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SUMMARY

The Energy Conversion Alternatives Study (ECAS) MHD/steam power plant is described. The NASA critical evaluation of the design is summarized. Performance of the MHD plant is compared to that of the other type ECAS plant designs on the basis of efficiency and the 30-year levelized cost of electricity. Techniques to improve the plant design and the potential performance of lower technology plants requiring shorter development time and lower development cost are then discussed.

INTRODUCTION

The Energy Conversion Alternatives Study (ECAS) studied, using common groundrules, various concepts for advanced power plants fired by coal or coal-derived fuel. This unique effort, ref. 1-9, was managed by the Lewis Research Center of NASA and was jointly funded by NSF, ERDA, and NASA. Prime contractors for the study were the General Electric Company and the Westinghouse Electric Corporation.

In the initial phase of the ECAS, various type power plants were studied parametrically. Subsequently, 11 specific plants were selected for conceptual design in Phase 2. One of these plants was an open-cycle MHD topped steam power plant. This MHD plant was investigated by the G.E. team which included the AVCO Everett Research Laboratory, the Foster Wheeler Energy Corporation, and the Bechtel Corporation. The other plants studied in Phase 2 of the ECAS were three advanced steam plants, four combined-cycle plants, a closed-cycle gas turbine plant, a potassium topped steam plant, and a high-temperature fuel cell topped steam plant. G.E. designed seven of these plants and Westinghouse designed three. The other plant (the fuel cell plant) was designed by the United Technologies Corporation under contract to Burns and Roe.

This paper will describe the ECAS open-cycle MHD power plant (refs. 5, 10, and 11) and summarize the NASA critical evaluation of the design and the comparison of the plant performance with the other plants studied in the ECAS (refs. 8, 10, and 12). Techniques to improve the MHD plant design and/or to lower the level of technology required to implement its development are then discussed.

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ECAS OPEN-CYCLE MHD POWER PLANT

The ECAS MHD/steam power plant was chosen to be a large coal-fired plant, nominally 2000 MWe. It uses a high temperature (2500F) so-called "direct" air preheater, i.e., the MHD oxidizer for the MHD combustor is preheated by the MHD exhaust in a high temperature refractory regenerative heat exchanger which is in series with a lower temperature metallic recuperative heat exchanger.

The MHD plant and all the other ECAS plants were assumed to operate with a capacity factor of 65%. The ECAS Utility Advisory Panel indicated that to obtain this capacity factor, a plant may typically need an availability of 90%. The plant produced 60 Hz power at 500 KV suitable for transmission to a grid and was designed to comply with existing EPA environmental regulations.

Figure 1 shows a schematic of the ECAS MHD/steam plant. The major plant parameters are summarized in Table 1. Illinois #6 coal is combusted with 2500F preheated air (without O_2 enrichment) in this single-stage MHD combustor. The coal is pulverized to 70% through 200 mesh and dried to 2% moisture. The coal is burned fuel-rich to minimize NO_x production. The single-stage combustor is assumed to reject 85% of the coal slag. The combustor is seeded with potassium carbonate to produce a 4634 F exhaust with 1% weight flow of K.

The MHD nozzle/generator/diffuser expands the flow from a total pressure of 9 atmospheres in the MHD combustor to 1.14 atm and 3662 F. The MHD generator produces 1420 MW of DC electrical power. The DC output of the MHD generator is converted to 60 Hz AC power through an inverter system.

The high-subsonic velocity, diagonal-wall MHD generator design is slag coated, has zero Hall current (axial current), and expands the flow in the generator at approximately constant velocity. The latter assumption is chosen to avoid the possibility of separation or so-called "stall." The MHD generator is designed for a constant load parameter of .8 (a current 80% of the short circuit current for this diagonal wall-type design) and utilizes three separate DC loads along its length. The maximum Hall field (axial electric field) and Faraday current density (transverse current) in the generator design are 2.7 kilovolts/meters and .74 A/cm^2, respectively. The diffuser recovery efficiency was assumed to be 70%. The MHD combustor/nozzle/generator/diffuser is cooled by high pressure (4800 psia) and high temperature (495 F) feed water. As a result of these selected operating conditions, the MHD generator isentropic efficiency is 0.76.

The MHD combustion products flowing from the MHD diffuser are slowly cooled to 2960 F in the radiant furnace. The residence time in this component is selected to insure that the NO_x has decomposed to an environmentally acceptable level. Before the flow exits the radiant furnace, secondary unpreheated air is added to complete combustion.

Exhaust of the radiant furnace provides the heat input into the high temperature refractory regenerative air preheaters. The thermal duty of these periodic flow, cored brick heat exchangers is limited by the mass flow of hot gas and the maximum temperature difference between the maximum inlet and minimum exit temperature of the combustion products. The maximum inlet temperature results from the NO_x constraints in the radiant furnace. The minimum exit temperature must be sufficiently high to avoid plugging the heat exchanger by condensing seed compounds. In the ECAS plant an exit temperature of 2225 F was selected which is slightly below the dew point of the potassium sulfate. Thus to obtain the desired 2500 F air preheat, the air needs to be heated to 1400 F in a metallic recuperative heat exchanger before entering the high temperature regenerators.

The exhaust products flowing from the high-temperature air heaters is split to provide heat to both the low-temperature air heater and the steam superheater/reheater. The flow is subsequently cooled to the 251 F stack temperature by the coal dryer and economizers.

Independent standard supercritical steam turbines are used to drive the air compressors and the AC generator. The steam condensers are maintained at 106 F (2.3 in. of mercury) by mechanical wet cooling towers. A split economizer configuration is utilized in the plant to permit use of additional feedwater heaters which improve the efficiency of the steam cycle.

The potassium carbonate (K_2CO_3) seed used to provide the electrical conductivity in the MHD generator reacts in the generator exhaust with sulfur introduced with the coal to form K_2SO_4. The seed thus also prevents plant SO_x emissions from exceeding EPA standards. The K_2SO_4 is collected and chemically reprocessed in an integral seed treatment facility to K_2CO_3 (which is recycled to the MHD combustor) and to H_2S (which is further reduced in a Claus plant to elemental sulfur for disposal). The synthesis gas required as input to the seed reprocessing facility is assumed in the ECAS plant to be provided by a non-integrated over-the-fence gasifier.

ECAS MHD PLANT PERFORMANCE AND COST

Table 2 summarizes the G.E. Phase 2 ECAS MHD/steam plant performance and cost. The net power plant output is 1932 MWe and the plant capital cost is $718 per KWe. The cost of electricity (COE) is 31.8 mills per kw-hr and is principally the result of the capital charges, 22.7 mills per kw-hr. Plant economics is, of course, sensitive to the assumed ground rules which will be discussed in a subsequent section entitled Comparison of ECAS Power Plants.

Based upon historical data and the total estimated construction site man-hours, the Bechtel Corporation estimated the construction time for this plant to be 6-1/2 years. This construction time was then used to calculate the portion of the capital cost associated with interest and escalation during construction which accounts for 40 percent of the plant capital cost.

The operating and maintenance cost includes, in addition to the normally expected plant maintenance, special maintenance for high technology MHD components. For example, every 10,000 hours the MHD combustor, nozzle, and generator are assumed to be replaced and checker bricks in the high-temperature air heater are assumed to require partial or complete replacement.

Figure 2 illustrates the simplified energy flow diagram for the ECAS MHD plant. The high plant thermodynamic efficiency, 54%, is obtained by dividing the gross electrical power output by the coal input. The power plant efficiency includes subtracting the auxiliary power and transformer losses and includes the input of the IBTU fuel gas needed to operate the seed reprocessing plant. The overall energy efficiency (coal-pile-to-bus-bar) is obtained by including the inefficiencies in the IBTU gasifier which by assumption was placed outside the power plant fence.

The total thermal input to the MHD generator is 5491 MW_{TH} of which 1420 or approximately 26% is converted to DC electric power in the MHD generator. The total heat transferred to cooling water in the combustor, generator, and diffuser is 235 MW_{TH} or 4.3% of the thermal flow. Slightly more than 36% of the thermal input to the downstream heat exchangers is recycled to the MHD combustor via the air heaters.

The steam turbine/generator and steam turbine/compressor bottoming cycles have thermodynamic efficiencies of 41.8 and 41.3%, respectively. These compare to a thermodynamic efficiency of approximately 45% for a free-standing large steam plant. The lower efficiency of the MHD steam bottoming cycle results from the fact that less regenerative feedwater heating can be used than is used in a free-standing steam plant. A slight improvement over the ECAS steam bottoming cycle performance can be obtained by rearrangement of the economizer and feedwater heater configuration. Specifically, The ECAS plant's full flow split economizer can be replaced by a single partial flow economizer which has in parallel regenerative feedwater heaters to heat the remaining feedwater.

In this MHD plant the seed reprocessing facilities and their gasifier were not integrated with the power plant. Estimates, ref. 8, indicate that tight integration of these systems with the power plant could increase the coal-pile-to-bus-bar efficiency of the total plant from 48.3% to approximately 50%. Other improvements in plant performance are obtainable through recuperatively preheating the secondary air and/or use of a less conventional full-flow coal dryer downstream of the economizer such as proposed for the Baseline plant (ref. 13).

Table 3 tabulates plant cost distribution and the installed cost of the most expensive major plant components. Surprisingly the low-temperature metallic recuperative air heater was the most expensive single component. Because of the high, 1400 F, low-temperature recuperative heat exchanger output temperature, the design used significant amounts of expensive Hastalloy. The high cost of this component was unexpected and was not identified until Phase 2 of the ECAS. Had it been anticipated, the cost of this heat exchanger could have been significantly reduced by lowering its upper temperature. To accomplish this, part of the low-temperature air heater duty must be shifted to the high-temperature air heater. The duty of the high-temperature air heater can be increased, without changing its inlet and exit temperatures, by mixing recycled stack gas with the MHD diffuser exhaust upstream of the radiant furnace. The resultant increased mass flow through the air heater and other heat recovery heat exchangers would, however, cause some increase in their cost, and a stack gas blower and additional piping would also be needed.

The other major plant components listed in Table 3 are and will be expensive. For one item, the high-temperature air heater, NASA estimates (ref. 8) that the cost could be significantly higher, up to as much as a factor of two. The major uncertainty is the type of refractory material required for the cored brick and its cost.

Generally, the uncertainties in cost in the high technology components of the MHD/steam plant will not, however, strongly affect the total plant cost and/or its COE. Table 4 from ref. 8 illustrates this point. In Table 4 the best judgment of NASA has been used to subdivide the construction cost of the MHD/steam plant into three categories: current technology, near-term technology, and advanced technology. The MHD plant has a relatively small fraction, 19%, of its cost in the advanced technology category. Therefore even if the cost of the advanced technology components doubled, the COE of this plant would be only increased by approximately 14%. Other advanced high performance plant concepts studied in ECAS in fact had at least equal or greater fractions of their costs in the advanced technology category.

COMPARISON OF ECAS POWER PLANTS

Table 5 summarizes the contractors' overall results for the 11 plant conceptual designs studied in the ECAS. The listed costs are on the basis of the ground rules specified to the contractors by NASA which included: start of construction of all plants in mid-1975, escalation during construction of 6-1/2% per year, interest during construction of 10% per year, a specified cash flow curve for construction, a fixed charge rate of 18% per year, specified fixed fuel costs ($1 per million BTU's for Illinois #6 coal delivered to site, etc.), and a fixed specified labor rate to be used for calculating operating and maintenance costs.

Since the time of construction for various plants differs, the contractor COE charges correspond to plants that come into operation in different years. The contractor total COE also do not include any escalation in fuel and in operating and maintenance costs.

The data of Table 5 does however provide the basis for: 1) comparing plant efficiencies, 2) comparing the sum of the fuel and the operating and maintenance charges (which is important to a utilities dispatch program) and 3) for calculating COE for these plants under various alternative economic ground rules. As indicated in Table 5, the MHD plant has one of the highest efficiencies of all the plants studied in the ECAS.

In calculating the COE for the ECAS plants, all plants have been assumed to operate with a capacity factor of 65%. From Table 5, however, it can be seen that the MHD/steam plant has the lowest sum of fuel plus operating and maintenance charges. Therefore, a typical utility dispatch program would like to operate this plant in preference to the other types of ECAS plants, except for the possible disadvantage of its large size.

Reference 14, an independent EPRI-funded study by Westinghouse shows that an MHD/steam plant such as the ECAS plant would essentially be operated in a typical utility whenever it is available and would not require an availability of 90% to obtain a capacity factor of 65%. In contrast, high operating plus fuel cost plants such as the H coal combined cycle plants in ECAS may have difficulty being dispatched enough by a utility to obtain a capacity factor of 65%.

Figure 3 shows the NASA calculation*, using the contractor data of Table 5, of the 30-year levelized cost of electricity (in mid-1975 dollars) for the various ECAS plants. This method has been adopted, ref. 15, for EPRI use in comparing power plant alternatives. The economic basis is that of comparing the present worth of the future revenue requirements for meeting all the cost associated with each alternative. The revenue requirments can for comparative purposes be stated in terms of levelized annual revenue or levelized cost of electricity. In performing such calculations, it is important that consistent rates are used for the fixed charge rate, the discount rate (weighted average cost of capital), and inflation. Escalation of fuel in fixed dollars may also be included. For the data shown in figure 3, NASA has assumed 18% fixed charge rate, 10% discount rate, 6.5% inflation, and no escalation of fuel in fixed dollars. The 30-year time corresponds to the assumed plant life for the ECAS plant designs. As previously described, however, special maintenance of the high technology MHD components has been included in the COE for the MHD plant.

Figure 3 shows that the open-cycle MHD/steam plant has by a slight amount the lowest cost of electricity in addition to its very high efficiency. If escalation of the coal price in fixed dollars (as projected by EPRI, ref. 15) had been included in calculating the COE of the plants, then the high performance plants in figure 3 would on a relative basis be even more attractive. The ECAS MHD plant was selected, on the basis of the best judgment available, to be representative of a mature MHD power plant. Detailed analysis was not performed to either maximize efficiency or minimize COE. Additional analysis is required to define plant efficiency as a function of operating conditions and the variation of plant COE as a function of efficiency.

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* The authors would like to acknowledge the assistance of R. M. Donovan in calculating these levelized COE's.

ECAS MHD PLANT CONCLUSIONS

The ECAS demonstrated: 1) that the MHD/steam power plant has an excellent potential for obtaining both high efficiency and low COE, and 2) that the estimated MHD plant COE is relatively insensitive to uncertainties in the cost of advanced technology components. The chief issues in commercializing the MHD/steam plant concept are associated with demonstrating the required performance and operating life of the plant components and demonstrating the viability of the concept as a plant system. G.E., as part of ECAS, estimates that to implement the development of its ECAS MHD plant concept would require approximately 20 years and approximately 1-1/2 billion mid-1975 dollars.

Subsequent to the completion of ECAS, G.E. under funding from ERPI has defined (ref. 16) techniques for assessing the desirability of advanced power plant alternatives. In ref. 16 these techniques are then used to evaluate the desirability of the ECAS/MHD steam plant for two scenarios, one being if the MHD plant is the only advanced technology plant developed and the other being if three attractive advanced technology plants are developed (the ECAS MHD/steam, a 44% efficient-3000F open-cycle water-cooled gas turbine combined cycle, and an atmospheric-fluidized-bed advanced steam). Results show that after it is available, the ECAS MHD/steam plant captures the future baseload power market.

In addition, the G.E. cost benefit analysis indicates that the MHD plant would have a worth from the viewpoint of the nation or the utilities of more than one or two orders of magnitude greater than the cost of developing the MHD plant (the specific value depends on alternatives developed and viewpoint). These large benefits resulted despite the fact that the MHD plant was assumed to have a high 20% forced outage rate and to have a small amount of turn-down capability. Results also indicate that the 2000 MWe ECAS plant was larger than desirable.

EARLY COMMERCIAL MHD PLANTS

The ECAS MHD plant conceptual design was based on some advanced technology components that may not be included in the first commercial plants. Specifically, high-temperature and high-pressure cooling was used for the MHD generator; the high-temperature air preheat for the MHD combustor was accomplished by refractory regenerative heat exchangers (direct preheaters); an advanced seed reprocessing concept was used; and (to obtain the required plant availability) a minimum operating life of approximately 6000 hours was required for the MHD channel.

NASA LeRC, under Interagency Agreement with the MHD Division of DOE, has recently initiated parallel contracts to the AVCO Everett Research Laboratory, Inc. and the General Electric Corporation to study early commercial MHD plants. The goal of these studies is to define coal-fired, open-cycle MHD power plants that have an efficiency greater than 45 percent and can generate electricity at reasonable cost. These plants should also have lower development risks and shorter development times than plants defined in the ECAS.

Specifically. these early commercial MHD plant studies will examine use of near-term, separately-fired, high-temperature, refractory stove technology to preheat the MHD combustor air. Preheater fuel will be obtained from coal gasifiers which are either presently available or projected to be available within a decade. Oxygen enrichment of the MHD combustor air, near-term technology for seed reprocessing, or other approaches avoiding seed reprocessing, and better optimization of the MHD channel and the plant design will also be assessed.

Aspects of the impact of plant design on plant availability and capacity factor are illustrated in references 17 and 18. Reference 17 shows that if the plant is constructed with a stand-by spare MHD combustor, channel, magnet, and diffuser; high plant availability can be obtained with substantially lower channel operating life than required in the ECAS MHD plant. Reference 18 indicates that an improvement in plant capacity factor may be obtainable if the configuration permits separate bottoming steam cycle operation during channel replacement.

MHD PLANT PERFORMANCE

The impact on the MHD plant performance of component performance and plant design can be examined with the aid of figure 4 from which the following expression for the thermodynamic efficient, η_T, of an MHD/steam plant can be obtained.

$$\eta_T = P_N/P_F \; (1 - \eta_S) + \eta_S \; (1 + P_S/P_F - P_L/P_F) \qquad (1)$$

Where

P_F is the chemical power in the total plant fuel input (HHV): MHD combustor fuel plus any separately-fired preheater fuel.

P_N is the net MHD electrical/mechanical power: MHD generator power minus the sum of the MHD compressor power and any power used to operate an oxygen plant.

P_L is the total power lost from the cycle: stack losses, coal dryer power, plus other heat losses.

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

η_S is the steam bottoming cycle thermodynamic efficiency.

The ECAS results indicate that the overall plant efficiency would for Illinois 6 coal be four to five percentage points lower than the thermodynamic efficiency (depending on the details of the seed reprocessing approach utilized).

For a given fuel input and seed-to-fuel ratio, eq. 1 shows that the plant thermodynamic efficiency is a linearly increasing function of both the net MHD power and the steam cycle efficiency and a linear decreasing function of the total thermal power loss. For ECAS plant conditions, a 1.7% increase in net MHD power or a 2.4% decrease in total power losses increases plant efficiency in percent by 1 point (or 1.85%). A point increase in steam cycle efficiency increase plant efficiency 0.625 points.

Eq. 1 also can be rearranged to show that η_T minus η_S is inversely proportional to P_F. P_F can be rewritten as the MHD combustor fuel times one plus the ratio of the separately-fired air preheater fuel to the MHD combustor fuel. Thus, one can see that a separately-fired plant has an inherent disadvantage in comparison to a directly-preheated plant. This disadvantage can be partly alleviated both by operating at a higher preheat temperature and by minimizing the preheater fuel required via maximum use of recuperation. One attractive concept is to use the MHD exhaust to recuperatively preheat the separately-fired preheater's combustor air and recycled stack gas (needed to limit combustor temperature and control NO_x).

RELATION OF MHD GENERATOR AND PLANT PERFORMANCE

Figure 5 shows for the ECAS fuel input and air preheat conditions, the NASA calculated net MHD power, P_N, as a function of MHD combustor pressure for four alternative MHD channel designs. Also indicated in figure 5 are the corresponding direct-preheated plant thermodynamic efficiencies where the other parameters in equation 1 are held fixed at the ECAS plant values. The optimum combustor pressure for each channel design occurs at the respective maximum net MHD power and η_T point. At these points the calculated MHD channel heat loss is indicated. Generator heat loss is calculated by integrating the turbulent heat flux over the generator wall surface. The slag-coated generator wall is assumed to be at 1700 K.

The four channel designs shown in figure 5 are two constant loading, K, designs using the ECAS specified magnetic field: one with constant velocity and an entrance Mach nunber of 0.8 (the ECAS assumptions), the other with approximately constant 0.9 Mach number (γM^2 = const). The other cases are also approximately constant 0.9 Mach number designs, but for two different length variable magnetic fields and variable loading. The two lengths, 25 and 21 meters, correspond respectively to the overall length of the ECAS magnet and the length of its high field portion. In both cases the loading and magnetic field was varied to define a channel design which was limited at each station either by the magnetic field being 6 tesla or by the Faraday current density, Hall electric field, or Hall parameter being equal to its maximum in the ECAS channel design.

Figure 5 shows the dependence of the MHD plant performance on channel design assumptions. Detailed studies are required to optimize the channel design and tradeoffs between channel performance and magnet cost will be required to minimize COE. If the dependence of channel operating life on the electric field and current density could be defined, then a variable magnetic field and loading channel could be defined which, for specified constraints, maximized channel operating life.

The NASA calculated MHD net power for the 9 atm combustor, constant velocity design differs by only 1.3% from the AVCO calculated ECAS plant result. The maximum of the net power curve occurs at 9 atm which supports selection of this operating pressure for the ECAS plant magnet design.

DIRECTLY AND SEPARATLY PREHEATED PLANT PERFORMANCE WITH O_2 ENRICHMENT

The potential impact on plant performance of oxygen enrichment of the MHD combustor is illustrated in figure 6 for both direct and separately-fired preheater MHD/steam plants. The power to operate the required gaseous-oxygen air separation plant is included in the thermodynamic efficiencies shown in figure 6. The energy for producing the oxygen is assumed to be 300 kW-hr per ton, a value corresponding to standard U.S. plant practice.

The other assumptions used in calculating figure 6 are that the following quantities are equal to the ECAS plant values: the MHD generator, diffuser and compressor efficiency; the MHD combustor/generator ratio of heat loss to enthalpy extraction; the steam bottoming plant efficiency; the coal and coal drying power; the stack losses; and the total temperature and pressure at the MHD generator exit. For the separately-fired plants, additional assumptions are that stack-gas is recycled to the preheater combustor to limit its exit temperature to obtain a 300 F minimum temperature difference in the preheater, and the preheater combustor air and recycled stack gas are recuperatively preheated to the same temperature by MHD exhaust. MHD compressor intercooling from 800 F down to 530 F is added as required in the higher pressure plant to limit compressor exit temperature to 890F. The high intercooler temperature was selected so that its thermal power could be assumed to be usefully used in the steam bottoming plant.

Figure 6 indicates that MHD plant efficiency can generally be improved by oxygen enrichment, but that the plant pressure ratio must be substantially increased. Separately-fired preheater plants benefit more from oxygen enrichment than directly-preheated plants. In fact, for very high temperature directly preheated plants addition of oxygen is detrimental. Other than the power required for its production, the two effects of oxygen enrichment are that it permits higher pressure ratio operation of the plant which is thermodynamically desirable, but that for a given thermal input the MHD combustor and generator mass flow is decreased. Thus, for a plant directly preheated to a given temperature, less power is recycled to the combustor by the preheater. For the separately-fired plants, however, the lower mass flow requires less preheater fuel.

Figure 6 indicates that approximately one half the separately-fired preheater plant performance difference for 3000 F and 2500 F preheat temperature plants can be made up by O_2 enriching the lower temperature plant to increase its pressure ratio to that of the higher temperature plant. Figure 6 also indicates the desirability of maximizing recuperation for separately-fired preheater plants.

Figure 7 shows this desirability of recuperation more directly. Figure 7 is calculated on the basis of the same assumptions as figure 6, except that MHD combustor is held fixed at 15 atm. As the preheat temperature is decreased, additional O_2 is required to maintain the combustor temperature necessary to hold the total temperature and pressure at the MHD generator exit constant at the ECAS values. For the assumptions made, almost no oxygen is used for 3000 F preheat; greater amount of oxygen is required for 2500 F preheat; and for the directly preheated plants, enrichment is increasing as preheat temperature is decreased down to the MHD compressor exit temperature. Results are presented in Figure 6 for two values of oxygen production energy: 300 and 200 kW-hr per ton corresponding, respectively, to a standard U.S. plant and to an available plant with minimum energy consumption.

Figure 6 shows that the simplest MHD plants, the low temperature directly preheated plants which use only available technology (1100-1400 F) metallic recuperation, are the lowest efficiency plants. The highest efficiency plants are the high temperature directly preheated plants similar to the ECAS plant. These plants are limited to preheat temperatures below 2700 F by NO_x considerations and preheater ΔT requirements.

Performance of the separately-fired preheater plants using available metallic recuperator technology is midway between the high and low temperature directly-preheated plants. Performance of the separately-fired preheater plants improves with recuperation (or regeneration) temperature, so that use of available refractory heat exchanger concepts to increase this temperature could be desirable. A possibility exists for using such a heat exchanger in the MHD exhaust after the MHD seed has condensed. The heat exchanger would have a low stress level if it is used to preheat the separately-fired preheater combustor air and recycled stack gas at approximately 1 atm.

CONCLUDING REMARKS

The ECAS study and subsequent EPRI study using the ECAS MHD/steam plant results demonstrated both the attractive potential and the benefits associated with implementing the development of MHD for baseload utility applications. Recently initiated early MHD power plant studies will attempt to define attractive MHD plants requiring less time and cost to implement their development than the ECAS MHD plant. Preliminary studies, such as described herein, indicate that the performance of these lower technology plants should be able to exceed 45%. Results of ongoing studies are required to define cost of electricity.

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TABLE 1. - MAJOR DESIGN PARAMETERS OF COAL/OPEN-CYCLE

MHD/STEAM SYSTEM - ECAS PHASE 2

Coal type	Illinois #6
Moisture content of coal delivered to combustor, percent	2
Air preheat temperature, ^{o}F	2500
Combustion pressure, atm	9
Combustion temperature, ^{o}F	4634
Combustor fuel-air ratio relative to stoichiometric	1.07
Combustor slag rejection, percent	85
Slag carryover to channel, percent	15
Generator type	Diagonal wall
Average magnetic flux density, T	5
Electrical load parameter	0.8
Potassium seed, percent	1
Steam-bottoming-cycle conditions, psig/^{o}F/^{o}F	3500/1000/1000
Cooling tower type	Wet mechanical draft
Stack-gas temperature, ^{o}F	251

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TABLE 2. - SUMMARY OF PERFORMANCE AND COST FOR COAL/

OPEN-CYCLE MHD/STEAM SYSTEM - ECAS PHASE 2

Net powerplant output (60 Hz; 500 kV), MWe	1932.2
Thermodynamic efficiency, percent	54.0
Powerplant efficiency, percent	49.8
Overall energy efficiency, percent	48.3
Coal consumption, lb/kW-hr	0.655
Total wastes, lb/kW-hr	0.082
Powerplant capital cost, dollars	1391.1×10^{6}
Powerplant capital cost, $/kWe	718
Cost of electricity (capacity factor, 0.65), mills/kW-hr:	
Capital	22.7
Fuel	7.3
Operation and maintenance	1.7
Total	31.8
Estimated time of construction, yr	6.5
G. E. estimate of approximate date of first commercial service	1996-1999

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TABLE 3. - OPEN-CYCLE MHD PLANT CONSTRUCTION

COST DISTRIBUTION

[General Electric - ECAS Task 2]

	$/kWe
Installed cost components < 10$/kWe:	
Coal processing and injection equipment	12
Magnet system	23
Air heaters:	
High temperature	14
Low temperature	31
Seed recovery and reprocessing	12
Radiant furnace	12
Steam furnace - SH/RH	14
Steam turbine/generator	13
Inversion equipment	24
Total	155
Other[a]	172
Total	172
Capital costs:	
Subtotal - construction cost estimate	328
Architect and engineering services	29
Contingency	71
Escalation and interest during construction	290
Total	718

[a]All other components and balance-of-plant materials plus additional direct and indirect site labor.

TABLE 4. - COST CATEGORIZATION FOR ECAS PHASE 2 MHD/STEAM PLANT

Cost category	Uncertainty category			
	Current technology	Near-term technology	Advanced technology	Total
	Cost, dollars			
1.0 - Land improvements and structures:				
Material	35.178×10^{6}	----------	----------	
Labor	50.609	----------	----------	
				85.787×10^{6}
2.0 - Coal and solids handling:				
Coal processing and injection equipment	11.480×10^{6}	11.490×10^{6}	----------	
Other materials	12.528	----------	----------	
Other labor	4.844	----------	----------	
				40.342×10^{6}
3.0 - Prime cycle:				
Coal combustor	----------	----------	5.185×10^{6}	
MHD generator-diffuser	----------	----------	16.940	
Magnet dewar	----------	----------	44.000	
Seed handling and injection	----------	----------	3.190	
Seed recovery and reprocessing	----------	----------	23.900	
Electrostatic precipitator	12.370×10^{6}	----------	----------	
High-temperature air heater	----------	----------	26.850	
Low-temperature air heater	----------	59.160×10^{6}	----------	
Steam turbine-compressor	8.320	8.830	----------	
Other materials	10.000	----------	----------	
Other labor	12.780	----------	----------	
				232.025×10^{6}
4.0 - Steam bottoming cycle:				
Steam turbine-generator	24.620×10^{6}	----------	----------	
Radiant boiler	----------	23.450×10^{6}	----------	
Superheater-reheater	----------	27.750	----------	
Economizers	6.320	----------	----------	
Other materials	31.615	----------	----------	
Other labor	37.662	----------	----------	
				151.417×10^{6}
5.0 - Electrical plant and instrumentation:				
Inverters	----------	47.430×10^{6}	----------	
Other material	29.698×10^{6}	----------	----------	
Other labor	36.434	----------	----------	
				113.562×10^{6}
6.0 - Cooling tower system	9.846×10^{6}	----------	----------	
				9.846×10^{6}
Total[a], dollars	334.804×10^{6}	178.110×10^{6}	120.065×10^{6}	632.979×10^{6}
Total, $/kW	174	92	62	328

[a]Materials and labor only.

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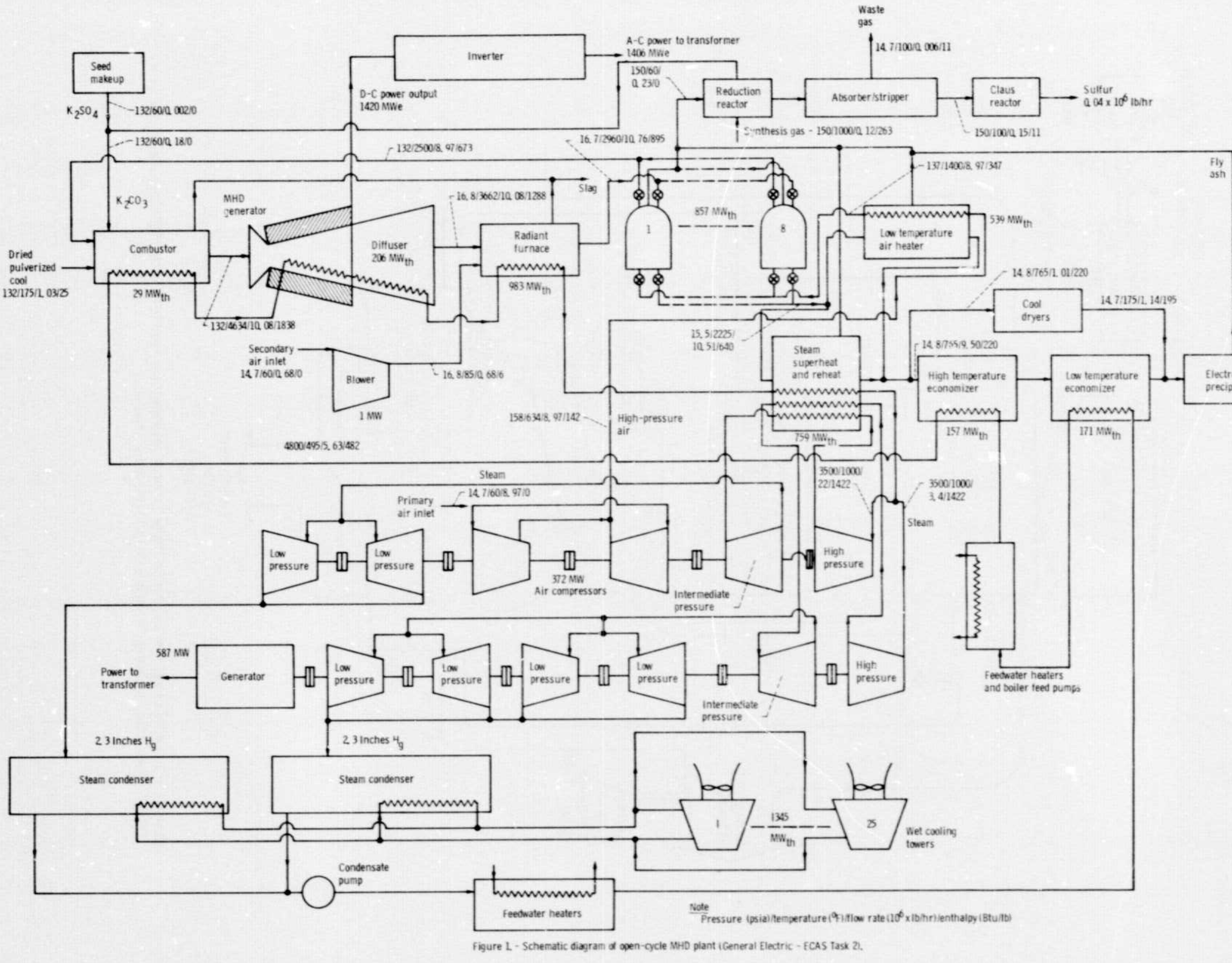
TABLE 5. - SUMMARY OF ECAS PHASE 2 CONTRACTOR PERFORMANCE AND COST RESULTS

System and contractor	Net power, MW	Efficiency, percent			Construction period, yr	Capital cost, $/kWe		Cost of electricity, mills/kW-hr				
		Thermodynamic	Powerplant	Overall		ECAS ground rules	Mid-1975, dollars	ECAS ground rules				30-year* levelized mid-1975, dollars
								Capital	Fuel	O&M	Total	
1 - AFB/steam (General Electric)	814	43.9	35.8	35.8	5.5	632	447	20.0	9.5	2.2	31.7	37.6
2 - PFB/steam (General Electric)	904	41.3	39.2	39.2	5.5	723	411	22.9	8.7	2.5	34.1	38.6
3 - PFB/steam (Westinghouse)	679	42.3	39.0	39.0	5.0	549	401	17.3	8.8	2.0	28.1	34.3
4 - PFB/potassium/steam (General Electric)	996	47.8	44.4	44.4	5.5	934	660	29.6	7.7	2.6	39.9	41.5
5 - AFB/closed-cycle gas turbine/organic (General Electric)	476	50.1	39.9	39.9	5.0	1232	899	38.9	8.6	1.8	49.3	49.2
6 - Low-Btu gasifier/gas turbine/steam (General Electric)	585	44.2	39.6	39.6	5.0	771	562	24.4	8.6	2.1	35.1	39.3
7 - Low-Btu gasifier/gas turbine/steam (Westinghouse)	786	48.5	46.8	46.8	5.0	614	448	19.4	7.3	2.4	29.1	33.6
8 - Semiclean-fuel-fired gas turbine/steam (Westinghouse)	874	53.6	52.2	39.6	4.0	329	256	10.4	14.7	.9	26.0	39.4
9 - Semiclean-fuel-fired gas turbine/steam (General Electric)	847	52.7	51.1	37.8	5.0	418	305	13.2	15.0	1.3	29.5	42.4
10 - Coal/MHD/steam (General Electric)	1932	54.0	49.8	48.3	6.5	718	477	22.7	7.3	1.7	31.8	33.2
11 - Low-Btu gasifier/molten-carbonate fuel cell/steam (United Technologies Corp.)	635	53.6	49.6	49.6	5.0	593	433	18.8	6.9	3.3	28.0	34.0
Reference - steam with stack-gas scrubbers, on site, calcination (General Electric), stack temperature, ^{o}F												
250	747	40.7	31.8	31.8	5.5	835	591	26.4	10.7	2.6	39.8	45.3
175	795	43.7	33.8	33.8	5.5	771	545	24.4	10.1	2.5	37.0	42.4

*Calculated by NASA.



Note
Pressure (psia)/temperature (°F)/flow rate (10^6 x lb/hr)/enthalpy (Btu/lb)

Figure 1. - Schematic diagram of open-cycle MHD plant (General Electric - ECAS Task 2).

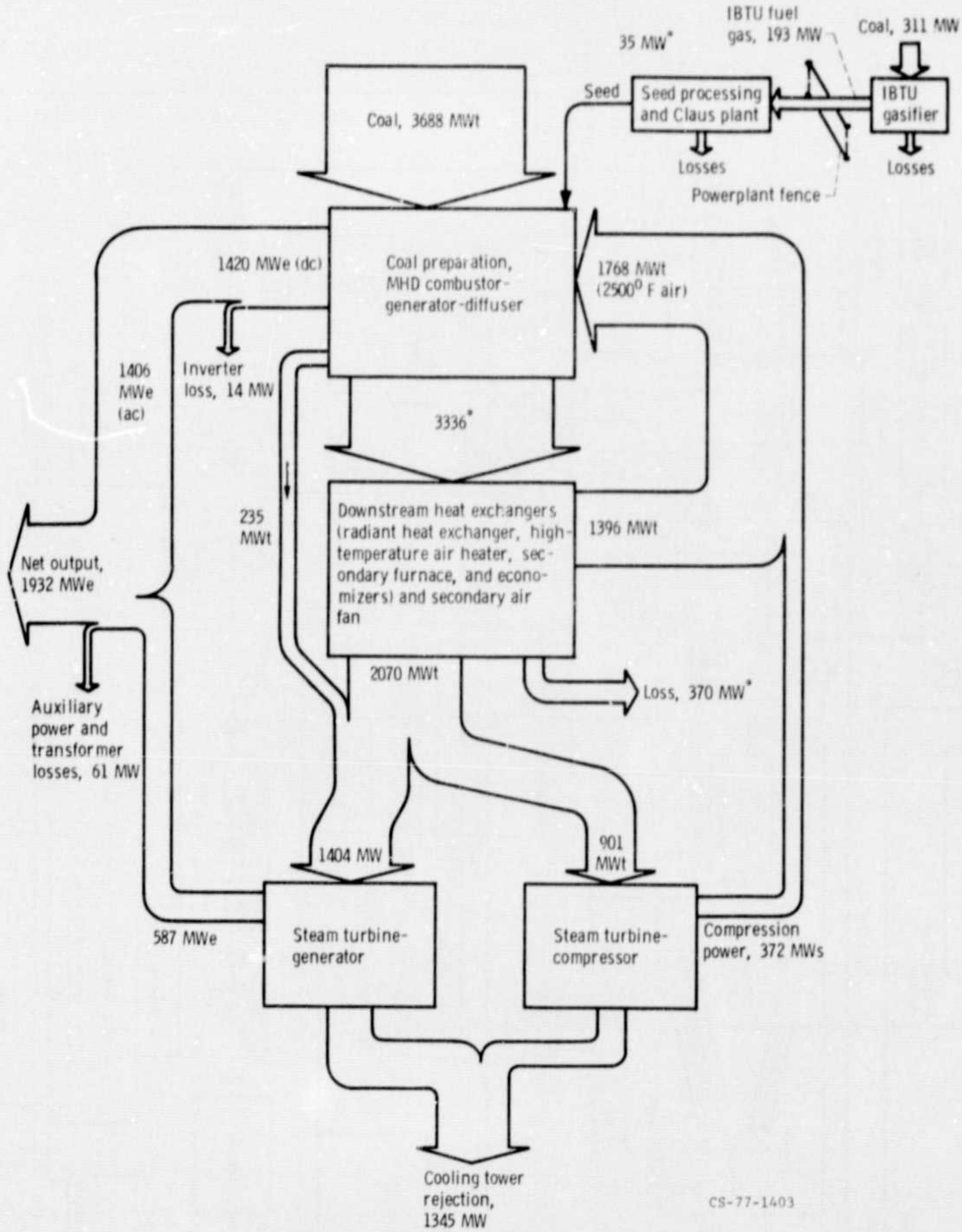


Figure 2. - Simplified energy flow diagram for Phase 2 conceptual powerplant - coal/open-cycle MHD/steam powerplant. (Single asterisk denotes that value includes actual seed-sulfur reaction.)

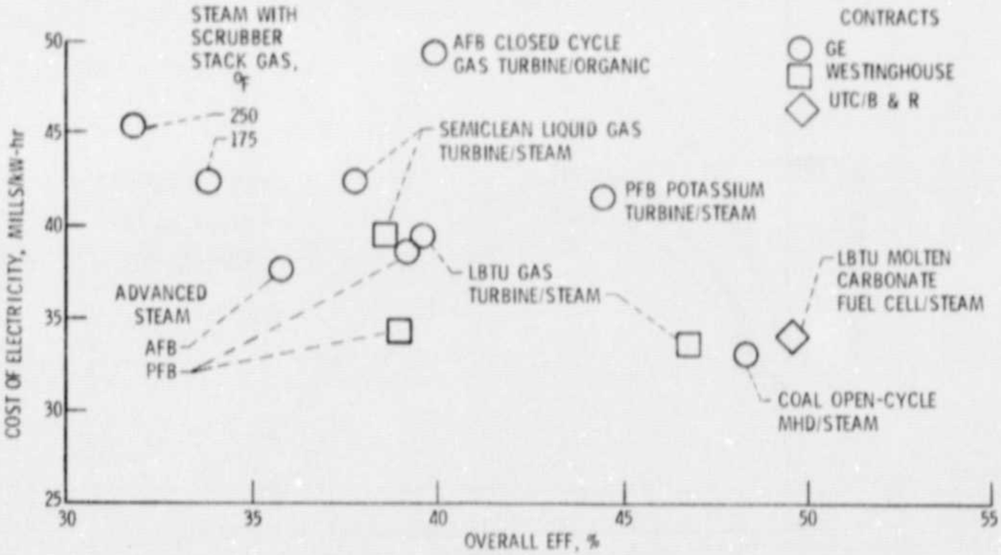


Figure 3. - ECAS Phase 2 results using 30 year levelized cost in MID 1975 dollars. Fuel cost assumed constant in fixed dollars.

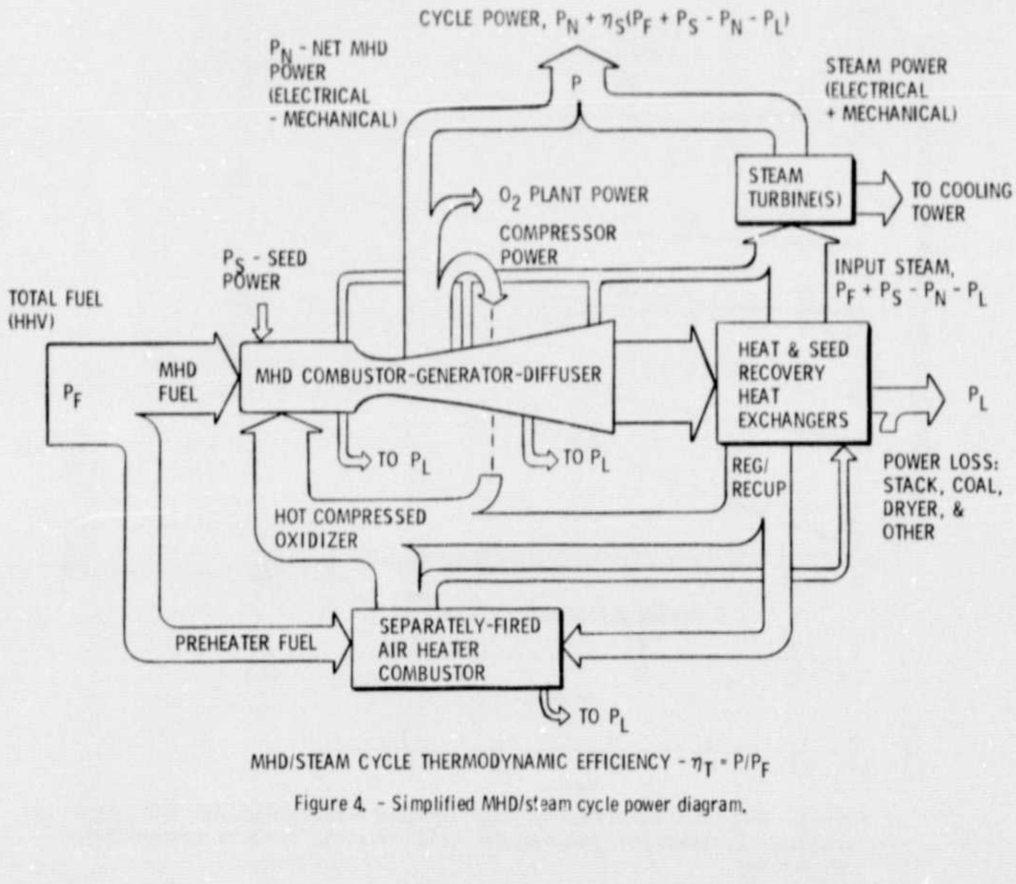


Figure 4. - Simplified MHD/steam cycle power diagram.

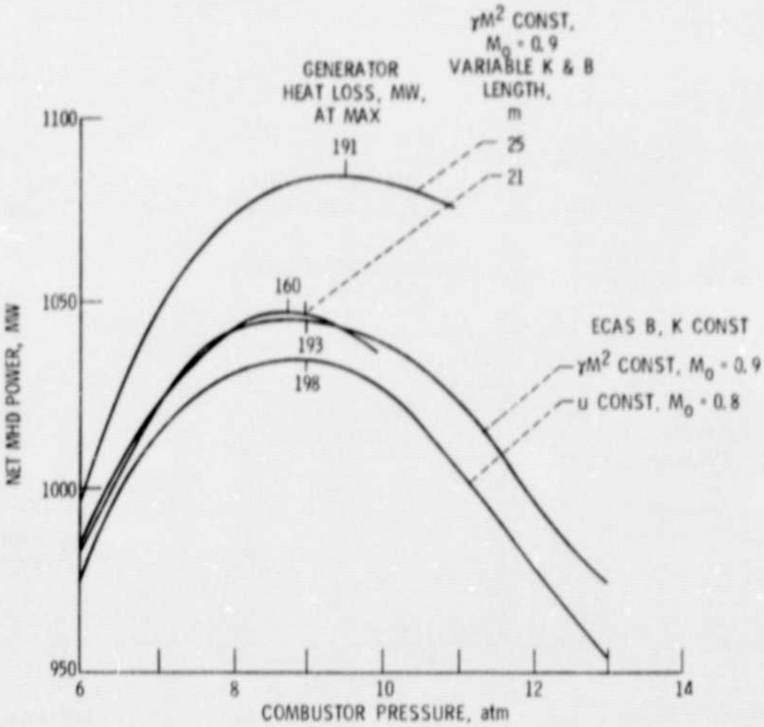


Figure 5. - Performance variation with generator design for ECAS type plants.

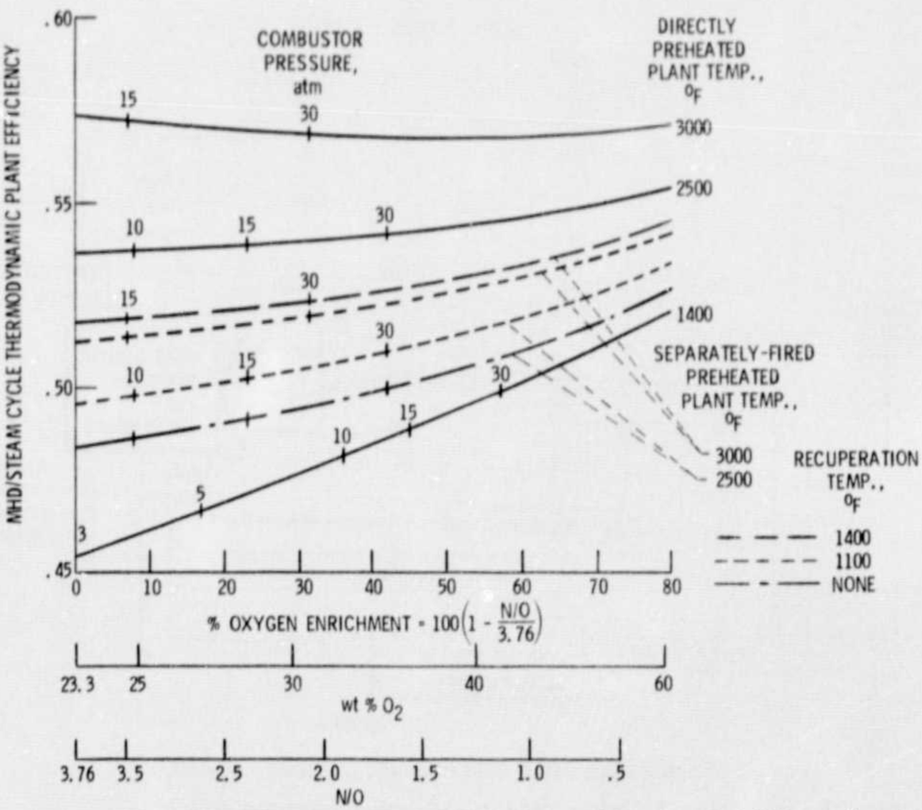


Figure 6. - Variation of MHD cycle performance with oxygen enrichment constant MHD generator exit conditions. Component performance equal or scaled from ECAS. Energy for oxygen production 300 kW-hr/ton.

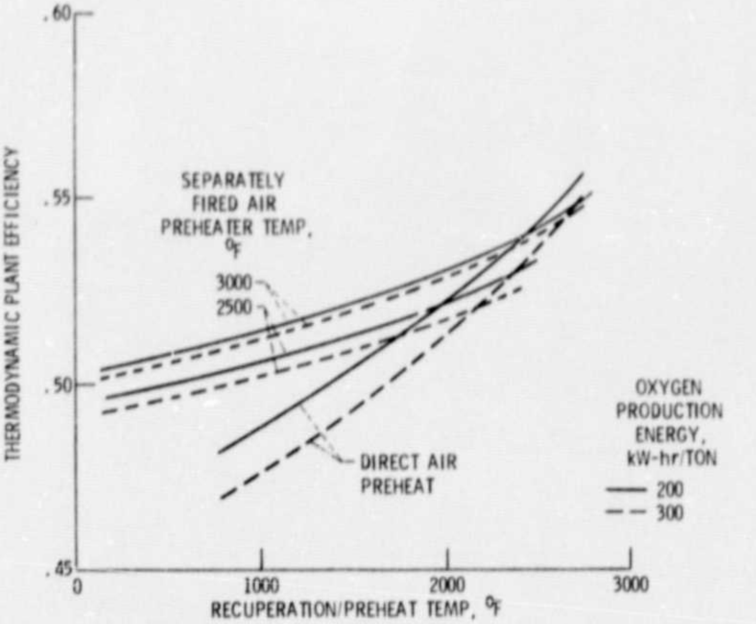


Figure 7. - Efficiency of altenative MHD/steam plants. 15 atm combustor pressure, O_2 added to maintain constant MHD generator exit T&P.