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U.S. DEPARTMENT OF ENERGY
Fossil Energy
Office of Magnetohydrodynamics

Prepared for
Nineteenth Aerospace Sciences Meeting sponsored by the
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E-688

Abstract

The effects of MHD generator operating conditions and constraints on the performance of MHD/steam power plants are investigated. Power plants using high-temperature combustion air preheat (2500F) and plants using intermediate-temperature preheat (1100F) with oxygen enrichment are considered. Variations of these two types of power plants are compared on the basis of fixed total electrical output (1000 MW_e). Results are presented to show the effects of generator length and level of oxygen enrichment on the plant thermodynamic efficiency and on the required generator mass flow rate. Factors affecting the optimum levels of oxygen enrichment are analyzed. It is shown that oxygen enrichment can reduce the magnet stored energy requirement.

Summary

The effects of MHD generator operating conditions and constraints on the performance of directly-preheated MHD/steam power plants are investigated. Two general types of directly preheated plants are considered. These are power plants using high-temperature combustion air preheat (2500 F) and plants using intermediate-temperature preheat with oxygen enrichment (1100 F). All the variations of these two general types studied are compared on the basis of a fixed total electrical output (1000 MW).

A calculational procedure is described which is ideally suited for studying the tradeoffs between the plant efficiency (operating costs) and the channel/magnet length and mass flow rate (capital costs). Such a tradeoff analysis is necessary to determine the plant with minimum cost-of-electricity.

Plant performance sensitivity to the channel and combustor performance assumptions is assessed. Consideration is given to the effects of the combustor heat loss model, the generator electrical stress limits, and the electrode voltage drop model.

The results of the oxygen enrichment studies show that there is an optimum amount of enrichment for a given oxygen production power requirement. The optimum enrichment level will: 1) increase with decreasing oxygen production power requirement, and 2) not be greatly affected by the length of the MHD generator.

Finally, it is shown that under certain conditions, oxygen enrichment may lead to a lower magnet stored energy requirement and thus to a lower magnet cost for the same power plant output.

Introduction

Cost and performance studies of advanced coal-fired power systems have shown the potential advantages of MHD/steam plants. These well-known studies were conducted by major utility system manufacturers and funded by both the government[1] and EPRI[2]. The coal-fired MHD systems were shown to have the potential for producing electricity at an attractive cost and in a highly efficient and environmentally acceptable manner. Subsequent and more detailed studies have reinforced the conclusion that open-cycle MHD power generation can be a viable approach to improve upon the present methods of generating electrical power from oil and coal.

As MHD moves toward a demonstration plant and toward eventual commercialization, the emphasis of MHD system studies has shifted from trying to achieve the highest possible plant efficiencies to such areas as reliability, availability, costs, and, where possible, to the use of more near-term technology subsystems.

The recently completed "Parametric Study of Potential Early Commercial MHD Power Plants" (PSPEC)[3,4] and the ongoing "Conceptual Design Study of Potential Early Commercial MHD Power Plants" (CSPEC) were initiated to evaluate various possible "moderate technology" power plants. The PSPEC parametrically investigated plant configurations which have the potential for

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earlier commercial implementation than advanced MHD plants. The major emphasis of PSPEC was to identify attractive system configurations that do not require the development of the high-temperature regenerative air preheaters assumed to be used in the more advanced plants. The results of the PSPEC studies were among the factors considered by the Department of Energy in its recommendation that the first commercial MHD plants be of the intermediate-temperature preheat type with oxygen enrichment of the combustion air. This recommended plant configuration was then selected for more detailed studies in CSPEC. Two contractor teams led by Avco Everett Research Laboratory, Inc. and by General Electric Company Space Sciences Laboratory were involved in these parallel studies. NASA Lewis Research Center managed the contracts for the Department of Energy under an interagency agreement. Supplementary studies were also performed in-house at NASA Lewis to help define, guide, and compare the results of these contracted studies. In this paper, some of the performance studies conducted at NASA Lewis will be presented. The summary and evaluation of the PSPEC contractors' results were presented earlier[5].

The effects of MHD generator operating conditions and constraints on the performance of directly-preheated MHD/steam plants are the subject of the present investigation. Power plants using high-temperature combustion air preheat (2500 F) and plants using intermediate-temperature preheat (1100 F) with oxygen enrichment are considered. All the variations of these two plant types studied are compared on the basis of fixed total electrical output (1000 MW_e). In the following section, the calculational procedure is presented. The procedure is then illustrated by applying it to a "base case" plant. Next, the plant performance sensitivity to channel and combustor assumptions is assessed. Consideration is given to the effects of the combustor heat loss model, the generator electrical stress limits, and the electrode voltage drop model. Finally, the results of the oxygen enrichment studies are presented. The effects of the oxygen production power requirement on the plant efficiency is examined. The influences of the required oxygen production power and the MHD generator length on the optimal level of enrichment are also studied.

Method of Analysis

In this section, the calculational procedure used in this study is described. The MHD/steam combined cycle plants investigated are baseload plants with an electrical output of 1000 MW. The combustor is fired with Illinois #6 bituminous coal dried to 2% moisture. The oxidant is directly-preheated air or oxygen-enriched air; the seed is potassium carbonate. Other design parameters are listed in Table I.

The MHD generator calculation requires that boundary conditions be specified at the two ends of the channel. The total enthalpy at the channel inlet is the combustion enthalpy less the heat loss in the combustor and nozzle. Generally, the combustor/nozzle heat loss is assumed to be 5% of the higher heating value (HHV) of the coal fed to the combustor. Another combustor/nozzle heat loss model, described in a later section, is also considered for comparison. The stagnation pressure at the diffuser exit is taken to be 1.0 atm. The diffuser pressure recovery coefficient is assumed to vary with the amount of inlet blockage. The functional relationship used is shown in Figure 1.

The generator calculations are performed with a quasi-one-dimensional flow model. This model consists of an inviscid central core flow with developing boundary layers along the walls. The turbulent boundary layers are analyzed by an integral approach. The thermodynamic and transport properties of the gas are calculated following Svehla and McBride[6]; the procedure of Smith and Nichols[7] is used to compute the electrical properties of the plasma. The generators are loaded in the Faraday mode and are lofted to yield an approximately constant Mach number[8].

The electrode-wall voltage drops are assumed to be of the form:

$$V_d = a + b\delta^* + c\delta^{*2}$$

where δ^* is the boundary layer displacement thickness. The constants in this polynomial should realistically be functions of the generator operating conditions as well as the current density and Hall parameter distributions along the channel. They are kept constant in the present analysis to limit the complexity of the generator model. The values of a, b, and c are selected to yield a streamwise V_d distribution similar to that used in the Avco PSPEC reference plant #3[3].

A procedure which has been previously reported is used to determine the operating conditions of the MHD generator[8]. This procedure ensures that the generator will produce the maximum power consistent with a set of specified internal generator constraints and consistent with maximizing the performance of the power plant as a whole. This technique was used at the outset of the present investigation to determine the conditions under which maximum net MHD power (i.e., MHD AC power output minus compressor power) is obtained. A set of typical results is presented in Figure 2. Here, the MHD power minus compressor power for generators of different lengths (15, 20, and 25 meters) is plotted for various combustor pressures. The corresponding values of K_{min} are also shown. K_{min} is the minimum value of the load factor and is used as a control parameter in the calculational procedure. To obtain the results of Figure 2, the value of K_{min} is adjusted in an iterative manner until the desired channel length and exit pressure are obtained for each of the given generator inlet conditions. The optimum operating pressure for the different length generators can then be determined from the locations of the maxima in the net MHD power curves. Results such as those presented in Figure 2 suggest that baseload power plant MHD generators (between 15 and 25 meters long) will yield nearly the maximum net MHD power when loaded at K_{min} = .78. Hence, in this study the loading is fixed at K_{min} = .78. The optimum combustor pressure will then be assumed to be that which results in matching the diffuser exit pressure for the given channel length.

The total gross AC electrical output of the plants considered in this study is fixed at 1000 MW_e or

$$P_T = \eta_I P_M + P_G = 1000\ MW_e \quad (1)$$

where P_M is the MHD generator DC output.
P_G is the net steam turbo-generator electrical output.
and η_I is the efficiency of the DC-AC inverter.

In order to satisfy the above condition, several iterations are usually required between the channel calculations and the plant performance calculations. The mass flux through the MHD power train, and hence the thermal input to the plant, is adjusted with each iteration until equation 1 is satisfied.

The definition of plant thermodynamic efficiency is as in reference 9: the gross AC power output divided by the higher heating value of the coal input to the plant. It may be written as

$$\eta_T = \frac{1}{P_F}\left[P_N\,(1 - \bar{\eta}_S) - P_O + \bar{\eta}_S(P_F + P_S - P_L)\right] \quad (2)$$

where P_C is the power required to drive the cycle compressor.

P_F is the power in the fuel input to the plant based on its higher heating value.

P_N is $\eta_I P_M - P_C$: the net power of the MHD topping cycle for specified mass flows of coal, seed, and oxidant to the MHD combustor.

P_L is the sum of stack losses and other losses and also includes the power required for coal drying.

P_S is the power in the seed associated with converting it from K_2CO_3 to K_2SO_4.

P_O is the power used to drive the air separation plant compressors, if required.

and $\bar{\eta}_S$ is $\dfrac{P_G + P_C + P_O}{P_G/\eta_G + P_C/\eta_C + P_G/\eta_O}$ an effective efficiency of the combination of the steam turbine/generator cycle and the steam turbine cycles which drive the MHD compressor and air separation plant compressor. η_G, η_C, and η_O are respectively the efficiencies of the steam turbine generator cycle and of the steam turbine cycle that drives the MHD compressor and the air separation plant compressor.

Base Case Plant Results

In this section, the methods described above will be illustrated by application to plants using air oxidizer preheated to 2500F. These plants will be referred to as the base case plants. The performance of the base case plants will be used as a point of reference when the assumed combustor or MHD generator operating conditions are changed and when oxygen-enriched air preheated to 1100F is used as the oxidizer.

The variations in the calculated plant efficiency and required mass flux as a function of the generator length are shown for the base case in Figure 3. The values of the combustor pressure in atmospheres are denoted along the curves. The combustor heat loss is 5% of the HHV of the coal input and 70% of the ash is assumed rejected by the single-stage combustor. Other important cycle parameters and performance assumptions used in the plant performance calculations are listed in Table I. It can be seen that as the generator is shortened, the mass flow rate through the MHD power train must be increased to maintain the total plant output at 1000 MW_e. Several effects can be identified as the length of the MHD generator is decreased. The channel power output as a fraction of the coal input to the plant is reduced. The power in the gas stream between the diffuser exit and the stack increases relative to the power in the coal input. This power in the gas stream is used by the bottoming plant and for oxidant preheat. The power required for oxidant preheat increases because of the increase in the oxidant flow rate and the decrease in the compressor exit temperature. The power needed to drive the MHD compressor decreases because of the decreased pressure ratio. The net result is an increase in the fraction of the total plant output attributed to the bottoming cycle and a decrease in the plant thermodynamic efficiency.

The results in Figure 3 give an indication of how much one has to sacrifice in decreased plant efficiency and increased downstream component costs (resulting from the increased mass flow rate) for the potential reduction in channel and magnet costs (resulting from shorter lengths). Hence, this method, as illustrated by the results presented, can provide the basis for minimizing the power plant's cost-of-electricity if component cost models, in particular a magnet cost model, are available.

Plant Performance with Variations in Channel and Combustor Assumptions

The results showing the sensitivity of the calculated plant efficiency to various channel and combustor assumptions are presented in this section. The effects investigated are variations in the generator electrical stress limits, the boundary layer voltage drop model, and the combustor/nozzle heat loss model. For each of these investigations, the power plant output was fixed at 1000 MW_e and the oxidizer was air preheated to 2500F.

Because of the nature of the generator optimization scheme used, the generator's operating constraints (the limiting values imposed on the axial and total electric fields, E_{crit} and $E_{x_{crit}}$) are very influential on the overall plant performance. Figure 4(a) shows the plant efficiency versus the generator length for different sets of assumed physical constraints. The MHD generators in the base case plants are operated with approximately the electrical stress limits that are experienced in present-day generator endurance tests. The peak magnetic fields are kept at less than approximately 6.5 Tesla so as to satisfy the given stress limits. By increasing the electrical stress limits to

$$E_{crit} = 5 \text{ kV/m and } E_{x_{crit}} = 3 \text{ kV/m}$$

higher magnetic field strengths (peak fields of approximately 8 tesla) can be utilized. As indicated in the figure, operation at the higher values of electrical stress and higher magnetic fields offers significant plant performance improvements. Figure 4(b) shows the plant performance sensitivity to the generator voltage drop model. The PSPEC-type voltage drop model used in the base-case generator calculations is of the form described previously beginning with about 10 volts at the channel inlet and ending with about 1 kilovolt at the channel exit. This streamwise distribution of the boundary layer voltage drop is substantially higher than those used in earlier plant studies[8,9] as typified in figure 4(b) by the ECAS-2 voltage drop model. One would anticipate that plants with long MHD generators should be more sensitive to the voltage drop model than those plants with shorter generators. Such a trend is shown in Figure 4(b).

Figure 4(c) shows the plant performance sensitivity to the combustor/nozzle heat loss and slag rejection models. A single-stage combustor was assumed in the base case plant calculations with a heat loss of 5% of the coal HHV and a slag rejection of 70%. As a comparison, plant performance was also calculated using a combustor/nozzle heat loss model of a two-stage cyclone combustor[10]. This model includes heat loss correlations that scale the effects of pressure, temperature, and mass flow rate. It is assumed that 85% of the coal ash is rejected by the two-stage combustor. The greater heat loss of the two-stage combustor contributes to the poorer performance compared to the base case plant. The greater performance penalty of the multi-stage combustor model at low combustor pressures (short channel lengths) is caused by a heat loss scaling factor that varies inversely with pressure.

Plant Performance for Oxygen-Enriched Cases

Directly-preheated plants using oxygen-enriched oxidizer preheated to 1100F were also investigated. Again, all of the results presented are for a fixed plant output of 1000 MW_e.

In Figure 5, the calculated plant thermodynamic efficiency versus the amount of oxygen enrichment is presented for different air separation plant compressor power requirements. The particular results shown are for channels 20 meters long, but are typical of the results for other channel lengths. Each point on this plot gives the maximum plant efficiency for a specified oxidizer oxygen content and a specified oxygen production power requirement.

There is an optimum enrichment which maximizes the plant efficiency for a given oxygen production power requirement. This result was explained in reference 9 and is briefly described as follows: As the level of enrichment increases, the enthalpy extraction of the MHD generator also increases. The power required for oxidant preheat decreases because of the decrease in oxidant mass flow rate and the increase in compressor exit temperature resulting from an increased pressure ratio. The power required to drive the MHD compressor and the air separation plant compressor increases slightly, because the effect of increased pressure ratio and increased enrichment outweighs the decrease in oxidant flow. The power in the gas stream available to the bottoming plant decreases because of the decrease in the gas flow rate. The net result is a decrease in the steam turbogenerator output. The gain in the MHD generator power output with increasing enrichment is sufficient at lower, but not at higher, oxygen enrichment levels to overcome the decrease in bottoming plant output. Thus, there is an optimum enrichment which maximizes the plant efficiency. The level of oxygen enrichment at which these maximum plant efficiencies are reached increases with decreasing oxygen production power requirement. The oxygen production requirement of 47 kW-hr/ton of equivalent pure oxygen represents the thermodynamic limiting case of minimum air separation work. This corresponds to the entropy change in mixing O_2 and N_2 gases initially divided in an adiabatic chamber. It is interesting to note that the optimum level of oxygen enrichment for this limiting case is less than 50 molar percent oxygen in the final blend stream. This result implies that baseload plants using pure oxygen as the oxidant, as advocated in reference 11, will operate far below optimum efficiency.

For a fixed level of oxygen enrichment and a fixed generator length, the MHD generator power output as a fraction of the plant coal input remains nearly independent of the oxygen production power requirement. However, as the oxygen requires increasingly more power to produce (i.e. descending along any imaginary vertical line in Figure 5), the steam turbogenerator power output (relative to the plant coal input) will decrease primarily because of the increased power requirements of the air separation plant compressor. Thus, the plant thermodynamic efficiency decreases with an increasing air separation plant power requirement.

Figure 6 presents typical results which show how little effect the length of the MHD generator has on the optimum degree of oxygen enrichment. Here, the calculated plant efficiencies are plotted versus oxidizer oxygen content for various generator lengths. The assumed oxygen production cost is 200 kW-hr/ton of equivalent pure O_2. The values of the combustor pressure are indicated by the dashed curves. Although the optimum pressure increases with longer channels, the optimum enrichment level remains at approximately 35 molar percent.

Figure 7 summarizes the results for the oxygen-enriched plants. In this figure, the plant thermodynamic efficiencies at the optimum levels of enrichment are plotted versus the oxygen production power requirement. The shaded region denotes oxygen production power requirements of less than 47 kW-hr/ton. The figure shows the substantial gains in plant performance possible if the oxygen production power can be reduced. Recent air separation plant studies have shown that oxygen production power requirements of the order of 200 kW-hr/ton of equivalent pure O_2 can be achieved[12].

In figure 8, the magnetic energy stored within the channel volume is plotted against the plant efficiency for various generator lengths and various oxygen production power requirements. The levels of oxygen enrichment are at the optimum values. The results for the base case plant (air oxidant preheated to 2500F) are also plotted for comparison. The stored magnetic energy within the MHD generator volume is computed from the streamwise distributions of the magnetic field and the generator cross-sectional area as predicted by the channel calculations. The stored energy within the magnet warm bore can then be estimated from:

$$\begin{bmatrix}\text{Magnetic Stored}\\ \text{Energy}\end{bmatrix}_{\substack{\text{warm bore}\\ \text{volume}}} = F_u \times \begin{bmatrix}\text{Magnetic Stored}\\ \text{Energy}\end{bmatrix}_{\text{Channel volume}}$$

where F_u is the ratio of the magnet warm bore cross-sectional area to channel cross-sectional area. Since the cost and weight of the magnet structure are directly related to the stored energy, a lower magnet energy requirement implies a lower magnet cost. Results of Figure 8 show that for an MHD generator of a given length, oxygen enrichment may lead to a lower magnet cost for the same power plant output. The advantage of the oxygen-enriched plant in this respect increases as the power required to produce the oxygen decreases. This happens because the optimum enrichment level increases with decreasing oxygen production power requirement (Figure 5) resulting in a lower mass flow rate through the MHD generator and thus a reduction in its volume. However, this advantage resulting from enrichment must be weighed against the lower plant efficiency compared to the base case plant. The results of Figure 8 also show that by reducing the channel length, substantial reduction in the magnetic stored energy requirement is possible with only a slight loss in plant efficiency. This is true whether or not the oxidizer is oxygen enriched.

Concluding Remarks

The results presented show the sensitivity of the performance of a 1000 MW_e MHD/steam plant to combustor and MHD generator operating assumptions. The results also show the significance of the choice of MHD generator length. The difference in plant performance with a generator 15 meters long and a generator 25 meters long is relatively small, but there is the potential for a significantly lower magnet cost with the shorter generator. For oxygen-enriched plants, the results show that significant plant performance gains are possible if the power required to produce the oxygen can be reduced. In addition, lower oxygen production power requirements affect the MHD generator design and operating point in a way which lowers the magnet stored energy requirement and thus its cost.

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Table I. Major Cycle Parameters

Coal type	Illinois #6
Moisture content of coal delivered to combustor, percent	2
Oxidizer preheat temperature, F	1100, 2500
Combustor pressure, atm	Variable
Combustor fuel-oxidizer ratio relative to stoichiometric	1.07
Combustor slag rejection, percent	70, 85
Generator type	Faraday
Potassium to coal weight ratio	0.0978
MHD generator inlet Mach number	0.8
Diffuser pressure recovery coefficient	Variable
Diffuser exit pressure, atm	1.0
Channel length, meters	15, 20, 25
Compressor polytropic efficiency	0.898
Sulfur removal by seed, percent removed	91
Final fuel-oxidizer ratio relative to stoichiometric	1.0
Stack temperature, F	260
Steam-turbine generator cycle efficiency, percent	41.8
Steam-turbine compressor cycle efficiency, percent (cycle compressor and air separation plant compressor)	41.3
Air separation plant compressor power requirement, kW-hr/ton of equivalent pure oxygen added	300, 250, 200, 150, 47
Pressure drop from compressor exit to combustor exit, percent of compressor exit pressure	0.163

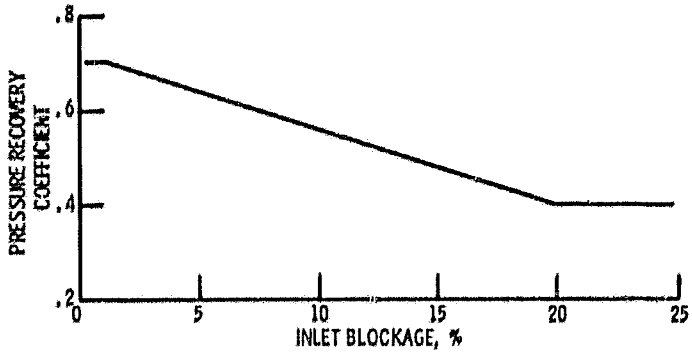

Figure 1. - Variation of pressure recovery coefficient with diffuser inlet blockage. Diffuser inlet mach number approximately 0.8.

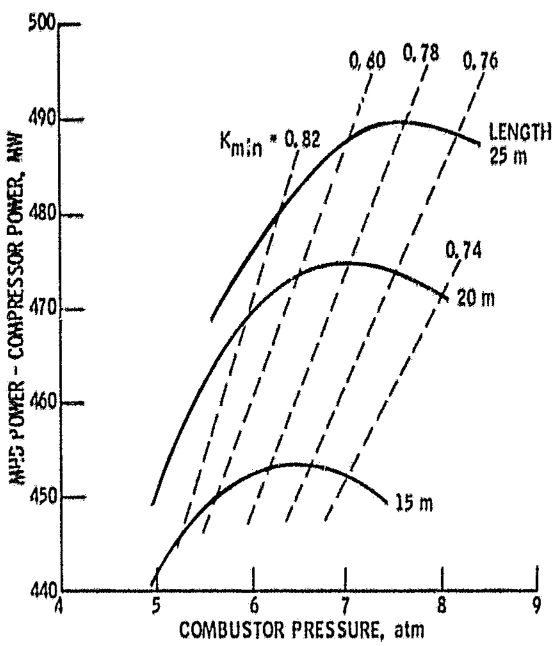

Figure 2. - Net MHD Power versus combustor pressure for various generator lengths. Generator mass flow rate = 660 kg/sec, air preheat temperature = 2500° F, E_{crit} = 4 kv/m, E_{xcrit} = 2.5 kv/m, J_{ycrit} = 1 A/cm^2, β_{crit} = 4.

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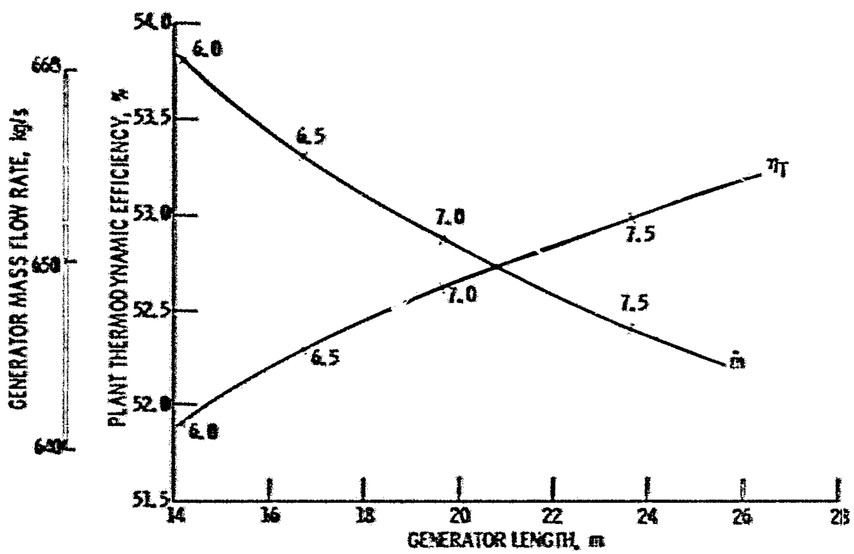
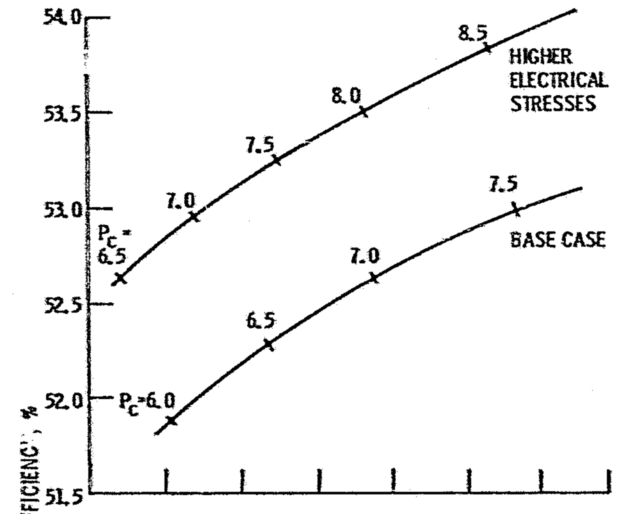
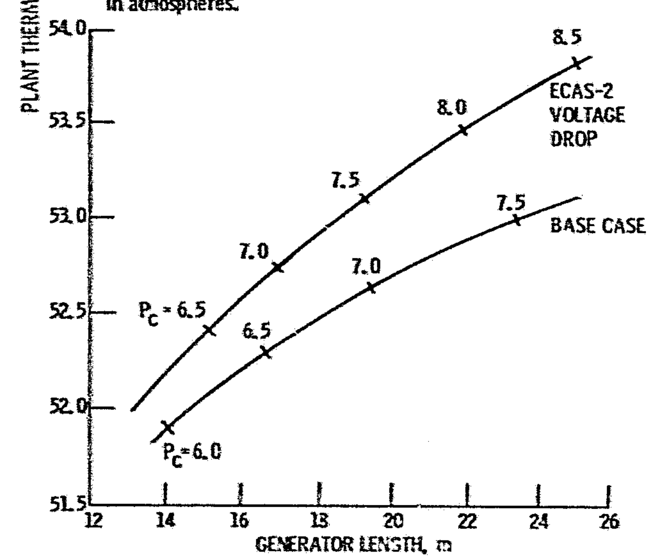


Figure 3. - Plant thermodynamic efficiency and generator mass flow rate versus generator length for 1000 MWe base case plant. 2500° F direct preheat, no oxygen enrichment, combustor heat loss = 5% of coal HHV; E_{crit} = 4 kv/m, E_{xcrit} = 2.5 kv/m, J_{ycrit} = 1 A/cm², β_{crit} = 4. Numbers along curves denote combustor pressure in atmospheres.

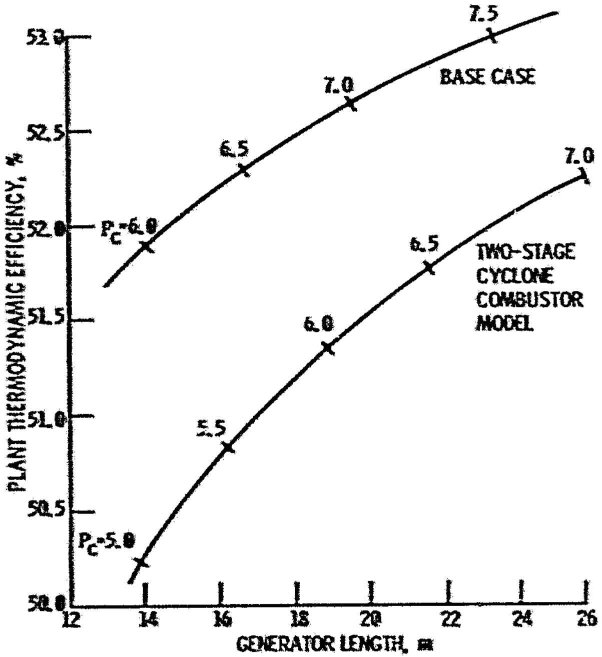


(a) Sensitivity to electrical stress assumptions. Base case: E_{crit} = 4 kv/m, E_{xcrit} = 2.5 kv/m, J_{ycrit} = 1 A/cm², β_{crit} = 4. Higher stress case: E_{crit} = 5 kv/m, E_{xcrit} = 3 kv/m, J_{ycrit} = 1 A/cm², β_{crit} = 4. P_c denotes combustor pressure in atmospheres.



(b) Sensitivity to electrode wall boundary layer voltage drop model.

Figure 4. - Plant thermodynamic efficiency variations with channel and combustor assumptions. 1000 MW_e plant, 2500° F preheat, no oxygen enrichment, approximately constant mach number.



(c) Sensitivity to combustor/nozzle heat loss model. Base case: heat loss = 5 % of coal HHV, slag rejection = 70 %. Two-stage combustor model: heat loss function of combustor pressure, temperature, and mass flow rate. Slag rejection = 85 %.

Figure 4. – Concluded.

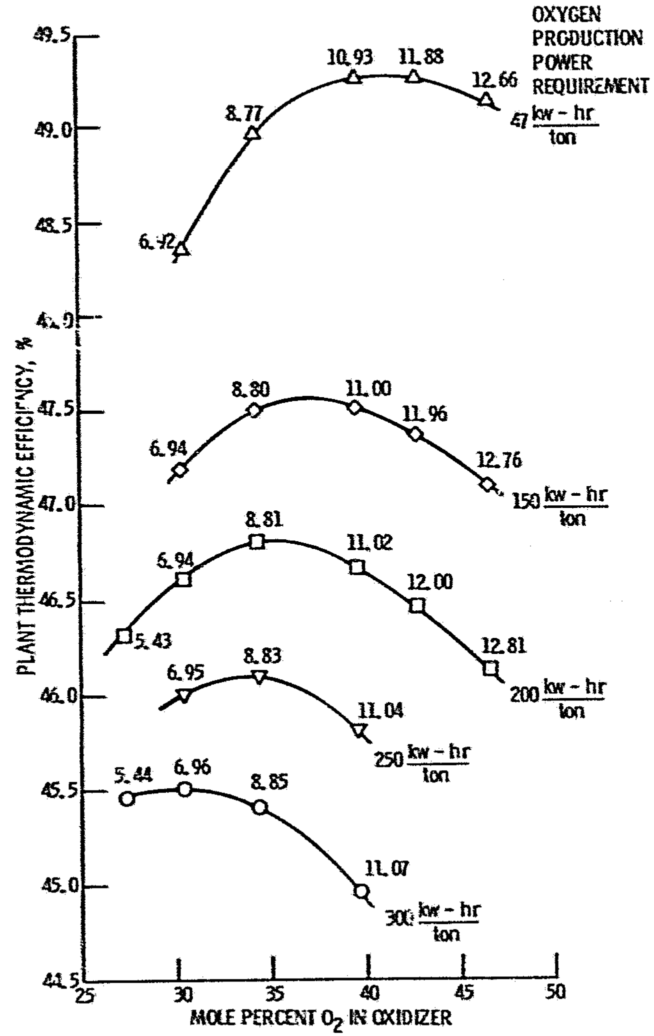


Figure 5. – Thermodynamic efficiency of 1000 MW_e power plants with 20 meter generators versus amount of oxygen enrichment for different oxygen production power requirements. 1100° F preh t, E_{crit} = kv/m, E_{xcrit} = 2.5 kV/m, J_{ycrit} = 1 A/cm², $_{crit}$ = 4, approximately constant mach number. The combustor pressure in atmospheres is noted along the curves.

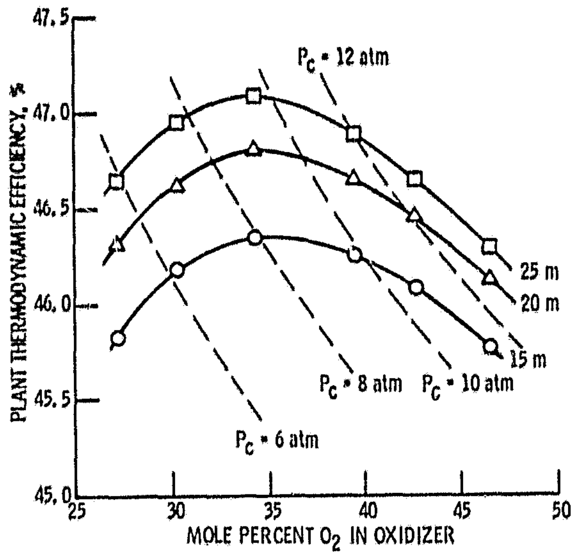


Figure 6. - Plant thermodynamic efficiency versus percent oxygen enrichment for 1000 MW_e power plants assuming 200 (kw - hr)/ton oxygen production power requirement. 1100° F preheat, E_{crit} = 4 kv/m, E_{xcrit} = 2.5 kv/m, J_{ycrit} = 1 A/m^2, β_{crit} = 4. Approximately constant mach number. P_c denotes combustor pressure.

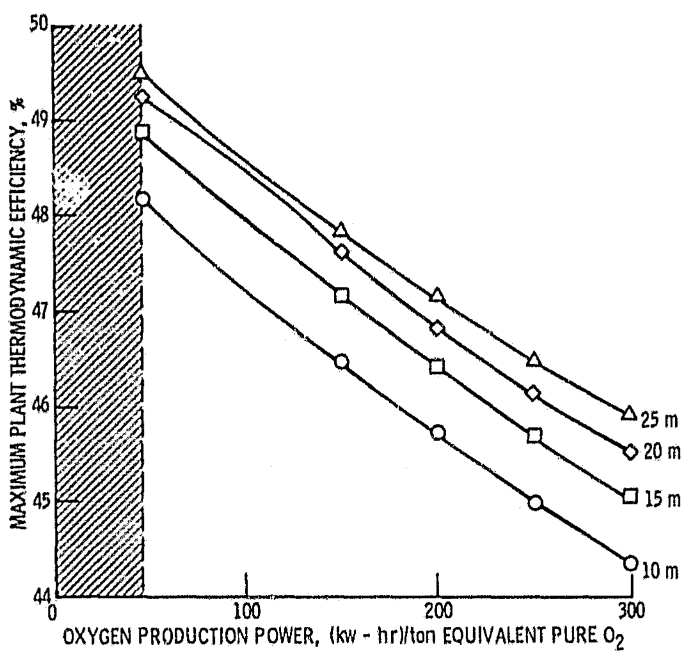


Figure 7. - Maximum plant thermodynamic efficiencies versus oxygen production power for different generator lengths. Total plant output = 1000 MW_e. 1100° F preheat, E_{crit} = 4 kv/m, E_{xcrit} = 2.5 kv/m, J_{ycrit} = 1 A/cm^2, β_{crit} = 4.

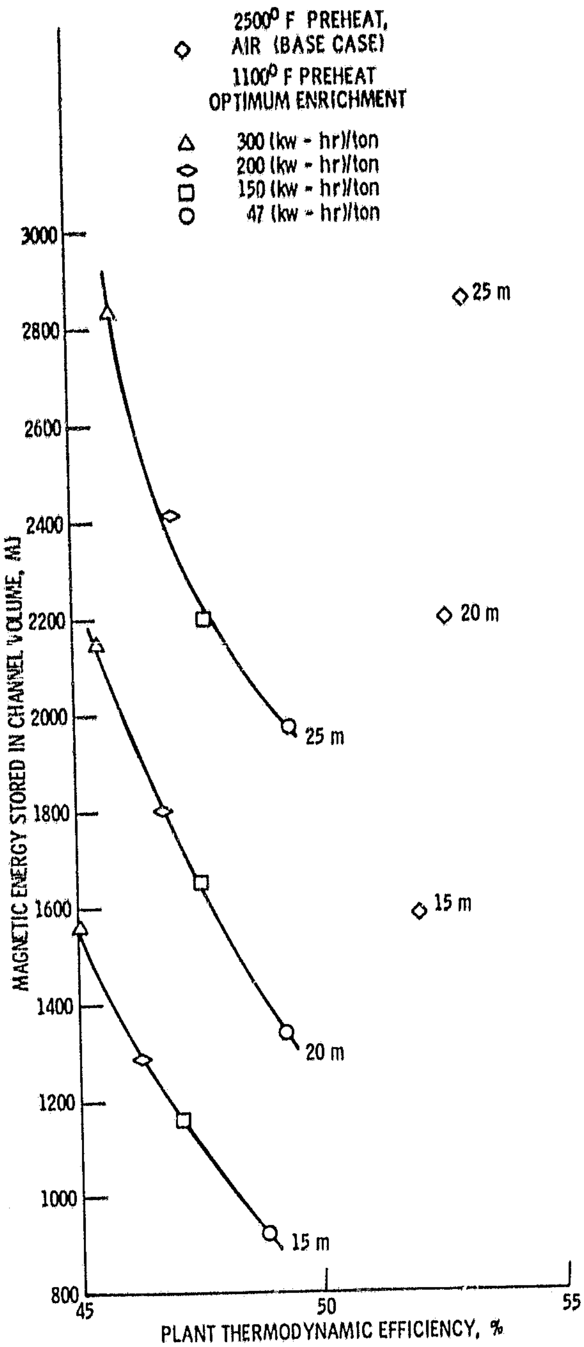


Figure 8. - Stored magnetic energy versus plant thermodynamic efficiency. Power plant output = 1000 MW_e, E_{crit} = 4 kv/m, E_{xcrit} = 2.5 kv/m, J_{ycrit} = 1 A/cm^2, β_{crit} = 4.

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16. Abstract

The effects of MHD generator operating conditions and constraints on the performance of MHD/steam power plants are investigated. Power plants using high-temperature combustion air preheat (2500 F) and plants using intermediate-temperature preheat (1100 F) with oxygen enrichment are considered. Variations of these two types of power plants are compared on the basis of fixed total electrical output (1000 MWe). Results are presented to show the effects of generator plant length and level of oxygen enrichment on the plant thermodynamic efficiency and on the required generator mass flow rate. Factors affecting the optimum levels of oxygen enrichment are analyzed. It is shown that oxygen enrichment can reduce the magnet stored energy requirement.

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