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COMPARATIVE ANALYSIS OF THE CONCEPTUAL DESIGN STUDIES OF POTENTIAL EARLY COMMERCIAL MHD POWER PLANTS (CSPEC)

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ABSTRACT

Tasks II and III of the Parametric Study of Potential Early Commercial MHD Plants (PSPEC) have essentially been completed. Task II (CSPEC) consisted of a conceptual design study of the MHD/steam plant that incorporated the use of oxygen enriched air preheated in a metallic heat exchanger as the combustor oxidant. This plant was found the most attractive for early commercial applications in Task I. In Task III the variation of performance and cost was investigated as a function of plant size. The efforts were performed by contractor teams led by Avco and General Electric Company. The Avco effort has been completed. The GE team has completed the plant design and performance studies but is presently reassessing the cost estimates for these plants. The contractors' results for the overall efficiencies are in reasonable agreement considering the slight differences in their plant designs. The Avco results varied from ~44 to 41 percent and GE's from ~43 to 39 percent as the plant size varied from ~1000 MW_e to 200 MW_e. Both contractors predicted reasonable performance (~42 percent) at a part load operating condition of 75 percent of full load. The Avco cost results were reasonably consistent with those presented in PSPEC and compare favorably with those for conventional coal-fired steam plants over the range of plant sizes from 200-950 MW_e.

There were some gross inconsistencies between the initial cost estimates presented by GE and their previous PSPEC results. GE is presently reevaluating the CSPEC costs.

NASA LeRC is currently performing a detailed review of these results. The cost and performance results are being examined for consistency with those of previous studies, including studies of conventional steam plants. LeRC in-house efforts have identified that there are still many tradeoffs to be considered for these oxygen enriched plants and that one can make considerable variations in channel length and level of oxygen enrichment with little change in overall plant efficiency. Calculations made for the GE Task II operating conditions indicate that one can reduce the level of oxygen enrichment from 37.6 to 30 mol percent O_2 in the oxidant (MPO) with an efficiency decrease of less than 0.1 percent. Thus, significant savings can be made in the oxygen plant costs. These results and a detailed discussion of some of the design approaches for some of the other major components indicate other tradeoffs to be considered in the final design of these plants.

Introduction

The Energy Conversion Alternatives Study (ECAS),[1,4] indicated the long range potential of open cycle MHD compared to alternative coal-fired power plant concepts. Open cycle MHD topped steam power plants were shown to have both one of the lowest costs of electricity and one of the highest efficiencies of all the concepts studied. The ECAS results showed that MHD plants could achieve efficiencies of ~50 percent, a 50 percent improvement over present steam plants. Two preliminary market penetration studies,[5,6] performed under EPRI contract indicated that such MHD plants could capture the future baseload power market. However, the MHD plants studied in ECAS were based on the use of directly-fired high temperature air heaters (HTAH) and the development of these air heaters to operate at 2500-3000°F appeared to be one of the pacing items in the development of these advanced MHD power plants.

Consequently, the PSPEC efforts were initiated to evaluate the potential of early commercial MHD plants that did not require the use of these directly-fired high temperature air heaters. The PSPEC effort was performed in three sequential tasks. In Task I, contracting teams investigated MHD/steam plants using separately-fired high temperature air preheaters and plants using intermediate temperature preheat and oxygen enrichment. Two categories of separately-fired air preheater plants were investigated; those using state-of-the-art gasifiers and those using advanced gasifier technology. In the evaluation of the plants using oxygen enriched air and intermediate temperature preheat the Lotepro Corporation oxygen plant data was used.

The results of Task I[7-9] indicated that the advanced gasifier technology plant efficiencies were a few points higher than those using state-of-the-art gasifiers and about equal to those using oxygen enriched air. Both the contractor and LeRC concluded that the cost and performance of the plants using oxygen enriched air preheated to 1100-1200°F in metallic tubular heat exchangers compared favorably with the higher technology separately-fired plants while requiring considerably less technology development. Thus these plants were chosen for further study in the Task II and Task III efforts.

Task II was a conceptual design study of a nominal 1000 MW_e MHD plant using oxygen enriched air preheated to 1200°F and was termed CSPEC. The goal of the study was to obtain a more detailed understanding and reach a more optimal design for this type of plant than was possible in Task I.

The purpose of Task III was to determine the performance and cost of power plants at the 500-600 MW_e and 200 MW_e size based on the conceptual designs developed in Task II. A comparative analysis of the Task II and Task III results is the subject of this report.

Two contracting teams performed this effort under LeRC contract and the effort was funded by the U. S. Department of Energy under an Interagency Agreement. The contracting teams were led by Avco and GE. The Avco team had Combustion Engineering and C. T. Main as subcontractors, while the GE subcontractors were Babcock and Wilcox, Mine Safety Appliances Company and Bechtel Group, Inc. In-house analyses were also performed at LeRC to supplement and guide the contractors' efforts.

In addition to the above-mentioned studies, the contracting teams also investigated part load performance, plant availability, and dual power trains. Avco varied the preheat temperature and GE studied alternate seed reprocessing systems.

The Avco efforts have been completed.[10,11] Due to the inconsistencies in the General Electric costs between the Task I and the Task II and III results, the GE effort is not as yet complete. LeRC is currently examining these differences in the light of past studies to ensure that these costs are generated on a common and consistent basis.

In this report a comparative analysis of the contractors' results and design approaches will be made. The effects of various design tradeoffs on performance and cost will be discussed and the results of LeRC's in-house performance analysis of these plants will be presented. In fairness to the contractor teams, it should be pointed out that due to programmatic decisions the Task II and III efforts were greatly accelerated. As the Task II and III reports were being written, the effort was halted. The analysis of the results has now been reinitiated, and we are just presently attempting to sort out the results with different staff members at both institutions.

Description of the CSPEC Power Plants

The plant arrangements investigated by the contractors had many similarities and some key differences. Many of the important design features and operating characteristics are listed in table 1. The main common design feature is that both incorporated the use of oxygen enriched air preheated to 1200°F in a metallic recuperative, tubular heat exhanger as the combustor oxidant. They did use different levels of oxygen enrichment, however, and this will be discussed in detail in a later section. Both contractors used Montana Rosebud coal dried to 5 percent moisture, diagonal channel designs, the formate seed reprocessing system and a 2400/1000/1000 steam bottoming plant.

Considering some of the differences, Avco uses one large single stage combustor whereas GE's two stage combustor approach consists of eight operating first stage units feeding a single second stage. Avco used nitrogen from the air separation plant as the coal drying medium after heating it in a flue gas to nitrogen heat exchanger. General Electric uses flue gas to dry the coal directly.

Even though both contractors use diagonal channels the method of construction used is different. Avco uses their 4-wall box type construction with split sidebars whereas GE uses diagonal window frames placed in a round pressure containment vessel. The GE construction technique is not as ammenable to efficient use of the magnet warm bore volume as the Avco approach. The Avco Magnet Volume Utilization (MVU) factor was ~0.46 whereas GE's was ~0.25.

Both contractors cooled their combustors with high temperature, high pressure boiler feedwater. Avco cooled the channel with low pressure boiler feedwater (LPBFW). GE has a separate cooling loop for the MHD channel which then heated the LPBFW through a heat exchanger.

The contractor steam bottoming cycles are both 2400 psig/1000 F/1000 F plants but each arranged their plants differently and integrated them with the topping cycle somewhat differently. In the Avco approach the steam turbines that drive the generator are in a tandem-compound arrangement. In parallel to these turbines is another turbine driven by main throttle steam to run the cycle and air separation unit (ASU) compressors. In the GE arrangement the steam turbines which drive the generators are in a cross-compound arrangement. GE used individual low pressure steam turbine drives for the five cycle compressors in Task II. In Task III a single large air compressor was used. Both GE plant designs use intercooled and aftercooled ASU compressors and GE transferred a portion of this energy to the steam bottoming cycle. The relatively high levels of oxygen enrichment used by GE forced them to higher pressures and the compressor pressure ratios used by them in Tasks II and III were 10.9 and 12 respectively. Consequently, GE also had to intercool and aftercool the oxidant stream as it passed through the cycle compressors. Again part of this energy was transferred to the steam bottoming cycle.

This larger amount of low grade heat transferred to the steam bottoming cycle had an impact on the bottoming cycle. GE was only able to incorporate four regenerative feedwater heaters in their steam plant whereas Avco had seven.

All plant designs met the NSPS for emissions of NO_x, SO_x, and particulates.

Plant Performance

The power plant efficiencies obtained by the contractors for the various plant sizes and operating conditions are given in table 2. The Avco results for the large scale plants (949 MW_e) were consistent from Task II to III and, in general, Avco's efficiencies are higher than GE's. The Avco efficiencies were reduced by 2.9 points as the plant size varied from 949 MW_e to 215 MW_e. The General Electric efficiency for the nominal 1100 MW_e plant varied between the Task II and Task III results and has n n the Task III data the performance dropped 3.7 points as the plant size was reduced to 200 MW_e.

LeRC's in-house analyses have shown that for plants at the optimal level of oxygen enrichment for each plant size and an 1100°F preheat level the performance variation was 2.5 points as the plant size was varied from 1000 to 200 MW_e.

Both contractors found that the plants performed reasonably well at a part load operating condition of 75 percent of full load. Both contractors kept the oxygen enrichment level constant as they went to the 75 percent load condition. Avco examined changes in the HRSR system as part of their part load analysis but did not attempt to optimize the HRSR design for the best part load performance. Avco found that at the 75 percent load condition the steam reheat and oxidant preheat levels were reduced to 955°F and 1070°F respectively. GE investigated part load ranges from 25 to 100 percent but did not consider any changes in the HRSR system as part of their analysis. Consequently, the GE results are most likely unrealistically optimistic for the part load conditions.

The Avco results for preheat temperatures of 1100 and 1300°F are also presented in table 2. The table shows about a 0.5 point variation in overall efficiency between these preheat levels. Avco oversimplified this study somewhat, however. The changes in preheat level were accompanied by changes in oxygen enrichment level to maintain the MHD generator performance and operating conditions identical to those at the 1200°F preheat level except for a slight variation in total gas flow rate resulting from changes in oxidizer flow rate. Consequently, the results are not optimized for the various preheat levels. However, analyses performed at LeRC for optimized power plants indicated about the same percentage increase in plant efficiency with each 100 degree increase in preheat temperature.

The significant power ratios for both contractors' results are presented in table 3. It is seen from the table that Avco had a lower combustor heat loss, and generally better generator and steam plant performance than GE. In addition Avco paid particular attention to low grade heat management and integration of the seed reprocessing plant with the overall power plant. These were the main reasons for the superior Avco performance. As one goes to smaller plant sizes, the performance decreases because of larger combustor heat losses and decreased channel performance.

For the 949 MW_e plant Avco used an oxygen enrichment level of 34 mol percent O_2, the channel was 21.5 m long; the inlet pressure was 8 atm.; and the enthalpy extraction was 24.5 percent. For the Task II 1110 MW_e plant the GE oxygen enrichment was 37.6 mol percent O_2, the channel was 18 m long, the inlet pressure was 9 atm.; and the enthalpy extraction 23.3 percent. The higher level of oxygen enrichment caused large compressor pressure ratios (10.9) and thus GE found it necessary to intercool and aftercool the oxidant (cycle) compressors for safety reasons. The further addition of this low grade heat to the steam plant feedwater heating chain lowers the steam plant efficiency. In addition, there are losses associated with these intercoolers.

The change in overall plant efficiency for the GE Task II (43.5) and Task III (42.7) 1100 MW_e plants is somewhat confusing. In the text of the draft Task III report GE stated that since the completion of the Task II they had modified their open cycle generator analysis code and that this modification would result in improved efficiencies. However, comparing the Task III channel with that of Task II we find that it is longer, 22 m vs. 18, operates at a higher inlet pressure, 10 atm. vs. 9, has a higher heat loss, 124 MW vs. 102 MW and a lower enthalpy extraction, 22.6 vs. 23.3 percent. In addition the compressor pressure ratio is increased to 12 which further accentuates the negative compressor intercooling impact on the bottom cycle efficiency. LeRC has performed a detailed investigation of the effect of oxygen enrichment and channel length on the performance of an 1100 MW_e plant using the GE specifications and operating conditions and these will be presented later. However, for the input conditions used for the GE Task III plant, LeRC's channel and plant design code yields an efficiency of ~43.1 percent. A final point to be made is that the Avco channel for the 949 MW plant and the GE Task III channel for the 1100 MW_e plant both generate 1.11 MW_e for each kg/s of gas flow so they are similar in that respect.

Capital Costs and Cost of Electricity

The economic parameters used in calculating the levelized cost of electricity are given in table 4 and the Avco cost and performance results are given in table 5. The results for the ECAS reference steam plant updated by Burns and Roe[12] to meet the NSPS emissions standards are also shown in table 5 as well as C. T. Main's cost estimates for conventional steam plants with stack gas scrubbers.

The results in table 5 show that the C. T. Main conventional steam plant estimates are consistent with those of the updated reference steam plant, that the steam plants have lower capital costs than the MHD plants, and that the superior efficiency of the MHD plants results in lower COE's at all plant sizes. It should be pointed out that these results are for a fuel cost of \$1.05/MBTU. At present day fuel costs of ~\$1.50/MBTU the $\overline{COE}$ advantage of MHD plants would be increased by another 2.3 mills/kWhr.

In the Avco efforts there was a consistency between Task I, II, and III efforts. However, there were vast inconsistencies in the GE results between Task I and Task II and III and inconsistencies in accounts between MHD plants and conventional steam plants that we could not easily reconcile or have not as yet been reconciled. Consequently, we have asked for further information on the GE costs. GE is currently preparing this information for LeRC. We are, however, comparing the GE preliminary data with the Avco results, past GE and/or Bechtel studies, the updated ECAS reference steam plant and cost data in the Gilbert Associates cost data book for MHD/steam and conventional steam power plants. The Gilbert data is referred to as the "Model" in the report and is based on the average cost data for components and cost categories taken from a large number of past studies. The purpose of LeRC's effort is to help reconcile any costing inconsistencies, identify potential improvements and compare design approaches.

However, before we present any specific results there are two items we would like to address that will aid in the following discussions. The first is the sensitivity relationship between efficiency and $\overline{COE}$ and the second is the impact of the use of low pressure boiler feedwater (LPBFW) as a channel coolant on the steam bottom plant efficiency.

Relationship between Capital Cost, Efficiency and $\overline{COE}$

The expression for the levelized $\overline{COE}$ is

$$\overline{COE} = \frac{(CAP)(FCR)}{(8760)(CF)\,P_E} + LEV\,\frac{3.413\,F}{\eta} + LEV\,\frac{OM}{(8760)(CF)\,P_E}\ \frac{mills}{kW\text{-}hr} \qquad (1)$$

where CAP is the plant capital cost, CF is the capacity factor, FCR is the fixed charge rate, P is the plant power output in MW, LEV is the levelization factor, F the fuel cost in \$/MBTU, η is the plant efficiency and OM the plant operating and maintenance costs in \$/yr.

For FCR = .18, CF = .65, LEV = 2.004, and $P_E = \eta P_{th}$ equation (1) becomes

$$\overline{COE} = 3.16 \times 10^{-5}\ \frac{CAP}{\eta P_{th}} + 6.84\,\frac{F}{\eta} + 3.52 \times 10^{-4}\ \frac{OM}{\eta P_{th}}\ \frac{mills}{kW\text{-}hr} \qquad (2)$$

For the Avco Task II MHD/steam plant, P_{th} = 2164 MW_t, F = \$1.05/MBTU, OM = 11.054 x 10^6 \$/yr so the relationship between $\overline{COE}$, η, and CAP becomes

$$\eta \cdot \overline{COE} = [.0146]\ CAP + 8.97\ mills/kWhr \qquad (3)$$

Or if we wish to hold the $\overline{COE}$ at a constant reference value say $\overline{COE}$ = 42.9 mills/kWhr one gets

$$CAP \approx (\eta - 0.209)\ 2.94 \times 10^3\ M\$ \qquad (4)$$

Equation (4) thus gives us a relation between the plant capital cost (CAP) in M\$ and the plant efficiency for a constant reference $\overline{COE}$ of 42.9 mills/kWhr. Thus the sensitivity between η and CAP for changes around the design point may be obtained. For the Avco Task II plant a single percentage point change in efficiency is worth ~34 M\$ in capital cost, meaning that if we make a change in the plant design that lowers η by one point we must reduce CAP by 34 M\$ to keep the $\overline{COE}$ constant. If CAP is lowered by more than 34 M\$ we are improving the $\overline{COE}$ and the change is recommended. If the reduction in CAP is less than 34 M\$ the plant COE increases and the change is not recommended. This relationship then serves as a guideline in making modifications to the initial plant designs.

Effect of MHD Channel Cooling Upon Steam Plant Efficiency

In some past studies of advanced MHD/steam plants the MHD generator was cooled with high pressure boiler feedwater and in that case the heat rejected by the MHD generator has little or no impact on the bottoming cycle steam plant efficiency. Thus if one optimized the MHD power output minus the required compressor power, the highest overall plant efficiency was generally obtained. However, in the early commercial MHD plants presently being studied the MHD generator is cooled by LPBFW and this has a direct effect on the steam plant efficiency since it affects the plant's regenerative feedwater heating arrangement.

In the LeRC systems analysis methods[13] the steam bottoming cycle efficiency is calculated along with the overall plant performance using a steam cycle computer code. Except for the feedwater heating arrangement the basic cycle configuration and method of integration with the topping cycle are kept constant as we make variations in conditions such as channel length, level of oxygen enrichment, etc. A fixed MHD generator cooling water outlet temperature of ~260°F is maintained for the LPBFW cooled cases. The feedwater heating train upstream of the generator cooling is varied to meet this condition as the generator heat loss changes by varying either the number of feedwater heaters in this portion of the train or their operating condition.

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 a 500 MW_e plant as a function of the MHD generator heat loss when the remaining factors discussed above are held fixed. The figure shows that there is a considerable variation in bottoming cycle efficiency with generator heat loss and consequently if one increases the channel heat loss by increasing the channel length or level of oxygen enrichment, etc., one may improve the net MHD power output but actually reduce the overall plant efficiency because of the low steam plant efficiency. This effect will be illustrated later in the analysis of variations in plant performance with level of oxygen enrichment and channel length. It should also be pointed out that the bottom cycle efficiency can be further reduced if the steam plant must also accept low grade heat from other sources such as the compressor intercoolers as was done in the GE study.

Specific Subsystem Cost Comparisons

Plant Layout

One area where extreme care must be taken is in the overall plant layout. LeRC found in the ECAS study that the overall plant costs could be reduced significantly by modifying the initial plant layout. Avco and GE followed quite different philosophies in the plant layouts for the nominal 1000 MW_e plants. The overall plant layouts are shown in figures 2 and 3. GE has an overall plant size of 450 acres, dominated by a 232 acre slurry pond. They also specified that 5 more slurry ponds would be required to last the 30 year life of the plant bringing the total acreage to 1500 acres. The Avco overall plant layout required 676 acres which included a 23 acre waste disposal area, which they indicated would store the ash and gypsum generated during the entire plant life.

The enlarged plant island sketches are shown in figures 4 and 5 for Avco and GE, respectively. Avco uses a 23 acre plant island and contain most functions in a single building having interconnected wings. GE has a 30 acre plant island with 8 major buildings, each separate and performing separate functions. LeRC is presently working with GE to improve the GE plant layout and is attempting to resolve some inconsistencies. On a $/$kW_e$ basis the GE Task II costs for structures and improvements increased by 167 percent between Task I and Task III. They are ~300 percent higher than those of Avco and the Model and 270 percent higher than the modified ECAS reference steam plant. The Model shows that in general fossil plants run 5-10 percent higher than MHD plants in this account because of the Flue Gas Desulfurization equipment. In the light of these comparisons, GE is currently reevaluating these costs and the overall plant layouts.

Variations in Oxygen Enrichment

In the CSPEC studies Avco used an oxygen level of 34 mole percent oxygen (MPO) in the oxidant and GE 37.6 for the nominal 1000 MW_e plants. LeRC feels strongly that particular attention should be paid to determining the optimum level of MPO for each plant under consideration. If the oxygen content is too high one not only encounters excessive oxygen plant costs but also may lower the overall plant efficiency when LPBFW channel cooling is used. LeRC felt that the GE 37.6 MPO level was too high and consequently we made a series of plant calculations for a nominal 1100 MW_e plant (same as GE's) using the GE component heat losses and channel constraints.

The results of these calculations are presented in figure 6. The overall plant thermal efficiency is plotted versus mole percentage oxygen in the oxidant for a variety of channel lengths and for two methods of channel cooling in this figure. The solid symbols represent cases in which high pressure boiler feedwater (HPBFW) is used for channel cooling and the open symbols represent those for which LPBFW was used.

It should be pointed out that each point on the figure is the result of a number of calculations and represents the optimum efficiency for that level of oxygen enrichment. The figure shows that for the HPBFW cases the plant efficiency increases with oxygen level, MPO, for all channel lengths considered and is higher than that for the LPBFW cases. This data indicates the potential improvements attainable if advanced channel designs are developed that can use HPBFW cooling. Also note that for a 20 m channel the increase in efficiency (~1.4 points) indicates that one could expend considerable resources (1 point = 34 M$) to improve the channel design and still have the potential for lower $\overline{COE}$.

For the LPBFW cases used in these early commercial plant studies the efficiencies do not change much over the MPO levels of oxygen enrichment considered. For the 18 m channel similar to that for the GE Task II effort the efficiency optimizes at an MPO of 32 percent. And at a 30 percent level the efficiency is less than 0.1 percent below the optimum. Consequently GE used a much higher enrichment level than was necessary and hence reductions in oxygen plant costs may be obtained for their 1100 MW_e plant by going to lower enrichment levels.

In order to estimate the potential savings attainable by reducing the MPO level we must first discuss the contractors' original oxygen plant costs. NASA supplied the contractors with cost data obtained from the Lotepro Corporation. These costs were turnkey overnight construction costs (ONCC) costs and included buildings, the main air separation units, the air boost and driver compressors, and the oxidant or main MHD cycle compressor. All contingencies, etc. were included in these estimates. For reference, using the Lotepro estimates, a 10,000 ton per day (TPD) (of contained oxygen) plant turnkey plant cost = $100.5 x 10^6 based on the use of four 2500 TPD trains, and a 7500 TPD plant = $77 x 10^6 on the same basis. Both contractors decided to supply their own oxidant (cycle) compressors for this study and neither arrived at the same ONCC for the ASU + cycle compressor as the Lotepro quotes.

In order to aid the discussion the Lotepro ONCC (excluding the cycle compressor) in mid 1978 $ is plotted versus oxygen train size in figure 7 and the tons per day required for the 1100 MW_e (GE) and 949 MW_e (Avco) plants is plotted in figure 8.

Considering figure 8, one sees that for a 950 MW_e plant using oxidant with a 34 percent O_2 concentration one requires ~ a 7300 TPD plant. Avco decided to use three 2500 TPD trains and estimated the overall oxygen system cost as $70.1 x 10^6, based on 60 M$ for the oxygen plant and 10.1 M$ for the cycle compressor. The Lotepro turnkey plant costs for the same system is 77 M$ based on the data in figure 7 and adding Lotepro's compressor costs. Avco's number is lower than Lotepro's because they broke the main oxygen plant into its major components and applied C. T. Mains' multipliers to obtain the final cost and these were smaller than Lotepro's. Avco also housed the compressor in the main MHD building and it is difficult to determine the portion of that building's cost that should be charged to the oxygen plant for comparison purposes. It does appear, however, that the Avco oxidizer system should perhaps be increased in cost by ~7 M$ to be consistent with the Lotepro cost estimates.

At the 37.6 MPO level one sees from figure 8 that GE required ~9900 TPD plant capacity and GE used five 2000 TPD plants. The GE cost estimate for this system was 155.6 M$ based on 102.7 M$ for the oxygen plant, 43.7 M$ for the cycle compressor system and 9.2 M$ for oxygen and air compressor buildings. The Lotepro turnkey cost for this system would be 105 M$ based on the data in figure 7 and a Lotepro supplied cycle compressor and drive system. Thus it appears that GE has overestimated the oxidant system cost by ~50 M$.

Further reductions in the GE oxidant system are easily attainable by going to lower MPO levels with essentially no change in overall plant efficiency. From the data in figure 6 and using the same 18 m channel we can use an MPO level of 30 percent with a net change in plant thermal efficiency of less than .05 percentage points. The required oxygen plant capacity is then 6640 TPD (figure 8) and the turnkey oxygen plant cost is 72 M$ based on three 2250 TPD trains. Thus a total reduction of 155 M$ - 72 M$ = 83 M$ is realizable based on the original GE estimate for this system.

In addition to this reduction, the overall plant is simplified since the combustion pressure is significantly reduced and the oxidant compressor intercoolers with their concommitant heat losses are no longer required.

The data in figure 6 would indicate that Avco may also reduce their oxygen enrichment level somewhat with little or no efficiency penalty.

However, the reduction in oxygen plant costs is not the whole story. In the LeRC channel analysis we find that as one goes to the lower levels of oxygen enrichment and B_{max} = 6T, the magnetic energy stored in the channel volume generally increases if the channel length is kept constant. The magnetic energy in the channel volume is plotted versus plant efficiency for the LPBFW data on figure 6 in figure 9. Figure 9 shows that changing the oxygen enrichment level from 37.6 to 30 MPO for L = 18 m increases the magnetic stored energy from 1375 to 1855 MJ because of the higher average B field and will hence cause an increase in the magnet cost that could partially offset the oxygen plant savings. LeRC cannot quantify the changes in magnet costs at this time. The increases in magnet costs can be partially overcome by reducing the channel length and hence the plant efficiency. Consequently, one would have to optimize the tradeoffs between the oxygen plant costs, the magnet costs and the plant efficiency using the relation 1 percentage point ≈ 34 M$.

<u>The Heat Recovery Seed Recovery System (HRSR)</u>

The HRSR is another major system in which there were significant cost differences that were driven by differences in design philosophy as will be shown below. Again, this is another area that requires careful investigation and perhaps the differences can be resolved as data from the DOE HRSR development program becomes available.

The costs for the HRSR systems are given in table 6. The table shows that the GE-Babcock and Wilcox HRSR costs approximately half that of the Avco-Combustion Engineering HRSR. In general, the capital cost differences of HRSR's of comparable generic design can be directly related to their total heat transfer areas and this holds true for the present Avco and GE HRSR's.

The heat transfer surfaces for both the Avco and GE systems are deployed in two sections — within a primary HRSR structure and in secondary heat exchangers external to the main structure. The component arrangements for the complete HRSR systems are shown schematically in figures 10 and 11 for Avco and GE, respectively.

Conceptually, the designs of the Avco and GE HRSR systems are similar; however, each HRSR configuration is influenced by the design of the respective coal drying systems. Referring to figure 10, the Avco system uses nitrogen heated by flue gases for coal drying. As shown in figure 11, the GE system uses flue gases directly for coal drying. The selection of nitrogen drying by Avco thereby impacts the cost of the HRSR, since the nitrogen heater is included as 25 percent of area in that system whereas the GE coal dryer is not a part of the HRSR cost.

The location of the electrostatic precipitators (ESP) also influences the heat transfer equipment design in the respective systems. Examining the quantities of seed and ash deposits predicted for the various sections of the Avco HRSR reveals that 62 percent of the total HRSR ash and seed input are still in the system before being removed in the ESP, which is downstream of all the HRSR components. This means that the flue gases flowing through the economizers, secondary air heater and nitrogen heater are heavily laden with seed and ash that can foul heat transfer surfaces. All of these units are equipped with sootblowers to remove fouling deposits. Locating the GE system ESP directly downstream of the convective section outlet precludes the downstream heat transfer fouling problem described above. The GE ESP must operate at 553 F vs. 252 F for the Avco ESP, but this is not a problem since hot-side ESP's have demonstrated high removal efficiencies with low sulfur bitiminous coals. The Avco system could perhaps benefit from similar ESP placement.

Referring to figures 10 and 11, both the Avco and GE HRSR systems combine a radiant boiler and convective heat transfer sections within a single structure to comprise the steam generator. The physical arrangement of the various heat transfer sections within the steam generators are shown in figures 12 and 13 for the Avco and GE systems, respectively. Briefly described, the Avco steam generator design is a three-pass systems (up, across, down) featuring a long horizontal traverse. The GE design is basically a two-pass system (up, down) with a short horizontal transition. The Avco heat transfer area is spread out over a greater horizontal distance than the GE system. The GE approach will result in a much more compact and simple configuration if the HRSR development program indicates that one can use the close tube spacings.

Both systems utilize refractory-lined radiant boilers having wet bottoms and convective sections with dry bottoms. Hot gases from the MHD diffuser enter both the Avco and GE radiant boiler sections at the bottom and flow upward, after which secondary air is admitted to complete the combustion of unburned fuel. The secondary air nozzles are at the top of the radiant boiler section in the Avco unit, the bottom-most nozzle being approximately 80 feet from the boiler bottom. After secondary combustion, the gases flow across arrangements of vertical pendants and panels for a distance of approximately 100 feet before flowing downward through the low temperature reheater tube banks and exiting at the bottom of this pass.

In contrast to the Avco flow path, gases leaving the GE secondary combustion zone 75 feet from the boiler bottom continue upward for another 40 feet to the "nose" section of the boiler. The purpose of the nose is to induce even gas flow across the vertical superheater pendants at the top of the boiler section and to prevent bypass around the pendant bottoms. After leaving the pendant area, the gases travel downward through tube banks in the convective section before exiting at the bottom.

A better understanding of the heat transfer configurations in the two systems can be obtained by studying the heat transfer area details provided in tables 7A and B. Comparing the transverse and longitudinal tube spacings for the Avco and GE surfaces shows that the Avco tubes are generally further apart. Thus, the Avco design concept requires a larger volume to deploy equivalent heat transfer areas.

The heat transfer surface areas and the volumes for the various HRSR sections are given in table 8. The surface areas were taken directly from the respective CSPEC reports, while the volumes were calculated from the dimensions shown in figures 12 and 13 based on right rectangular shapes. Using the table 8 area and volume information and the HRSR operating conditions, heat transfer parameters were calculated. Packing densities were calculated by dividing the heat transfer areas by the volumes of each HRSR section. These values serve as relative indicators of the tube spacing effects discussed above, i.e., the larger the value, the tighter the packing. Significantly, the GE packing density in the convective section is approximately twice that of Avco's. The Avco convection section contains 51 percent of the steam-producing heat transfer area and the corresponding value for GE is 55 percent.

Superficial mass velocities were calculated by dividing the HRSR gas flow rates by the respective contact areas. These mass velocities can be used as pseudo heat transfer coefficients on a comparative basis. Thus, comparing values for Avco and GE in the convective sections shows that with the exception of the reheater, the GE coefficients are much larger than the corresponding Avco coefficients. The higher GE coefficients are the result of higher packing densities and low fouling factors. The net result is that under the GE assumptions one requires less heat transfer area to produce a larger amount of steam.

On the basis of the foregoing analyses, the primary difference in the Avco and GE HRSR design concepts is that Avco is much more conservative than GE regarding anticipated fouling and corrosion/erosion problems. Both Avco and GE used essentially the same tube materials for corresponding duties, so corrosion and stress problems are not an issue. The large tube spacings used by Avco relative to GE indicate a concern with lowering gas velocities to reduce erosion from ash and seed particles, but another reason is to eliminate bridging of particles and thus reducing fouling.[14]

To further reduce fouling, Avco uses vertically-oriented tube assemblies in the convective sections. Avco also provides 320 soot blowers throughout the HRSR to periodically clean the fouled surfaces. The GE design uses horizontal tube banks in the convective section, which provide greater heat transfer rates but are more susceptible to fouling. A total of 156 sootblowers is used by GE, all in the superheater (nose) and convection sections.

The operating ratios in table 9 depict the relationship of the Avco and GE steam generators, in that Avco requires 40 percent more heat transfer area to produce 85 percent of GE's gross steam power. On a gross power basis, the Avco design requires 66 percent more area per MWe than GE.

Based on the foregoing discussion, Avco has adopted a conservative HRSR design philosophy that results in a large heat transfer area relative to GE. Until the DOE HRSR development program produces sufficient data to compare with the CSPEC design assumptions it will be difficult to fully evaluate these design approaches. However, it does appear that the Avco team might benefit from a reexamination of their design philosophy (ESP placement, etc.).

GE attempted to demonstrate that their design approach was conservative by comparing their calculated steam-producing heat transfer area with those in two commercial fossil steam generators. On a ft^2/MWe basis, the GE HRSR design has 2.0 to 2.7 times more area. However, these comparisons are difficult to make since the GE boiler size compared was the net MWe rating rather than the gross size. The GE HRSR system uses 206 MWe of steam to drive compressors, whereas the commercial boiler auxiliary steam requirements, if any, are not known. In addition the GE HRSR sees 184,300 lb/hr of seed flow, which does not exist in commercial boilers. It would appear that the GE HRSR design approach is more conservative than that for a conventional plant but the exact degree of conservatism is difficult to assess.

MHD Magnets

In general, the MHD magnet costs for the two contractors are in agreement considering the different magnet and channel design approaches followed by the contractors. The costs are given in table 10. The table shows that the major component costs are roughly equivalent and the final difference is ~18 M$ after the different A and E's multipliers are included. There are two reasons why the GE costs, which are based on a scale-up of the CDIF magnet design, are higher.

Avco used a 4 wall square box type construction for the MHD channel that makes good use of the magnet warm bore volume. The Magnet Volume Utilization factor (MVU) for Avco is ~0.46. GE, on the other hand, used a square window frame construction enclosed in a round pressure vessel which did not make good use of the magnet's warm bore volume. GE's MVU was ~0.28. The Avco magnet warm bore dimensions were 1.73x1.73 m at the inlet and 3.3x3.3 m at the exit for an active channel length of 21.5 m. General Electric's were 2.7x2.25 m at the inlet and 4.5x4.5 m at the exit for an active channel length of 18 m. Consequently, one sees that the GE approach requires a much larger magnet warm bore volume.

Another difference is in the manner in which the channel designers specified the required B-field profile to the magnet designer. Avco followed the method usually used by LeRC. Performance calculations are determined assuming a specific B-field profile and once an optimum design point is obtained the channel results are modified to use the natural B-field profile given by a rectangular saddle coil magnet. This is usually accomplished with a negligible change in the overall plant performance. GE, on the other hand, specified a uniform B-field of 6T for nearly the whole first half of the channel and the magnet design was modified to attempt to supply this field profile. GE estimated that this increased the magnet cost by ~15 percent. Relaxing this constraint could then reduce the magnet cost by ~12 M$.

Thus from table 10 one sees that the costs are well in agreement considering the different MVU's for each contractor and that perhaps the GE design approach could result in even cheaper magnets if their channel design philosophy were modified to make better use of the magnets warm bore volume.

Concluding Remarks and Future Efforts

The authors apologize for the fact that a complete cost comparison cannot be made with the data at hand. We feel that we have pointed out, however, the types of problems that we are investigating and the extreme importance of paying very close attention to such items as plant layout, levels of oxygen enrichment, HRSR design and channel and magnet designs. In addition one must pay close attention to the integration of the steam plant and seed recovery system with the overall plant to obtain the best plant efficiencies. There is a tendency to modify plant and/or channel designs to find methods to reduce the magnet costs. If nothing else, we hope the above exercise has shown that there are many other tradeoffs to be considered that can also result in significant capital cost savings and lower COE's.

Figure 14 summarizes the efficiency and cost of electricity results from all the NASA-managed coal-fired, open-cycle, intermediate or high-temperature directly preheated, MHD plant conceptual design studies conducted for DOE: CSPEC and the parallel ETF conceptual design,[15,16] previous contractor ETF conceptual studies,[14,17] and ECAS. For comparison, the updated ECAS reference steam plant is also included. Variation of steam plant COE with plant size is based on Avco/C. T. Main CSPEC estimates, which are in excellent agreement with the reference steam plant. All COE's are calculated in mid-1978 dollars using the CSPEC ground rules and a coal cost of $1.05/10^6 Btu. Figure 14 presents the COE's relative to that of the reference steam plant which is more meaningful and less sensitive to the year of calculation and other economic assumptions.

Figure 14 shows that even very small 100 MW MHD plants offer an efficiency potential competitive to large steam plants. Two hundred MW_e prototype size plants have an efficiency potential of approximately 40 percent; significantly higher in efficiency than steam plants and competitive in COE to equivalent sized steam plants.

Comparing larger MHD plants with steam plants: early commercial MHD plants offer potential improvements of both 30 percent in efficiency (an efficiency approaching 45 percent) and 10 percent in COE, and more advanced MHD plants have potential for improvements of both nearly 50 percent in efficiency (an efficiency of 50 percent) and 25 percent in COE. An efficiency of 50 percent, which is higher than the ECAS plant, can readily be configured by replacing that plant's inefficient non-integrated seed reprocessing plant with a well-integrated low loss approach such as defined in the subsequent Avco ETF studies and CSPEC.

The PSPEC studies completed to date have shown the excellent potential of early commercial MHD/steam plants for high performance at a reasonable COE. Some of the key areas that LeRC is investigating in their comparative analysis and that will be modified in the GE reevaluation have been pointed out. The importance of identifying the optimum level of oxygen enrichment for each set of operating conditions and careful integration of the steam plant and seed reprocessing plant with the overall plant have also been identified.

There are many areas that still required further investigation, however; the tradeoffs between plant efficiency, level of oxygen enrichment, and stored magnetic energy must be pursued more fully from an economic viewpoint, the use of supersonic Mach number and lower B fields should also be investigated. An area of particular interest would be to extend the technology somewhat to study plants intermediate in performance to the early and advanced commercial plant designs. These intermediate plants could use either regenerative or recuperative refractory heat exchangers to preheat the combustor oxidizer to 1600-1700F.

The inlet MHD exhaust gas temperature to the heat exchanger would be limited so as to only expose the heater to solid particulates of the seed and slag compounds. Reference 18 evaluates alternative ceramic heater approaches to obtain 1600F preheat and concludes that design and construction of 1600F regenerative heaters could be accomplished with presently available industrial materials and technology.

New oxygen plant designs that can result in higher overall plant efficiencies have been identified by LeRC and Lotepro and these will be included in future MHD/steam plant studies. Finally, the ECAS reference MHD plant should be updated to include using the Formate seed reprocessing plant. A potential gain in efficiency of ~4 percentage points may be obtained by using the Formate process. Many of these areas are being addressed in the LeRC managed Phase I APT Program Definition effort that is just getting underway.

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TABLE 1 - CSPEC POWER PLANTS

	AVCO			GENERAL ELECTRIC			
	Task II	Task III		Task II	Task III		
Plant Size MW_e	949	504	215	1110	1090	600	200
Coal Type	Montana Rosebud						
% moisture as fired	5						
coal drying medium	Nitrogen			Flue Gas			
Combustor Type	Single Stage			Two Stage			
% ash rejection	80			90			
Design pressure, atm	8.3	7.5	5.5	9	10	9.6	6.1
Oxidizer mole % O_2	34	34	32	37.6			
O/F ratio	0.9						
Seed % K by weight	1.0			1.6			
MHD Generator Type	Diagonal						
Construction	4 Wall Box-Split Sidebar			Diagonal Window Frame-Round Pressure Shell			
Length	21.5	18	12	18	22	17	12
Cooling	LPBFW			LPBFW - Separate Loop			
Peak Magnetic Field, T	6.5	6.0					
Bore area/gen. flow area	1.5	2.3	2.7	3.0		3.0	
Seed regeneration	Format e						
Bottoming Steam Cycle	2400/1000/1000						
Generator drive arrangement	Tandem Compound			Cross Compound			
Air Separation Plant							
Trains	3	2	1	5	5	3	1
Capacity TPD contained oxygen	7344	3996	1618	9828	9828	5896	1966
Product purity made %	80						
Approx. power consumption kWhr/ton equiv. pure O_2	200						

TABLE 2 - POWER PLANT EFFICIENCIES

	AVCO				GE			
TASK	II	III			II	II		
Plant Size (MW_e)	949	949	504	215	1110	1090	637	200
Overall Efficiency %	43.9	43.9	42.9	41	43.5	42.7	41.5	39
Part Load Eff. 75% of nominal	41.8	-	-	-	42.3	-	-	-
Preheat Temperature								
1100F	43.6	-	-	-				
1300F	44.1	-	-	-				

TABLE 3 - POWER RATIO VALUES

	AVCO			GE			
				TASK II		TASK III	
PLANT SIZE (MW_e)	949	504	215	1110	1090	637	200
1. MHD generator input / Combustor input	.975	.968	.964	.943	.947	.935	.892
2. MHD DC output / MHD generator input	.224	.206	.169	.232	.222	.202	.158
3. MHD AC output / Power plant output	.537	.502	.432	.544	.534	.492	.391
4. Bottoming cycle output / Bottoming cycle input	.418	.416	.414	.414	.412	.413	.416
5. ASU compressor drive / Coal input (HVV)	.027	.027	.024	.030	.030	.030	.031
6. Plant auxiliary / Coal input	.018	.017	.017	.014	.015	.015	.016
7. Stack loss / Coal input	.091	.092	.091	.099	.099	.099	.099
8. Other losses / Coal input	.014	.014	.017	.020	.020	.020	.021
9. Coal/coke to seed plant / Coal input	.013	.014	.013	.014	.011	.011	.012
10. Overall plant efficiency	.439	.429	.409	.435	.427	.415	.390

TABLE 4 - ECONOMIC PARAMETERS USED IN CALCULATING LEVELIZED COST OF ELECTRICITY

Capital cost portion including escalation and interest during construction

"Overnight" construction cost estimated by contractor
Construction period estimated by contractor
ECAS[7] cash flow curve during construction
6.5 percent annual escalation rate
10 percent annual interest rate
18 percent fixed charge rate
65 percent capacity factor

Fuel cost portion

$1.05 per million Btu mid-1978 fuel prices

Operation and Maintenance (O and M) cost portion

Estimated by contractor

Fuel and O and M costs levelized with factor 2.004[10]; this corresponds to

Escalation and interest as above
No real fuel price escalation
30 year plant life

Final levelized COE is expressed in mid-1978 dollars

TABLE 5 - SUMMARY OF THE AVCO COST AND PERFORMANCE RESULTS

	MHD/STEAM PLANTS-AVCO			C. T. MAIN CONVENTIONAL STEAM PLANTS			ECAS REFERENCE STEAM PLANT
Plant Size (MW_e)	950	500	200	950	500	200	800
Overall Efficiency %	43.9	42.9	41.0	34.3	34.3	34.3	34.4
Levelized COE (mill/kWhr)	43.8	48.5	57.5	47.8	52.2	59.6	48.6
Overnight Capital Cost (M$, mid-1978)	614	390	219	570	367	185	490
$/KW_e$, (mid-1978)	646	780	1095	600	734	924	613

Table 6

HRSR COST ESTIMATES

(Mid-1978 Dollars x 10^{-3})

Estimator	Account	Major Component	Balance of Plant	Installation Cost	Indirect Cost	Contingency	Total Cost
Avco-CE	HRSR	72,769	1,896	20,071	10,036	10,477	115,249
GE-Bechtel and B&W	HRSR	35,560	2,017	14,275	2,273*	5,413	59,538
		(1)	(2)	(3)	(4)		

Indirect Cost: Avco - 50 percent of Installation Cost
GE - *Indirect Cost of Electrical equipment (BOP) only; no Indirect Costs associated with B&W boiler erection per appendix C of GE report.

Contingency: Avco - 10 percent (1 + 2 + 3 + 4)
GE - 10 percent (1 + 2 + 3 + 4)

Table 7A

HRSR HEAT TRANSFER AREA DETAILS

AVCO

Item	Location	Tube OD (Inches)	Transverse Spacing (Inches)	Longitudinal Spacing (Inches)
SH-Finishing	CS	2	6	4.5
SH-Front Platen	SRS	2.13	22.5	2.38
SH-Panels	SRS	2	45	2.25, 2.38
SH-Rear Pendant	CS	2	6	4.5
RH-Finishing	CS	2.5	9	2.75
RH-Low Temperature	RP	2.5	6	4.5
Oxidant Heater	CS	2.5	6	4.5
Econ-LP	E	2	5.5	4.5
Econ-HP	E	2.5	5	4
Lt Air Htr	LA	1.25	4.25	3.25
Lt N_2 Htr	LN	1.25	4.25	3.25

SRS - Seed Recovery System

CS - Convective Section

RP - Rear Pass

E - Economizer Section

LA - LT Air Section

LN - LT N_2 Section

Table 7B

HRSR HEAT TRANSFER AREA DETAILS (continued)

GE

Item	Location	Tube OD (Inches)	Transverse Spacing (Inches)	Longitudinal Spacing (Inches)
Secondary Superheater	AN	2.5	24	3.25
Primary Superheater	CS	2	4	2.75
Reheater, Upper	CS	2.5	8	3.25
Reheater, Lower	CS	2.5	4	3.25
Economizer	CS	2	4	2.75
Oxidant Heater	CS	3	6	3.75
A.H. (SAH-1)	LA	2	9/6/3	2.75
A.H. (SAH-2)	LA	2	3	2.75
Low Level Economizer	LA	2	3	2.75

AN - Above Nose Section

CS - Convective Section

LA - LT Air Section

Table 8

HRSR HEAT TRANSFER AREAS AND VOLUMES

Item	Avco		GE	
	Surface Area, Ft^2	Type of Unit	Surface Area, Ft^2	Type of Unit
Radiant boiler	72,182	Refractory furnace	50,483	Refractory furnace
Superheaters	301,758	Panels, platens	166,763	Pendants
Oxidant heater	301,403	Pendants	166,320	Tube banks
Reheaters	269,830	Pendants, tube banks	361,636	Tube banks
Economizers	448,855	Tube banks	250,821	Tube banks
Low temp. air heaters	305,585	Tube banks	249,191	Tube banks
Nitrogen heater	569,217	Tube banks	---	---
Low level economizer	---	---	5,498	Tube banks
TOTAL	2,268,830		1,250,712	
	Volume, Ft^3*	Dimensions, Ft	Volume, Ft^3*	Dimensions, Ft
Radiant boiler	225,576	48 x 46.3 x 115	313,650	51 x 82 x 75
Convection section	1,110,780	187 x 54 x 110	373,428	33 x 82 x 138
Economizers	217,095	150 x 35.3 x 123	In convect. sect.	---
L.T. air heaters	159,068	92 x 19 x 91	16,092 13,230	29.8 x 18 x 30 24.5 x 18 x 30
Nitrogen heater	299,725	92 x 33.5 x 97.25	---	---
L.L. economizer	---	---	3,969	24.5 x 18 x 9

*Right rectangular volum

Table 9

HRSR OPERATING PARAMETERS

HRSR Parameter	Avco	GE	Steam Plant Operating Ratios - Avco/GE
Primary steam flow rate, lb/hr	4,713,710	4,831,900	0.98
Reheat steam flow rate, lb/hr	2,775,956	4,230,100	0.66
Gross boiler output, MWe	647.3	861.1	0.85
Boiler plus convection area, ft^2	1,394,028	996,023	1.40
Area/boiler output, ft^2/MWe	2,154	1,297	1.66

Table 10

MAGNET COSTS (M$)

	Major Comp.	POA	Inst.	Ind.	Cont.	Total
Avco	51,970	-	437	219	10,520	63,152
GE	58,330	2800	3505	3155	13,558	81,348

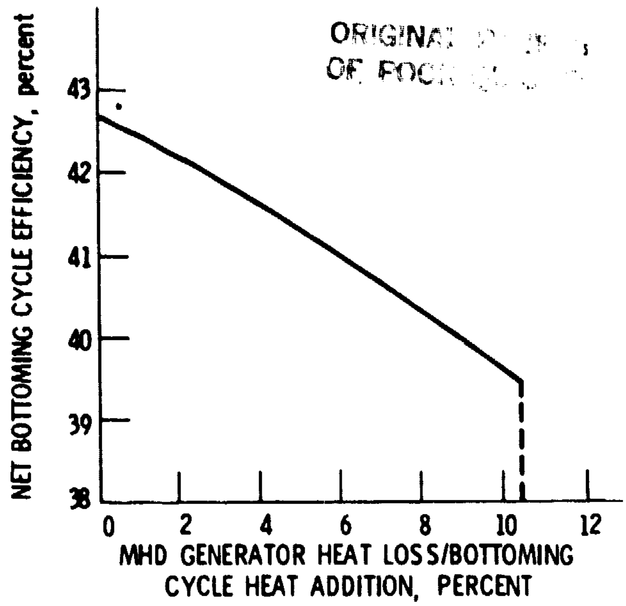

Figure 1. - Bottoming steam cycle efficiency as a function of the percentage of bottoming cycle heat addition contributed by MHD generator heat loss. MHD generator cooling water outlet temperature fixed at 260° F.

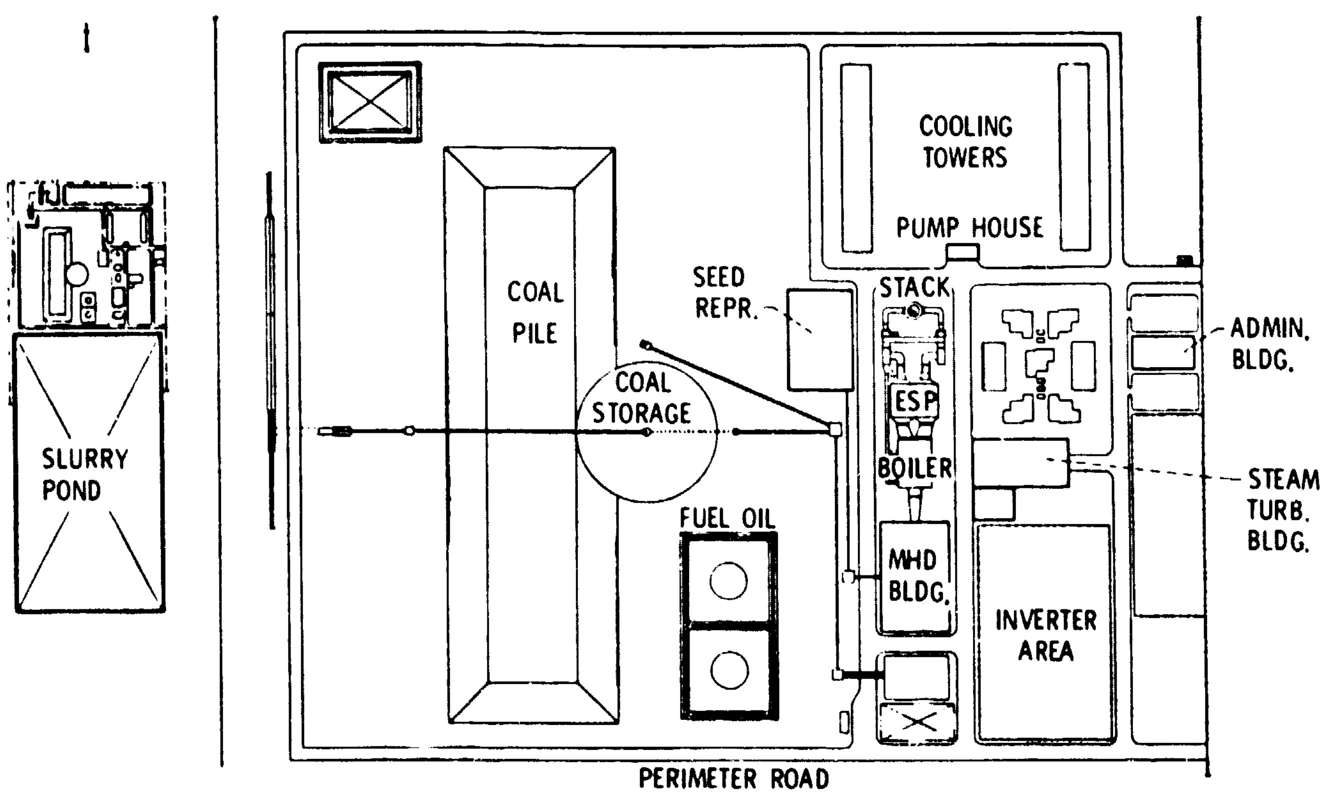

Figure 2. - General Electric plot plan for conceptual early commercial MHD/steam powerplant.

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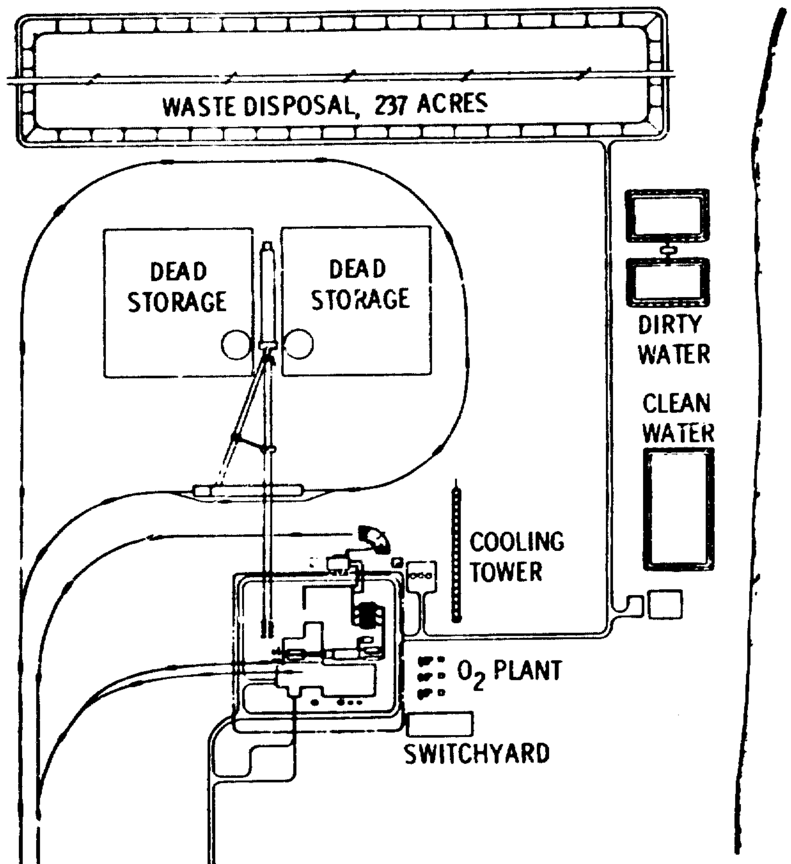

Figure 3. - Avco plot plan for conceptual early commercial MHD/steam powerplant.

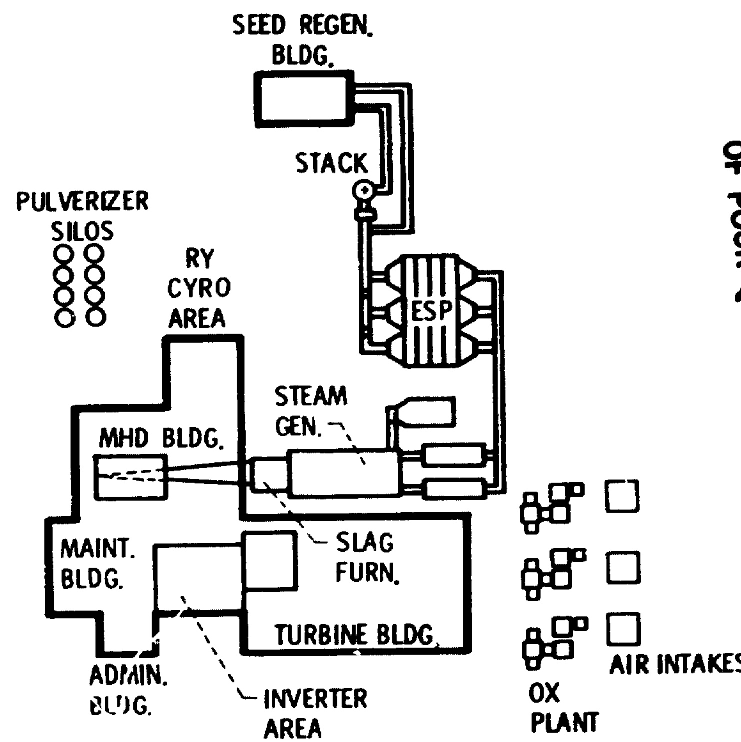

Figure 4. - Avco plant island building layout - 950 MW_e plant.

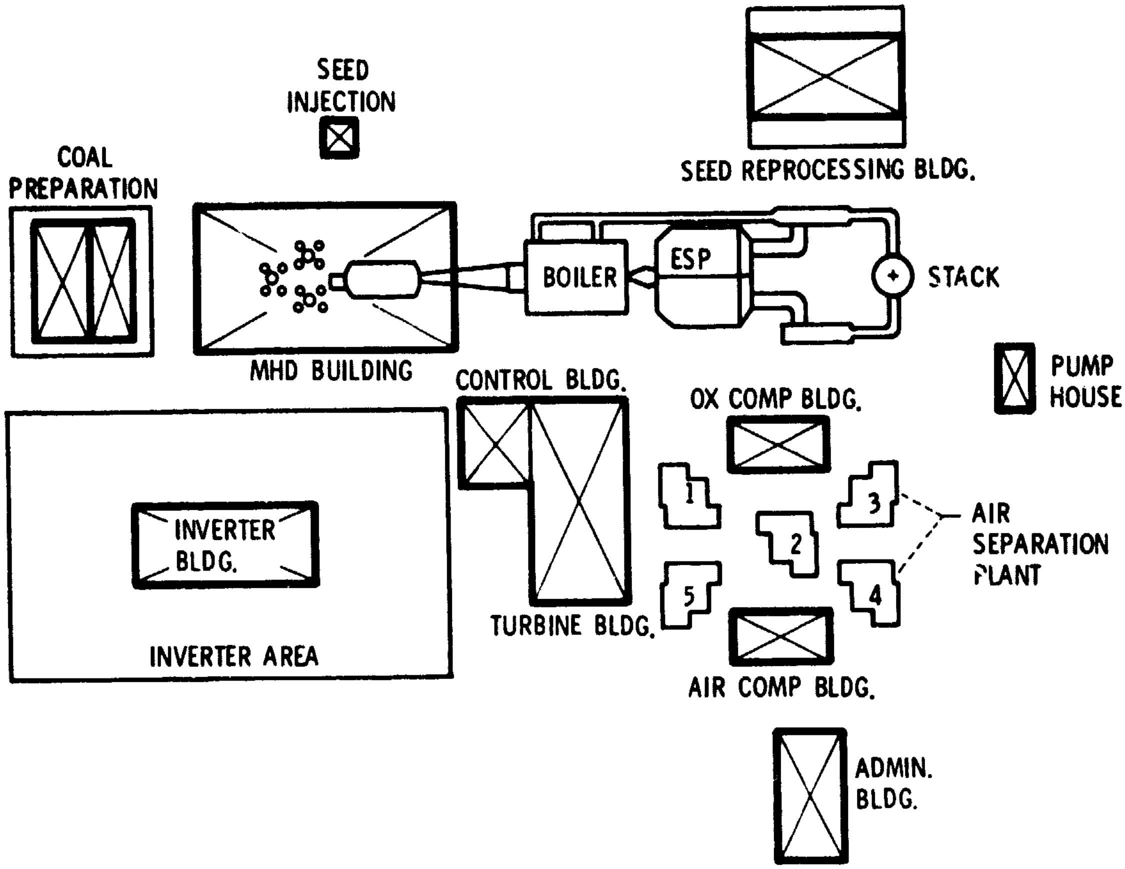

Figure 5. - G. E. plant island building layout - 1100 MW_e plant (same scale as Figure 4).

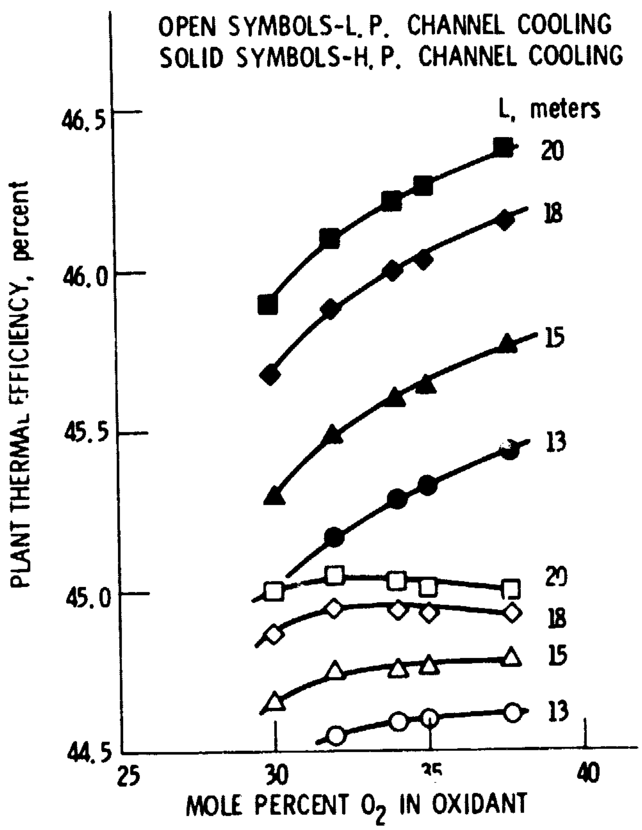

Figure 6. - 1100 MW_e MHD power plant efficiencies (NASA calculations).

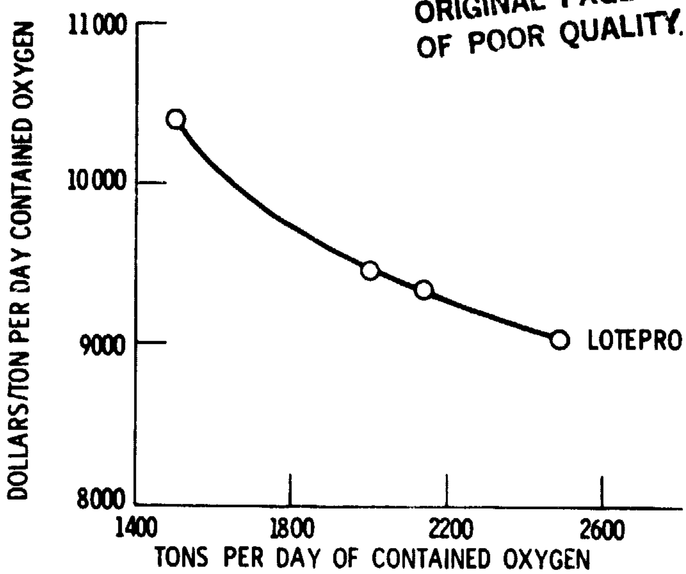

Figure 7. - Air separation plant costs for a range of sizes. Lotepro data for Turnkey plant - overnight construction costs (mid 1978 dollars).

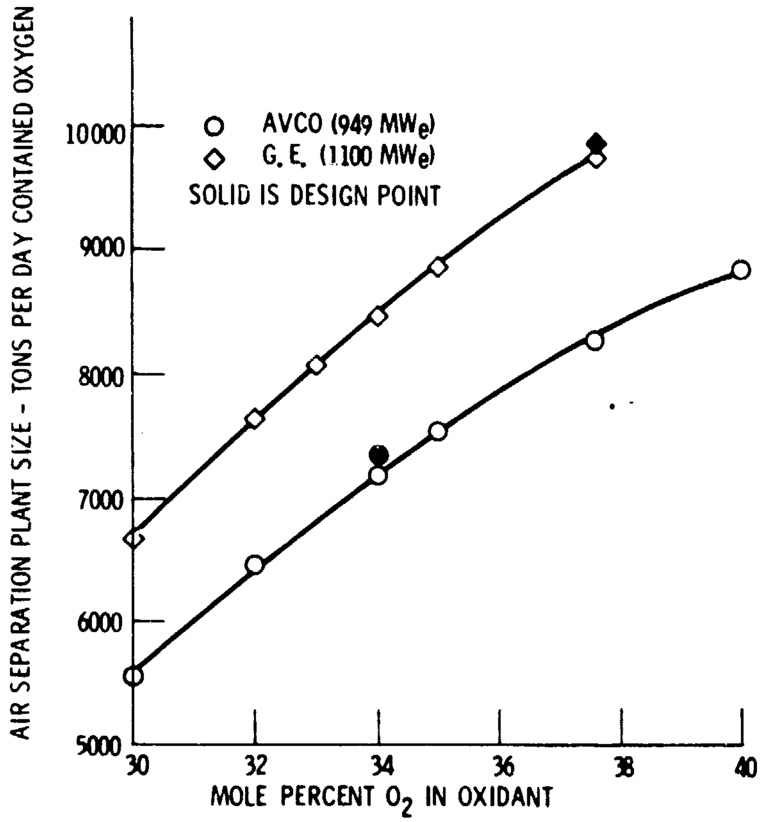

Figure 8. - Air separation plant size requirement. Product purity - 80% (NASA calculations).

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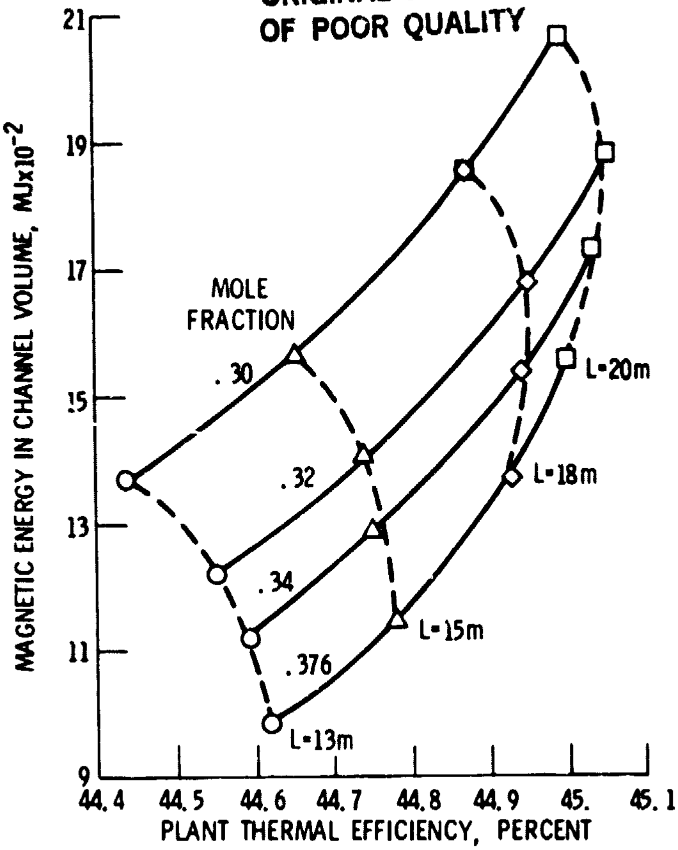


Figure 9. - NASA powerplant efficiency and stored magnetic energy for a range of generator lengths and oxygen enrichment levels.

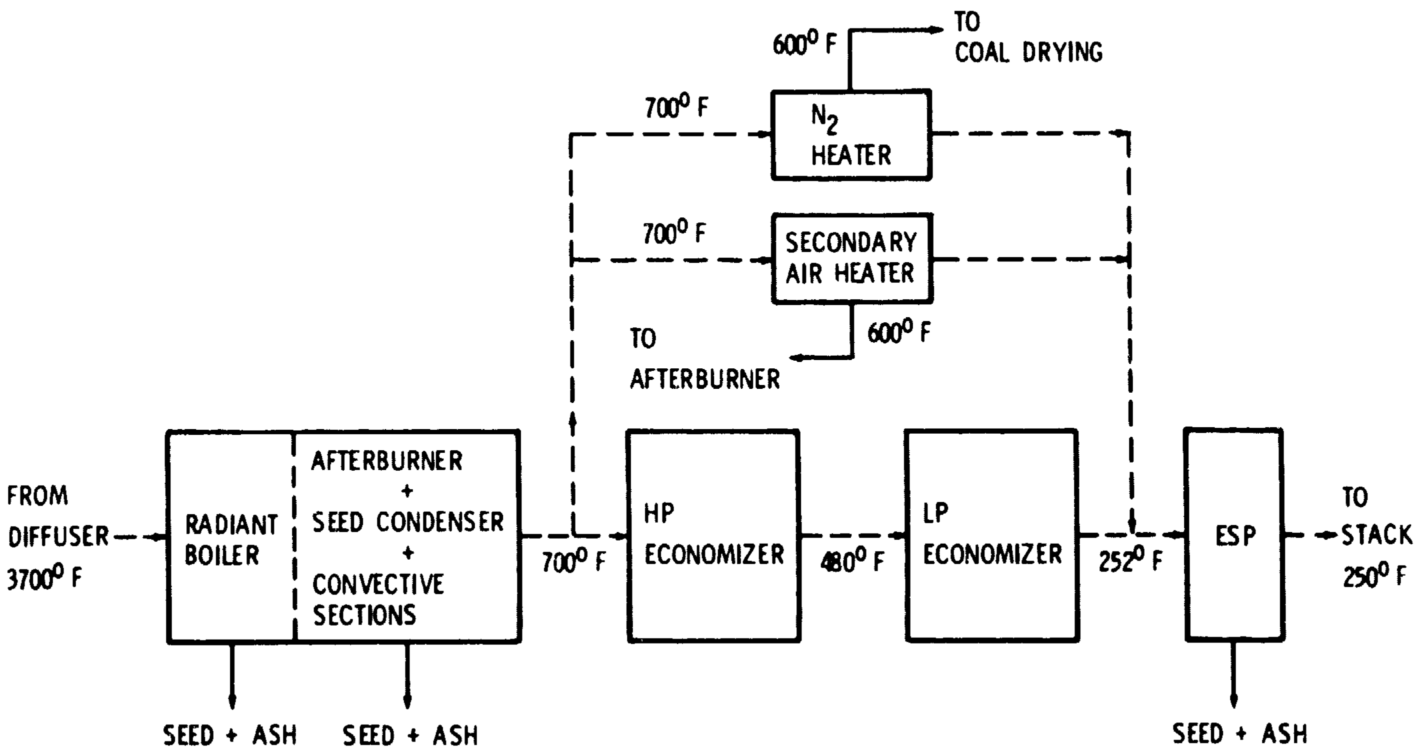


Figure 10. - Avco heat recovery/seed recovery component arrangement.

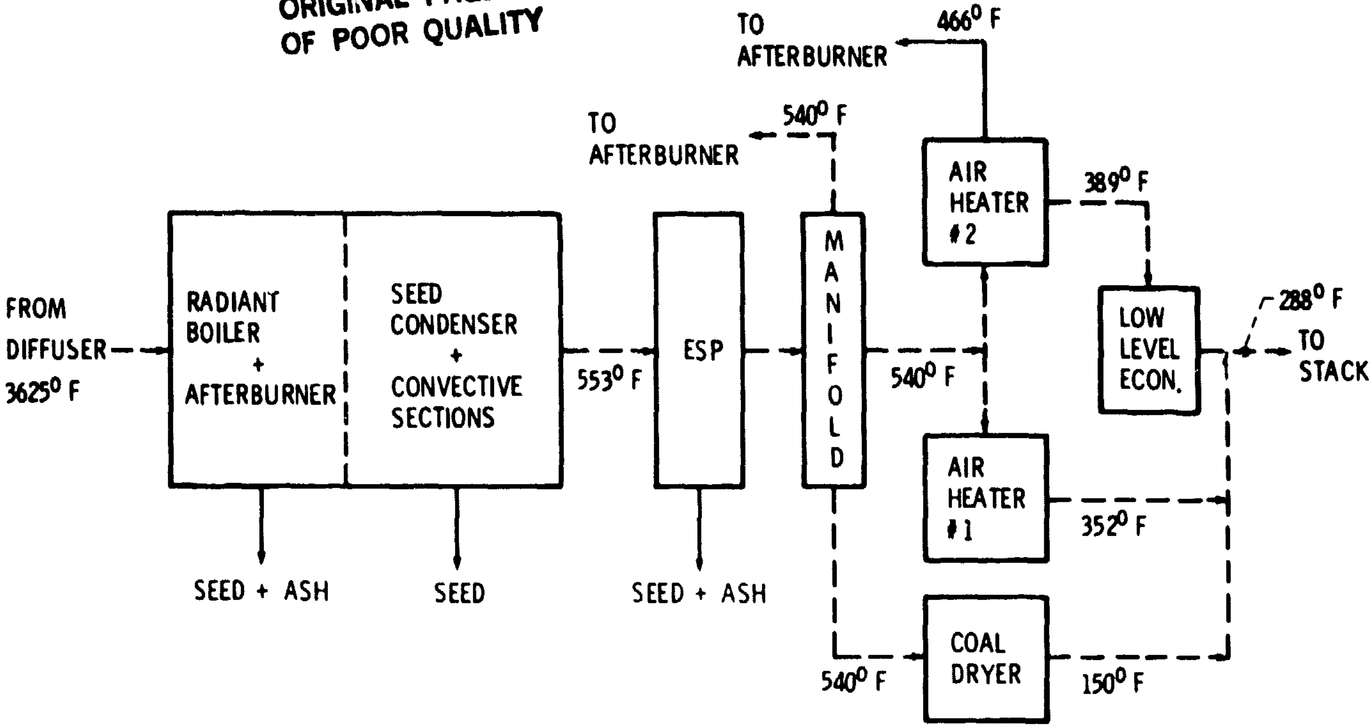


Figure 11. - General Electric heat recovery/seed recovery component arrangement.

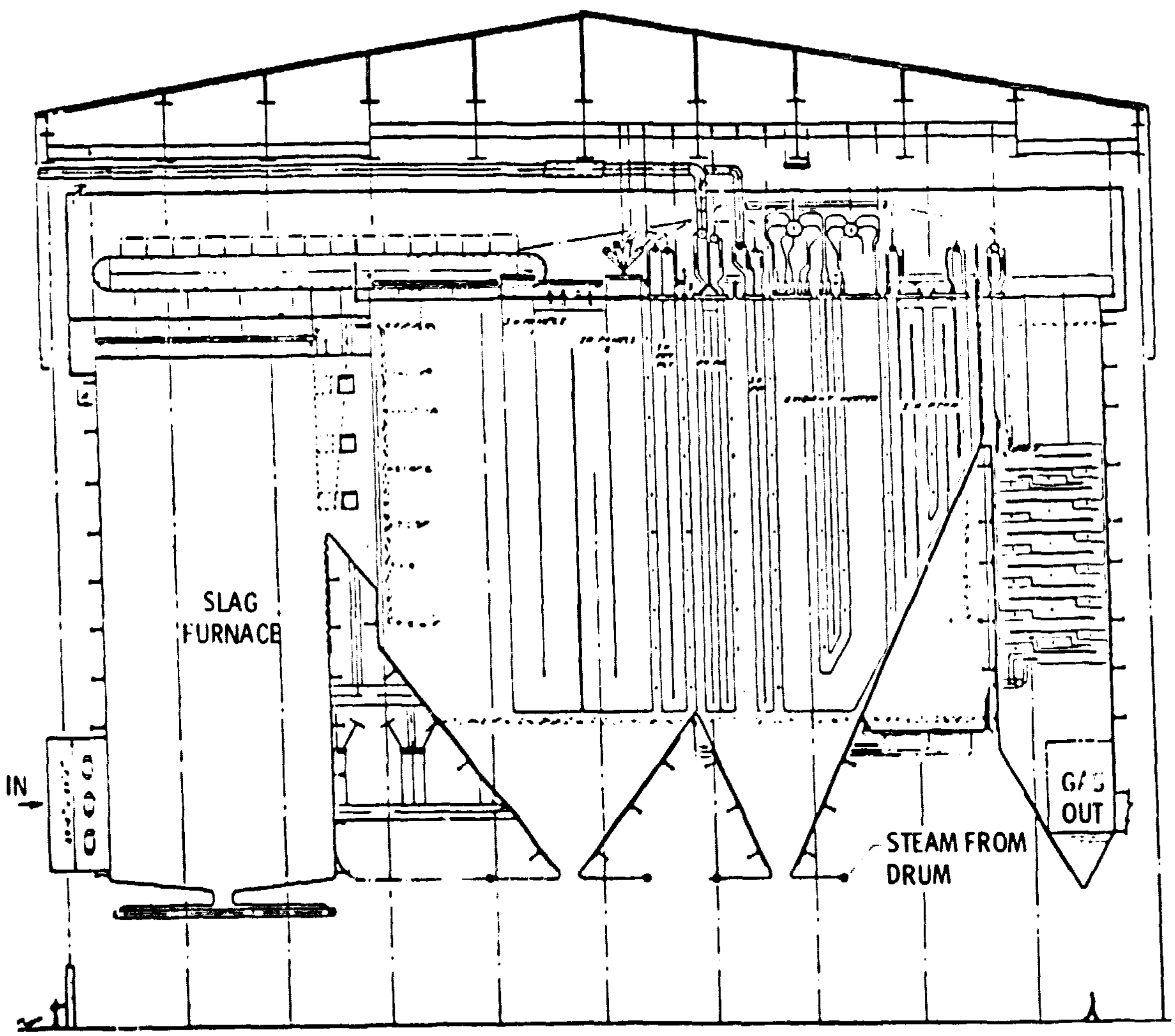


Figure 12. - Combustion engineering heat recovery/seed recovery steam generator.

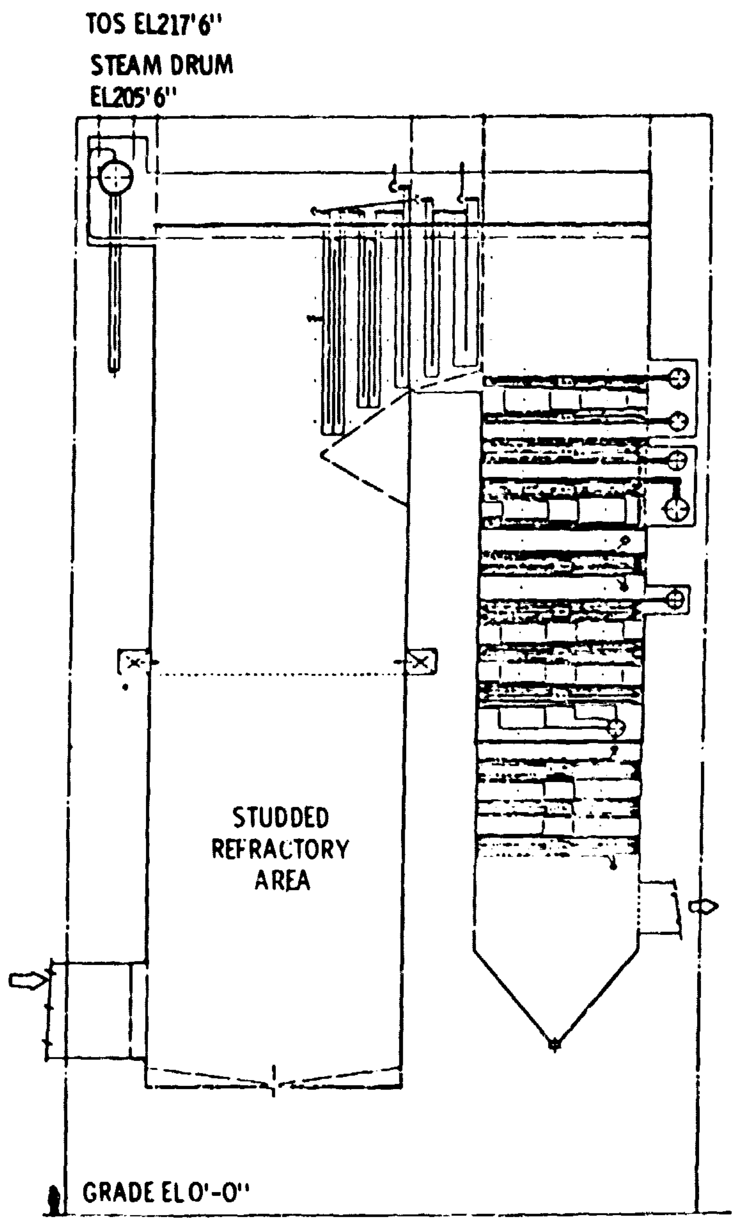
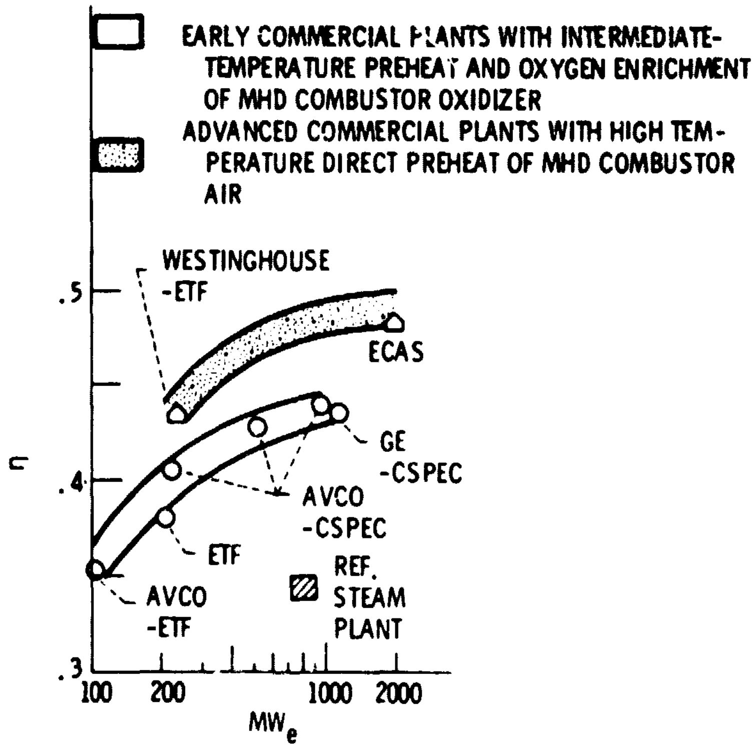
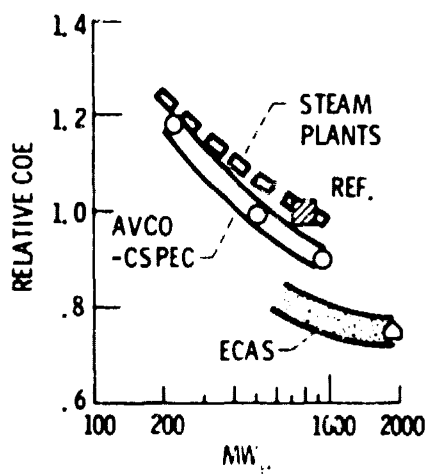


Figure 13. - G. E. - Babcock & Wilcox heat recovery/seed recovery steam generator.



POWER PLANT COAL-PILE TO BUS BAR EFFICIENCY



RATIO OF LEVELIZED COE TO THAT OF REFERENCE STEAM PLANT

Figure 14. - Summary of efficiency and cost of electricity results from coal-fired open-cycle MHD plant conceptual design studies.