DOE/NASA/10769-16
NASA TM-81775

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(NASA-TM-81775) PERFORMANCE CALCULATIONS FOR 200-1000 MWe MHD/STEAM POWER PLANTS (NASA) 11 p HC A02/MF A01 CSCL 10B

N81-22476

Unclas
G3/44 42172

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Work performed for
U.S. DEPARTMENT OF ENERGY
Fossil Energy
Office of Magnetohydrodynamics

Prepared for
Nineteenth Symposium on the Engineering
Aspects of Magnetohydrodynamics
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Washington, D.C. 20545
Under Interagency Agreement DE-AI01-77ET10769

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E-836

Abstract

The effects of MHD generator length, level of oxygen enrichment, and oxygen production power on the performance of MHD/steam power plants ranging from 200 to 1000 MW in electrical output are investigated. The plants considered use oxygen enriched combustion air preheated to 1100° F. Both plants in which the MHD generator is cooled with low temperature and pressure boiler feedwater and plants in which the generator is cooled with high temperature and pressure boiler feedwater are considered. It is shown that for plants using low temperature boiler feedwater for generator cooling the maximum thermodynamic efficiency is obtained with shorter generators and a lower level of oxygen enrichment compared to plants using high temperature boiler feedwater for generator cooling. It is also shown that the generator length at which the maximum plant efficiency occurs increases with power plant size for plants with a generator cooled by low temperature feedwater. Also shown is the relationship of the magnet stored energy requirement to the generator length and the power plant performance. Possible cost/performance tradeoffs between magnet cost and plant performance are indicated.

Introduction

Recent cost/performance studies such as the "Parametric Study of Potential Early Commercial MHD Power Plants" (PSPEC)[1-3] have helped to identify plant configurations using oxygen enriched air preheated to an intermediate temperature as most attractive for an early commercial MHD/steam plant. Such a plant at a size of about 1000 MWe is being considered in more detail in the "Conceptual Design Study of Early Commercial MHD Power Plant" (CSPEC).[4,5] In a previous paper,[6] the effect of generator length on the performance, optimum level of oxygen enrichment, and magnet stored energy requirement of a 1000 MWe plant with 1100° F preheat was considered. Calculations were made for generator lengths of 10, 15, 20, and 25 meters. It was found that the optimum enrichment level was about 35 volume percent oxygen at all these generator lengths. The power plant efficiency increased with generator length as did the magnet stored energy required. However, it was shown that using a shorter length generator to limit magnet costs imposed only a modest penalty on the plant performance.

In the present study the methods of this previous paper are used to investigate power plants with power outputs of 200 to 1000 MWe. In addition, one other important effect is investigated. The type of construction contemplated for the MHD generators which would be used in early commercial plants limits the maximum temperature of the water used to cool the generator to about 250° to 300° F.[1,2] If the generator heat loss is recovered by cooling the generator with boiler feedwater from the steam bottoming cycle, this temperature limitation requires displacing low pressure regenerative feedwater heaters which could otherwise be used. This means that the efficiency of the bottoming steam cycle is adversely affected, the more so the greater the generator heat loss. Using such low temperature generator cooling significantly modifies the results given in the previous paper where a constant bottoming cycle efficiency was assumed. The results given there apply to the case when the MHD generator is cooled with boiler feedwater at a temperature higher than the temperature of the feedwater leaving the final regenerative feedwater heater. Such high temperature generator cooling is also considered in this paper over the range of plant sizes so that comparison between the two cooling methods can be made.

Analysis Method

The power plant performance and design parameters used in this study are listed in Table I. The combustor operating conditions, namely the heat loss of 5 percent of the coal higher heating value (HHV) and the 80 percent slag rejection, were assumed to be the same for all the plant sizes considered. The seed material was a mixture of potassium carbonate and potassium sulfate in a proportion sufficient to meet NSPS emission standards[7] and in amount sufficient to give the specified coal to potassium weight ratio. For the Montana Rosebud coal, the NSPS requires that SO_x emissions be reduced by 70 percent over the uncontrolled emission level.

The MHD generator performance was calculated by methods described in previous papers.[6,8,9] The generator performance calculations were 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 generators are Faraday loaded and are lofted to operate at an approximately constant Mach number. The electrode voltage drops are assumed to be a quadratic function of the boundary layer displacement thickness. The values of the constant coefficients were selected to give an axial voltage drop distribution similar to that used in the Avco PSPEC reference plant no. 3.[1]

The generator operating conditions were chosen by a procedure which ensures that the generator will produce the maximum power consistent with a specified set of internal generator constraints and consistent with maximizing the performance of the power plant as a whole. This procedure, which is briefly described below, was carried out for each combination of generator length, oxygen enrichment level and power plant size considered in this study. For each such combination and for each pressure in a range of inlet stagnation pressures, the minimum value of the load parameter (K_{MIN}) was adjusted until the desired generator length and exit pressure were obtained. For each inlet pressure, the resulting

*Prepared under NASA/DOE Interagency Agreement No. DEAI01-77ET10769.

generator design operates at the specified Mach number and at two of several specified limiting values of generator parameters at every axial location. The two limiting values are selected from among K_{MIN} and those listed in Table II so that the local power density is a maximum.

The generator inlet stagnation pressure for each combination of generator length, oxygen enrichment level and plant size under consideration was then chosen so that the power plant thermodynamic efficiency is maximized. The power plant thermodynamic efficiency is defined as the gross AC power output of the power plant divided by the higher heating value of the coal input to the plant.[6] It may be written as

$$\eta_T = \frac{1}{P_F}[P_N(1 - \eta_S) - P_o + \eta_S(P_F + P_S - P_L)]$$

where

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 oxidizer;

P_M is the MHD generator DC output;

η_I is the efficiency of the DC-AC inverter;

P_c is the power required to drive the cycle compressor;

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; and

η_S is an effective efficiency of the combination of the steam turbine-generator cycle and the steam turbine-compressor cycles given by

$$\frac{P_G + P_c + P_o}{P_G/\eta_G + P_c/\eta_c + P_o/\eta_o}$$

where

η_G, η_c, η_o are, respectively, the efficiencies of the steam turbine-generator cycle and of the steam turbine cycles that drive the MHD compressor and the air separation plant compressor.

P_G is the net steam turbine-generator electrical output.

The desired power plant gross AC electrical output

$$P_T = \eta_I P_M + P_G$$

is obtained by adjusting the mass flow rate through the MHD generator.

If the effective bottom cycle efficiency, η_S, is constant, then for a given level of oxygen enrichment and a given MHD generator mass flow rate the above expression shows that the thermodynamic efficiency is a maximum if the net MHD power, P_N, is a maximum. Several previous studies have used this criterion to determine the operating pressure for given generator lengths.[6,9] In the present study η_S varies with the generator heat loss in the cases in which the generator is cooled with low temperature boiler feedwater. For this reason the plant thermodynamic efficiency is calculated for the entire range of inlet pressures rather than for only the pressure selected by the maximum P_N. The desired operating pressure is then the pressure corresponding to the maximum efficiency. However, since large variations in η_S are primarily a result of changes in generator length and oxygen enrichment level, the maximum P_N procedure still gives very good results for the optimum pressure for a fixed generator length and oxygen enrichment level.

The bottoming cycle performance was calculated using a steam cycle computer code.[10] At each plant size, except for the feedwater heater arrangement, the basic cycle configuration and method of integration with the topping cycle was kept fixed as the generator length and level of oxygen enrichment were changed. Minimum temperature differences were maintained between the gas and steam sides in all cases. A fixed MHD generator cooling water outlet temperature was maintained for the low temperature feedwater cooled cases. The feedwater heater train upstream of the generator cooling was varied to meet this condition as the generator heat loss changed. Either the number of feedwater heaters in this portion of the train or their operating conditions were varied as necessary. For the bottoming cycles considered in this study, the number of feedwater heaters preceeding the generator cooling can vary between none and two. At each plant size the calculated bottoming cycle performance is then a function of the heat added to the bottoming cycle, the MHD generator heat loss, the work required by the cycle and air separation plant (ASU) compressors, the gas side mass flow rate, and the coal mass flow rate. Of these factors, the MHD generator heat loss has by far the largest influence on the bottoming cycle efficiency. Figure 1 illustrates the variation in bottoming cycle efficiency for the 500 MW plant as a function of the MHD generator heat loss when the remaining factors discussed above are held fixed.

The bottoming cycle configuration for the 200 MW plant is based on that developed for the MHD Engineering Test Facility (ETF) by Gilbert Associates, Inc. (GAI).[11] This is an 1800 psig/1000° F/1000° F cycle with a 2 in Hga condenser pressure. The turbine which drives the compressors is driven with reheat steam. For the purposes of this study the cycle and ASU compressors are assumed to be driven by a single turbine. The feedwater train includes from three to five feedwater heaters, the generator cooling, and two economizers. The MHD generator cooling water outlet temperature is held at the 280° F limit used by GAI. The cycle has been adjusted for a stack temperature of 250° F.

The bottoming cycles for the 500 MW and 1000 MW plants are based on the Avco CSPEC bottoming cycle.[4] This is a 2400 psig/1005° F/1000° F cycle with a condenser pressure of 2 in Hga. The cycle compressor and the ASU compressor are driven by a single turbine fed by main throttle steam. The feedwater train includes from six to eight feedwater heaters, the generator cooling, and two economizers. The MHD generator cooling water outlet temperature is held at the 260° F limit used by Avco.

Results

In Fig. 2 are plots of the power plant thermodynamic efficiency versus oxygen enrichment level for each of the three power plant sizes considered. Each plot gives results for generator lengths of 10, 15, and 20 meters and for MHD generator cooling with low temperature boiler feedwater and with high temperature boiler feedwater. The plots are for an oxygen production power requirement of 200 kW-hr/ton of equivalent pure oxygen. The 200 MW plant results are for a Mach number of 0.9, which at this plant size gives slightly better performance than the Mach number of 0.8 used for the other sizes. The results show that for high temperature generator cooling the plant performance increases with generator length for all the plant sizes considered. The optimum level of oxygen enrichment is about 35 volume percent oxygen in all cases. This is in agreement with previous results,[6,9] although there are some differences in the assumed generator and plant operating conditions and constraints among the present and previous studies.

The results for generators cooled with low temperature boiler feedwater are significantly different. In this case smaller plant sizes favor progressively shorter generators. The maximum plant efficiency occurs at a lower level of oxygen enrichment, at about 31 or 32 volume percent oxygen. These effects are the result of the generator heat loss increasing in relation to the power generated as the mass flow through the generator is decreased, the generator length increased, or the level of oxygen enrichment increased. The first of these factors accounts for the increasing separation of the curves for the two different generator cooling methods as the plant size decreases. It also accounts, together with the second factor, for the dominance of the shorter generators at the smaller plant sizes. The third factor results in the peak efficiency for the low temperature cooling method occurring at a lower level of enrichment.

The next figure, Fig. 3, plots the magnetic energy stored in the MHD generator volume versus the plant thermodynamic efficiency at optimum enrichment for various generator lengths and oxygen production power requirements for each of the three plant sizes. Only the low temperature generator cooling cases are shown. The 200 kW-hr/ton points correspond to data included in the previous figure, namely the maximum thermodynamic efficiency as a function of generator length. The figure shows that from a performance point of view the optimum generator length increases with increasing plant size at a given level of oxygen production power. (The figure of 47 kW-hr/ton corresponds to the thermodynamic minimum air separation work). This figure indicates possible tradeoffs between the generator length as it affects magnet cost and as it affects plant performance. It is clear that from this standpoint there is no incentive for going to generators longer than 10 meters for a 200 MW power plant, at least for the generator and plant operating conditions and constraints assumed in this study. At the larger plant sizes it is clear that in many cases the plant efficiency at the optimum generator length is not significantly greater than at shorter lengths. In these cases it is likely that the efficiency gain possible with a longer generator is not worth the increased magnet cost resulting from a significantly greater stored energy requirement.

Figure 3 also shows the penalty imposed on the plant efficiency by the power required to produce the oxygen. Many current air separation plants require about 300 kW-hr/ton of equivalent pure oxygen. Air separation plants with a power requirement approaching 200 kW-hr/ton are in operation in Europe.[12] This power requirement may be taken as representing air separation plants that could be available for an early commercial MHD/steam plant. The figure also shows that considerable gains in plant performance are possible if the ASU power requirement can be lowered below 200 kW-hr/ton.

Figure 4 shows the maximum plant thermodynamic efficiency (the efficiency at optimum enrichment) as a function of net plant power output for the conditions considered in this study. Curves are shown for both the low temperature and high temperature feedwater cooled generator cases for different generator lengths. The plant performance is clearly less sensitive to generator length for the low temperature feedwater cooling cases. The small change in performance with changes in generator length again indicates the importance of choosing the "correct" generator length to avoid a higher than necessary magnet capital cost.

Conclusions

The results of this study have shown that the MHD generator length and level of oxygen enrichment which give the maximum plant efficiency depend strongly on how the MHD generator is cooled. If the generator is cooled with high temperature boiler feedwater, the plant thermodynamic efficiency increases with generator length over the 10 to 20 meter length range considered. If the generator is cooled with low temperature boiler feedwater, the plant thermodynamic efficiency reaches a maximum value at some generator length within approximately this range. The optimum generator length increases with plant size. The level of oxygen enrichment at which the maximum plant efficiency occurs does not depend strongly on plant size, but is 3 to 4 volume percent of oxygen lower for the cases in which the MHD generator is cooled with low temperature boiler feedwater.

The results also show the relationship between the required magnet stored energy, the generator length, and the power required to produce oxygen. The cost of the magnet depends strongly on its stored energy. The results show that in many cases consideration can be given to reducing the MHD generator length to less than its optimum with only a small penalty in plant efficiency but with a potentially large reduction in magnet capital cost. The results also show that the plant efficiency depends strongly on the power required to produce oxygen and that there is a strong incentive to lower this requirement as much as possible.

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TABLE I. - MAJOR CYCLE PARAMETERS

Coal type	Montana Rosebud
Moisture content of coal delivered to combustor, percent	5
Oxidizer preheat temperature, F	1100
Combustor pressure, atm	Selected to maximize plant efficiency
Combustor oxidizer-fuel ratio relative to stoichiometric	0.90
Combustor slag rejection, percent	80
Generator type	Faraday
Potassium-coal mass ratio	0.0859
MHD generator inlet Mach number	0.9 (200 MWe) 0.8 (500, 1000 MWe)
Diffuser pressure recovery coefficient	0.4 (200 MWe) 0.6 (500, 1000 MWe)
Diffuser exit pressure, atm	1.0
MHD generator length, meters	10, 15, 20
Cycle compressor polytropic efficiency	0.90
Sulfur removal by seed, percent	70
Final oxidizer-fuel ratio relative to stoichiometric	1.05
Stack temperature, F	250
Steam-turbine cycle efficiency, percent	Dependent on feedwater heater arrangement
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	0.1

TABLE II. - GENERATOR CONSTRAINTS

Maximum axial electric field, kV/m	2.5
Maximum transverse electric field, kV/m	4.0
Maximum transverse current density, A/cm^2	1.0
Maximum Hall parameter	4.0
Maximum magnetic field, T	6.0

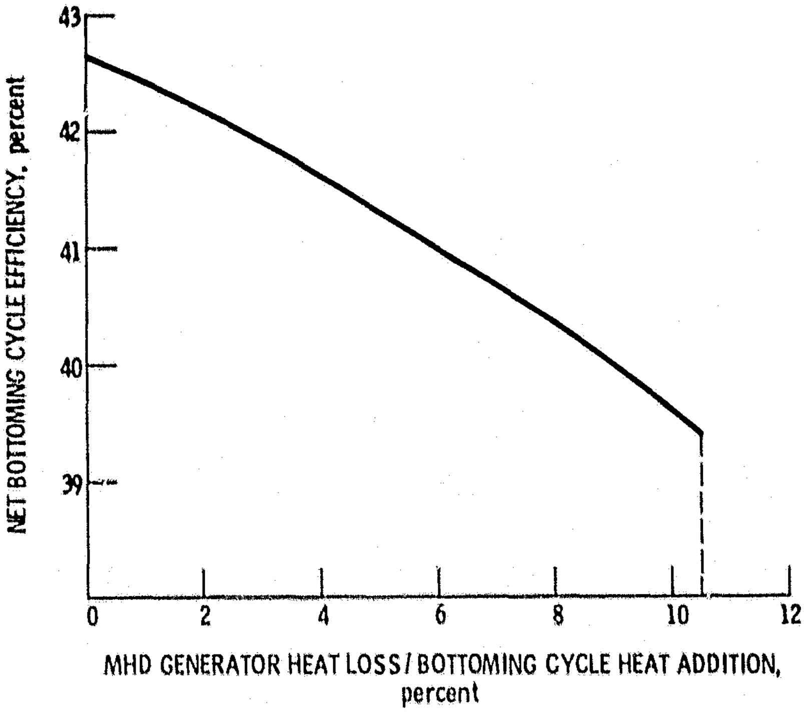
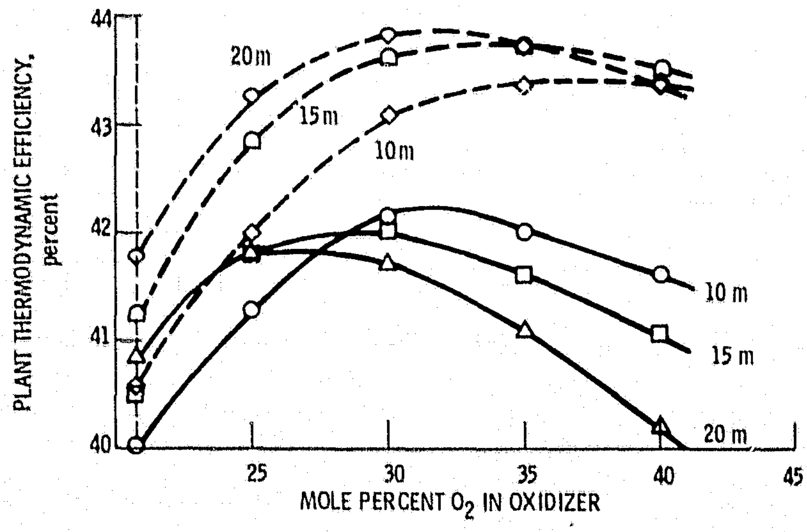
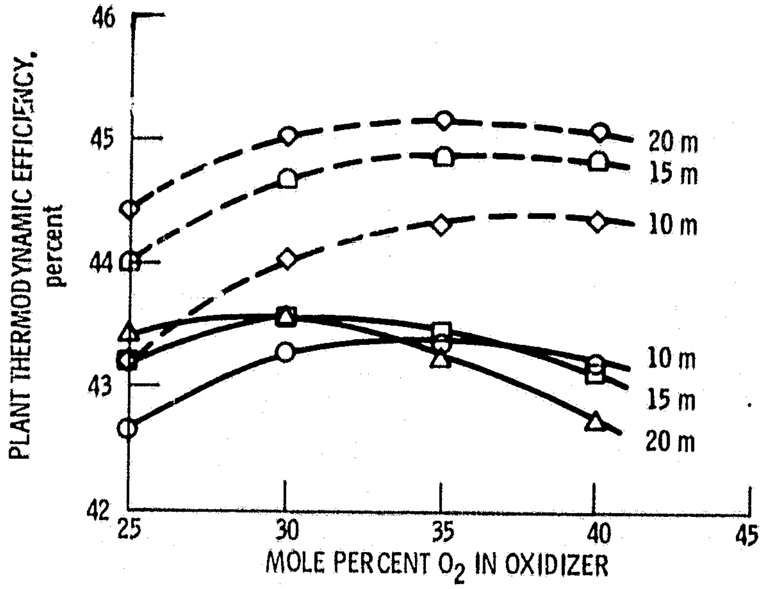


Figure 1. - Bottoming steam cycle efficiency as a function of the percentage of bottoming cycle heat addition contributed by MHD generator heat loss. MHD generator cooling water outlet temperature fixed at 260° F. Total heat addition is 906 MW, compressor work is 102 MW. Approximate power plant output for these conditions is 500 MWe.



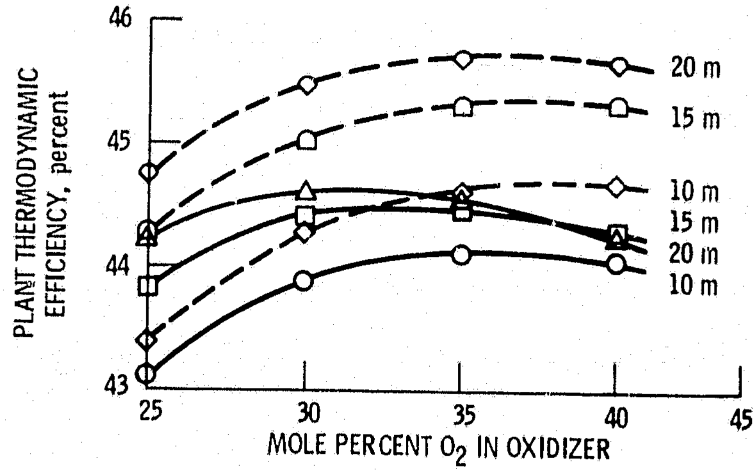
(a) 200 MWe power plant.

Figure 2. - Power plant thermodynamic efficiency as a function of oxygen enrichment for different MHD generator lengths. Solid lines are for an MHD generator cooled with low temperature boiler feedwater; dashed lines, high temperature boiler feedwater. Oxygen production power is 200 kW-hr/ton of equivalent pure oxygen.



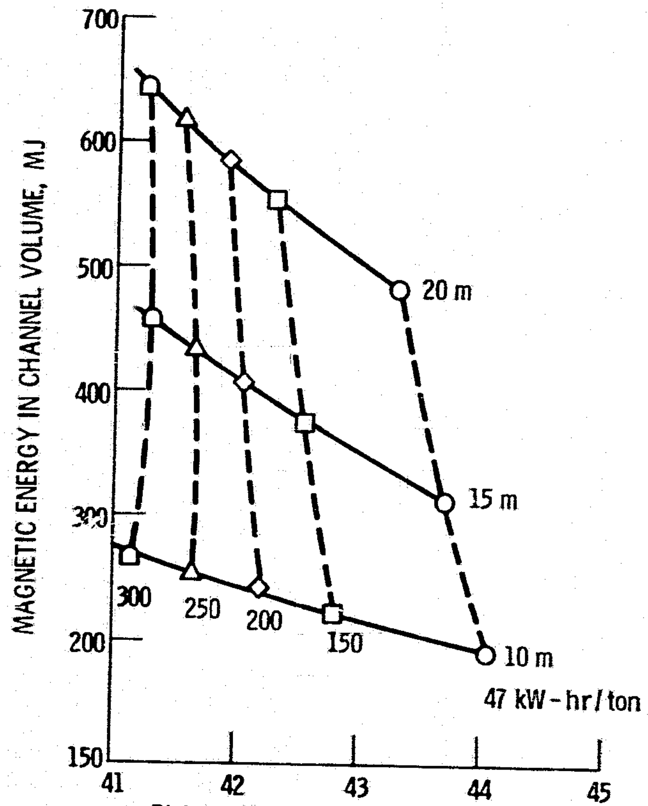
(b) 500 MWe power plant.

Figure 2. - Continued.



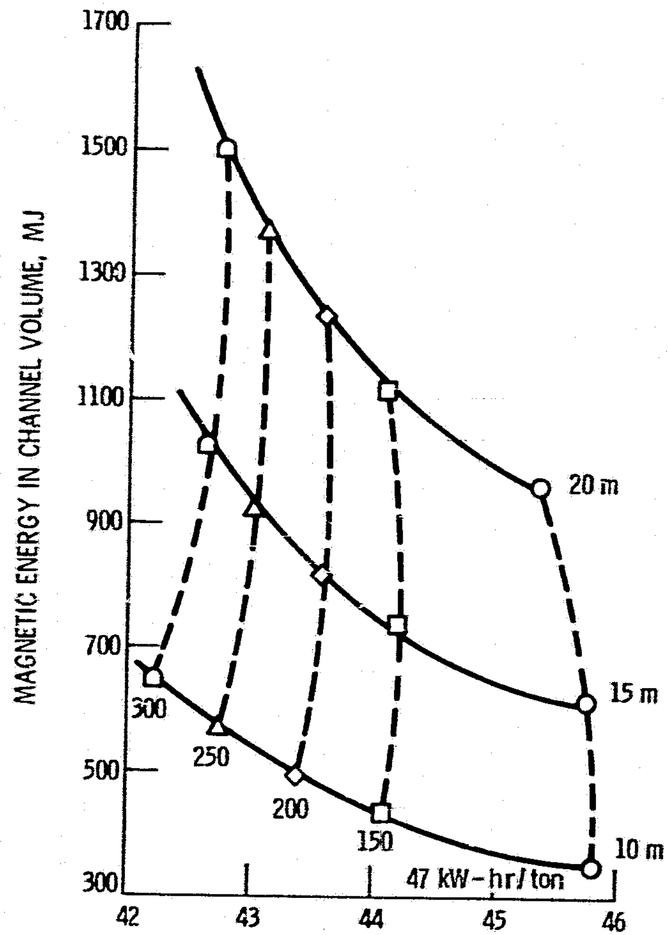
(c) 1000 MWe power plant.

Figure 2. - Concluded.



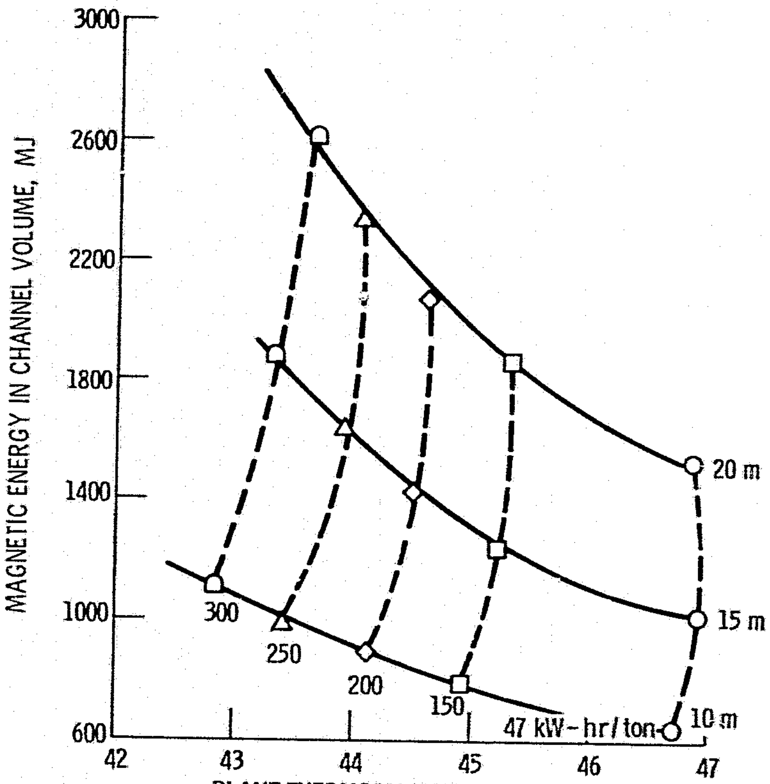
(a) 200 MWe power plant.

Figure 3. - Magnetic energy stored in MHD generator volume as a function of the plant thermodynamic efficiency for different MHD generator lengths and oxygen production power requirements. The MHD generator is cooled with low temperature boiler feedwater.



(b) 500 MWe power plant.

Figure 3. - Continued.



(c) 1000 MWe power plant.

Figure 3. - Concluded.

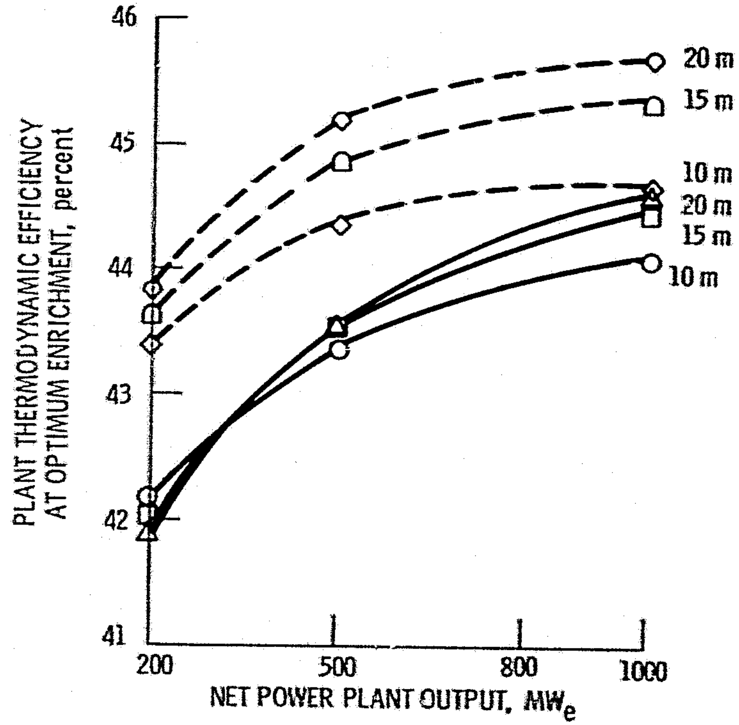


Figure 4. - Power plant thermodynamic efficiency as a function of power plant electrical output for different MHD generator lengths. Solid lines are for an MHD generator cooled with low temperature boiler feedwater; dashed lines, high temperature boiler feedwater. Oxygen production power is 200 kW-hr/ton of equivalent pure oxygen.