MAGNETOHYDRODYNAMIC POWER PLANTS

Magnetohydrodynamic (MHD) power generation refers to a technique in which a conducting gas is moved through a magnetic field to produce an electric field, which is utilized to produce power. A conventional generator is illustrated in Fig. 1, in which an electrical conductor is moved through a magnetic field and an electric field is generated in the wire. In the MHD case, as illustrated in Fig. 2, the electrical field is generated in the conducting gas which is passing through a magnetic field. In order to utilize this power, electrodes must be in physical contact with the gas to permit current flow. The cathode emits electrons and the anode collects them, the same convention as in an electron tube.

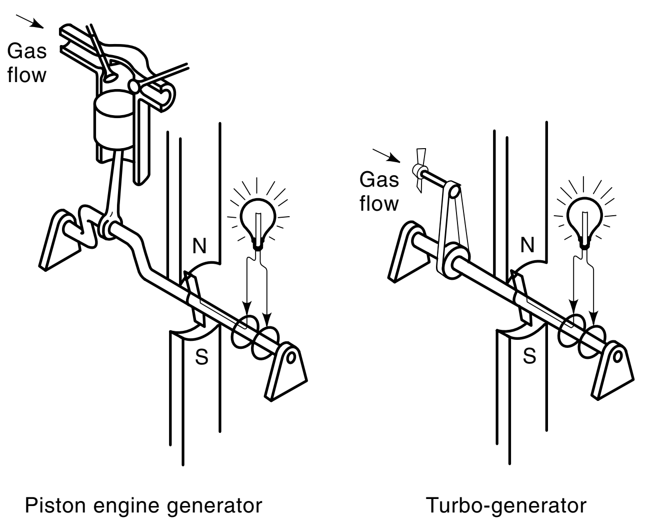

Figure 1. Illustration of conventional generator concepts showing a copper conductor moving through magnetic flux lines to generate an electric field.

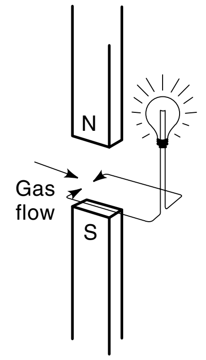

Figure 2. Illustration of MHD generator concept in showing electrical conducting gas moving through magnetic flux lines to generate an electric field. Note that electrodes must be placed in contact with the gas to permit the current to flow through an external circuit.

The conducting gas used in power generation is a partially ionized gas. In the regime of central power generation, it is described as slightly ionized, having free electron densities on the order of 10^{16} electrons/m^3. The method of producing the conducting gas, or plasma, as it is more correctly called, leads to a classification of type of MHD generators: equilibrium and nonequilibrium. In the equilibrium case, the gas is heated to a temperature such that a small fraction (around 1 in 10,000 of the atoms in the gas) are thermally ionized. In nonequilibrium ionization, energy is selectively added to the electrons, resulting in a fraction of ionization that exceeds that due to thermal excitation alone. In the latter case, the physics of the gas (especially collision cross section of electrons with heavier particles and the mean time between collisions) must be such that the ionization rate is greater than the recombination rate. The conditions that meet this requirement are very low pressures for combustion gases or the use of noble gases that have low collision cross sections, preferably also at reasonably low pressures. The low-pressure condition severely limits application of combustion gases for nonequilibrium applications. The use of a noble gas, such as argon, forces the constraint that the gas be reused and, hence, is called closed-cycle MHD. By contrast, the equilibrium ionization technique has been applied primarily to combustion products which are utilized once and then exhausted to the atmosphere. Thus, it is classified as open-cycle MHD.

To produce the plasma for open-cycle MHD power generation, a fossil fuel such as coal, char, oil, or gas is burned at a high enough temperature to produce the required ionization. This temperature required for ionization is too high for a practical power system if just the normal combustion products are present. The lowest possible temperature is about 4500 K, the temperature at which nitrogen oxide (NO) begins to ionize. However, an element that has a lower ionization potential can be added to reduce this temperature to more manageable levels. Potassium, with an ionization potential of 4.34 eV, is the most practical choice [cesium (with an ionization potential of 3.89 eV) and rubidium (with an ionization potential of 4.16 eV) are the only elements that are lower, but both are very expensive]. With 1% potassium in the flow, efficient MHD power production requires a flame temperature of about 2800 K. To achieve this high a flame temperature with fossil fuel requires significant preheating of the combustion air or oxygen enrichment of the air or some combination of the two techniques.

Fuels that have been considered for MHD power plants include coal, natural gas, oil, bitumen, char, and refinery coke. Fuels that have a high carbon-to-hydrogen ratio produce better electrical conductivity at the same conditions. This is because the water that is formed when hydrogen burns disassociates into monatomic hydrogen and an OH radical. The latter has an affinity for electrons. When it joins with an electron to become a negative ion, its mass is so much larger than an electron that it effectively removes that electron from the conductivity process. However, fuels that are high in hydrogen, such as natural gas, can be used but require a few tens of degrees Kelvin higher temperature to achieve the same electrical conductivity. Calculated electrical conductivity and flame temperature for coal with 1% potassium added as potassium carbonate is shown in Fig. 3(a) and (b), respectively, for a range of air preheat temperatures and pressures. These calculations are all for a fuel-rich condition, 85% of theoretical oxygen. The reasons for choosing this fuel-rich condition are twofold: It optimizes the electrical conductivity, and it is essential for the control of nitrogen oxide emissions to a very low level.

The actual configuration of the MHD generator, in its simplest form, is shown in Fig. 4(a). This arrangement is called a continuous electrode Faraday generator because the electrodes are continuous along the generator length. This configuration is used in some short-duty time applications, such as the Russian PAMIR, which generates a pulse of several megawatts for several seconds. However, it is inefficient because there is a completed path for circulating axial currents to flow through the plasma and back along the length of the electrode, causing electrical losses. This problem is circumvented in the segmented Faraday generator as shown in Fig. 4(b). In this design, the electrodes are narrow strips with insulators between the electrodes, preventing a return path for circulating currents through the electrodes in the axial direction. The segmented Faraday generator is the most efficient configuration, but it suffers from one disadvantage for application to commercial power generation: It requires a separate loading circuit for each pair of electrodes, as shown in Fig. 4(b).

The diagonally conducting generator, as illustrated in Fig. 4(c), avoids this problem and its efficiency approaches that of the segmented Faraday generator when properly designed and loaded. In an MHD generator, when current flows in the direction mutually perpendicular to the velocity and the magnetic field, it is called the Faraday current and is in the y-direction on the coordinate system shown in Fig. 4. When current flows in a magnetic field, there is a force on moving charged particles that tends to separate the electrons from the positive ions. This effect is called the Hall effect. The result is an electric field along the length of the generator, called the Hall field. The diagonal generator loads the vector sum of the Faraday field and the Hall field, and the wall angle is determined as $\tan^{-1} \boldsymbol{E}_F/\boldsymbol{E}_H$, where $\boldsymbol{E}_F$ is the Faraday electric field and $\boldsymbol{E}_H$ is the Hall electric field. Electrodes at this wall angle lie along equipotential lines at design conditions because the electric field vector is perpendicular to the electrode. This generator can be loaded from one end to the other, or it can be loaded with more than one load connection along the length of the generator. For a generator designed for central power application, where high efficiency and high reliability are desired, it would normally be loaded with multiple loads to approximate the optimum current. This would result in something like four to six separate load circuits versus several hundred for the segmented Faraday configuration. Insofar as known to the author, the diagonal connection is the only configuration considered for commercial power generation in a linear open-cycle system.

A principal attraction of the MHD generator for central power generation is its high conversion efficiency, as mea-

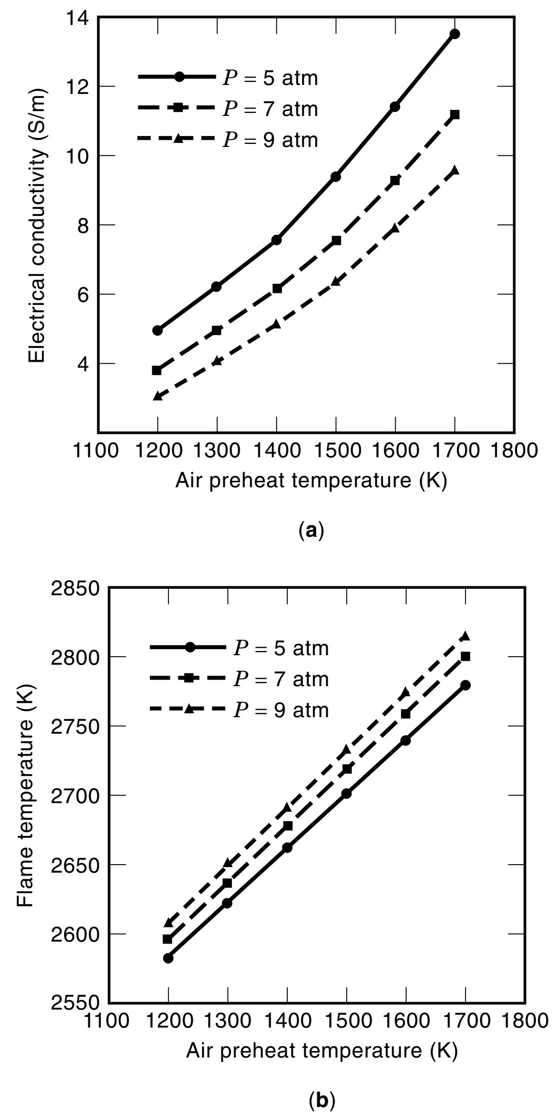

Figure 3. (a) Electrical conductivity versus air preheat temperature for Illinois #6 coal dried to 2% moisture with 1% potassium added as potassium carbonate. (b) Flame temperature versus air preheat temperature for Illinois #6 coal dried to 2% moisture with 1% potassium. Note the preheat temperature required to achieve 2800 K flame temperature.

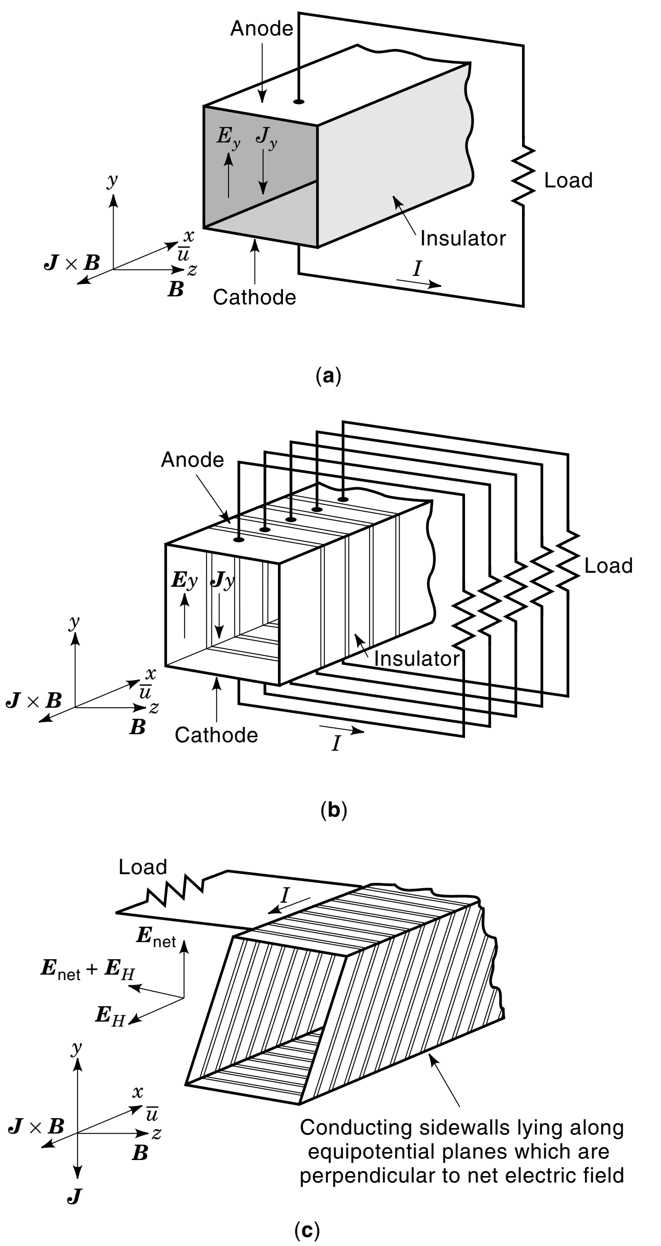

Figure 4. (a) Continuous electrode Faraday MHD generator. (This is the simplest MHD generator.) (b) Segmented electrode Faraday MHD generator. The electrodes are segmented in the X-direction to avoid a return path for circulating currents. (c) Diagonal conducting wall MHD generator. The sidewalls are perpendicular to the net electrical field and lie along equipotential lines.

sured on the basis of the first law of thermodynamics (energy conservation). That efficiency is defined as the electrical power output divided by the energy lost by the gas stream while passing through the generator. Alternatively, it may be calculated as the electrical power generated divided by the sum of the electrical power generated plus the heat loss to the walls. Efficiency as so defined can typically be around 90%, depending on the size and pressure ratio (thus length) of the generator. The MHD generator is only useful in the temperature range in which there is sufficient electrical conductivity. At about 2200 K and at exhaust pressures typically slightly less than 100 kPa, the conductivity has decreased to around 1 S/m and MHD generation is no longer attractive. However, the working gas still contains considerable sensible energy.

This leads to the concept of a combined cycle MHD steam power plant in which a MHD topping cycle is used on a steam Rankine bottoming cycle. This concept is shown schematically in Fig. 5. Note that there are numerous opportunities to integrate the topping and bottoming cycles for improved efficiency and resource allocation. The requirement for heating the combustion air can be incorporated into the bottoming cycle furnace and result in a large efficiency improvement because the energy is recycled from the less efficient bottoming cycle to the more efficient topping cycle. Also, the mechanical power to run the compressors for the topping cycle combustion can be met with a steam turbine economically, especially in large plants. The cooling water from the topping cycle can be incorporated into the boiler feedwater heating design to utilize that energy. The potassium used as seed in the topping cycle needs to be recovered in the bottoming cycle and processed for reuse.

The low levels of environmental intrusion from the MHD steam combined cycle power plant are one of its attractive features. Department of Energy studies (1) have shown that such plants have the lowest levels of any of the possible coal-fired combined cycles. Sulfur dioxide emissions are completely eliminated by combination of the sulfur in the fuel with potassium seed, which is collected as solid potassium sulfate in the particulate control system. Nitrogen oxides are formed in large amounts (10 kppm to 12 kppm) in the high-temperature combustors of MHD plants, even at fuel-rich stoichiometries. However, by cooling the gases in a radiant furnace before completing the combustion, the nitrogen oxides (actually, almost completely nitric oxide, NO, at fuel-rich conditions) relax toward equilibrium at lower temperatures and at a secondary combustion temperature of about 1000 K (1350°F), very little NO remains (2). The secondary combustion must be made in a way that avoids much temperature rise to avoid the formation of additional nitrogen oxides.

The MHD plant has a higher particle loading in the exhaust because of the potassium seed added. Furthermore, the size distribution tends to be smaller due to the higher temperatures having vaporized some of the solids. However, the resistivity of the ash is lower due to the high potassium content, and electrostatic precipitators (ESPs) are very efficient in removing the solids, although more capability is required than would be required for a normal coal plant. In addition to needing to remove the particulate to meet Clean Air Act standards, it needs to be removed in the MHD case in order to recycle the potassium seed. MHD pilot plants have operated with a completely invisible stack plume. Volatile organic compound (VOC) emissions, which are essential components for formation of fine particulate in the atmosphere, are almost completely eliminated in the MHD plant because combustion efficient enough to produce electrically conducting plasma has been shown to contain no unburned elemental or organic compound carbon (3). This is an important advantage because power plants seek to control particulates in the atmosphere having mean diameters of 2.5 μm and less because the troublesome part of these particulates are formed in the atmosphere from unburned VOCs, sulfur oxides, and nitrogen oxides.

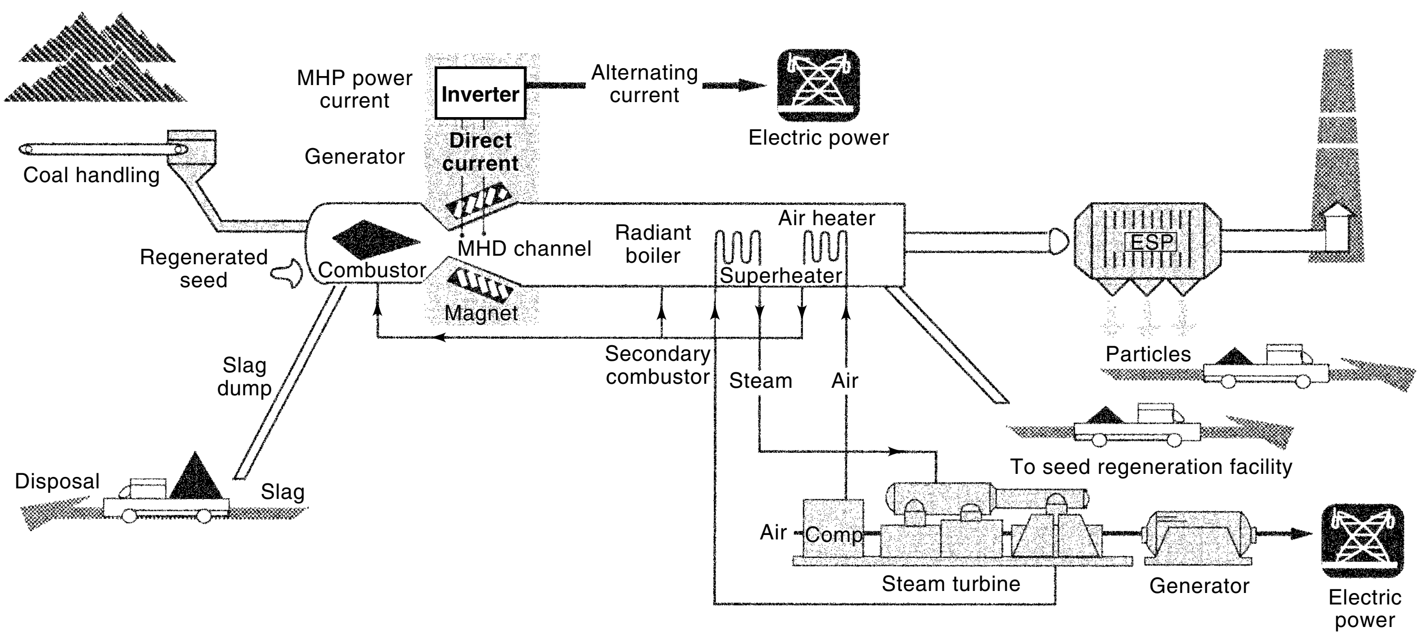

Figure 5. Schematic of MHD/steam combined cycle power plant.

THE MHD TOPPING CYCLE

The MHD topping cycle consists of a means of generating the plasma (generally a combustor), a nozzle to accelerate the plasma, an MHD generator with associated control, power take-off system, inverters to convert the generated direct current power to alternating current, a magnet to provide a magnetic field in the generator volume, and a diffuser to reduce the plasma velocity and recover static pressure before it enters the radiant furnace. As previously noted, there are several streams that are integrated with the bottoming cycle including air preheat and/or oxygen production, recovery and reprocessing of the potassium seed, and use of boiler feedwater for cooling of all topping cycle components.

Combustor

The combustor used in a MHD power plant faces some extreme conditions compared with the burners in other fossil plants. It must generate a plasma at about 2800 K and deliver it at pressures of perhaps 0.2 MPa to 1.0 MPa. In order to reach this temperature, it is necessary to have a small volume, with good mixing of fuel and oxidant and extremely rapid heat release. When burning coal, the volume must be a compromise (optimization) whereby time is allowed for carbon burnout while keeping the combustor small enough to limit the heat losses to the walls. There have been two successful coal combustors demonstrated that differ substantially in design.

One of these is a single-stage, full-slag-carryover combustor modeled somewhat after rocket engine technology (4). A sketch of this combustor is shown in Fig. 6. In this design, the pulverized coal is injected in a conical pattern from the middle of the injector plate. Air is fed through a number of small holes in the injector plate where a pressure drop is taken to accelerate the air. These jets of air mix very rapidly with the coal and produce high heat release concentrations, typically over 120 MW/m^3. The walls of the combustor rapidly become covered with coal slag, solidified next to the wall and molten on the flame side. In spite of insulation effects of this slag layer, heat fluxes to the walls average about 100 W/cm^2. The potassium seed is pulverized with the coal and fed together in this configuration. The solids, consisting of coal ash and seed, are molten at the exit of the combustor and are blown over with the gas for separation later in the steam bottoming plant. Scale-up of this combustor concept is feasible by using clusters of these burners, firing into a common chamber.

The advantages of this type of combustor are simplicity, low cost, and higher, more uniform electrical conductivity because of the time available for the seed to reach chemical and thermal equilibrium with the gas.

The other type of combustor that has been developed is the two-stage, slag-rejecting combustor (5). The concept for this

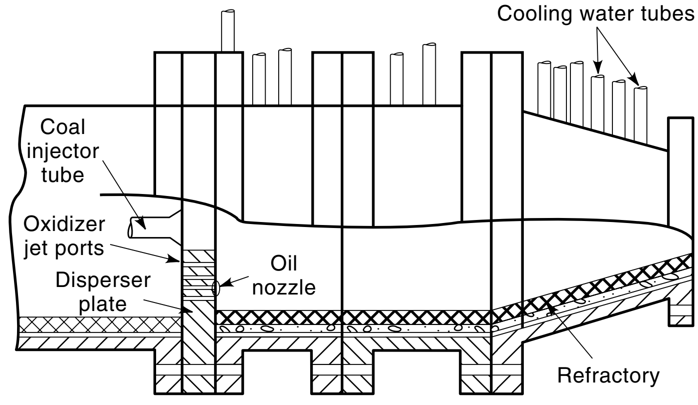

Figure 6. Single stage MHD coal combustor concept. This design is optimized for rapid turbulent mixing and for minimum heat loss to the walls.

design is to produce mixing in the first stage by injecting the air tangentially to produce swirl for mixing. The air preheat temperature and stoichiometry are chosen so that the coal ash is liquid in this stage and it is tapped out at the bottom of this first stage. The gases are taken off tangentially so as to get a deswirl effect going into the second stage. The seed and additional air are added in the second stage. The objective of this design is to remove as much coal slag as possible before adding the potassium seed to minimize the amount of potassium seed that chemically combines with the slag and may be more difficult to recover. Slag removal efficiencies of up to 50% were demonstrated experimentally with coal ground to 70% through 200 mesh (6). Additional slag removal can be achieved with larger particles of coal, but the carbon burnout suffers as the coal particle size increases. Also, this combustor has problems in scale-up because as the size of the combustor increases, slag removal decreases unless the air injection velocity is increased accordingly. As noted, the advantage of this design is that it removes some of the coal ash before the potassium seed is injected. The disadvantages are larger size, more heat loss, and possibly lower electrical conductivity due to insufficient residence time for the potassium seed to reach thermal and chemical equilibrium.

Regardless of which type of combustor is used, the primary stoichiometry should be chosen to meet two objectives: to maximize the electrical conductivity and minimize the nitrogen oxides emitted by the plant. A plot of flame temperature and electrical conductivity versus primary stoichiometry is shown in Fig. 7. It shows that the primary combustor should be operated under fuel-rich conditions at about 85% to 90% of theoretical oxygen to maximize temperature and electrical conductivity. This happily turns out to be compatible with very low nitrogen oxide emissions as well.

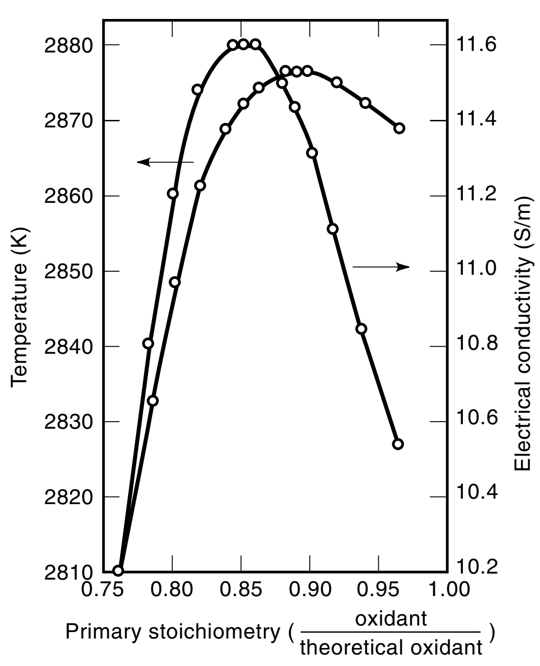

Figure 7. Flame temperature and electrical conductivity versus primary stoichiometry; coal with oxygen-enriched air, 1% potassium, pressure = 7 atm. Note that the electrical conductivity peaks at a stoichiometry of ~0.85.

The Nozzle

A gas dynamic nozzle is needed between the primary combustor and the MHD generator to accelerate the flow to the desired entrance condition. The voltage generated in the MHD generator is the product of gas velocity, magnetic field flux density, and the distance over which it acts. From this viewpoint alone, the velocity should be high. Other considerations such as convective heat transfer coefficient, size of generator, and total amount of power that can be generated from a unit of fuel, however, place upper limits on the desired entrance velocity. In practice, a high subsonic flow (Mach number 0.8 to 0.9) or low supersonic flow (Mach number 1.1 to 1.3) is normally chosen for central power generation. It is desirable to choose the velocity and area lofting to avoid the formation of a shock in the generator. Thus, a subsonic generator should be lofted to remain subsonic throughout its length, and a supersonic generator should be designed to remain supersonic throughout its length and under all operating conditions. This places some difficult restrictions on turn-down of the generator to operate at part load conditions.

The isentropic one-dimensional gas dynamic relations can be used to design the nozzle. The supersonic nozzle cross-sectional area converges to a throat, and then it diverges to the area required for the desired entrance Mach number. The subsonic nozzle must be lofted to provide a throat (a short supersonic region) and then it converges to produce the desired subsonic entrance Mach number. Heat fluxes to the walls are normally higher in the nozzle throat than in any other part of the plant. Design of the cooling for the nozzle, especially at the throat, is a challenge. The best success has been demonstrated with channeled cooling water passages with high-velocity water to ensure good convective heat transfer between the inside of the cooling water passage and the water.

The MHD Generator

Analysis and characterization of the MHD generator involves the consideration of both Maxwell's equations for electromagnetic fields and the conservation of mass, energy, and momentum equations for fluid flow (7). In addition, of course, an equation of state is required for the fluid. In MHD calculations, these sets of equations are coupled. The electrical effect, $\boldsymbol{J} \times \boldsymbol{B}$, is a body force which must be considered in the fluid flow. Similarly, the electric field produced by the motion of the electrically conducting gas in the magnetic field must be considered in the electromagnetic solution. This is illustrated in Fig. 8. There are no cases of practical interest for which the equations can be solved in closed form. Thus, the equations must be solved numerically for analysis or design of the MHD generator. In cases where the interaction is low, it may be a satisfactory approximation to neglect the effect of the body force, $\boldsymbol{J} \times \boldsymbol{B}$, in the flow calculations. In those cases where the body force is neglected in the calculation of flow quantities, the flow is said to be uncoupled. We consider here only the regime of MHD generation for central power plants. In this regime, the $\boldsymbol{J} \times \boldsymbol{B}$ body force is the major sink for momentum and cannot be neglected in the design calculations for the MHD generator. Full solutions to this set of equations are available. See, for example, Ref. 8, which is a public domain code published by Argonne National Laboratory.

The problem can be simplified for preliminary design calculations by considering the problem as one-dimensional (9).

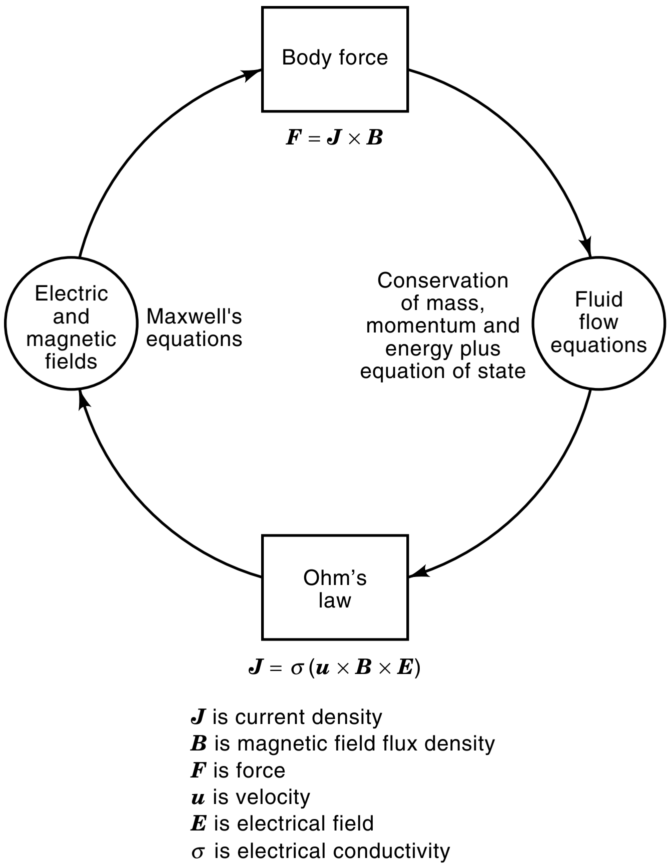

Figure 8. Illustration of coupling of the gas-dynamic and electromagnetic relations.

This simplification involves the assumption that the magnetic field is aligned with one axis—for example, the z-axis as shown in Fig. 4. This implies that induced magnetic fields due to currents in the generator are negligible. This is certainly the case in the central power generation regime. We also need to assume that the current density and flow quantities are uniform in a plane perpendicular to the direction of flow, the yz-plane, and are represented by the average value in the plane. With such assumptions, the simplified equations become:

Conservation of Momentum Equation:

$$\rho u \frac{d\boldsymbol{u}}{dx} + \frac{dP}{dx} = -\boldsymbol{J}_y \boldsymbol{B} = 4 \frac{P_w}{D} \tag{1}$$

where

τ_W = shear stress
D = hydraulic diameter
ρ = density of the plasma

Conservation of Energy Equation:

$$\rho \boldsymbol{u} \frac{dh}{dx} + \rho \boldsymbol{u}^2 \frac{d\boldsymbol{u}}{dx} = \boldsymbol{J} \cdot \boldsymbol{E} + 4 \frac{q_w}{D} \tag{2}$$

where q_w = heat flux to walls.

Conservation of Mass or Continuity Equation:

$$\rho u A = \dot{m} \tag{3}$$

where A = cross-sectional area of duct and

$\dot{m}$ = mass flow rate through duct

Ohm's Law (including only significant terms for this case):

$$\boldsymbol{J} = \sigma(\boldsymbol{E} + \boldsymbol{u} \times \boldsymbol{B} + \boldsymbol{E}_d) - \frac{\Omega}{\boldsymbol{B}}(\boldsymbol{J} \times \boldsymbol{B}) \tag{4}$$

where $\boldsymbol{E}_d$ is an electrical field loss due to plasma to electrode voltage drop. The electrical field corresponding to a potential drop, Δ, defined as

$\Delta = \frac{E_d}{uB} = \frac{V_d}{uBd}$
Ω = Hall parameter = electron cyclotron frequency times mean time between collision of electron with heavy particles

From Ohm's law, an equation for $\boldsymbol{J} \cdot \boldsymbol{E}$ can be derived for use in the energy equation (10)

$$\boldsymbol{J} \cdot \boldsymbol{E} = \frac{J^2}{\sigma} - J_y B(1 - \Delta) \tag{5}$$

An equation of state is required. That is, given two thermodynamic variables such as T and P, a relationship is required such that the other thermodynamic variables can be calculated. This is typically a table of values calculated from a chemical equilibrium code such as the NASA SP-273 Code or one of its variants. An alternative that is now feasible due to the greatly expanded capability of modern computers is to use a chemical equilibrium code to calculate the other variables at each point.

The electrical conductivity, σ, must also be available from the table or calculation. The method used by the author was originally described by Frost (11).

Equations (1), (2), (3), and (5) can be simplified to three independent differential equations in four unknowns, P, T, U, and A. If one of these variables is fixed or known, a solution for the other variables can be computed along the length of the generator. Once the flow variables are calculated, the electrical variables can be computed via the relations tabulated in Table 1 of Ref. 10.

For a practical design calculation, constant velocity is the case of most interest because this is very near to the maximum power generation point for a given gas. The equations can be modified to perform a constant Mach number case which is useful in designing for the absence of shocks in the generator. Either case then gives all the electrical and thermodynamic variables along the generator and the cross-sectional area at each point along the length. A loading factor, which relates the impedance of the load to that of the generator, is also required. This is defined as

$$K = \frac{R_L}{R_L + R_g} \quad \text{or} \quad \frac{V_L}{V_G}$$

where

R_L is load resistance
R_g is internal generator resistance
V_L is load voltage
V_G is generated voltage

There is an elementary theorem in electrical engineering that says the maximum power transfer from a circuit to a load occurs when the load resistance equals the generator internal resistance. Thus, one is tempted to set $K = 0.5$. This is not a good choice, however, because it means that half the generated power is dissipated by the current flowing through the gas. If a higher K is chosen, the generator becomes longer and more efficient. The correct choice, in general, will depend on the overall plant economics in terms of levelized cost of electricity being minimized. The MHD generator tends to be relatively cheap, but making the magnet longer adds considerable expense. A loading factor, K, of 0.88 to 0.90 is typical.

For a given load factor and gas conditions, the amount of power that can be generated depends on the pressure ratio across the generator. The exit pressure must be determined by the conditions needed at the diffuser entrance in order to recover to the pressure needed at the furnace inlet (it may be slightly less than atmospheric for induced draft designs).

Some common efficiency definitions that apply to the MHD generator are given below

$$\text{Enthalpy extraction} = \frac{\text{Electrical power output}}{\text{Sensible enthalpy of gas}} = \frac{P_{\text{out}}}{(h_{0_{\text{in}}} - h_{\text{ref}})\dot{m}}$$

where

$h_{0_{\text{in}}}$ is total enthalpy at generator entrance
h_{ref} is static enthalpy at reference condition of 1 atm, 298 K (77°F)

Note that since the only energy loss from the gas is electrical power output and heat transfer to the walls, we obtain

$$\text{Generator efficiency} = \frac{\text{Electrical power output}}{\text{Decrease in enthalpy across generator}} = \frac{P_0}{(h_{0_{\text{in}}} - h_{0_{\text{out}}})\dot{m}}$$

where $h_{0_{\text{out}}}$ = total enthalpy at generator exit. Also, since the only energy loss from the gas is electrical power output and heat transfer to the walls, we obtain

$$\text{Generator efficiency} = \frac{P_{\text{out}}}{P_{\text{out}} + Q_{\text{w}}}$$

when Q_w = total heat transferred from gas to walls.

The Diffuser

The function of the diffuser is to slow the gas down and recover (convert) as much of the dynamic pressure as possible to static pressure. The diffuser for a subsonic generator is just a diverging duct, with (a) the wall angles chosen to be small enough to avoid flow separation at the walls and (b) the length sufficient to recover as much static pressure as possible but no longer so as to minimize the heat loss to the walls. For a supersonic generator, a constant area section is placed at the generator outlet to cause the flow to shock to subsonic, then the same type diffuser is used as for the subsonic diffuser. A common measure of performance of the diffuser is called the pressure recovery coefficient, C_p, which is the ratio of the recovered static pressure to the dynamic pressure available. It may be expressed as

$$Cp = \frac{P_2 - P_1}{\frac{1}{2}\rho u^2}$$

where

P_2 is static pressure at the outlet
P_1 is static presure at the inlet
ρ is fluid density at the inlet
u is fluid velocity at the inlet

The coefficient of performance for practical diffusers in MHD topping cycles are expected to be 0.5 to 0.6. Heat loss in the diffuser walls is incorporated into the boiler feedwater heating chain and, in some aggressive designs, may be used for boiling surface.

THE STEAM BOTTOMING CYCLE

The steam bottoming cycle takes the hot gases from the MHD diffuser and uses the sensible heat in them to generate electrical power by a Rankine cycle in a manner that is similar to a conventional coal-fired steam power plant. There are some differences in the MHD bottoming cycle application, and these will be emphasized in this treatment.

Boiler Design

The first difference from a conventional steam plant is that the hot gases enter from a single duct rather than distributed burners. The gas is at a higher temperature (2000 K to 2200 K, 3140°F to 3500°F) and is reducing. The gas is reducing because the gases exiting the MHD cycle must be cooled before completing the combustion. At this point they contain carbon monoxide, hydrogen, and hydrogen sulfide, which are known to be corrosive to power plant materials. The basic structure can be a boiler fabricated of membrane boiler tube, but the interior metal surface must be protected from corrosion.

A standard technique is to weld studs to the interior surface of the boiler tube and refractory coat all metal surfaces that will come into contact with the combustion gases (12).

This technique is well established commercially because it is used in cyclone-fired boilers, in some gasifier applications, and in the black liquor boilers of paper plants. The refractory selected must be rated to withstand the expected gas temperatures. It can be anticipated that the refractory will burn back to an equilibrium thickness, thinner in the lower, hotter regions and thicker in the upper, lower-temperature regions. The effect of the total flow entering the boiler at a single point primarily affects the desirability of distributing the flow of hot combustion gases uniformly over the interior surface of the boiler so as to utilize all the boiling surface efficiently.

Air Heating

As noted previously, preheating combustion air is one of the techniques used to attain a flame temperature sufficient to get adequate equilibrium ionization of the potassium seed. This temperature needs to be around 2800 K (4580°F). With standard atmospheric air, a preheat temperature of 1900 K (2960°F) to 2000 K (3140°F) is needed to achieve this flame temperature. A method of heating air to this temperature economically is one of the biggest remaining development problems for the MHD steam combined cycle power plant. (It should also be noted that there are a myriad of other power plant applications of such an air heater if it were developed.) It has generally been presumed that a metallic tube air heater is not applicable to heating air to these temperatures, although it may be the most economical solution for heating the air to an intermediate temperature. The original MHD plant concept envisioned the use of recuperative heat exchangers such as those used to preheat the air for blast furnaces. Clearly these are technically feasible, but the huge investments and operational problems inherent in these type heaters for a power plant make them unlikely final choices. More recently, ceramic materials for heat transfer tubes have been developed. Tests of individual tubes have shown satisfactory results for this application, but the problems of manifolding, treatment of thermal stress, and so on, remain to be solved. In the absence of an air heater that will preheat air to these temperatures, the design solution for the plant is to heat the air to as high as feasible with metallic air heaters and use some oxygen enrichment to achieve the required flame temperatures (13). A typical solution to this problem is to add oxygen so that the fraction by weight is about 36% and preheat the resulting mixture to 922 K (1200°F) in a metallic air heater.

Secondary Combustion

As previously noted, the primary combustor must operate fuel rich for optimum conductivity and low NO_x emissions. After the combustion products are cooled to the point that nitrogen oxide has decomposed to the desired level, the combustion must be completed to recover the remaining fuel energy and prevent emission of unburned and corrosive compounds, especially CO, H_2, and H_2S. The design goals are to achieve as complete a combustion as possible and to avoid a temperature increase that will increase the formation of nitrogen oxides. These goals are contradictory, of course, and a compromise must be chosen that is acceptable in both respects. The completeness of combustion is largely a function of the efficiency of mixing the exhaust gases with the air. This can be modeled numerically or by a laboratory simulation. In order to avoid a significant temperature increase with the accompanying increase in the formation of NO_x, the air can be introduced over a time period during which heat is removed from the gas. An alternative technique is to use exhaust gas recirculation, which involves taking exhaust gases from a lower-temperature region in the plant and, by use of a blower or fan, reinjecting them into the secondary combustor region so as to keep the mixture temperature from rising. From a combustion kinetics viewpoint and an overall steam plant efficiency viewpoint, it is desirable to preheat the secondary combustion air to some modest temperature such as 589 K (600°F). This can be done as an alternative to economizer surface in the plant. Another design issue is the overall plant stoichiometry, or the amount of excess air added. The impact of increasing excess air is increased stack losses. Experimental work with a pilot plant showed that 5% to 10% excess air is a reasonable design point with control by measurement of CO emissions in the stack. Conventional coal plants typically operate at much higher excess air levels. Staged combustion and stack gas monitoring permit operating at this low level of excess air to gain the benefit of increased efficiency.

Particulate Loading

The particulate loading in the steam plant portion of the MHD steam combined cycle power plant is inherently higher than in a conventional coal-fired power plant. This is because of the potassium seed added to permit equilibrium ionization at reasonable temperatures. Potassium is needed to the extent of something like 1% of the total flow. If the potassium is added as a compound such as potassium carbonate or potassium formate, the total weight percentage of compound added is 1.77% and 2.15%, respectively, of the total flow. The carbonate or formate disassociates in the combustor of course, but it re-forms potassium sulfate or potassium carbonate in the lower-temperature regions of the steam plant. This turns out to result in typically a doubling of solids content in the plant components compared to operation with just the coal ash particulate. In addition, these potassium compound particulates tend to be much smaller in size than the coal ash particles. It should be noted that potassium sulfate forms preferentially as long as any sulfur is available. After all the sulfur is used, the remaining potassium forms carbonate. The significance of this observation here is that the carbonate has a lower melting point (1170 K, 1646°F) than the sulfate (1342 K, 1955°F). Any heat transfer surface having a gas side temperature higher than this will encounter liquid deposits that are harder to remove by soot-blowing. Since the larger particles are more likely to be removed in the furnace or elsewhere in the plant, the fraction of the total particulate that is composed of small potassium compounds in the flue gas toward the lower temperature part of the plant often approaches 80% to 90%. The design implications of this are threefold: (i) The tendency to collect on convective heat transfer surfaces and block the gas passages is greatly increased, (ii) heat transfer efficiency of convective sections is reduced (higher fouling factors), and (iii) the removal of sufficient particles to meet stack gas emission requirements may be more difficult. Early experiments with potassium seed resulted in convective sections that were completely plugged to gas flow with deposits. The boiler must be designed with wide tube spacing, at least as wide as those in used for the worst fouling coals and lignites. If the plant will ever burn low sulfur coal, the spacings should be further increased to provide a margin of safety from the expected potassium carbonate deposits. In any case, adequate soot-blowing capability must be provided. The amount of soot-blowing provided must be balanced against the design fouling factor used in calculating the amount of heat transfer surface required, but it should be noted that fouling factors tend to be higher in the MHD case due to the potassium compounds present.

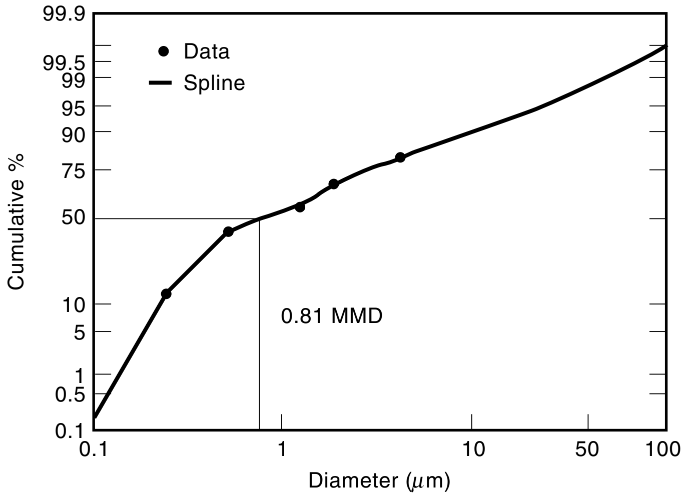

Figure 9. Typical particle size distribution in particulate from MHD pilot plant, upstream of the ESP/baghouse. Note the bimodal distribution with the smaller particles being potassium compounds and the larger ones coal ash.

Particulate Collection

As previously noted, the principal differences between the particulate in the MHD steam plant and that in a conventional coal-fired steam plant are the higher mass loading, smaller particulate, and different chemical composition in that it is high in potassium compounds.

In pilot plant tests designed to simulate a commercial plant (14), the particle loading was measured to be 14 g/m^3 to 16 g/m^3 (6 grains/ft^3 to 7 grains/ft^3). A typical particle size distribution is shown in Fig. 9. The mean mass diameter was about 0.6 μm. The size distribution is bimodal, with the larger particles tending to be coal ash and the smaller ones potassium sulfate. The resistivity of this mixture for two similar cases is shown in Fig. 10. The resistivity for temperatures of interest are in the range of 10^9 $\Omega \cdot$ cm to 10^{10} $\Omega \cdot$ cm. This is a desirable range for good ESP operation and tends to partially compensate for the very heavy mass loading and small size. A four-field dry ESP with a design specific collection area (SCA) of 475 ft^2/1000 acfm performed in the pilot plant with 99.5% removal efficiency. With such a fine particulate, a major problem with greatly improved efficiency is reintrainment of small particles when the plates are rapped to remove the collected particles. An attractive alternative to the dry ESP seems to be the wet ESP, in which the plates are washed continuously with water. A baghouse is also a feasible choice. The bag fabric must be chosen to avoid blinding. A Gore-Tex fabric, manufactured by W. L. Gore & Co., Knoxville, TN, was used successfully in the pilot plant.

If a dry ESP is used, it has been suggested that if should be designed to operate at a high enough gas temperature so that it can be placed before the economizer/low temperature air heater surface. Since the temperature difference between flue gas and feedwater or air is low in this region, a large amount of convective surface is required and substantial savings result from having a cleaner gas and lower fouling factor.

Seed Recovery and Regeneration

The economics of the MHD steam power plant depend on recovery and reuse of the potassium seed. If the potassium is recovered as a sulfur or chlorine compound, chemical processing to convert it to a sulfur and chlorine free compound is required. Potassium is largely recovered from the exhaust by the ESP or baghouse, but significant quantities may also be recovered from hoppers under heat transfer surfaces.

If the plant has a slag rejecting combustor or wet bottom furnace, it can be anticipated that some potassium will be present with the coal slag from these effluent streams. The chemical form of potassium in these streams may be as compounds with the coal slag components, especially silicates. A method has been devised to economically recover this potassium by leaching with calcium hydroxide to recover potassium hydroxide, which integrates well with the formate seed regeneration process (15,16). A number of possible processes were studied during the US Department of Energy MHD development program with the conclusion that the formate process, which was used in Germany during World War II, is the best choice for converting the potassium sulfate recovered to potassium formate for reuse. The recovered potassium carbonate can be separated from the sulfate and chloride by differences in their solubility in water. Separation of sulfate from carbonate was performed well in the pilot plant program by a

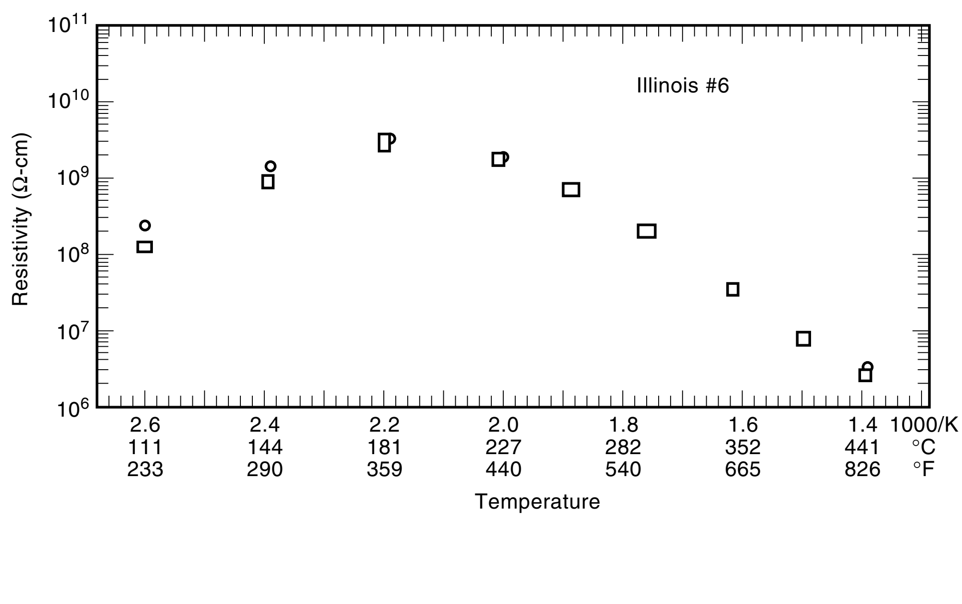

Figure 10. Ash resistivity from MHD pilot plant as a function of temperatures. Resistivities from 10^9 to 10^{10} $\Omega \cdot$ cm are desirable from ESP operation.

rotary vacuum filter working on the water from the wet ESP. The system was saturated with carbonate, and the sulfate was removed by the filter.

Economic Plant Design

In order to adequately optimize the performance of the MHD steam combined cycle power plant, a model of the cost and performance is needed. The Electric Power Research Institute (EPRI) has developed a methodology for calculating the levelized cost of electricity over the planned lifetime of the plant (17). The complexities and trade-offs in the MHD plant require a model that calculates performance and cost for use in the EPRI methodology. Potential designers should develop such a model or use one of those listed in the references (9,18–20).

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MAGNETOOPTIC EFFECT. See FARADAY EFFECT.