NASA TECHNICAL MEMORANDUM

NASA TM X-73491

NASA TM X-73491

A SUMMARY OF THE ECAS MHD POWER PLANT RESULTS

by George R. Seikel and L. P. Harris
Lewis Research Center
Cleveland, Ohio 44135

TECHNICAL PAPER to be presented at
Third US - USSR Colloquium on Magnetohydrodynamics
Moscow, USSR, October 21-22, 1976

(NASA-TM-X-73491) A SUMMARY OF THE ECAS MHD POWER PLANT RESULTS (NASA) 24 p HC A02/MF A01 CSCL 10B

N77-10642

Unclas
G3/44 09529

A SUMMARY OF THE ECAS MHD POWER PLANT RESULTS

George R. Seikel
Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio USA

and

L. P. Harris
Corporate Research and Development
General Electric Company
Schenectady, New York USA

E-8884

SUMMARY

The interagency-funded, NASA-coordinated Energy Conversion Alternatives Study (ECAS) has studied the potential of various concepts for advanced power plants using coal and coal-derived fuel. Principle studies were conducted through prime contracts with the General Electric Company and the Westinghouse Electric Corporation.

In Task 1 performance, power plant cost, and cost of electricity (COE) for ten types of plants including open-cycle, closed-cycle inert-gas, and liquid-metal MHD were analyzed parametrically. Estimates were further refined for an open-cycle MHD plant in Task 2 in which a total of 11 conceptual power plants were designed, one of which was an open-cycle MHD plant. Performance and COE for MHD systems are summarized herein along with the conceptual open-cycle MHD plant design.

The results show that open-cycle coal-fired recuperatively-preheated MHD systems have potentially one of the highest coal-pile-to-bus-bar efficiencies (48.3%, Task 2) and also one of the lowest COE systems studied. Closed-cycle, inert-gas systems may have the potential to approach the efficiency and COE of open-cycle MHD. The 1200-1500 F liquid-metal MHD systems studied do not appear to have the potential of exceeding the efficiency or competing with the COE of advanced steam plants.

INTRODUCTION

The Energy Conversion Alternatives Study (ECAS) has studied, using common ground rules, concepts for advanced power plants fired by coal or coal-derived fuel. This unique effort combined resources of three U.S. agencies (NSF, ERDA, and NASA) and the contracted expertise and experience of teams led by the General Electric Company and the Westinghouse Electric Corporation. Independent comparative evaluation studies and overall coordination were provided by NASA's Lewis Research Center (LeRC). The supporting LeRC ECAS team received assistance from Burns and Roe, Inc. and subcontractors to them.

Thus, ECAS involved a broad base of both U.S. Federal and private sector participation. An Interagency Steering Committee provided to NASA the necessary guidance and direction for study execution. The steering committee received advice and counsel from two supporting panels: An Interagency Technical Review Panel and a Utility Advisory Panel.

ECAS included three primary tasks, parametric analysis (Task 1), conceptual design (Task 2), and implementation assessment (Task 3). In Task 1 (ref. 1-3) ten types of power plant were analyzed parametrically: three types of MHD systems (open-cycle, closed-cycle, and liquid-metal), two open-cycle turbine systems (simple and combined cycle), four closed-cycle turbine systems (advanced steam, gas turbine, liquid metal Rankine, and supercritical CO_2), and fuel cells.

On the basis of the parametric results, 11 specific power plants were selected for conceptual design (Task 2) (ref. 4-6) and for assessment of the resources required to implement development of the first commercial plant (Task 3). The plants studied in Tasks 2 and 3 include an open-cycle MHD/steam plant, three advanced steam plants, four combined-cycle plants, a closed-cycle gas turbine plant, a potassium topping plant, and a high-temperature fuel-cell/steam plant. G.E. designed seven of these plants and Westinghouse designed three. The other plant (fuel cell) was designed by Burns and Roe in conjunction with United Technology Corporation.

The General Electric Company team included an advocate for each type power plant. Avco Everett Research Laboratory, G.E. Space Products Division, and Argonne National Laboratory served as advocates for the open-cycle, closed-cycle, and liquid-metal MHD systems, respectively. The General Electric Corporate Research and Development team also included the Foster Wheeler Energy Corporation and the Bechtel Corporation. In contrast, Westinghouse Electric Corporation conducted all the MHD system studies in-house in their Research Laboratory except for the assistance of Chas. T. Main, Inc.

To attempt to achieve common and consistent treatment of systems in ECAS, the contractors were given by LeRC a common set of specifications and ground rules. These are summarized in ref. 7 and further discussed in ref. 1-6. It is important to note that the economic ground rules chosen can significantly affect the apparent relative attractiveness of alternative systems as will be indicated later in this paper (this is also discussed further in ref. 3). Therefore, the contractor results must be viewed in this perspective.

The COE calculated by the contractors consists of the sum of a capital, an operating and maintenance (O&M), and a fuel portion. The plan's capital cost are estimated in mid 1974 (1975) dollars for Task 1 (Task 2) interest and escalation during the construction period are then added using an assumed cash flow curve. The resulting cost is used to calculate the capital portion of COE. The O&M portion of COE is calculated using mid 1974 (1975) dollars. The fuel portion of COE is based on specified fuel costs for coal, \$0.85 and \$1.00 per million BTU in Task 1 and Task 2 respectively. This method of estimating COE use by the contractors assumes a common start of construction for all plants.

The contractors overall efficiency results include all processes required to convert from coal to appropriate high voltage AC power for transmission (500 kV 60 Hertz for large plants). Thus, for systems using clean or semi-clean coal-derived fuels, the efficiency of the coal to fuel conversion has been included in the overall energy efficiency.

The intention of having independent and parallel contractor studies in ECAS Task 1 was well served. For although the common ground rules were used by both contractors, substantial capital cost differences were obtained for equivalent power plants. Generally the G.E. team estimated higher capital costs. Because of the relatively large difference in Task 1 costing, caution must be exercised in comparing the results of the G.E. and the Westinghouse studies with each other. The level of detail in Task 1 was structured to obtain broad parametric coverage of the ten conversion systems and focused on obtaining comparisons on a relative not absolute basis. In Task 2 the greater level of detail permitted a more definitive plant design cost.

This paper will briefly:

1. Summarize the ECAS performance and cost results for MHD systems contained in ref. 7 including illustrating the impact on the results of possible alternative economic ground rules.
2. Describe the conceptual design of the open-cycle MHD plant developed by the G.E. team in ECAS Task 2 (ref. 4).

SUMMARY OF THE ECAS PERFORMANCE AND COST RESULTS FOR MHD SYSTEMS

Open-Cycle Magnetohydrodynamic Systems

Task 1. - General Electric studied 30 parametric cases, 23 of which used direct-coal firing and 7 of which used solvent-refined coal (SRC) as the fuel. All but one case used a steam bottoming cycle; that exception used a gas-turbine bottoming cycle. All but two cases used a high-temperature (2000°F and higher) regenerative heat exchanger to preheat the air with MHD generator exhaust gas (i.e., direct air preheat). One used lower temperature (1500^{O}F) direct air preheat with oxygen enrichment, and the other assumed the air to be preheated by a separate clean fuel gas obtained from a coal gasifier (i.e., separately-fired air preheat).

Westinghouse in Task 1 studied 39 parametric cases, 34 of which were direct-coal fired and 5 of which used a low-BTU fuel gas obtained from an integrated gasifier. Half of their direct-coal-fired cases used direct air preheat to about 2400^{O}F, the others assumed direct air preheat to as high as 2400^{O}F, followed by additional heating in an indirect air preheater. The fuel for the indirect air preheater was the volatiles obtained by carbonizing the coal before using it in the main combustor. All the Westinghouse cases used a steam-bottoming cycle.

The G.E. coal-fired cases ranged from 44 to 53 percent in overall efficiency and their SRC cases ranged from 40 to 46 percent. The efficiency of SRC fuel cases is reduced by the 78 percent fuel conversion efficiency; their power plant efficiency, not including this fuel conversion efficiency, ranged from 52 to 59 percent. The costs of electricity (COE) ranged from 41 to 48 mills/kw-hr.

The Westinghouse coal-fired, direct-air-preheat cases range from 44 to 49 percent in efficiency and 27 to 31 mills/kw-hr in COE. The coal-fired cases with direct and indirect air preheat range from 44 to 54 percent in efficiency and 27 to 35 mills/kW-hr in COE. The higher efficiency was obtained by air preheat to about 3500^{O}F. With indirect air preheat to about 3000^{O}F, 50 percent efficiency was obtained. The cases using low-BTU fuel gas ranged from 46 to 54 percent in efficiency and 34 to 42 mills/kW-hr in COE.

For nearly comparable conditions, both G.E. and Westinghouse obtained efficiencies of 48-49 percent. This is for a direct-coal-fired plant using direct-air preheat to 2400^{o}-2500^{O}F and a 3500 psi/1000^{O}F/1000^{O}F steam-bottoming cycle. The results indicate that by using the best features of each, the efficiency could reach 50 percent. The cost estimates, however, are substantially different. The G.E. COE for these conditions is 43.9 mills/kw-hr, and the Westinghouse COE is 27 mills/kw-hr. Most of this difference is due to estimates for balance-of-plant costs. The conceptual design completed in Task 2 essentially eliminated the balance-of-plant cost differences.

Both contractors show a loss in efficiency of about 3 percentage points associated with seed reprocessing when high-sulfur coal is used. Alternative reprocessing concepts with lower performance penalties should be investigated. The system with an integrated gasifier and in-bed sulfur removal appears to have the potential to be competitive with direct-coal-fired MHD systems when high-sulfur coal is used.

Task 2. - General Electric examined in greater detail and developed a conceptual plant design for a modification of one of their more attractive Task 1 points. This was a nominal 2000 MW_e direct-Illinois #6 coal-fired system with direct-air-preheat to 2500°F, 9 atm MHD combustor, and 0.8 MHD generator load parameter. It differed from Task 1 Base Case 1 in that a diagonal wall generator was used to decrease inverter cost, and a split economizer was used to increase the steam bottoming plant efficiency. The resulting thermodynamic cycle efficiency was increased to 54% or 1.2 percentage points over the Task 1 value. The overall efficiency, however, remained at 48.3% because a larger loss in efficiency was estimated for modified coal drying and seed reprocessing equipment.

In the Task 2 conceptual plant design, a substantial effort was made to develop a plant layout with lower balance-of-plant costs. This plus other cost improvements resulted in a Task 2 power plant capital cost of $718/kWe, a reduction of $384/kWe from the Task 1 value which was, in addition, estimated for a year earlier economic base year. The corresponding cost of electricity for the Task 2 plant is 31.8 mills/kW-hr compared to 43.9 mills/kW-hr for the corresponding Task 1 plant.

Closed-Cycle, Inert-Gas Magnetohydrodynamic Systems

This study represents the first serious attempt to mate the closed-cycle, inert-gas MHD system with fossil-fuel-fired heat sources for utility applications. Since there was no data base of results from previous studies, a variety of power plant configurations were considered, and some of the initially chosen configurations did not result in attractive systems. The contractors differed in both the power-plant configurations considered and in their approach to evaluating the systems performance. The initial configurations chosen in the G.E. study were an MHD topping cycle using a clean over-the-fence fuel and a direct-coal-fired parallel cycle. As the study progressed, G.E. added two direct-coal-fired MHD topping cycles.

The MHD topped steam cycle was the only configuration considered by Westinghouse. The fuel used in the majority of cases was a low-BTU gas derived from an on-site gasifier that was closely coupled.

The G.E. results for the parallel cycle and the clean over-the-fence fuel MHD topping cycle indicate that these are not attractive systems. The best G.E. results were obtained for the direct-coal-fired MHD topping systems. The case with an inlet temperature of 3000°F, an MHD generator adiabatic efficiency of 0.7 and magnetic field strength of 3.5 tesla resulted in an overall energy efficiency of 41.8 percent, a capital cost of $1551/kWe, and a COE of 61.6 mills/kW-hr. An iteration made on this configuration, in which temperature is 3121°F, MHD generator adiabatic efficiency is 78 percent, magnetic field is 4.5 tesla, and the power-plant layout was considerably modified, improved the efficiency, capital cost, and COE to 46 percent, $1109/kWe, and 45.6 mills/kW-hr, respectively. The effect of pressurizing the combustion system of the above case to 4 atmospheres was found to change the efficiency, capital cost, and COE to 47.4%, $1015/kWe and 42 mills/kw-hr, respectively.

The Westinghouse overall energy efficiencies for the LBTU gasifier configuration were 46.1 percent at an inlet temperature of 3800°F and 42.2 percent at 3100°F. This includes an effective efficiency of the gasifier/combustion loop combination of about 79.6 percent. At 3100°F, the capital costs were $1912/kWe and the COE was 68 mills/kW-hr.

The Westinghouse capital costs for a nearly equivalent system were approximately $400/kWe higher than G.E.'s. This difference is mainly due to the differences in the costs of the refractory regenerative heat-exchanger system. NASA estimates on the basis of independent studies performed by the FluiDyne Engineering Corporation that the Westinghouse COE could probably be reduced to approximately 44 mills/kW-hr by using a more compact heat-exchanger system.

It is anticipated that further study of these closed-cycle inert-gas systems would result in lower costs and perhaps higher efficiencies. For example, the G.E. capital costs could be lowered by $52/kWe by incorporating the three terminal MHD generator power output connections used for the open-cycle MHD systems in Task 2. This change greatly reduces the system's inverter costs.

Liquid-Metal Magnetohydrodynamic Systems

The two-phase flow liquid-metal MHD (LMMHD) power cycle which uses an inert gas as the primary thermodynamic working fluid and a liquid metal as the electrodynamic fluid in the MHD generator was the only type of LMMHD system treated in this study. Temperature ranges from 1200-1500°F were considered. The working fluids were Ar/Na and He/Na in the 1200-1300°F range and Ar/Na and He/Li in the 1400-1500°F range.

The majority of cases studied by both contractors included the use of a binary LMMHD/steam cycle, the use of a steam cycle with little regenerative feedwater heating, and the use of pumps to recirculate the liquid metal. Cases were included, however, to determine the effect of eliminating the liquid-metal pumps.

The overall energy efficiencies ranged from 33.6 to 37.3 percent for the 1200-1300°F temperatures and from 37 to 39.5 for the 1400-1500°F cases. The contractors costs differed significantly. For the lower temperature cases, the General Electric costs ranged from $1450/kWe-$2750/kWe and 77-93 mills/kW-hr. The Westinghouse costs were in the range $790/kWe-$1177/kWe and 33.9-46.2 mills/kW-hr.

At the 1400-1500°F temperatures, the General Electric costs were $2500-$3000/kWe and 92-100 mills/kW-hr; Westinghouse's were $1165-2140/kWe and 45-78 mills/kW-hr.

A detailed analysis of these costs showed major differences in nearly every item. Differences in the costs of some components such as the MHD generator, magnet, and inverters have been reconciled. However, there are still large unresolved differences in the contractors costs.

The highest overall energy efficiency obtained by the contractors at the temperature limits dictated by the present sodium technology (1200° to 1300°F) was 37.3 percent. Their results indicate that the maximum potential efficiency at these temperatures would be approximately 40 percent, because at these temperatures the liquid-metal MHD system cannot be effectively coupled to an advanced steam plant.

At the higher temperature considered in this study (1500°F), these problems may be alleviated. Westinghouse has calculated an overall energy efficiency of 43 percent by assuming that the sodium technology can be extended to 1500°F and that the system can be coupled to a 45 percent steam plant. The sodium vapor carryover could be a considerable problem at these temperatures. This problem can be avoided by using lithium. But the 1400-1500°F Li/He plants studied had slightly lower efficiency than Na/A plants at the same temperature and also significantly higher COE. Resolution of the large differences in cost estimates requires more detailed component design and plant integration optimization.

Comparison of MHD Systems with Alternative Plants Studied

This section compares the MHD systems studied in Task 1 and the open-cycle MHD system studied in Task 2 with the other plants studied in the two respective tasks.

Figure 1 is a plot of the COE (mills/kW-hr) vs overall energy efficiency (coal pile to a.c. bus bar) for the Task 1 data. Since Task 1 involved hundreds of parametric data points, only ranges of costing and performance are shown. A Task 1 reference steam system (conventional furnace with 3500 psi/1000°F/1000°F steam conditions) is also cited on the graphs of figure 1 and a set of coordinate axis drawn through this reference point. Data are plotted on two separate graphs, one for G.E. and one for Westinghouse.

Power plants located in the lower right-hand quadrant of the graphs of figure 1 are the most desirable, being lower in COE and higher in efficiency than the reference steam plant. Only a few gas turbine combined cycle (LBTU integrated gasifier) points by G.E. (figure 1a) actually fall in this quadrant.

Points in either the lower left-hand quadrant or the upper right-hand quadrant of figure 1 are the next most attractive points. Additional points for the G.E. gas turbine combined cycle (LBTU gasifier) appear within the lower left quadrant at COE values lower than the reference steam plant and at efficiencies competitive with steam. Both G.E. and Westinghouse have advanced steam plants which essentially surround the reference steam plants. G.E. has both open-cycle gas turbine (high BTU fuel) and combined cycle (clean fuel) points in the lower left quadrant with low COE, but efficiencies much lower than the reference steam.

In the upper right-hand quadrant, three G.E. plants are shown with efficiencies better than the advanced steam and with COE's not much greater than the reference steam. These plants are: liquid metal rankine/steam, OCMHD/steam, and CCMHD/steam. The LMMHD system appears in this quadrant, but with efficiency values lower or at best comparable to the advanced steam plant and COE's that are much higher.

In the Westinghouse data of figure 1b, the molten carbonate fuel cell/steam bottoming plant is also in the desirable range of the upper right-hand quadrant. Westinghouse examined the molten carbonate fuel cell in much greater detail than G.E. The 31 mill/kW-hr point shown in figure 1b was, however, calculated by NASA (ref. 3) using the technical and costing base of Westinghouse, but assuming a 30,000 to 50,000 hour operating life rather than the 10,000 hour life assumed by Westinghouse.

From the data of figures 1a and 1b, the advanced steam plants, the combined-cycle plants, the high-temperature fuel cell/steam plants, the open-cycle MHD/steam plants and closed-cycle MHD/steam plants appear to offer the promise of improved efficiency with a very moderate increase or decrease in the COE compared to the reference steam plants. All of these systems were carried into Task 2 with the exception of closed-cycle MHD/steam plant. The more attractive CCMHD points were generated as part of an iteration of the Task 1 studies which was conducted in conjunction with the Task 1 review. This occurred concurrently with the Task 2 effort.

This ECAS Task 1 data indicates that CCMHD/steam bottoming needs to be analyzed at a Task 2 level of effort. The data have also shown that the 1200-1500^{o}F LMMHD is much higher in COE than advanced steam plants and either a slight bit lower or at most competitive in efficiency.

In figures 2a through 2d the data for the 11 Task 2 conceptual plants are presented showing the sensitivity of COE to the various economic ground rules. Analysis and evaluation of the data from the three contractors represented (G.E., Westinghouse, United Technologies Corp./Burns and Roe) is presently underway at NASA. Differences in cost due to different costing and accounting procedures are present in the figure 2 data. The reader should, therefore, be cautious in comparing plant COE's, particularly between plants estimated by different contractors.

Figure 2 shows the sensitivity of COE to "construction time" assumptions. In figure 2a the data is displayed as costed by the contractors. A common "start-of-construction" date (1975½) is assumed for all power plants. One plant, the Westinghouse combined cycle with semi-clean liquid fuel appears to offer a lower COE than the various steam plants displayed and with no penalty in overall energy efficiency. Three other plants, the OCMHD/steam bottoming, the Westinghouse combined cycle/LBTU integrated gasifier, and the UTC molten carbonate fuel cell/steam bottoming plant have the potential of high efficiency (46.8% to 50%) with a COE (nominally 30 mills/kW-hr) very competitive with the steam systems shown.

In figure 2b a common "end-of-construction" time (1982) is assumed compared to the common "start-of-construction" used in figure 2a. In figure 2c COE is plotted using constant 1975½ dollars. This removes the escalation from capital cost. Hence both the higher capital cost and more efficient plants appear relatively more attractive.

Figure 2d assumes a plant life of 30 years and that, after construction, fuel and operation and maintenance inflate at the rate of 3.25% per year. The COE shown is the average over the 30-year plant lifetime, expressed in 1975½ dollars. Again the three high efficiency plants appear to offer a COE competitive with each other and nearly identical to the lower efficiency best advanced steam plant.

OPEN-CYCLE TASK 2 MHD CONCEPTUAL PLANT DESIGN

The configuration of the nominally 2000 MWe open-cycle MHD power plant selected for the ECAS Task 2 conceptual design by the General Electric team was the result of several compromises. A schematic diagram of the plant is shown in figure 3. Pressure, temperature, flow rate, and enthalpy are indicated at various points in the cycle as is the power of most major components. The enthalpies used here are zero at 60 F for air, combustion gas, solid coal, and seed compounds.

The fuel used is Illinois No. 6 coal, dried and pulverized as required by specifications set for the Petrocarb coal injection equipment. The combustor is a special Avco design intended to yield 4634 F (2380 K) combustion gas, with air preheated to 2500 F (1644 K) and a fuel/air ratio 1.07 the stoichiometric value. Approximately 85 percent of the coal ash is removed from the bottom of the combustor before K_2CO_3 powder seed is injected into the gas stream. Sufficient K_2CO_3 is injected to provide 1 percent by weight of potassium in the combustion gas flow. Drying of the coal fuel from the approximately 13 percent water content as received to the approximately 2 percent required for proper operation of the pressurized, lock hopper fed coal injection apparatus is accomplished in conventional equipment using low-temperature combustion gases (765 F (680 K)) extracted upstream from the economizers and returned to the main flow upstream from the electrostatic precipitators and stack.

Atmospheric air is compressed in the steam-driven air compressor, then heated in the air preheaters and fed to the combustor. Combustion air heating is provided in two stages, a tubular low-temperature air heater stage and a refractory storage high-temperature air heater stage, both heated directly by the exhaust gases from the MHD generator.

The MHD generator operates with an average magnetic flux density of 5 tesla, and inlet and outlet stagnation pressures of 9 and 1.14 atm (0.909 and 0.115 MN/m^2), respectively. The generator electrical interconnections are of the "diagonal" type, in which electrodes on lines displaced from the generator axis by angles of approximately 45^o are connected electrically and the electrical loading is designed to draw a load voltage that is 80 percent of short circuit current. The "diagonal wall" MHD generator has three separate electrical load circuits having a common upstream terminal and operating voltages of 8, 18, and 43 kV.

The flow enthalpy extracted from the combustion gas in the MHD generator as d.c. power is changed to 60 Hz a.c. power in the dc/ac inverters for transformation to the 500 kV transmission voltage. After passing through the MHD generator and its diffuser, the combustion gas working fluid flows on to the radiant steam furnace in which the fuel rich gas is slowly cooled to reduce NO_x to an acceptable level before additional air is added and combustion is completed. The combustion products then flow on to the air and the remaining steam heaters, where the combustion air preheat is accomplished, where superheated steam is generated for the steam turbines, and where most of the potassium and sulfur are condensed from the gas. After leaving the air and steam heaters, most of the combustion gases flow through the economizers and on to the electrostatic precipitators and stack, but a small fraction passes around the economizers and goes instead through coal dryers and precipitators to the stack.

The potassium carbonate powder used as the seed to provide usable electric conductivity in the MHD generator, reacts in the generator exhaust with sulfur introduced with the coal to form K_2SO_4. The K_2SO_4 condenses from the gas stream at temperatures below 2500 F (1644 K). The potassium seed thus also prevents SO_x emissions from the system from exceeding EPA standards. The K_2SO_4 is collected and chemically reduced in an integral treatment facility to K_2CO_3, which is recycled to the seed injection apparatus, and to H_2S, which is further reduced in an integral Claus plant to bulk sulfur for disposal.

The bottoming cycle used is a 3500 psi/1000 F/1000 F (24 MN/m^2/811K/811K) supercritical single reheat steam cycle that is essentially conventional except at its heat input interfaces. Water and steam heating is accomplished mainly in two furnaces. There is a radiant furnace upstream from the high-temperature air heater and a secondary furnace, which contains steam superheating and reheating equipment as well as the low temperature air heater, downstream from the high-temperature air heater.

The water flow may be followed from the outlet of the condensers. It goes first through a series of pumps, regenerative feedwater heaters, and economizers; then to the walls of the combustor, MHD generator and diffuser, and then to the steam heaters. After reaching throttle temperature the steam goes through the high-pressure turbine, then back to the steam heater for a reheat. The reheated steam then passes through intermediate-pressure and low-pressure steam turbines before returning to the condensers.

Two chains of steam turbines are shown in figure 3, one driving the main air compressor and one driving a conventional synchronous generator. The output of this generator, less power consumed locally by auxiliaries, also is transformed to transmission voltage. The two steam turbine chains used have slightly different thermal efficiencies because of their different ratings and different low-pressure turbines. Both exhaust to condensers operating at 2.3-in. Hg (7.8 kN/m^2) back pressure.

The condensers are cooled by a flow of water that takes the rejected heat to 25 evaporative, mechanical draft cooling towers for disposal in the atmosphere.

The design and cost estimation of the Task 2 open-cycle MHD power system has been a joint effort by Avco-Everett Research Laboratory (cycle advocate), Foster Wheeler Energy Corporation (combustion and heat transfer specialist), Bechtel Corporation (architect/engineer), and General Electric. In general, equipment cost estimates by Avco Everett, Foster Wheeler, and General Electric are for equipment components and assemblies as delivered to the construction site. All on-site labor and materials for field assembly and erection are included in balance-of-plant (BOP) estimates by Bechtel. In addition, General Electric also performed the system integration function.

Figure 4 shows the plan of the main plant island containing the major energy conversion equipment and most of the buildings required for the system. The coal processing and injection equipment is at the upper left in this figure. The main flow of mass is from left to right: from coal processing equipment to the combustor; through MHD generator/diffuser; through radiant furnace, high-temperature air heater, secondary furnace, and economizers; and on to the electrostatic precipitators and the stack. Below the coal-processing equipment and the MHD building are the inverter building and administration building. Below the main furnaces are the control building and buildings containing the turbine-generator and turbine-compressor and associated equipment.

Some services are provided throughout the plant. All buildings are heated and ventilated and provided with potable water and sewers. The plant control room is air conditioned. A plant compressed air system is provided for general maintenance, control actuation, and soot blowing. Fire protection systems are provided in buildings, in the general yard area, and in particular in all areas where fuel or other combustibles are stored.

Most of the plant, especially the large heat-exchange equipment is constructed out-of-doors; however, some of the equipment which requires extra protection or extensive maintenance is installed in buildings.

The MHD building provides a personnel exclusion area from exposed high voltages to ground which exist when the generator is operating. The building also provides laydown space during assembly of the superconducting magnet and dewar vessel and the disassembly and maintenance of the MHD channel. A crane is included in the building to aid in these operations. Some auxiliary equipment for the magnet, such as the cryogenic helium refrigeration system and a vacuum system, are also installed in the building. The foundation for this building and the equipment is a concrete slab at grade level. Structures in the building include supports for the diffuser, burner, and piping. Supports for the latter two items include electrical insulators.

Adjacent to the MHD building is housing for the dc/ac inverters. Also in this building are some of the other auxiliaries for the magnet, such as the power supply and the water-cooled dump resistor.

Also adjacent to the MHD building is housing for the coal-preparation equipment: pulverizers and pneumatic coal feeders. Pneumatic seed feed equipment is also in this building.

Buildings for the steam power turbine and the mechanical drive steam turbine are designed following standard practice for modern power turbine halls. The turbines are mounted on concrete pedestals, with condensers below. Feedwater heaters and turbine auxiliary equipment are arranged in this building to suit the cycle and piping designs. Cranes are includes in the buildings to aid in assembly and maintenance.

Figure 5 shows a cross section of the major conversion equipment in the combustion gas flow path. The coal processing equipment is on the left; the combustor, MHD generator, and diffuser are within the MHD building; and the main air and steam heaters and the precipitators and stack are further to the right.

Performance and Cost

The principal measures of performance and cost for the open-cycle MHD plant are summarized in Table 1. The net plant output of 1932 MWe is produced at a plant efficiency of 0.498. This results from subtracting the auxiliary power requirements (2.5% of the gross power) and the energy input of the intermediate BTU fuel gas to the seed reprocessing plant from the plant 54% thermodynamic efficiency.

The overall energy efficiency, 48.3% (coal pile to bus bar), is obtained by accounting for the coal-to-fuel conversion efficiency for fuel used for the seed recovery plant. The resulting plant uses

0.655 lb (0.297 kg) of Illinois No. 6 coal per kWe-hr. Total solid wastes of ash and sulfur are approximately 0.08 lb/kWe-hr (0.04 kg/kWe-hr). The total plant capital cost of $1387.5 million corresponds to $718/kWe. This $718/kWe is the sum of $327/kWe for all components, materials, and direct and indirect site labor costs; $29/kWe for architect and engineering services; $71/kWe for contingency; and $290/kWe for escalation and interest during construction. Table 2 shows the installed cost for the nine components with a cost greater than $10/kWe. The sum of these nine components comprises approximately one half of the total direct-plus-indirect plant costs.

The estimated cost of electricity of 31.8 mills per kWe-hr is mainly due to a 22.7 mill capital charge. The 6.5-year estimate for construction time is due largely to the very large plant size. The estimated date of first commercial service is over 20 years in the future and reflects the major development work that must be accomplished before the efficiencies and costs projected here will be attainable in plants capable of reliable and long-lived operation.

CONCLUSIONS

The ECAS Task 1 and 2 studies both show that open-cycle coal-fired MHD power plants have the potential for very high efficiency and relatively low COE. The Task 2 conceptual design plant has an overall (coal-pile-to-bus-bar) efficiency of 48.3 percent and one of the lowest COE's of all plants studied. This plant efficiency could probably be increased to over 50 percent primarily by lowering the energy losses associated with seed reprocessing. Major development work must, however, be accomplished before these projected MHD efficiencies and costs will be attained in plants capable of reliable and long-lived operation.

The Task 1 studies, particularly those conducted in conjunction with the Task 1 review, indicate that closed-cycle inert-gas coal-fired MHD plants may have the potential to approach the efficiency and COE of open-cycle MHD systems. These inert-gas MHD systems thus warrant further investigation.

The Task 1 studies of coal-fired liquid-metal MHD plants indicate that they have a somewhat limited efficiency and cost of electricity potential. For the temperature range studied (1200-1500°F), they have significantly higher cost of electricity and at best only equal efficiency to the advanced steam plants investigated. Higher temperature Li/He systems would have higher efficiency, but even the 1400-1500°F Li/He plants studied have COE's substantially above the low temperature Na/A plants.

REFERENCES

1. "Energy Conversion Alternatives Study - ECAS - Phase 1", 1976, General Electric Company, also CR-134948, NASA.

2. "Energy Conversion Alternatives Study - ECAS - Phase 1," Volumes 1-12, 1976, Westinghouse, also CR-134941, NASA.

3. "Comparative Evaluation of Phase 1 Results from the Energy Conversion Alternatives Study (ECAS)", TM X-71855, 1976, NASA.

4. "Study of Advanced Energy Conversion Techniques for Utility Applications Using Coal or Coal-Derived Fuels - Oral Briefing Document on the Results of Task 2", 1976, General Electric Company, Schenectady, NY.

5. "Energy Conversion Alternatives Study (ECAS) Westinghouse Phase 2 Oral Report," 1976, Westinghouse Electric Corporation.

6. King, J. M.: "Energy Conversion Alternatives Study (ECAS) Integrated Coal Gasification/Molten Carbonate Fuel Cell Power Plant Conceptual Design Briefing," 1976, United Technologies, South Windsor, Conn.

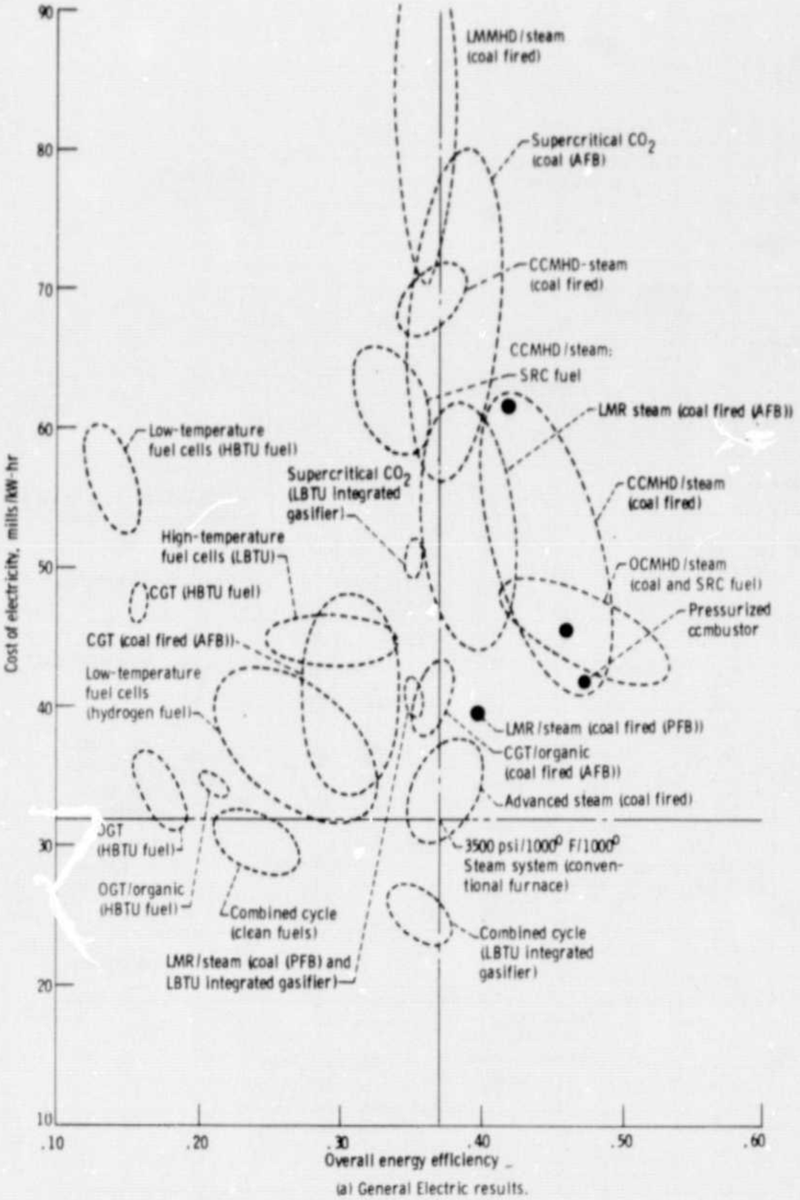
7. Seikel, G. R.; Sovie, R. J.; Burns, R. K.; Barna, G. J.; Burkhart, J. A.; Nainiger, J. J.; and Smith, J. M.: "A Summary of the ECAS Performance and Cost Results for MHD Systems," Proceedings of the Fifteenth Symposium on the Engineering Aspects of Magnetohydrodynamics, Philadelphia, PA, June 24-26, 1976. Also TM X-71913. NASA.

TABLE 1. - SUMMARY PERFORMANCE AND COST OPEN-CYCLE MHD
(General Electric - Task 2)

Net power plant output (MW_e - 60 Hz-500 kV)		1932.2
Thermodynamic efficiency (%)		54.0
Power plant efficiency (%)		49.8
Overall energy efficiency (%)		48.3
Coal consumption (LB/kWh)		0.655
Total wastes (LB/kWh)		0.082
Plant capital cost ($ million)		1387.5
Plant capital cost ($\$/kW_e$)		718.1
Cost of electricity, capacity factor = 0.65		
Capital	(mills/kWh)	22.7
Fuel	(mills/kWh)	7.3
Maintenance & operation	(mills/kWh)	1.7
Total	(mills/kWh)	31.8
Estimated time of construction (years)		6.5
Approximate date of first commercial service		1996-1999

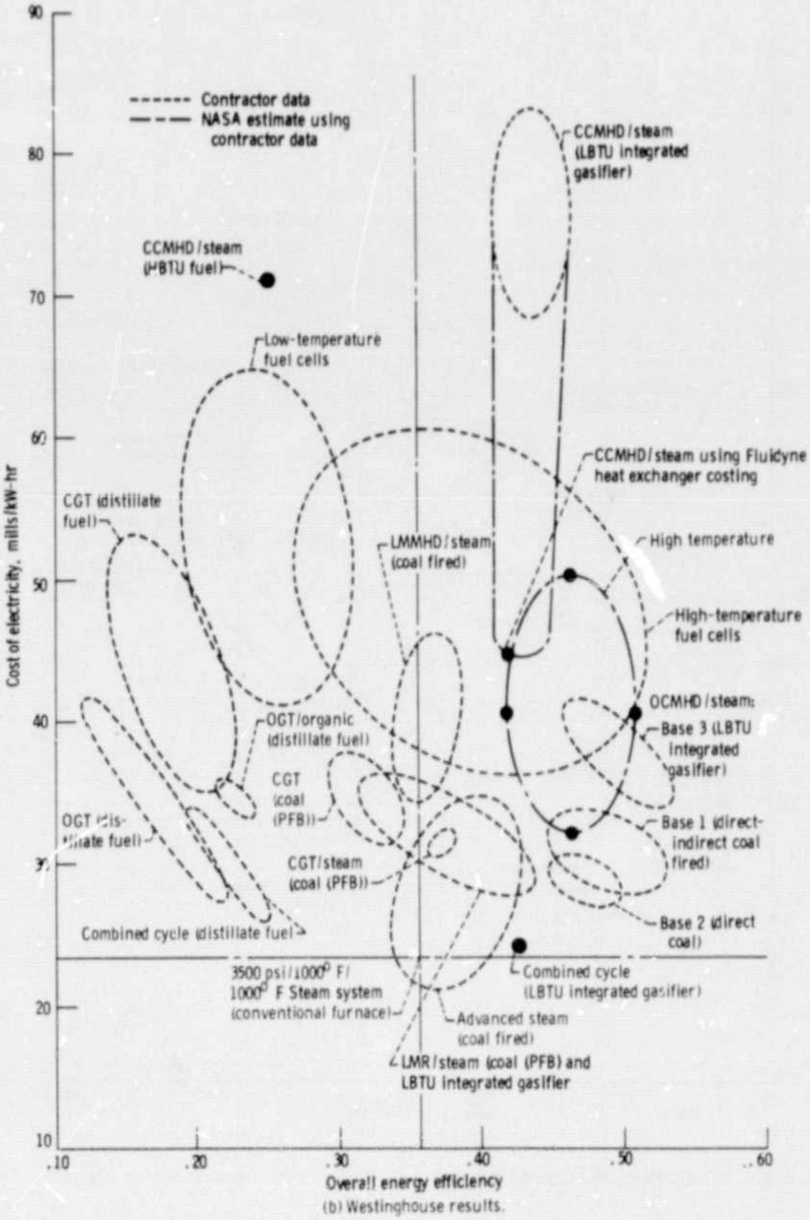
TABLE 2. - OPEN-CYCLE MHD PLANT CONSTRUCTION COST DISTRIBUTION
(General Electric - Task 2)

Installed cost components > 10$/kWe		($/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
	Subtotal ($/kWe)	155
Other ($/kWe)		172
(All other components and balance-of-plant materials plus additional direct and indirect site labor)		
Subtotal - construction cost estimate	($/kWe)	327
Architect & engineering services	($/kWe)	29
Contingency	($/kWe)	71
Escalation & interest during construction	($/kWe)	290
Total - capital cost	($/kWe)	718



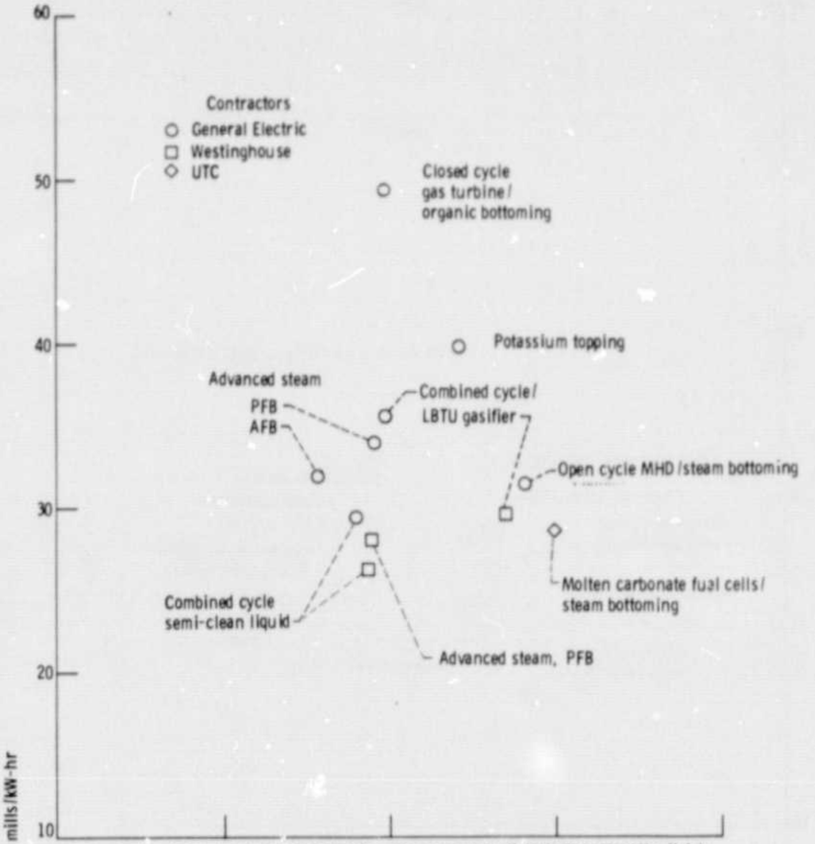
(a) General Electric results.

Figure 1. - Effect of overall energy efficiency on cost of electricity - comparison of systems for Task I.

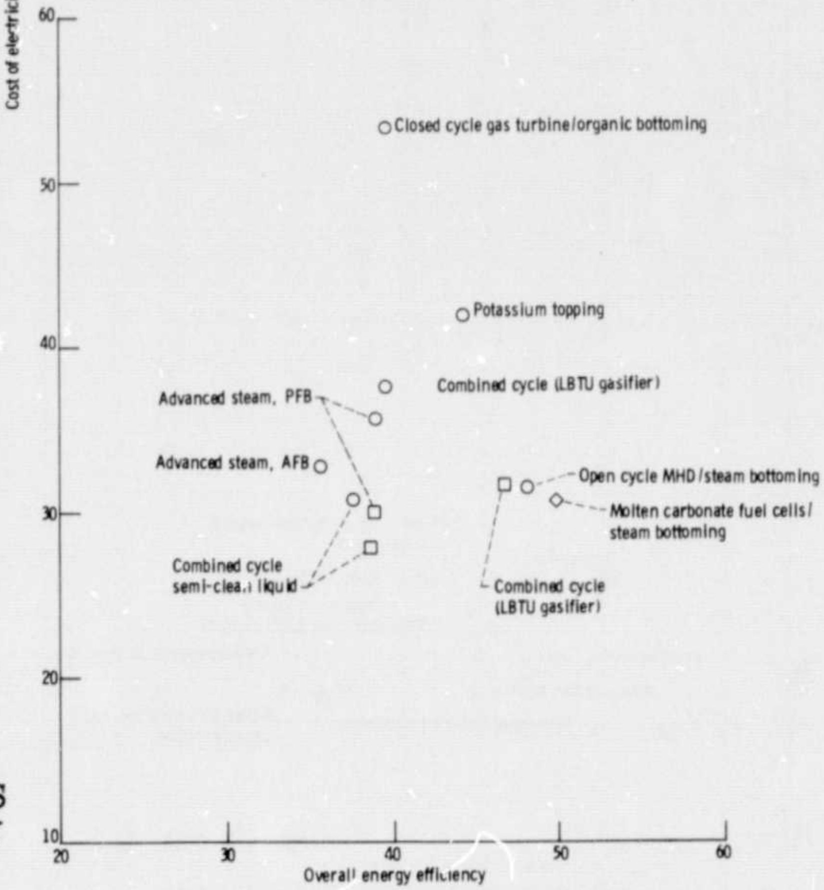


(b) Westinghouse results.

Figure 1.- Concluded.

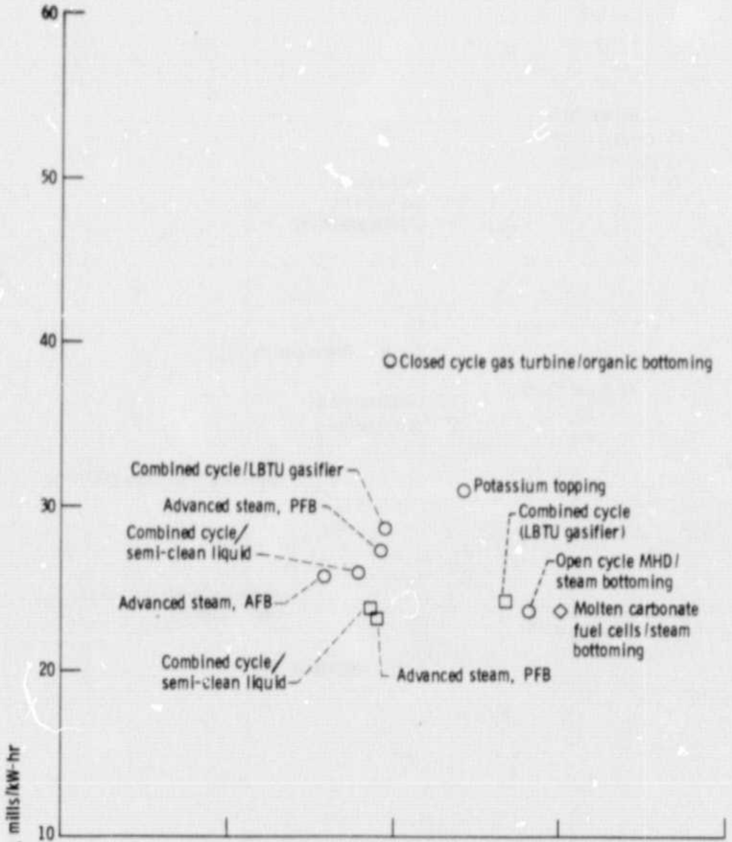


(a) Contractor determined cost of electricity using a common "start of construction" date.

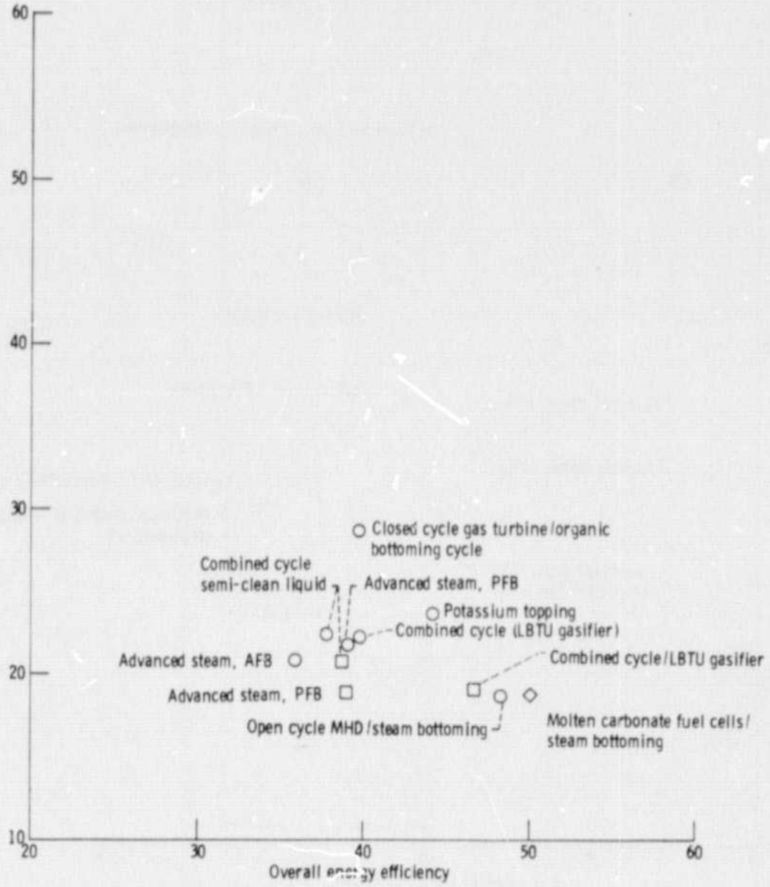


(b) Cost of electricity using a common "end of construction" date.

Figure 2. - Effect of economic ground rules on the cost of electricity for ECAS - Task 2 results.



(c) Cost of electricity using constant 1975 1/2 dollars.



(d) Average cost of electricity for 30 year plant lifetime in constant dollars (1975 1/2) assuming an inflation rate of 0.0325 per year.

Figure 2. - Concluded.

ORIGINAL PAGE IS
OF POOR QUALITY

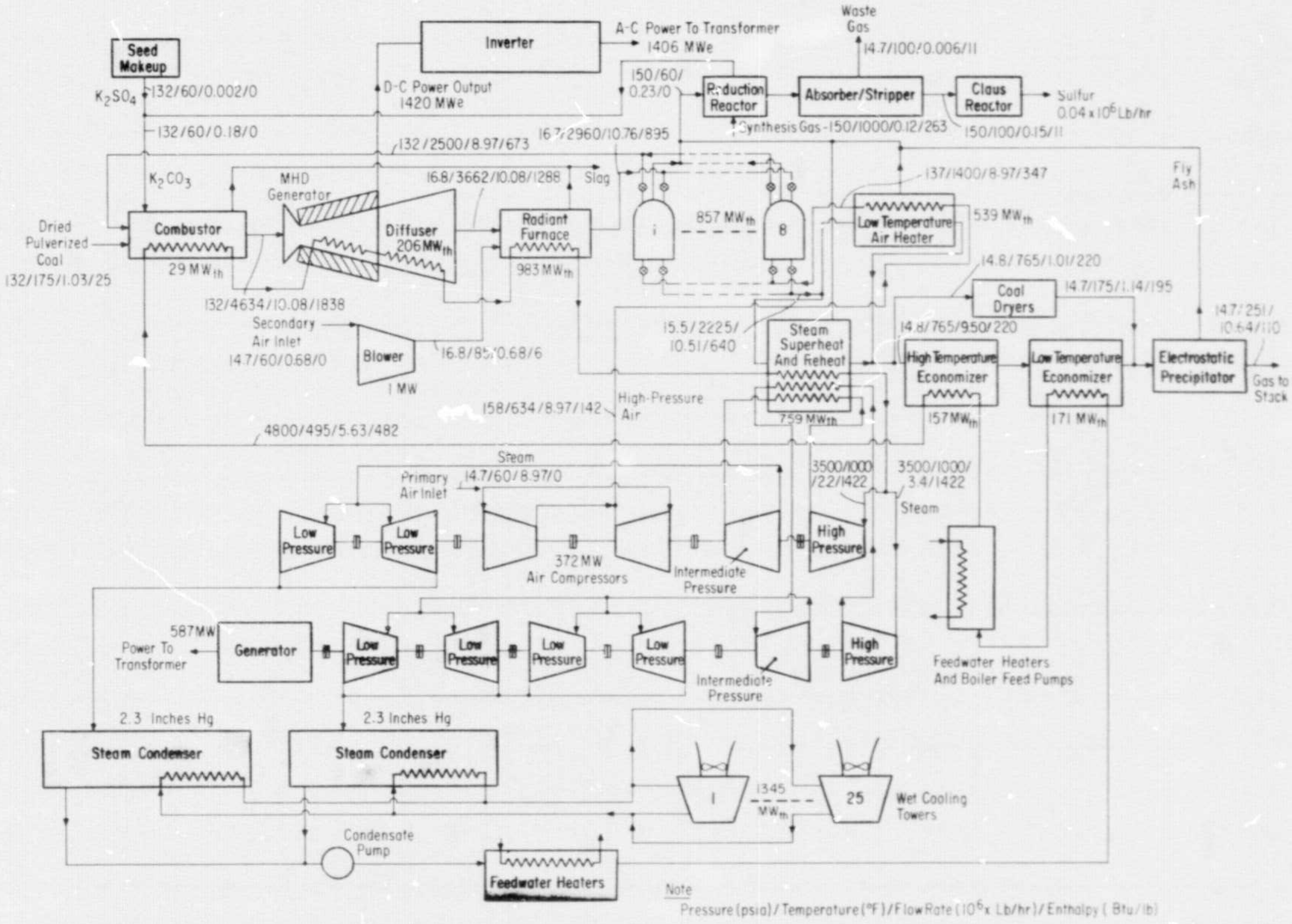


Figure 3. Schematic Diagram of Open-Cycle MHD Plant
(General Electric--Task 2)

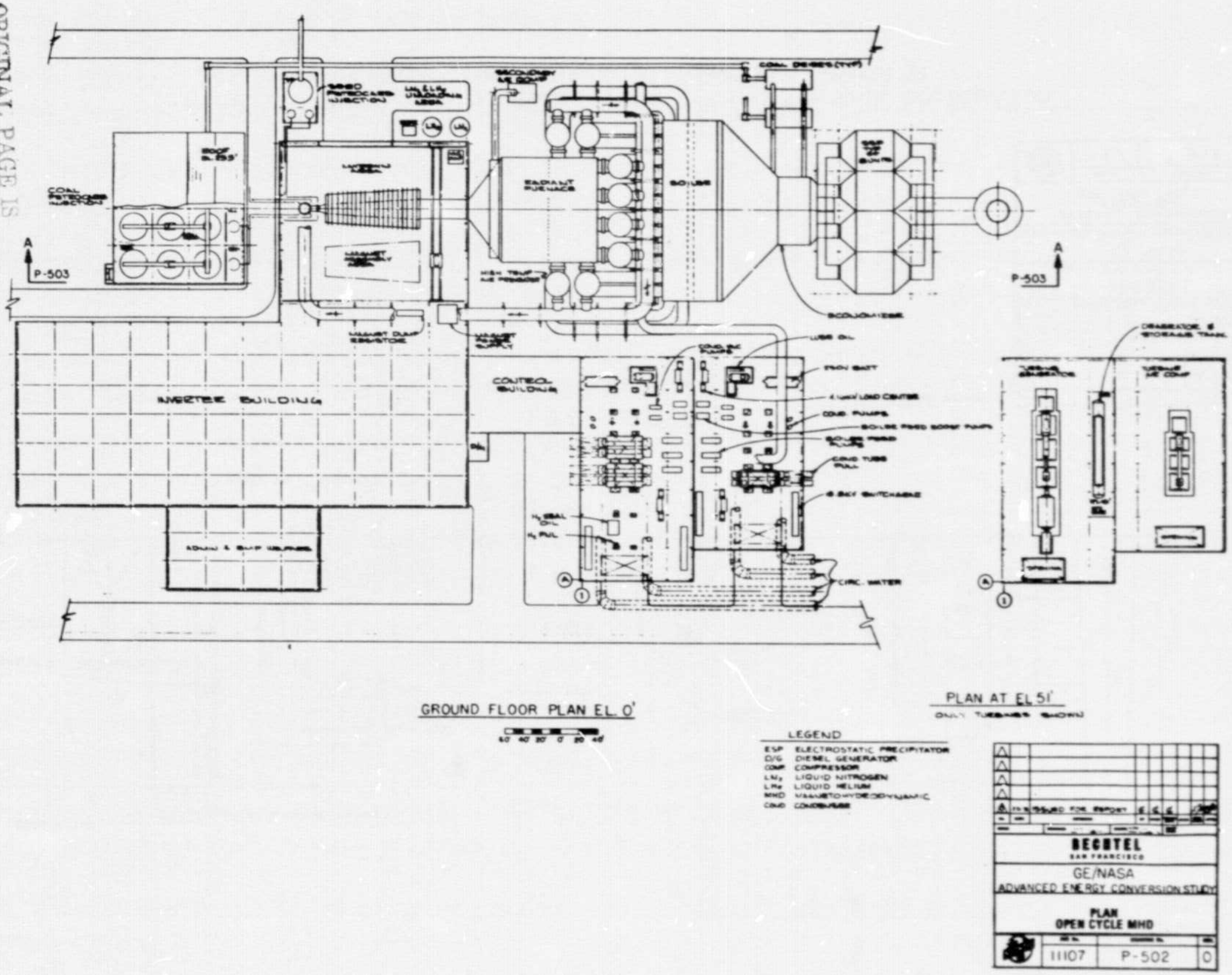


Figure 4. Plan of Main Plant Island (General Electric--Task 2)

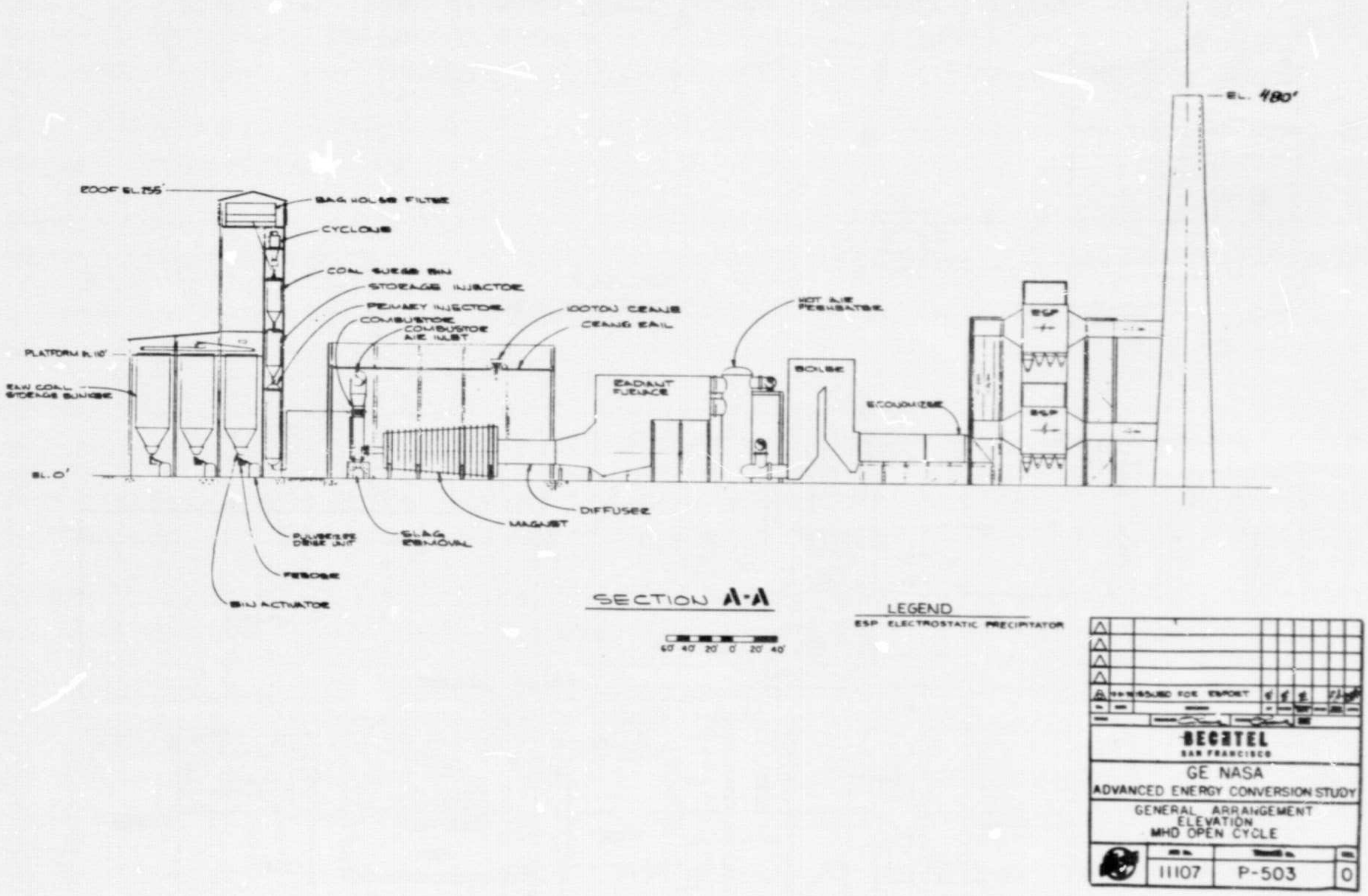


Figure 5. Elevation of Main Plant Island Through Combustion Gas Flow Path (General Electric--Task 2)