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PERFORMANCE OPTIMIZATION OF AN MHD GENERATOR WITH PHYSICAL CONSTRAINTS

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ABSTRACT

A technique has been described which optimizes the power out of a Faraday MHD generator operating under a prescribed set of electrical and magnetic constraints. The method does not rely on complicated numerical optimization techniques. Instead the magnetic field and the electrical loading are adjusted at each streamwise location such that the resultant generator design operates at the most limiting of the cited stress levels. The simplicity of the procedure makes it ideal for optimizing generator designs for system analysis studies of power plants. The resultant locally optimum channel designs are, however, not necessarily the global optimum designs.

The results of generator performance calculations are presented for an approximately 2000 MW_e size plant. The differences between the maximum power generator design and the optimal design which maximizes net MHD power are described. The sensitivity of the generator performance to the various operational parameters are also presented.

INTRODUCTION

MHD power generation, using fossil fuel, promises both high efficiency and low cost of electricity. One of the most critical components in the MHD/steam power plant is the MHD generator. Its performance strongly influences the overall performance of the power plant. The generator design should be selected to maximize the overall plant efficiency. The optimal design is, however, a function of the generator operating parameters including the combustor oxidant preheat temperature, pressure, and oxygen enrichment; the magnetic field strength and profile; the generator electrical load parameter profile and the Mach number; and the state of generator technology in terms of allowable electrical stresses, etc.

This paper describes a technique which predicts the variations of the magnetic field and the electrical loading along a Faraday MHD generator for optimum power out. Illustrative results of generator performance calculations using this technique are presented for an ECAS-2 size plant ≃ 2000 MW_e. The sensitivity of generator performance to the various operational parameters is investigated.

OPTIMIZATION PROCEDURE

A prescribed set of electrical and magnetic constraints is imposed in the present procedure to optimize the power of a generator with specified length, diffuser exit pressure, and the streamwise distribution of either velocity or Mach number. The magnetic field, B, and the electrical loading, K, are adjusted in such a way that the generator attempts to operate over a large fraction of its length at specified stress limits; thus, the generator performance is maximized. The electrical loading is defined as: $K = \frac{E_y}{uB}$, where Ey is the Faraday electric field and u is the channel axial velocity. The prescribed constraints may include limits on the Faraday current density, Jy, the Hall field, Ex, the total electric field, $E = \sqrt{E_x^2 + E_y^2}$, and the Hall parameter, β. The channel design is such that at each streamwise location all of the following conditions are satisified:

$$\beta \le \beta_{crit} \qquad (1)$$

$$K \ge 1 - \frac{|J_{y_{crit}}|}{\sigma u B} \qquad (2)$$

$$K \ge 1 - \frac{|E_{x_{crit}}|}{\beta u B} \qquad (3)$$

$$E \le E_{crit} \qquad (4)$$

$$K \ge K_{min} \qquad (5)$$

and

$$B \le B_{max}. \qquad (6)$$

Appearing in equation (2) is the electrical conductivity, σ. The magnitudes of B and K are determined at each station by only two appropriate criteria. Which two criteria prevail at a location depend on the generator operating conditions and the assumed values for the electrical and magnetic constraints. The values of B_{max}, $E_{x_{crit}}$, $J_{y_{crit}}$, and β_{crit} should be selected to reflect the current or projected states of magnet and channel technology. The channel operatring life would also be strongly influenced by the values assigned to these limits.

The insulating sidewalls of the Faraday generators are subjected to both axial and transverse electric fields. In order to limit this electrical stress on the sidewalls, the total electric field strength is bounded by condition (4) in the present procedure. When selecting a suitable value for E_{crit}, one must consider such factors as: the particular sidewall design, the slag layer behavior, and the wall temperature. Whether the transverse electric field, E_y, should be limited instead of E would also depend on these factors. In that case, $E_y \le E_{y_{crit}}$ would replace condition (4).

Excessively high values of E_x should be avoided within the generator in order to prevent interelectrode breakdowns. This critical E_x has been verified experimentally to be approximately 4 kV/m. The traditional approach to generator design is to limit E_x by limiting of the generator magnetic field via condition (1). In the present formulation, one has the option of using either condition (3) or condition (1) to accomplish this.

The bulk plasma non-uniformities in combustion-driven generators can become severe at high values of Hall parameter as in inert-gas generators. This effect, however, generally occurs in open-cycle generators at a much higher value of β. One can conveniently use condition (1) to limit the Hall effect. However, electrothermal and/or magnetoacoustic wave instability in combustion generators are still poorly understood and the critical β associated with these wave phenomena have yet to be defined; a β_{crit} value of 4 is widely assumed as a reasonably safe value.

K_{min} is the minimum value of the load factor and is used as a control parameter in the calculation procedure. For a given generator inlet condition, K_{min} is adjusted in an iterative manner until the desired channel length and exit pressure are satisfied. The calculated MHD power for the various operating conditions are then compared to ascertain the optimum MHD power condition.

An optimum magnetic field profile is calculated by the present procedure. This can then be used as guidelines by the magnet designer. After the magnet design is finalized, the generator loading should be reoptimized using the actual magnetic field profile in place of conditions (1) and (6).

An approach to the optimization of the Faraday channel loading to maximize the gross MHD power has been previously suggested by Doss and Geyer[1]. Their sectional optimization technique uses the Hall field strength and the Faraday current density as criteria for controlling the load factor distribution. The magnetic field was kept constant at a value of 5 Tesla. The controlling criteria to maximize the MHD power in the present formulation become identical to those of reference 1 if $B = 5$ Tesla replaces condition (6), $\beta_{crit} \to \infty$, and $E_{crit} \to \infty$. However, as discussed below, the maximum MHD power design is no optimum from a system viewpoint.

CHANNEL PERFORMANCE CALCULATIONS

To illustrate results of generator performance calculations using the technique described, generator design was examined for an ECAS-2 size plant[2]. The fuel is Illinois #6 coal and the seed is potassium carbonate. Other design parameters are listed in Table I. Boundary conditions are specified at the two ends of the MHD generator. The total enthalpy at the generator inlet is given as the enthalpy after the combustion less the heat loss in the combustor and nozzle. The ECAS-2 diffuser exit stagnation pressure of 1.14 atm, diffuser pressure recovery coefficient of 0.7, and generator length of 25 meters are assumed in this study. The generators are also assumed to be operating at approximately constant Mach number ($\gamma_s M^2$ = constant). The comparison between the performance of the approximately constant Mach number and the constant velocity designs and the sensitivity of generator performance to shorter channels and less efficient diffusers are presented elsewhere[2,3].

The generator calculations are performed with a quasi-one-dimensional flow model. The model consists of an inviscid central core flow with boundary layer developing along the walls. The turbulent boundary layers are treated with a momentum integral method. The combustion chamber conditions and the thermodynamic and transport properties of the combustion gas are calculated following Svehla and McBride[4]. The electrical properties of the gas were computed as in reference 5. The electrode voltage drop distributions are taken to be of the form: $V_d = a + b\,\delta^*$ where δ^* is the displacement thickness. The values of a and b should generally be functions of the generator operating conditions; however, they are kept constant in the analysis to limit the complexity of the generator model. The value of $a = 100$ V and $b = 20.14$ V/cm are taken from reference 6.

The typical variation of power out for an MHD generator is shown in figure 1. The gross MHD power as a function of the minimum load factor, K_{min}, is shown in figure 1a. The net channel power out, MHD minus compressor power, versus the MHD combustor pressure, P_c, is shown in figure 1b. In the computation of compressor power, an initial oxidant temperature of 60F and a compressor polytropic efficiency of 0.898 are assumed. A pressure drop of 0.163 P_c is assumed between the air compressors and the MHD combustor. As indicated in figure 1a, there is a maximum power and corresponding combustor pressure which the specified length (in this case 25 meters) generator can be operated at without exceeding the specified electric and magnetic stresses. Or in effect, for a given combustor pressure there is a minimum length channel. In the majority of the cases, this minimum length condition coincides with the maximum power out condition for the given chamber pressure. The optimum operating combustor pressure is, however, at the maximum of the net power curve of figure 1b.

The channel design is vastly different for the maximum power and maximum net power generators. In figure 2, distributions of the electrical variables and the magnetic field for these two generator designs are compared. For this example, the maximum <u>net</u> power generator operates at a combustor pressure of 9 atm. The channel has a constant load parameter, $K = 0.798$. Conditions (4) and (5) dominated over a major portion of this generator. The maximum power generator has a higher combustor pressure of 12.786 atm and variable loading is required. The load factor tends to decrease near the channel entrance (trend dictated by conditions (2) and (4)), then increases rapidly downstream (trend dictated by conditions (3) and (4)). The β_{crit} condition prevails beyond $\simeq$ 23 meters causing the drop in the magnetic field and K profiles. The J_y, E_x, and K profiles for the maximum power design are similar to the results of Doss and Geyer[1]. The optimum net power generator design is preferred, however, from overall plant efficiency considerations[2,3].

Typical net generator power variations are plotted in figure 3 for different oxidant preheat temperatures. The trend towards higher plant operating pressures with increasing preheat temperatures is clearly shown. The thermal input to the generator was maintained at the 5373 MW_{th} level in these calculations by adjusting the mass flow rate for the various preheat temperatures.

The sensitivity of generator net power to the design constraints is shown in figure 4. Figure 4a shows the net power versus chamber pressure for different sets of assumed electric and magnetic field limits. For $E_{crit} = 4$ kV/m, $E_{x_{crit}} = 2.5$ kV/m, and $J_{y_{crit}} = 1$ A/cm^2 (approximately the electrical stress limits in present generator endurance tests), no further increase in power out is possible if the peak magnetic field strength is increased (except at nonoptimally high values of combustor pressure). Only by increasing the limits on the electrical constraints can the higher magnetic field be utilized. As shown, however, operation at higher values of electrical stress offers significant performance improvement.

Figure 4b shows the sensitivity of net generator power to the assumed value of $J_{y_{crit}}$. The minimal effect of $J_{y_{crit}}$ on net power is due to the fact that very small part (if any) of the maximum net power generator operates at the $J_{y_{crit}}$ limit. By contrast, a large portion of the maximum MHD power generator is stressed to the allowable J_y limit. For the sample calculations of figure 4b, the net power decreases by only ≃ 1.5% when the value of $J_{y_{crit}}$ is lowered to .5 A/cm^2. Operation at the reduced current densities might greatly benefit the channel reliability and lifetime.

The influence of Mach number on channel performance is shown in figure 5. Results are presented for different $J_{y_{crit}}$ and B_{max} limits. Variable pressure recovery coefficient as a function of Mach number was assumed for the supersonic diffusers. The optimum Mach number decreases as the peak magnetic field is increased. A slightly higher Mach number is desirable for generators operating at the higher current densities. The reason for the insensitiveness of net power to $J_{y_{crit}}$ is as mentioned previously.

Enthalpy extraction for supersonic channels are substantially lower than for the subsonic channels operating at the same electrical stress levels. This results from the need in the supersonic generators to restrict the magnetic field strength in order to satisfy the given constraints.

CONCLUDING REMARKS

The "local" optimization approach of the present formulation or that of reference 1 may not yield a global optimum design, as discussed in reference 7. Whether a global optimization with constraints on E_y or E will still give better maximum net P_{MHD} than the present technique needs to be examined. Under the present formulation, the maximum net power channel design is forced to a constant generator loading by condition (5). Whether this is a desirable trait needs to be verified by comparing with a global optimization.

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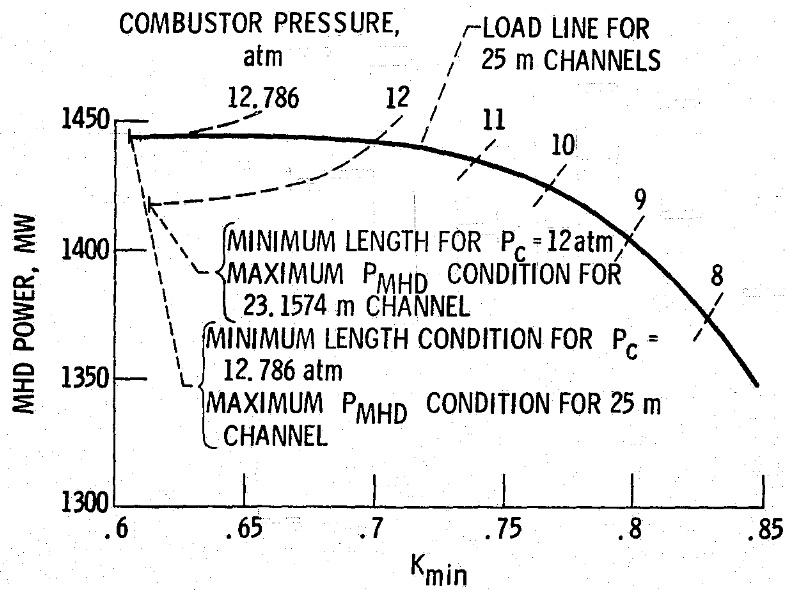
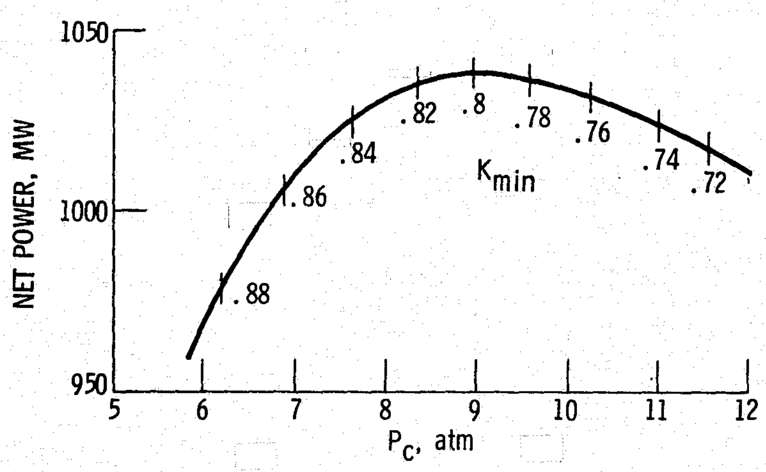
Table I - Major Parameters

Coal type	Illinois #6
Moisture content of coal delivered to combustor, percent	2
Oxidizer preheat temperature, F	2000, 2500, 3000
Combustor pressure, atm	variable
Combustor fuel-oxidizer ratio relative to stoichiometric	1.07
Combustor slag rejection, percent	85
Generator type	Faraday
Potassium seed, seed-coal weight ratio	.108
Diffuser exit pressure, atm	1.14
Diffuser pressure recovery coefficient	0.7
Generator length, meters	25
Compressor polytropic efficiency	0.898
Thermal input to combustor, MW_{th}	5373

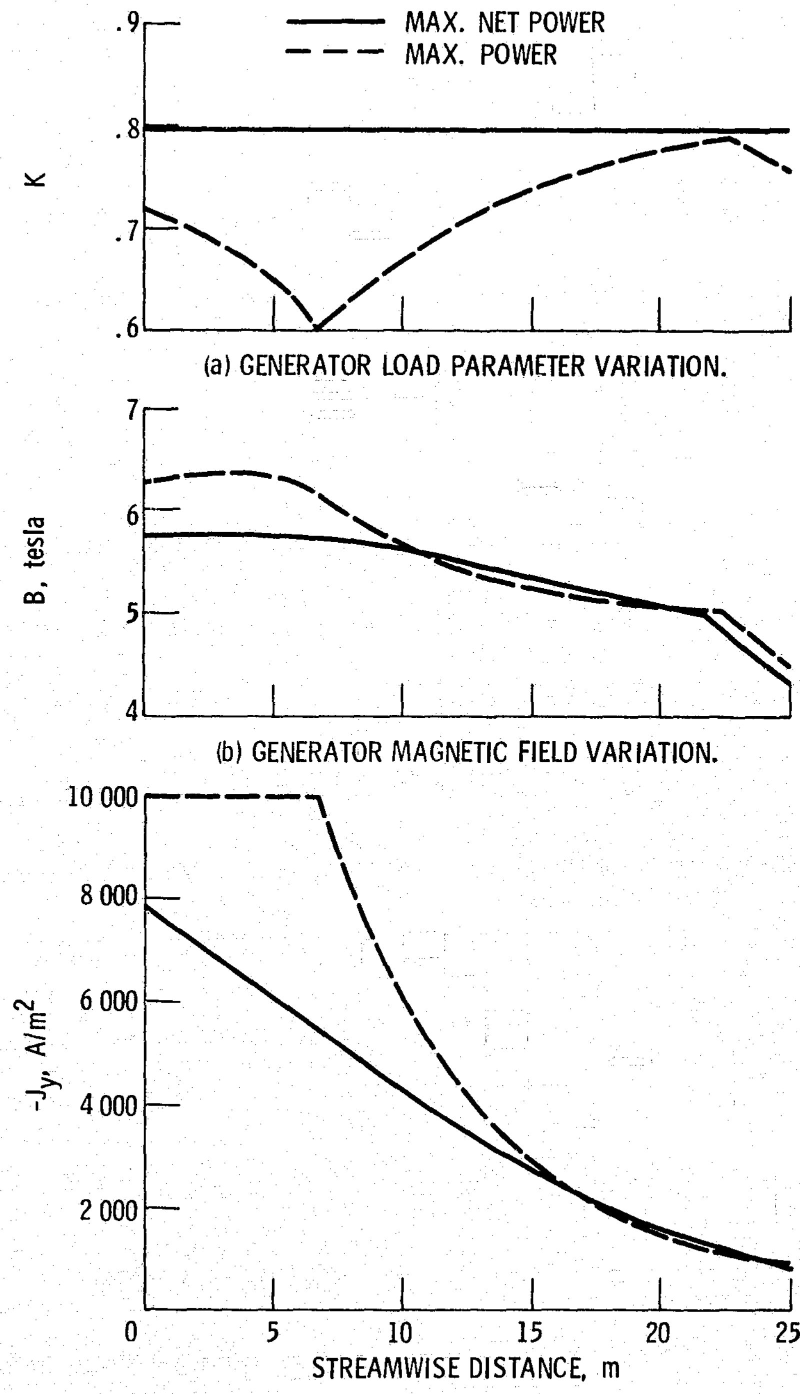


(a) GENERATOR POWER AS A FUNCTION OF MINIMUM LOAD PARAMETER, K_{min}.



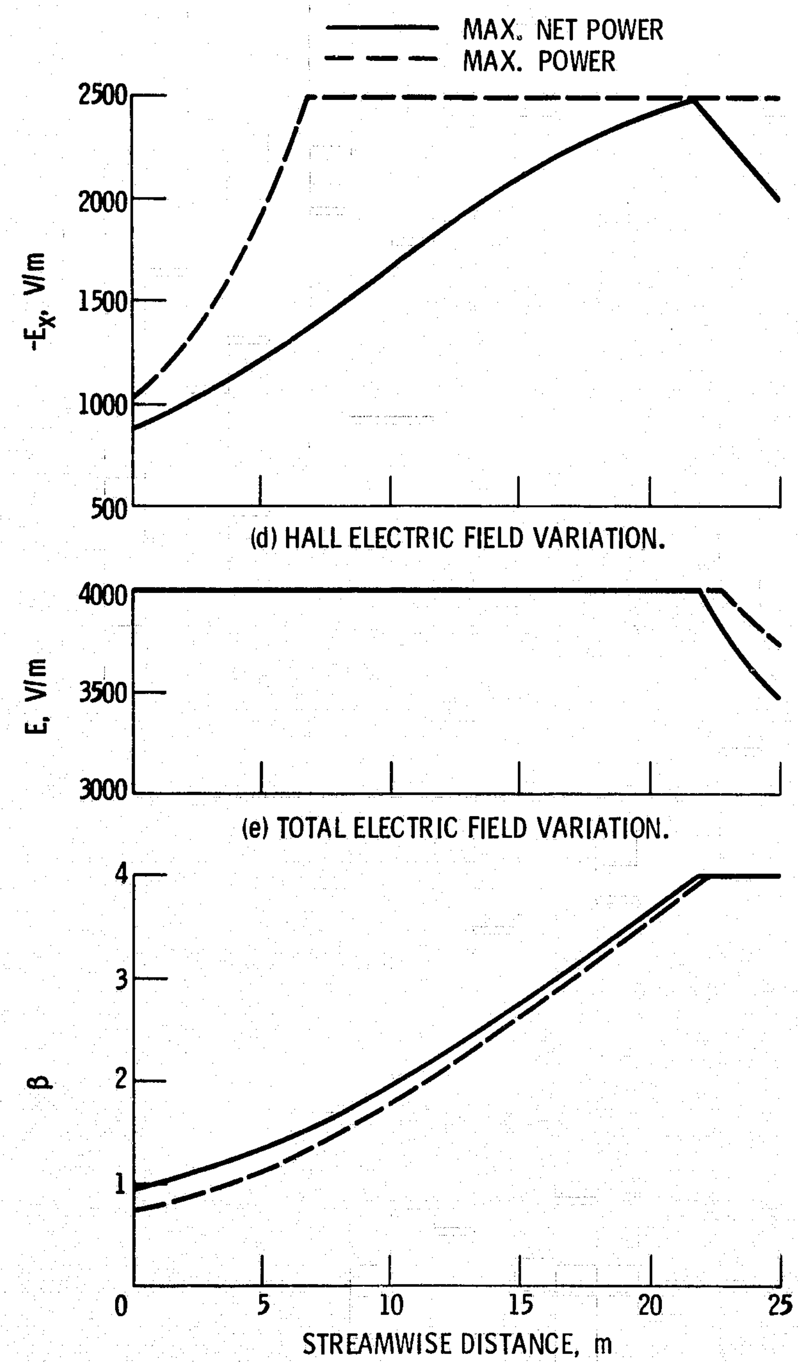
(b) MHD GENERATOR POWER MINUS COMPRESSOR POWER AS A FUNCTION OF COMBUSTOR PRESSURE, P_c.

Figure 1. - Typical MHD generator power variation. Oxidizer 2500° F preheated air, generator length 25 m, thermal input 5373 MW, $\gamma_s M^2$ = const., M_{inlet} = 0.9, E_{crit} = 4000 V/m, $E_{x_{crit}}$ = 2500 V/m, $J_{y_{crit}}$ = 10 000 A/m^2, β_{crit} = 4.



(c) ELECTRODE CURRENT DENSITY VARIATION.

Figure 2. - Parameter distributions for typical MHD generator case. Oxidizer 2500^0 F preheated air, generator length 25 m, thermal input 5373 MW, $\gamma_s M^2$ = const., M_{inlet} = 0.9, E_{crit} = 4000 V/m, $E_{x_{crit}}$ = 2500 V/m, $J_{y_{crit}}$ = 10 000 A/m^2, β_{crit} = 4.



(d) HALL ELECTRIC FIELD VARIATION.

(e) TOTAL ELECTRIC FIELD VARIATION.

(f) HALL PARAMETER VARIATION.

Figure 2. - Concluded.

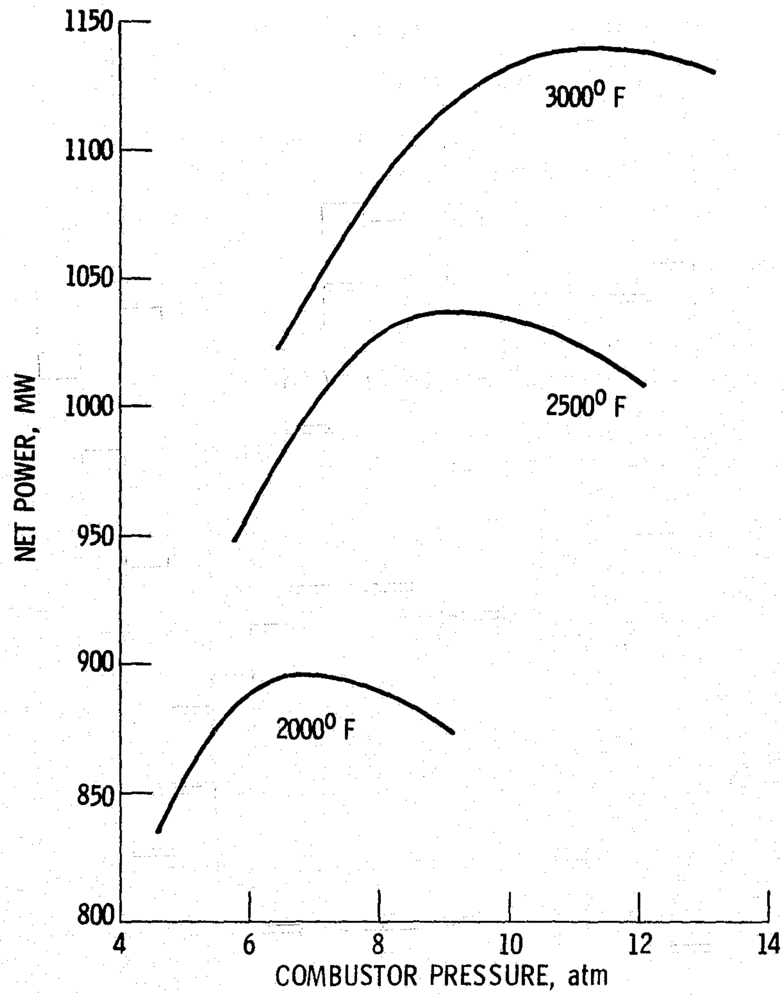
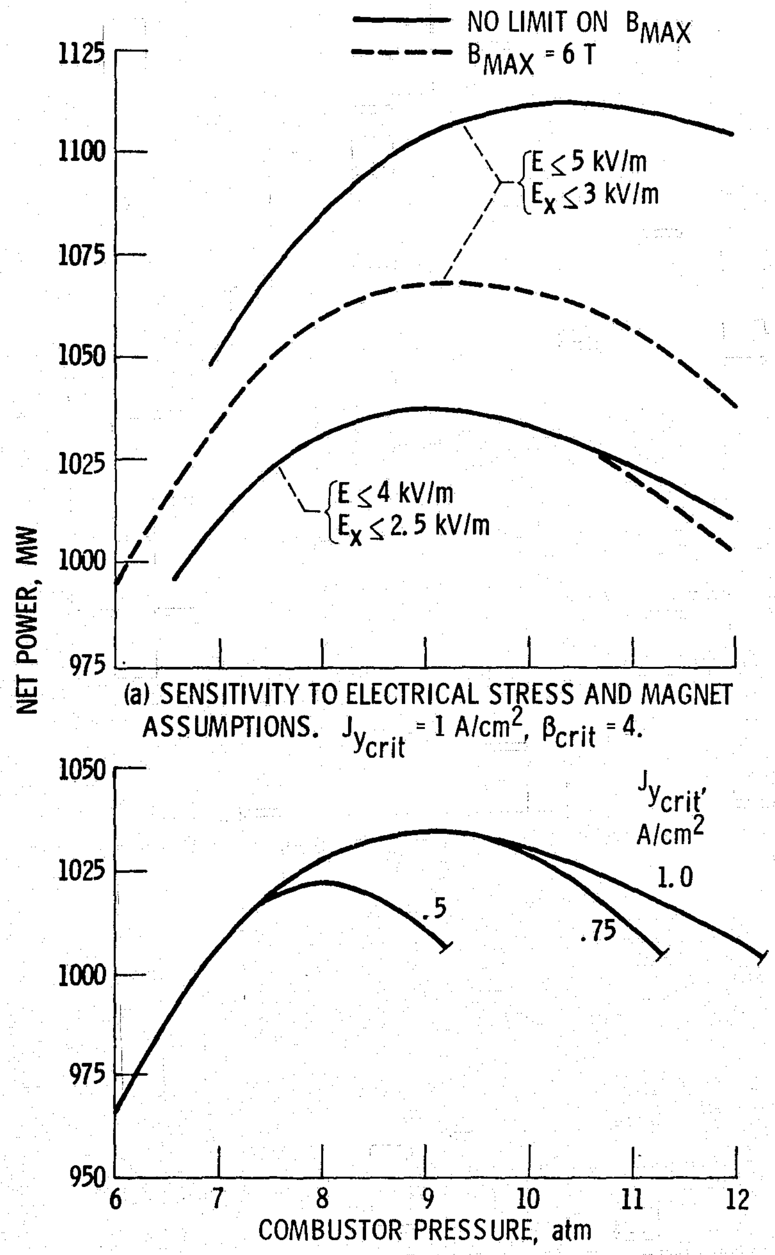


Figure 3. - Net MHD power as a function of combustor pressure for various oxidant preheat temperatures. Generator length 25 m, thermal input 5373 MW, $\gamma_s M^2$ = const., M_{inlet} = 0.9, E_{crit} = 4000 V/m, $E_{x_{crit}}$ = 2500 V/m, $J_{y_{crit}}$ = 10 000 A/m^2, β_{crit} = 4.



(b) SENSITIVITY TO CURRENT DENSITY ASSUMPTION E_{crit} = 4 kV/m, $E_{x_{crit}}$ = 2.5 kV/m, NO LIMIT ON B_{MAX}, β_{crit} = 4.

Figure 4. - MHD generator minus compressor power as a function of combustor pressure for various design limits.

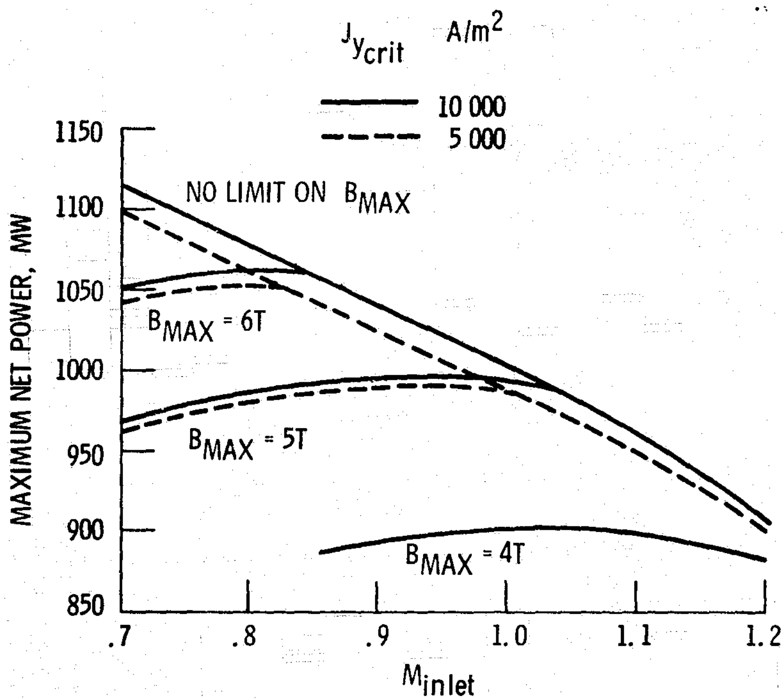


Figure 5. - Maximum net power as a function of generator Mach number. Oxidizer 2500^0 F preheated air, generator length 25 m, thermal input 5373 MW, $\gamma_s M^2$ = const., E_{crit} = 4000 V/m, $E_{x_{crit}}$ = 2500 V/m, β_{crit} = 4, diffuser pressure recovery coefficient = 0.7 for $M_i \leq 1$; = 0.98 - 0.28 M_i for $M_i \geq 1$.