established, fault power can be limited only by reducing the length of the electrode parallel to the magnetic field, i.e., by transverse segmentation of the electrodes. In all cases, the electrode current must be controlled to avoid large current overloads that can greatly increase the available fault power. Acceptable values of fault power are of the order of a few hundred watts (per electrode) for existing channel designs.[7,8]

Voltage nonuniformities occur over cathode walls of MHD channels operating with slag-laden flows. This voltage nonuniformity phenomenon has been extensively reported.[10,11] Voltage nonuniformities arise when groups of adjacent cathodes are shorted by polarized slag. The polarization of the slag is thought to arise from the ionic nature of the current transport across the slag layer, causing the deposition of metallic potassium at the electrode surface.[12,13] As a result of the slag-induced shortings, the generator Hall voltage is sustained by only a few nonshorted intercathode gaps. The voltages across these open cathode gaps are substantially higher than when no slag shorting occurs. An example of cathode voltage nonuniformities from a coal-fired MHD generator channel is shown in Fig. 3a. The Hall voltage of the generator is sustained along the cathode wall by ~60 insulator gaps (out of 280 available intercathode gaps for this particular generator). Voltage across these open gaps sometimes exceeds 120 V. The remaining gaps are shorted by the polarized slag. For comparison, a typical measured intercathode voltage distribution in the absence of nonuniformities is shown in Fig. 3b. In this case, the generator axial voltage is distributed among all of the insulator gaps, with a typical intercathode voltage of less than 35 V. The appearance of cathode voltage nonuniformities can reduce the generator's lifetime reliability. Locally, the high-voltage intercathode gaps cause the insulator walls to experience high electrical stresses.

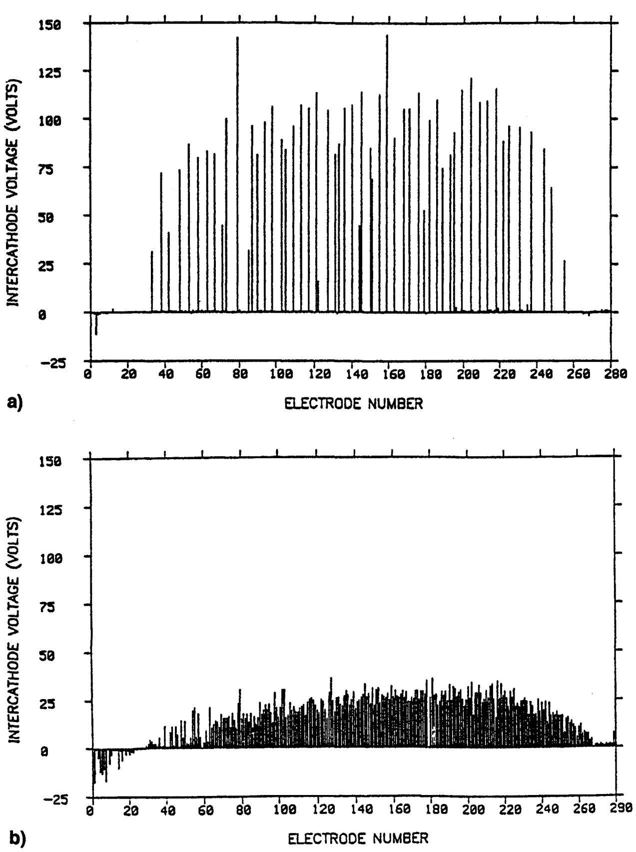


Fig. 3 Cathode wall voltage distributions with and without slag-induced shortings.

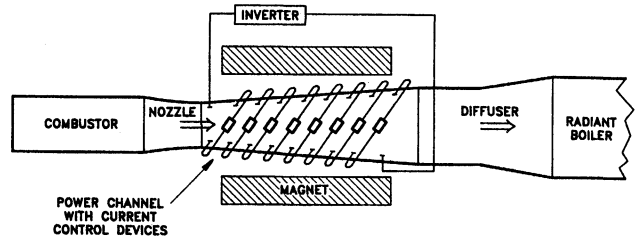


Fig. 4 Schematic of MHD power generator components.

Current control circuits are an important part of the overall strategy to prevent fault damage to the anode wall.[14] Experience has shown that the anode wall of a slagging diagonally loaded MHD generator (without current controls) is prone to fault damage. This damage is a consequence of the transfer of cathode voltage nonuniformities to the anode wall through the external diagonal connections of the generator. Unlike the cathode wall, the anode wall cannot tolerate the high interelectrode voltage characteristics of the cathode nonuniformities. Electrical breakdowns at the high-voltage interanode gaps lead to the creation of faults, which are then driven by the Lorentz force into the interanode insulators, resulting in localized channel wall damage (see Fig. 2). The current control devices are installed in each diagonal connection to prevent the high-voltage cathode nonuniformities from reaching the anode wall (see Fig. 4).

III. Channel Gas-Side Designs

A. Electrode Walls

The development of durable electrode walls is one of the most critical issues for MHD generators, and has proceeded in two basic directions: ceramic electrodes operating at very high surface temperatures (2000 K or higher) for use in generator channels operating with clean fuels, and cooled metal electrodes with surface temperatures in the range of 500–800 K for generators operating with slag or ash-laden flows.

The hot ceramic electrodes tend to operate with diffuse transport of current from the plasma to the electrode surface, reduced tendency for interelectrode breakdown, and lowered wall heat losses. The most common designs, developed by the High Temperature Institute in Moscow for their natural gas-fired U-25 channel, use zirconia electrodes either brazed to metal substrates made of special stainless steel or chromium alloys, or otherwise rammed onto metal substrates reinforced with wire mesh.[15,16] The zirconia is doped with rare earth oxides, such as yttria or ceria; other oxides such as calcia have also been used, particularly in the formations designed for ramming.[17] Electrical current is transported to the electrodes primarily by oxygen anions. Maximum operating temperatures of these ceramics are from 2000 to 2200 K. Another class of ceramic electrodes is based on materials such as lanthanum chromite or silicon carbide; in these materials, current transport is electronic rather than ionic, and electrical conductivity is higher.[18] Also, thermal conductivity is higher than in zirconia-based ceramics. A disadvantage is that their maximum operating temperatures are lower, in the range of 1400–1600 K.

Although ceramic electrodes have received, and continue to receive, much attention, up to the present time they have not been successful in channels operating with slag-laden flows because of excessive slag corrosion.[19] Only well-cooled metallic electrode elements have been tested successfully in slagging applications, and these will be the focus of the following text.

An important feature of slag-covered metallic electrodes is that current transport to both electrode walls, i.e., anode and cathode, is via arcs.[10] Hence, to dissipate the heat, a well-cooled structure with good thermal diffusivity is required. Water-cooled copper-based electrodes have been used successfully for many years in the developmental channels. Metal electrode walls are designed to retain a slag coating so that a higher gas-side surface temperature (~1700 K) can be maintained than is possible with bare metal walls. This reduces electrode voltage drops and wall heat losses.

A viable slagging anode design is shown in Fig. 5. This particular anode design was adopted for the Integrated Topping Cycle (ITC) MHD generator, which was used for proof-of-concept duration testing at the U.S. Department of Energy's Component Development and Integration Facility (CDIF) in Butte, Montana. The project goals and details of the ITC MHD test program are described in Ref. 20. The electrode element is constructed of water-cooled copper substrate with brazed platinum-on-tungsten caps to provide oxidation and sulfidation resistance. The upstream corner of the anode, where Faraday arcs tend to concentrate because of the Hall effect, is reinforced with thicker square strips of platinum. The tungsten serves as backup protection in the event that the platinum primary cap fails. Arc-stretching gaps are machined into the base of each anode, on both the front and back sides. The purpose of these gaps is to extinguish interanode arcs, should they occur, and to prevent them from being pushed by the magnetic field into, and damaging, the plastic back wall. Furthermore, a thin sheet of nonarc-tracking material (typically NEMA Grade G7) is installed between the base of the anodes and the back wall to prevent arc-induced charring of the plastic backboard, which can create permanent interanode shorts. Aluminum nitride (AlN) insulator caps are used in the corner joint regions for reinforcement against electrical breakdowns between the anode wall and the adjacent sidewalls. Finally, the interanode insulators are recessed at the gas surface to provide a foothold for slag attachment.

The prototypic ITC anodes were tested for more than 500 h, at wall stresses (electrical and thermal) similar to those expected in commercial-sized generators. Lessons learned about this anode design, during coal-fired proof-of-concept (POC) tests, are reported in Ref. 21. Other cap materials and anode designs have also been tested in subscale generators. In regions of the channel where the wall stresses are the highest, the most successful, i.e., longest lifetime, anode design to date has platinum caps operated at low electrode temperatures (~500 K). Anodes of similar design, but without the tungsten backup layer (Fig. 6), have been operated successfully for more than 1300 h (with 8000-h projected lifetime) in a slag- and sulfur-laden flow.[22]

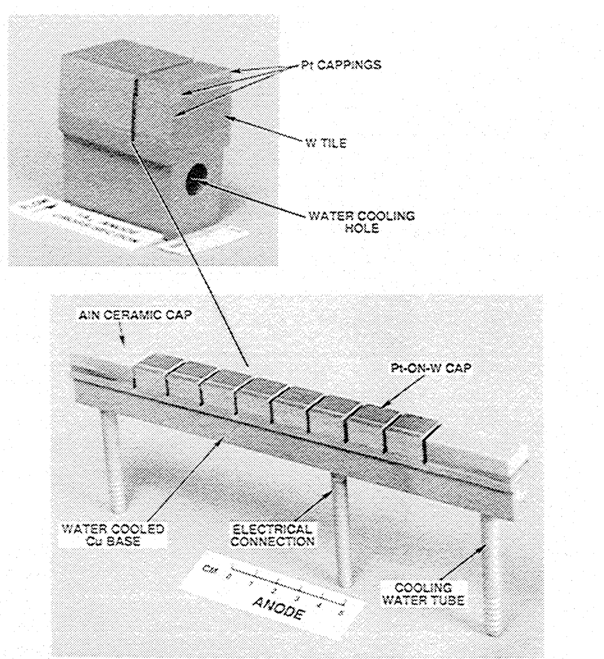


Fig. 5 ITC MHD power generator anode design.

A viable cathode design, adopted for the ITC MHD generator, is shown in Fig. 7. The electrode elements are constructed of water-cooled copper bases capped with tungsten tiles. Tungsten was used for the gas-side protective caps because it is superior in resisting both arc erosion, caused by slag-induced shorting of groups of cathode wall electrodes, and electrochemical corrosion, caused by ionic current leakage in the cathode slag layer.[23] Grooves are machined into the surface of the tungsten pieces to facilitate slag adhesion. Finally, like the anode bars, AlN insulator caps are used in the corner joint regions for reinforcement against electrical breakdowns.

The cathodes were in excellent condition following the completion of POC testing. Material wear measurements indicated that the cathode design can easily exceed the ITC 2000-h lifetime requirement.[24] The small amounts of wear were mostly observed at the leading edges of the tungsten caps, where the surfaces are anodic with respect to the upstream cathode. Molybdenum, nickel, and tungsten copper alloy have also been successfully tested as cathode capping materials.[23,25]

The interelectrode insulators are an integral part of the electrode wall structure. The insulators are required to stand off interelectrode voltages and resist attack by slag. Well-cooled

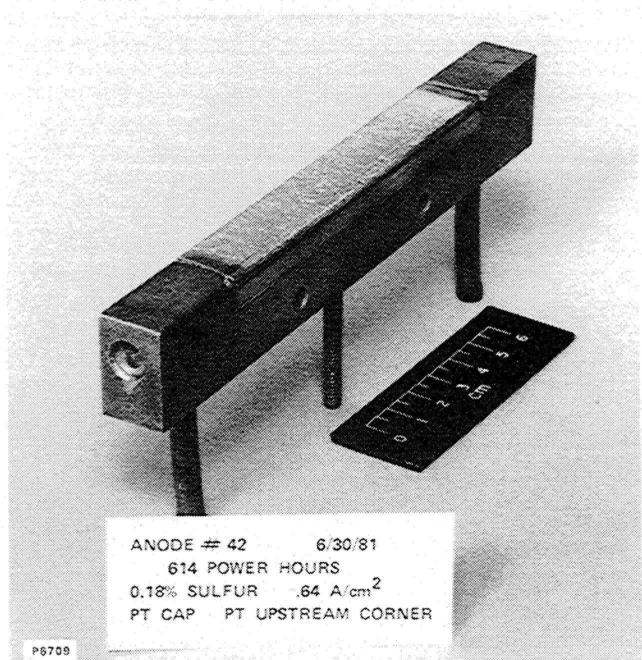


Fig. 6 Anode after 614 h of operation. One-thousand-hour anode test of 1981.

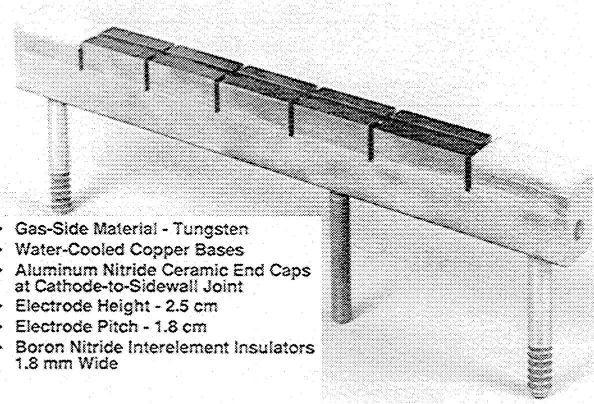


Fig. 7 ITC MHD generator cathode design.

thin insulators (by contact with neighboring metallic electrode bars) have proven to be very effective, particularly those made of alumina or boron nitride. Alumina is cheaper and also provides good anchoring points for the slag layer. Boron nitride has superior thermal conductivity and thermal shock resistance.

B. Insulator Walls

Because of the unavailability of electrically insulating materials that can reliably withstand the harsh environment inside coal-fired generator channels, the insulator walls of the channel are typically constructed of metal elements that are insulated from each other to prevent any net flow of current. Like electrode walls, insulator walls are designed to operate with a slag coating.

Figure 8a shows a so-called peg wall design. These walls are constructed of rectangular or square metallic elements (pegs), typically 2–3 cm on a side, and separated by thin strips of insulator material. The advantage of this design is its electrical flexibility and its superior electrical insulating properties under all kinds of generator operating conditions. The disadvantages are the mechanical complexity arising from the large number of small elements and the need for internal manifolding within each row of pegs for cooling. However, with proper engineering and assembly procedures, such walls can be made to operate fairly reliably, and have, in fact, been tested at the 20 MW (thermal) scale for hundreds of hours.[25] Scaling of the peg wall to large commercial sizes is difficult because of the large number of wall elements.

To simplify insulator wall design, the conducting-bar sidewall, shown in Fig. 8b, is used. The sidebar elements lie nominally along the direction of equipotential planes in the generator. The sidebars also serve as the diagonal connections for electrode currents to flow from the cathodes to the anodes. This design is hydraulically more reliable than the peg design, having no internal manifolding of coolant. Such continuous bar design, however, can only be used in diagonally loaded generators, and it does not allow external current control or fault power control.

To alleviate the problem, the conducting sidebar is split, as shown in Fig. 8c, which allows the use of external circuits for electrode current control. Each sidebar segment is large enough to be individually cooled. In comparison with the continuous sidebar design discussed earlier, the segmented bar design requires a larger number of coolant hoses and penetrations of the pressure vessel.

A disadvantage of the bar-style sidewall designs is their inability to follow changing potential distribution in the plasma. When the bar orientation becomes misaligned with the plasma equipotential plane, sidebar elements span voltage gradients, which can cause the flow of circulating currents between the sidebars and the plasma, as well as current leakage and arcing between the bars. Misalignment can occur in the electrode boundary-layer regions of the channel or when the generator is operated at off-design conditions.

A variation of the straight-segmented sidebar design is the Z-bar design, shown in Fig. 9, in which the wall elements more closely follow the actual equipotential planes in the generator. This sidewall design was selected for the ITC MHD generator.[21] The height of the two vertical elements within the Z-shaped rows are selected to approximate the thickness of electrode wall boundary layers. The sidebars were found to align very closely with the plasma equipotential distribution, which resulted in the low sidebar wear during duration tests. An assessment of sidebar alignment was accomplished by estimating the magnitudes of recirculating currents in the sidewall elements. Material analyses indicated that most of the observed sidebar wear appeared to have been caused by the recirculating currents flowing from the sidebars into the gas, driven by the voltage potential set up by mismatches between the sidebar inclination and the equipotential plane of the gas. The greater this mismatch, the larger the magnitude of recirculating current, and greater the sidebar wear. Based on the amounts of material wear measured after the ITC duration test, one can conclude that the magnitudes of the recirculating current in the sidewall elements were typically much lower than 1 A, averaged over the >300 h of power testing. These low values of bar currents imply that the Z-bar sidewall design matched the plasma equipotential distribution far better than the straight-bar design used previously in coal-fired generators. Details on how the recirculating currents were estimated are described in Ref. 24.

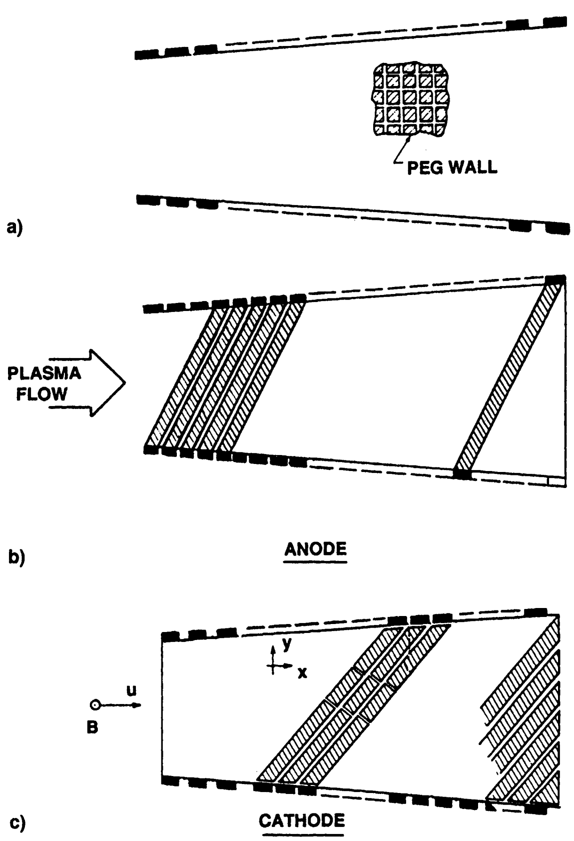


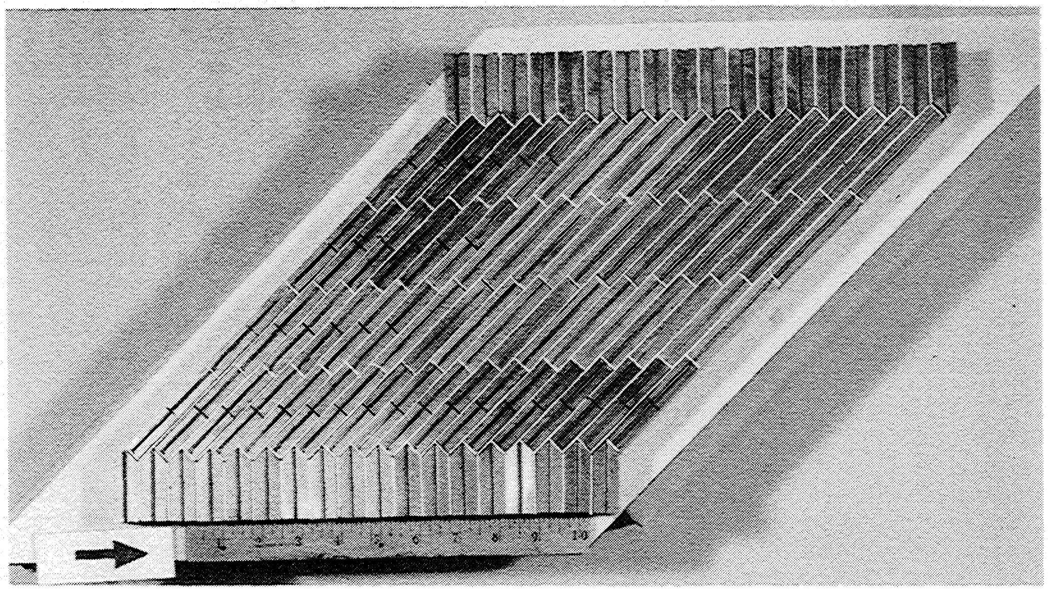
Fig. 8 MHD insulator wall designs: a) peg, b) conducting bar, and c) segmented bar walls.

IV. Channel Mechanical and Thermal Design

The main objectives of channel mechanical and thermal design are to maintain structural and gas sealing integrity, to provide adequate cooling of gas-side surface elements, and to efficiently use the magnet bore volume, i.e., to maximize the ratio of the channel flow cross-sectional area to the magnet bore cross-sectional area. This last requirement affects not only the channel mechanical design but also the packaging of channel electrical wirings, cooling hoses, and manifolds that occupy the space between the channel and the magnet.

In broad terms, MHD generator channels built to date have fallen into one of three types of construction categories. These are 1) plastic box construction, 2) window-frame construction, and 3) reinforced window-frame construction. Features of these designs are discussed next.

Plastic box construction is shown in Fig. 10. In this type of construction, the generator channel is assembled from four separable diverging walls, which are bolted and sealed at the corners to form the rectangular cross-sectioned duct. Each wall consists of the individual gas-side surface elements mounted on an electrically insulating board, which is typically made of a fiberglass-reinforced material such as NEMA Grade G-11. The box serves as the main structural member and the pressure vessel of the generator channel. Final contouring of the gas-side duct geometry is done by varying the height of the elec-



- CONSTANT HEIGHT SIDEWALL
- SEGMENTED Z-BAR CONSTRUCTION
- SIDEWALL DIAGONAL - 45 DEGREES
- SIX ROWS OF ELEMENTS
- GAS - SIDE MATERIALS
  - TUNGSTEN
  - TUNGSTEN - COPPER COMPOSITE
- BASE MATERIAL - COPPER
- SLAGGING GROOVES
- BORON NITRIDE INSULATORS

Fig. 9 Prototypic Z-bar insulator wall design.

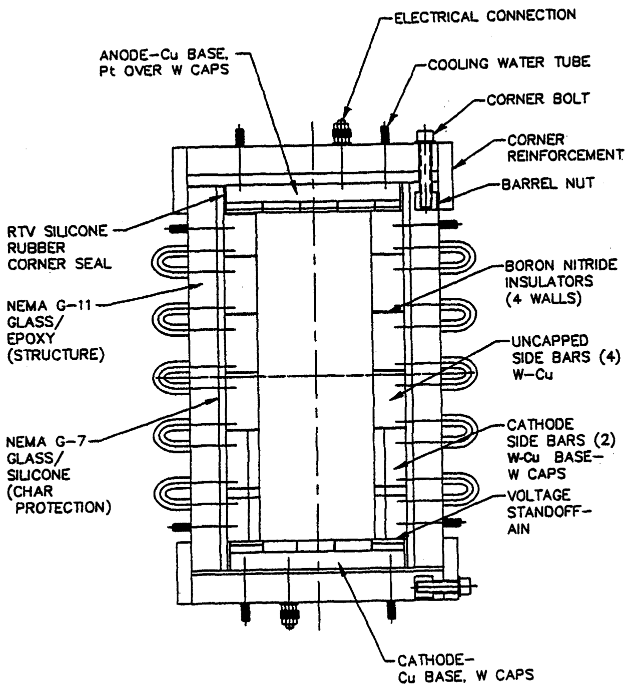


Fig. 10 Cross-sectional view of typical box channel construction.

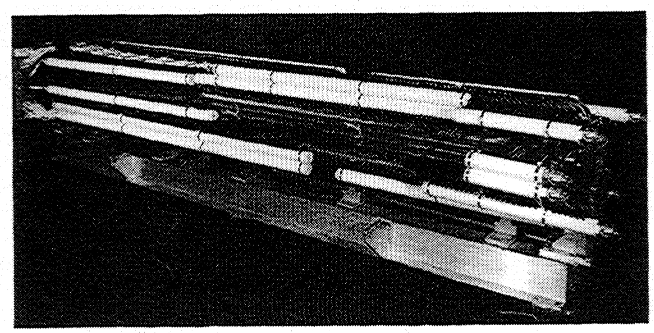


Fig. 11 Prototypic ITC MHD generator channel.

trode and insulating wall elements. Figure 10 is a schematic diagram showing the cross section of the Textron ITC generator channel.[24] An exterior view of this channel is shown in Fig. 11. Other MHD channels built in this manner include the Mark VI and Mark VII channels built by Avco,[26] the high performance demonstration experiment (HPDE) channel,[27] and several others. It is with this type of construction that the most extensive database has been accumulated.

Box construction has several advantages. It is readily scalable to large commercial sizes. The walls can be easily separated, so that assembly, disassembly, and refurbishing of the walls are relatively simple, fast, and inexpensive. Noncurrent carrying sidewalls can be used, which permits the use of local current controls. Gas sealing and interelectrode insulator functions are separated in boxed channels, thus minimizing the risk of plasma leakage in the event of interelectrode breakdown and arcing. Finally, there are only four main gas seals, along the corners of the box, thus further minimizing the risk of plasma leakage.

The main disadvantage is the relatively large number of cooled elements that either carry current or must be electrically insulated from one another, and the associated large number of cooling hoses and electrical wires that are required.

The so-called window-frame channel design, is made by stacking together metallic frames inclined at the same angle as the equipotential planes of the generator plasma. A schematic diagram of a typical window-frame design is shown in Fig. 12. The frames serve both as the current-carrying elements and as the pressure vessel of the channel. Gas sealing is done around the perimeter of each frame, at some distance from the gas. Window-frame construction was used for the LORHO generator,[28] a large Hall generator built by Avco, and for another large channel built in the U.S. for use in the Russian U-25 MHD facility.[29]

The window-frame generator channels offer some advantages. Electrical simplicity is achieved by using the frames

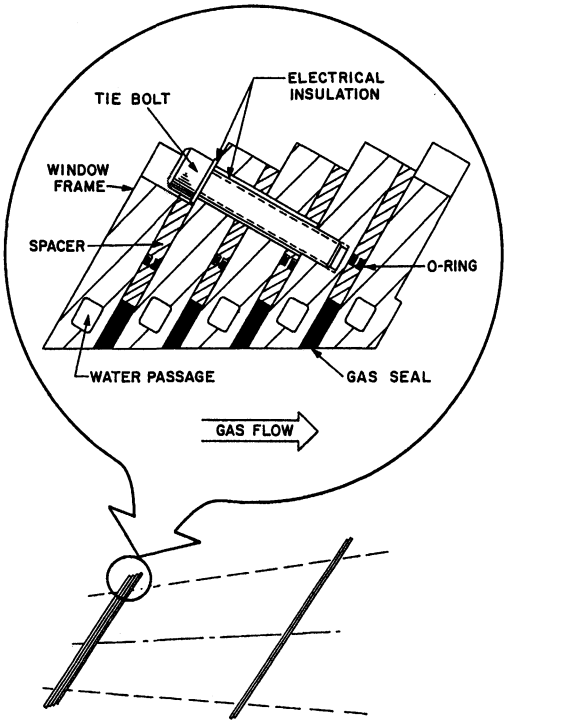


Fig. 12 Window-frame MHD channel construction.

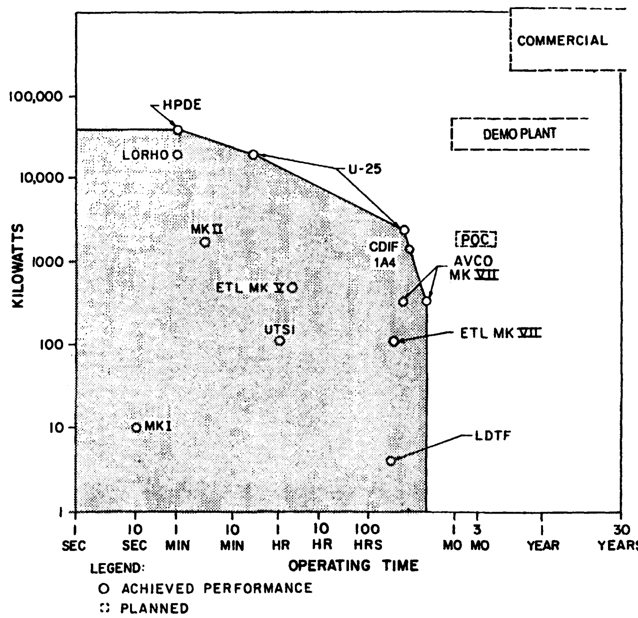


Fig. 13 MHD generator operation time.

for carrying the diagonal link currents, thus minimizing the amount of external wiring for this purpose. Also, hydraulic reliability is maximized by reducing the number of hydraulic circuits.

Offsetting these advantages presents some serious disadvantages. First, the great length of sealing surface (equal to the frame perimeter times the number of frames), together with the fact that gas sealing and structural functions are combined, make this type of construction vulnerable to hot gas leaks. Second, scaling to large commercial sizes is difficult because of the problems associated with fabrication and maintenance of large window-frame channels. A pilot plant size generator channel may have over 500 individual frames, each about 2 cm thick and about 1 m long on a side, requiring great care to avoid bending and distortion during handling. Also, coolant passages are difficult to incorporate into such frames. Third, a commercial-scale window-frame generator channel of minimum practical electrode pitch (frame thickness), at conditions typical of full-scale operation, has a very high fault power because of the large continuous length of frame, and offers no possibility of fault power control either by segmentation or by frame current control.

Finally, the reinforced window-frame generator channel is essentially a window-frame channel inside a plastic box that serves as the pressure vessel and main structural member. It combines some features of both window-frame and plastic box construction. Frames can be transversely segmented, although with some difficulty, for fault power control. This construction is hard to disassemble for inspection and/or refurbishment. The large RM generator channel for the Russian U-25 facility was of reinforced window-frame construction,[30] as was the smaller Russian U-25B generator channel.[31]

Generator channel thermal design, although requiring care, poses no major engineering problem. Heat fluxes from gas to the wall of the channel can range from 50 W/cm^2 at the exit of a well-slagged channel to about 500 W/cm^2 at the inlet of an unslagged channel. Coolant flow velocities in the channel wall elements are typically in the range of 2–5 m/s. Coolant hoses and manifolds must have adequate mechanical and thermal properties, and also be electrically insulating, to avoid electrical shorting of channel wall elements. These requirements limit the types of hoses and manifolds that can be used, and therefore, the allowable cooling water pressure and temperature.

V. Current Status of Channel Development

Figure 13 shows the operating durations achieved by various combustion-driven experimental channels. Two significant demonstrations are noted. The first was the operation of an Avco Mk VI channel, at 20-MW (thermal) scale, for 500 power hours.[25] The electrochemical and thermal stress levels were similar to those expected in commercial coal-fired MHD power plants. Results from this test indicate that durability of properly designed and operated channels can be extrapolated to several thousand hours. This test was performed prior to the availability of adequate MHD coal combustors. Coal-burning operating conditions were simulated by injecting ash and sulfur into an oil-fired MHD combustor.

The second significant demonstration is with actual coal-fired operation, at 50-MW (thermal) scale at the CDIF test facility for over 300 power hours, with the channel shown in Fig. 11. The generator was operated at power outputs up to 1.5 MW (electric).

Figure 14 shows predicted and achieved values of channel enthalpy extraction ratio, as a fraction of the scaling parameter shown, for a number of channels operated to date. Enthalpy extraction equal to that required by the retrofit plant has been achieved, in the HPDE channel, a combustion-driven linear channel of 300 MW (thermal) size, operated at the Arnold Engineering Development Center, although only for a short duration and on clean fuel.[32] The channel operated at over 50% isentropic efficiency. Most channels operated in the U.S. to date were used for duration testing and have been much smaller [20–50 MW (thermal)]. Therefore, they cannot achieve the performance projected for larger-size channels because of the adverse influence of effects that depend on the surface-to-volume ratio. Although the major value of subscale channel testing is in the development of a long-duration operating capability at realistic electric and thermal stress levels, one use of subscale channel testing is in verification of channel scaling laws and performance predictive capabilities of computer models. Figure 14 shows that channels have performed generally in accordance with predictions, and that measured performance does support scaling laws from which the performance of a full-scale channel is projected.

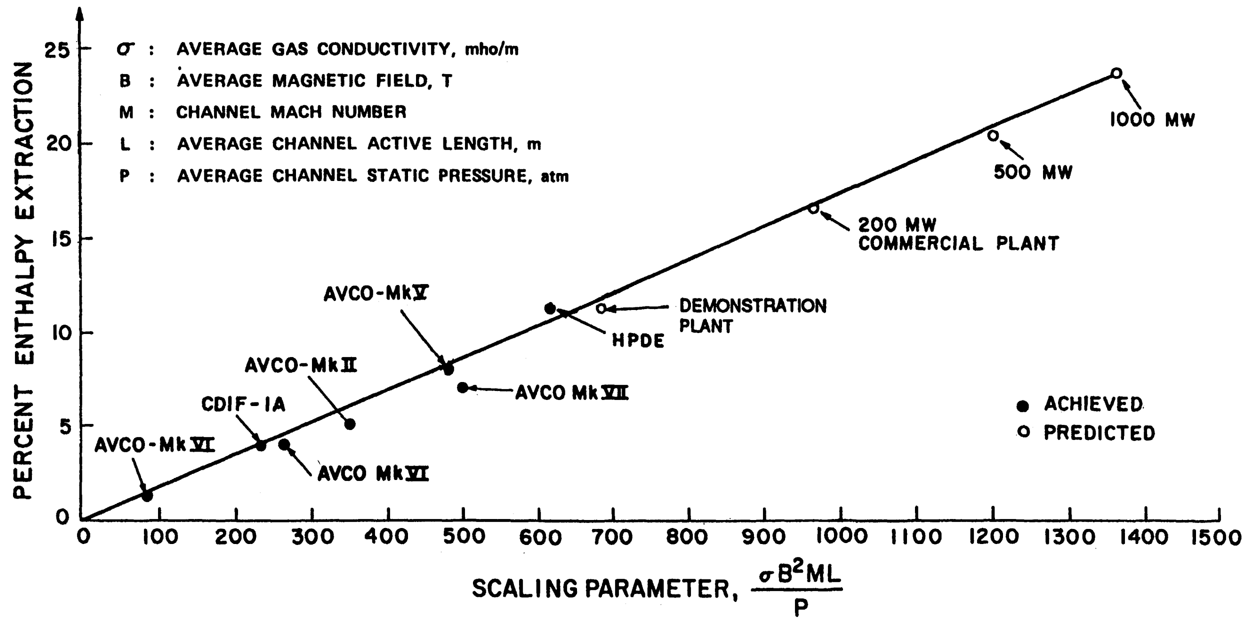


Fig. 14 Scaling of MHD generator enthalpy extraction.

An overall question exists regarding the economic viability of MHD; this can be answered only by actually building and operating a pilot scale plant, such as that mentioned in Refs. 33–35, so that projections of capital and operating costs, component durability, and plant availability can be verified.

VI. Summary

Coal-burning MHD/steam power plants promise significant economic and environmental advantages compared with other coal-burning power-generation technologies. Conceptual designs of early and mature commercial MHD powerplants have defined the performance requirements and operating specifications of the MHD generator, as well as other plant components and subsystems. A well-defined POC program in the U.S. has been carried out to provide the necessary information on the design, performance, and lifetime of all major components and subsystems, so that a complete integrated MHD/steam power system of sufficient scale can be designed, constructed, and operated to provide sound evidence that the attractive economic and environmental objectives of commercial MHD power generation can be achieved.

The current status of open-cycle coal-fired MHD generator development is reviewed. An extensive engineering database has been developed, including design information and test data from experimental facilities at substantial scale. The overall generator performance demonstrated at various facilities agreed with analytical projections. Considerable progress has been made toward achieving acceptable generator performance (power and enthalpy extraction) and durability. The development experience to date provides encouragement that there are no insurmountable technological problems that will prevent the successful development of a MHD generator for utility applications.

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