NASA CR-134941
VOLUME X

ENERGY CONVERSION ALTERNATIVES STUDY

-ECAS-

WESTINGHOUSE PHASE I FINAL REPORT

Volume X — LIQUID-METAL MHD SYSTEMS

by
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Prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION
NATIONAL SCIENCE FOUNDATION

NASA Lewis Research Center
Contract NAS 3-19407

(NASA-CR-134941-Vol-10) ENERGY CONVERSION ALTERNATIVES STUDY (ECAS), WESTINGHOUSE PHASE 1. VOLUME 10: LIQUID-METAL MHD SYSTEMS Final Report (Westinghouse Research Labs.) 200 p HC $7.50 CSCL 10B G3/44
N76-23701
Unclas
28175

1. Report No. NASA CR-134941 Volume X	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle ENERGY CONVERSION ALTERNATIVES STUDY (ECAS), WESTINGHOUSE PHASE I FINAL REPORT VOLUME X - LIQUID-METAL MHD SYSTEMS		5. Report Date February 12, 1976 6. Performing Organization Code
7. Author(s) R. R. Holman and T. E. Lippert		8. Performing Organization Report No. Westinghouse Report No. 76-9E9-ECAS-R1v.10 10. Work Unit No.
9. Performing Organization Name and Address Westinghouse Electric Corporation Research Laboratories Pittsburgh, PA 15235		11. Contract or Grant No. NAS 3-19407 13. Type of Report and Period Covered Contractor Report
12. Sponsoring Agency Name and Address Energy Research and Development Administration National Aeronautics and Space Administration National Science Foundation Washington, D.C.		14. Sponsoring Agency Code

15. Supplementary Notes

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16. Abstract

Plant costs and efficiencies are presented for two basic liquid-metal cycles corresponding to 922 and 1089°K (1200 and 1500°F) for a commercial application using direct coal firing. Sixteen plant designs are considered for which major component equipment were sized and costed. The design basis for each major component is discussed. Also described is the overall systems computer model that was developed to analyze the thermodynamics of the various cycle configurations that were considered.

17. Key Words (Suggested by Author(s))			18. Distribution Statement
sodium	MHD	efficiency	Unclassified - Unlimited
argon	steam turbine	cost	
lithium	plant		
helium	coal		

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified	191	

* For sale by the National Technical Information Service, Springfield, Virginia 22161

NASA-C-168 (Rev. 10-75)

ACKNOWLEDGMENTS

Section 11 entitled, "Liquid-Metal MHD Systems", was centered in the Westinghouse Research Laboratories. It was directed by R. R. Holman of the Westinghouse Astronuclear Laboratories and T. E. Lippert of the Westinghouse Research Laboratories.

Those making significant contributions were:

- R. Draper, who developed the design relations for the heat recovery steam generator.
- P. W. Eckels and J. M. Makiel, who provided the design analysis for various heat transfer components.
- R. E. Grimble, who developed and programmed the procedure used to analyze the overall thermodynamic characteristics and for calculating cycle performance. He also contributed significantly to developing the understanding of the physics associated with the liquid metal, two-phase processes.
- J. H. Murphy and F. O. Roach, who developed the required magnet design and model.
- J. L. Steinberg and G. J. Silvestri of the Westinghouse Steam Turbine Division who calculated the performance and price of certain steam turbines.
- C. T. McCreedy and S. M. Scherer of Chas. T. Main, Inc. of Boston, who prepared the balance of plant description and costing, site drawings, and provided consultation on plant island arrangements and plant constructability.

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SUMMARY

The liquid-metal MHD systems study emphasis is placed on a direct coal fired design using a bubbly two-component flow of sodium and argon in the MHD generator and a Rankine steam bottoming plant. Two basic cycles are studied, corresponding to argon temperatures of 922 and 1089°K (1200 and 1500°F) at the duct inlet. Corresponding to these basic cycles, a total of nine plant designs were sized and costed. The basic systems compresses a two-component bubbly flow of sodium and argon at 8.27 MPa (1200 psi) that expands to about 2.76 MPa (400 psi) in the duct system. The liquid metal and gas are then separated. The argon gives up heat to superheat, reheat and generate steam, and to preheat the combustion air. It is then compressed and passed through the fired heater where its temperature is again increased to 1089°K (1500°F). Lithium-helium is assumed in one plant design.

The MHD duct system that was designed consisted of multiple ducts arranged in clusters and separated by iron magnet pole pieces. The ducts each with an output of about 100 MW were in parallel to the flow but were connected in series electrically to provide a higher MHD voltage. Nonetheless the inversion equipment costs 20% of the total plant cost due to the high currents involved at low-MHD output voltages.

In analyzing the overall systems, the factors that were found to affect most directly the cycle efficiency of this plant are the efficiency of the MHD channel, compressor and pumps, and the pressure losses associated with the large liquid-metal flows. These are areas of great uncertainty, especially in the large component sizes required for commercial operation. The costs determined for both the fired and coupling heat exchanger components were large, comprising nearly 35% of the total capital investment. Due to the large mass of liquid metal circulated, over

63,090 ℓ/s (10^6 gpm) at the 5.51 MPa (800 psi) pressure head, the liquid-metal pump costs and technology are critical system parameters.

With an assumed MHD channel efficiency of 80%, a pump efficiency of 90% and a 45% efficient steam-bottoming plant, the efficiency of the 1089°K (1500°F) combined liquid-metal steam cycle was 43%. The complexity and high cost of this plant ($1,165/kW) result in a cost of electricity of greater than 12.5 mills/MJ (45 mills/kWh). Lower plant costs can be achieved with lower peak cycle temperatures but overall the energy efficiency is penalized.

With these relatively high plant costs and with the low potential for improving cycle efficiencies over conventional plants, commercial development of this plant would not appear warranted.

11. LIQUID-METAL MAGNETOHYDRODYNAMIC SYSTEMS

11.1 State of the Art

The liquid-metal magnetohydrodynamic (LM-MHD) power conversion cycle is a developing technology where progress to date has been in the basic theoretical studies of the thermodynamic cycle (s) and small-scale experimental test programs (References 11.1 through 11.4). Probable levels of performance, component technology, and plant costs, however, have not been established for commercial-size systems.

The basic liquid-metal MHD cycle operates by accelerating the liquid through the magnetic field with a gas and, in some instances, maintaining desired velocity by leaving the gas in the liquid for further expansion in the MHD duct and nozzle. Four of the options that exist for embodying this cycle in concept are

- Nozzle fluid acceleration and gas separation (separator type)
- Injector-condenser (two-phase condensing type)
- Bubbly flow (Brayton-type-cycle)
- Slug flow (same principle as bubbly flow).

Present technology and experience have indicated that the two-component, bubbly-flow, Brayton-type cycle (using an inert gas as the drawing fluid and a liquid metal as the prime conversion or electrodynamic fluid) offers the simplest and closest available technology. On this basis, the Brayton cycle was selected for the systems evaluated in this study.

This cycle has been under development in several countries, for several years, but particularly at Argonne National Laboratory, where it was funded primarily by the Office of Naval Research and the National Science Foundation.

The factors that would appear to limit the thermodynamic potential of this cycle are the limits imposed by practical design and safety considerations on liquid-metal and structural temperatures and pressure, and uncertainties associated with the efficiencies of the components.

Operating a liquid-metal system above the atmospheric boiling conditions would impose design safety considerations that lead to significantly increased costs and risk. For sodium and lithium systems a maximum temperature of about 1088°K (1500°F) represents an upper limit that would appear practical. Materials and component design technology to this temperature level are not developed for liquid metals, but the significant advancements being made in the breeder reactor programs should provide a well-founded technology springboard.

The necessity for minimizing liquid-metal vapor carry-over in the gas in the lower temperature portions of the cycle and the relatively high flow void fractions needed within the working fluid to achieve maximum MHD duct efficiencies require high duct inlet pressures, 5.516 to 8.274 MPa (800 to 1200 psi). Such system pressure levels can restrict large-scale designs. This consideration, along with certain low voltage limitations that arise with this particular MHD conversion process, lead to small size, multiple ducts that are operated hydraulically in parallel but are connected electrically in series. This arrangement, however, magnifies the electrical end and friction flow losses for the duct and related components. These practical design considerations suggest that a single, liquid-metal MHD duct be limited to about 100 MWe or less. Large plant sizes (600 to 3000 MWe) would utilize modular duct construction. For such cases the major cost benefit from large-scale plants would be in the economics of the larger heat exchange equipment.

With the emphasis on direct coal-fired systems, the combined LM-MHD steam binary power plant would appear to offer the maximum potential for performance. Within the temperature limits cited above, and based on current steam plant technology, the thermodynamic efficiency of this combined cycle would range around 45%. Current or very near term emission control technology should be adequate to minimize the environmental impact of this power plant.

The factors that affect the cycle efficiency of this plant most directly are MHD duct efficiency, compressor and pump efficiencies, and the pressure losses associated with the large liquid-metal flows. These are areas of great uncertainty, especially in the large component sizes required for commercial operation, and are subject to varied expert opinions. The principal system technology and component designs, therefore, have been reviewed with regard to the current state of the art which is briefly summarized in Table 11.1. None of the key system components reviewed were found to be sufficiently developed in the required commercial sizes for LM-MHD systems. The results of this study, then, are compared on a relative basis. Specific conclusions on performance and cost are made but should be considered preliminary in that with increased understanding of large-scale LM-MHD component design performance, the various cost tradeoffs would change.

11.2 Description of Parametric Points to Be Investigated

11.2.1 Selection of Parametric Study Points

Table 11.2 summarizes the LM-MHD cases studied and the major variable(s) that characterize each of the cases. Common assumptions concerning each case are also listed. Eighteen cases are shown, including the base case (Point 16). Thermodynamic state point data and plant efficiencies have been developed for each of these cases. In concurrence with NASA-Lewis technical direction,* however, only ten of these cases have been completely costed. The costed cases are indicated by an asterisk. The noncosted cases represent direct variations of the base case that result in decreased system performance and only a nominal change in the major factors that affect costs. The ten costed cases reflect variation of the parameters that were found to impact most directly on plant performance and cost. These variables include:

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* Letter from W. J. Brown (NASA-Lewis) dated April 22, 1975.

Table 11.1 Summary of Status of Liquid-Metal, MHD Key Component Development

Component	Summary of Development Status and Experience
MHD-Duct	• Intensive theoretical studies in progress • Most experience with two-component-homogeneous flow • Small-scale tests show duct efficiencies to 50%; Trends in data and theory suggest higher efficiencies are obtainable • Major duct losses are slip and electrical end losses • Materials compatability at 922°K (1200°F) appears near term, constant temperature operation favorable
Mixer	• No design basis available for high void fractions required
Nozzle	• Test conducted on small nozzles with two-phase flow show efficiencies to 85% • Data on material erosion problem at high temperature required • Application of jet pump at high voids needs to be demonstrated
Separator	• Several design concepts under evaluation • Separator efficiency to 99%, higher recovery may require staged separators • Energy efficiency to 90% • Materials and design untested in commercial-scale systems
Diffusers	• Single-phase flow diffusers design technology established • Achievable efficiency to 85 to 90%
Liquid-Metal Pumps	• Sodium pump technology available at low heads, low flow • Pump costs high; development of direct sodium seals required • Technology extension to 922°K (1200°K) deemed feasible for near term development
Liquid-Metal Purification	• Adequate technology base available • May require larger-scaled system to be economical
Heat Exchange Equipment	• Materials technology to 1088°K (1500°F) needs to be developed for utility applications • Design basis for clean gas systems available • Flue gas/liquid-metal materials compatability require more cost-effective design and technology base

Table 11.2 — Summary of Parametric Point Data for LM-MHD Study

Case No.	Combustor	LM-MHD	Bottom Plant
16* Base case (Fig. 11.1) 1000 MWe base load 30 yr life	Direct coal – fired cyclone furnace and stack Illinois No. 6 Coal	Na/A-1200°F, 1200 psi MHD Conversion = ft Duct = 0.75; Pump = 0.85 Compressor Efficiency=0.85 Magnetic Fld. = 0.55T Induction	Steam – 3500 psi 1000°F/1000°F Wet Cooling Tower
1. 600 MWe	Same as base case	Same as base case	Same as base case
2. 3000 MWe	"	"	"
3. 1000 MWe	Atm fluidized bed	"	"
4.* 1000 MWe (Fig. 11.5)	MHD open cycle	"	No steam plant
5.* "	Pres. fluidized bed (100 atm)	"	Same as base case
6.* "	Same as base case	Li/He, 1500°F, 1200 psi	"
7. "	"	Na/A, 1200°F, 440 psi	"
8.* " (Fig. 11.4)	"	Na/A, 1500°F, 1200 psi	"
9.* "	"	High-comp. efficiencies	"
10. "	"	Low-comp. efficiencies	"
11.* "	"	Liquid metal electromagnetic pump	"
12.* "	"	Liquid metal jet nozzle pump	"
13.* " (Fig. 11.6)	"	Na/A, 1500°F, 1200 psi	No bottom plant- Once-through cooling
14.* "	"	Na/A, 1500°F, 1200 psi High-component eff.	Same as base case
15. "	"	Same as case 14	Same as base case but higher cycle eff.
16. Base case	See above	See above	See above
17. "	"	Multistaged ducts	"
18.* "	Atm fluidized bed	Same as base case	Same as base case

Assumptions – Common to all Points

Liquid metal aerosol carry-over < 0.1% in gas
Purity level – 2 ppm O_2 and 0.2 ppm H_2
Gas to liquid-metal reheat in combustor heat exchanger, but no direct LM heating in combustor
Liquid-metal system technology commensurate with liquid-metal fast breeder reactor
MHD output voltage $\geq$ 500 V_{dc} for converters to obtain 99% conversion efficiency
System design and component performance with exception of MHD loop will conform to existing central power station practices and all safety requirements

- MHD duct efficiency
- MHD compressor and pump efficiency
- MHD duct inlet temperature
- MHD working fluids
- Steam bottoming plant efficiency
- Power plant cycle configuration

11.2.2 Discussion of Study Parameters

MHD duct performance at the flow rates and component sizes considered for the commercial plants in this study are without direct experimental support and, therefore, require substantial extrapolation. Because of this uncertainty, a range of values (from 70 to 85%) of duct efficiency were assigned for study. The lower numbers (70 to 75%) are values that would appear obtainable in large systems, based on current theory and trends in existing data (References 11.4 through 11.6).

As with any thermodynamic cycle, compressor and pump efficiencies are important performance parameters. Large, highly efficient compressors are state of the art in conventional gas turbine cycles. With the LM-MHD system, however, the effect of liquid-metal carry-over (in the form of an aerosol or oxide) on compressor performance has not been quantified. For these reasons, values of compressor efficiency of 85% and 87.5% are used in the study. Values for the liquid-metal pump efficiency were taken from 80 to 90%. Breeder reactor sodium pump studies indicate efficiencies of around 85% (Reference 11.7). These are single-stage, low-head designs.

The duct inlet temperature and MHD working fluids affect the performance of the cycle in the usual straightforward manner. The impact of these parameters on costs are significant because of component material requirements. Two temperature levels were chosen, 922°K (1200°F) and 1088°K (1500°F). The 922°K (1200°F) is considered as near term technology, but the 1088°K (1500°F) would require a longer range development program. Liquid sodium and argon gas were selected as the working fluids for the base case and all parametric points except for one study case. (For this case, lithium/helium were used). Argon, although requiring significantly larger flow rates, was chosen in consideration of the more limited helium resource and economics of recovery. Liquid sodium was chosen because of the wider experience and technology base now existing.

11.2.3 Description of LM-MHD/Steam Binary Cycle Configuration

The direct coal-fired combined LM-MHD/steam binary power plant was emphasized in the study. Figure 11.1 shows the schematic diagram of this power plant which represents the base case study point.

The major items of the MHD loop are the mixer, the MHD channel (including superconducting magnet), the nozzle-separator, and the liquid-metal primary pumps. The other major loop components include the argon compressor(s) and the interfacing heat exchangers. Not included in the schematic but included as major cost items are the power conversion equipment (inverters, transformers, and circuit breakers) and the liquid-metal auxiliary systems (such as purification, emergency dump, and storage).

The Brayton-type MHD cycle operates by mixing the inert gas and liquid metal at high pressures to form a bubbly, homogeneous flow. The initial void fraction of this mixture is approximately 65%. The mixture is then introduced into the MHD channel, where the gas is allowed to expand through the channel carrying the liquid metal along. The interaction of the flowing liquid metal with the applied magneti_ field produces the desired electric field. In the channel the gas phase is expanded to a degree sufficient to produce a two-phase mixture of 85% void.

At the exit of the channel the two components are slightly accelerated, then separated (by momentum differences). Both components then progress separately through the system and are later remixed back at the inlet of the MHD channel.

Prior to being remixed, the liquid metal is pumped back to its MHD inlet head condition, 8.274 MPa (1200 psi). Three methods of liquid-metal pumping were considered in the study:

- Conventional, staged, centrifugal mechanical pumps
- Electromagnetic pumps
- Two-phase nozzle and diffuser.

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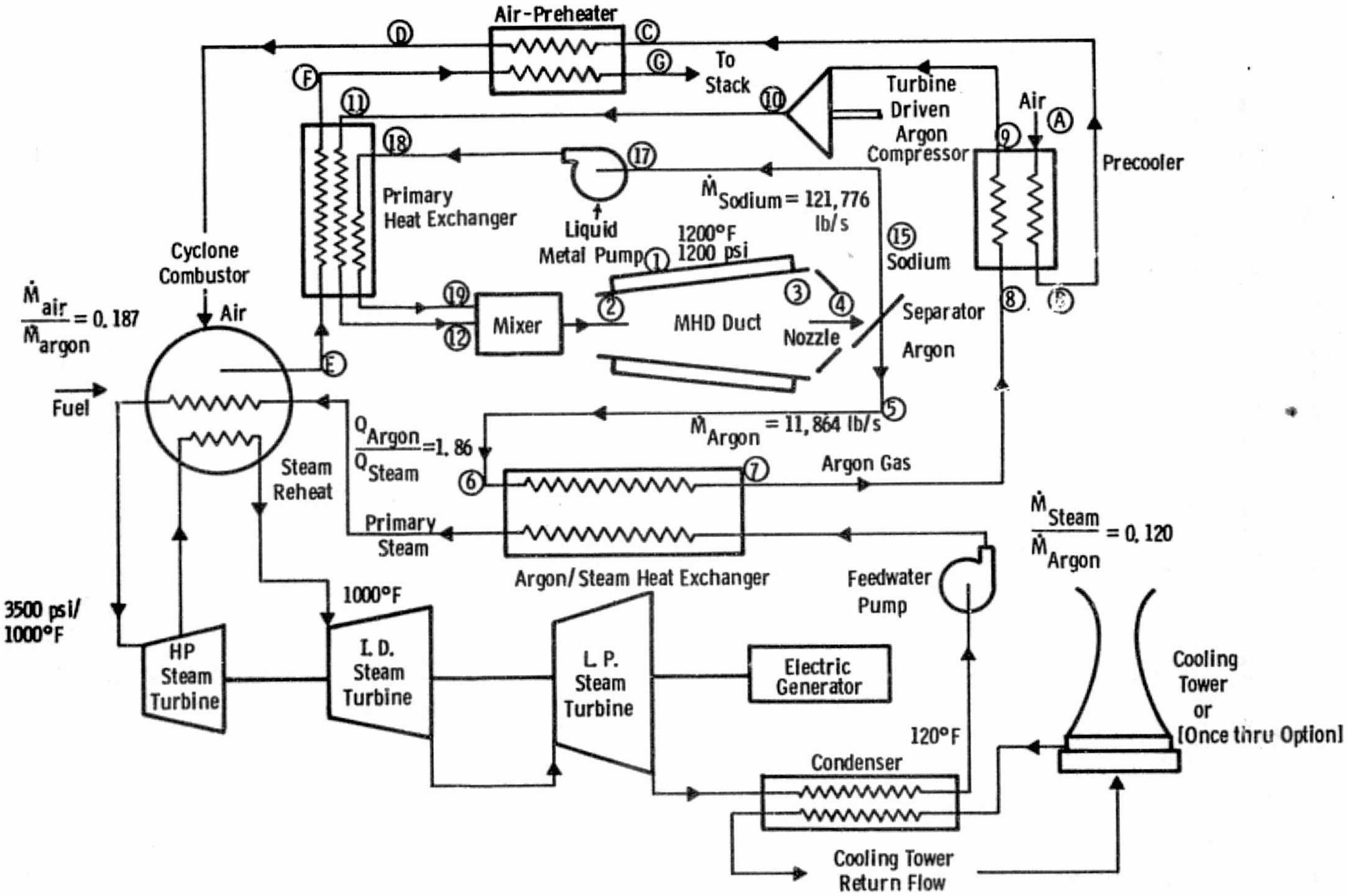

Fig. 11.1—Power plant flow schematic for the base case (Point 16) and Points 1, 2, 6, 7, 9 and 10 (See Appendix A 11.2 for state point valves for the base case)

The high-temperature argon gas, after leaving the separator, gives its heat to a conventional 24.131 MPa/811°K/811°K (3500 psi/1000°F/1000°F) steam turbine plant. The gas is then cooled further, compressed, and returned to the heat source (in this case, a conventional, atmospheric cyclone combustor).

For the low-temperature base case [922°K (1200°F) sodium], the steam plant bottoming the MHD cycle not only makes use of the sensible heat of the argon but also receives heat directly from the combustion system. Although this arrangement leads to a more complex thermodynamic cycle, it was found to yield the best plant performance for this low-temperature case. The steam finish superheating [700 to 811°K (800 to 1000°F)] and all the reheating is done directly in the fired part of the system. Approximately 35% of the total steam plant heat load comes directly from the fired system. The steam plant design uses no extracted steam for feed heating but uses argon feedwater heaters instead. This gives a lower steam plant cycle performance, but overall plant performance is higher because of the heat rejection requirements on the LM-MHD cycle side that would occur with extractive feedwater heating.

Figure 11.2 shows the respective heating and cooling curves for the two working fluids (argon and water) at the interface(s) between the two cycles—in other words, at the steam generator and cyclone furnace. The argon cooling curve has been approximated by the straight line (i.e., constant specific heat) from 910 to 339°K (1178 to 150°F) corresponding to a 16.7°K (30°F) steam plant condenser approach at 11.852 kPa (3.5 in Hg) abs.

As seen from the figure, however, this 16.7°K (30°F) temperature difference does not represent the limiting pinch-point consideration. The actual pinch point occurs farther along the cooling curve. Because of the approximate nature of both the argon-cooling curve and the water-heating curve [this curve will depend somewhat on pressure drop - 0.6894 MPa (100 psi) assumed herein] no attempt has been made to design to a given pinch-point; instead, end conditions were chosen that would be nominally

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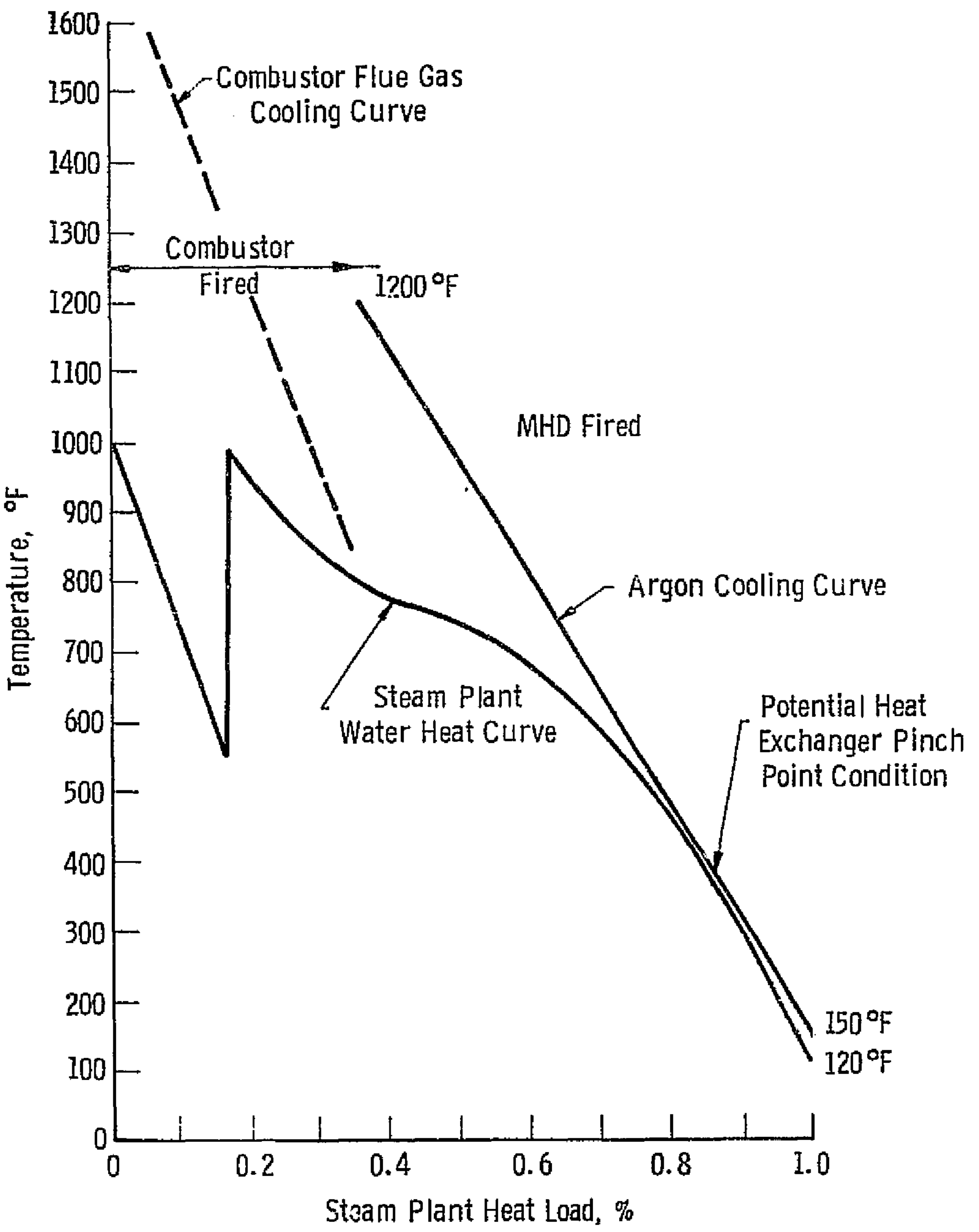

Fig. 11.2—Steam plant heat load curve for LM-MHD topping cycle and supplementary steam plant firing. Base case

acceptable and representative of a reasonable design approach.

For this base case design, single-stage compression preceeded by an argon precooler was found to give the best system performance. The argon precooler serves as the combustion air preheater. Thus, there is no argon heat that is directly rejected to a water heat sink. Most of the argon precooler heat is returned back to the MHD system. The only portion of the heat that is lost is through the combustor stack losses, the specific quantity being dependent on the boiler efficiency of the combustor.

The compressor inlet temperature is determined by the air to argon mass ratio and the design effectiveness of the precooler. The air to argon mass ratio is determined by interfacing conditions at the combustor-primary heat exchanger. These conditions are the desired duct inlet temperature, the approach temperature difference between the argon and flue gas in the primary heat exchanger and the combustion characteristics of the coal. The stack gas temperature will depend primarily on the exit temperature of the flue gas from the primary heat exchanger and the effectiveness of the air economizer.

If there were no direct firing of the steam plant in this base case, the terminal argon temperature would be 450°K (350°F). Various bottom cycle arrangements using this terminal temperature were investigated to determine if higher (than the base case configuration) plant efficiencies could be achieved. Results showed that the heat rejection and a compressor work requirement precluded any efficiency gain.

Figure 11.3 is the schematic diagram for the LM-MHD/steam binary plant for the 1089°K (1500°F) sodium case, and for lithium/helium study point. Because of the higher temperatures, supplementary firing of the steam plant directly from the combustor could be avoided. The terminal argon temperature at the exit of the steam/argon heat exchanger (steam generator) is 380°K (225°F), which leads to a 350°K (170°F) compressor inlet temperature at the precooler exit. The basic elements and components of this cycle are otherwise similar to the low-temperature base case.

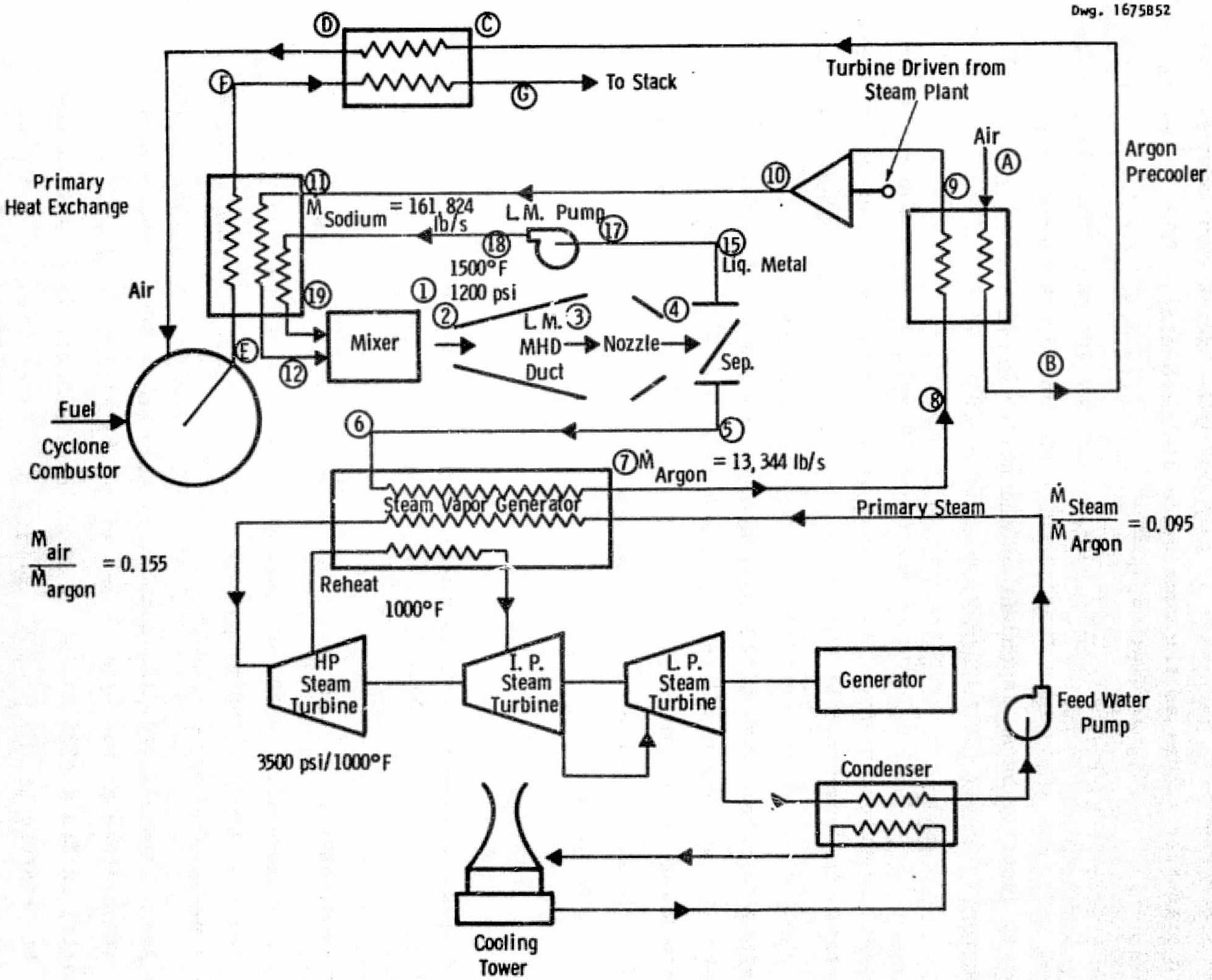

Fig. 11.3—Power plant flow schematic for high temperature parametric cases - Points 8 and 14

Two of the cases studied in this program were all MHD-type plants. Point 4 uses an open-cycle MHD plant to top the LM-MHD. Figure 11.4 shows a schematic diagram of this all-MHD binary plant. In theory, this combination could lead to relatively high plant efficiencies since, with this combination, the temperature at which energy conversion is occurring has been extended for both the topping and bottoming cycle.

Point 13 is an all LM-MHD plant. Figure 11.5 shows the schematic with this study point; once-through cooling was employed. The components in this plant are essentially those previously identified in the MHD loop of the base case. The major advantage of this all-MHD plant would be its mechanical simplicity. Note in this case that the total flow rate is substantially larger than in the other plant configurations (all are plants based on 1000 MWe net).

In subsequent sections of this report further analysis is made of these power cycles, which includes the determination of plant efficiency and costs.

11.3 Approach

11.3.1 Assumptions

The LM-MHD study presented in this section was begun with the presumption of stipulated near state-of-the-art component performance and conversion efficiency (Reference 11.7). MHD duct conversion efficiency and key flow parameters were fixed at estimated attainable, near-optimum values. The study effort was, therefore, originally conceived to place major emphasis on the overall power plant system optimization and performance and cost assessments.

Early in this study, however, the need was established not only to develop some key component concepts for a full-scale system, but also to establish performance estimates in more detail in the MHD loop before any overall system evaluation could be undertaken. The study of interaction of slip ratio, end losses, voltage, aspect ratio, mixer, nozzle

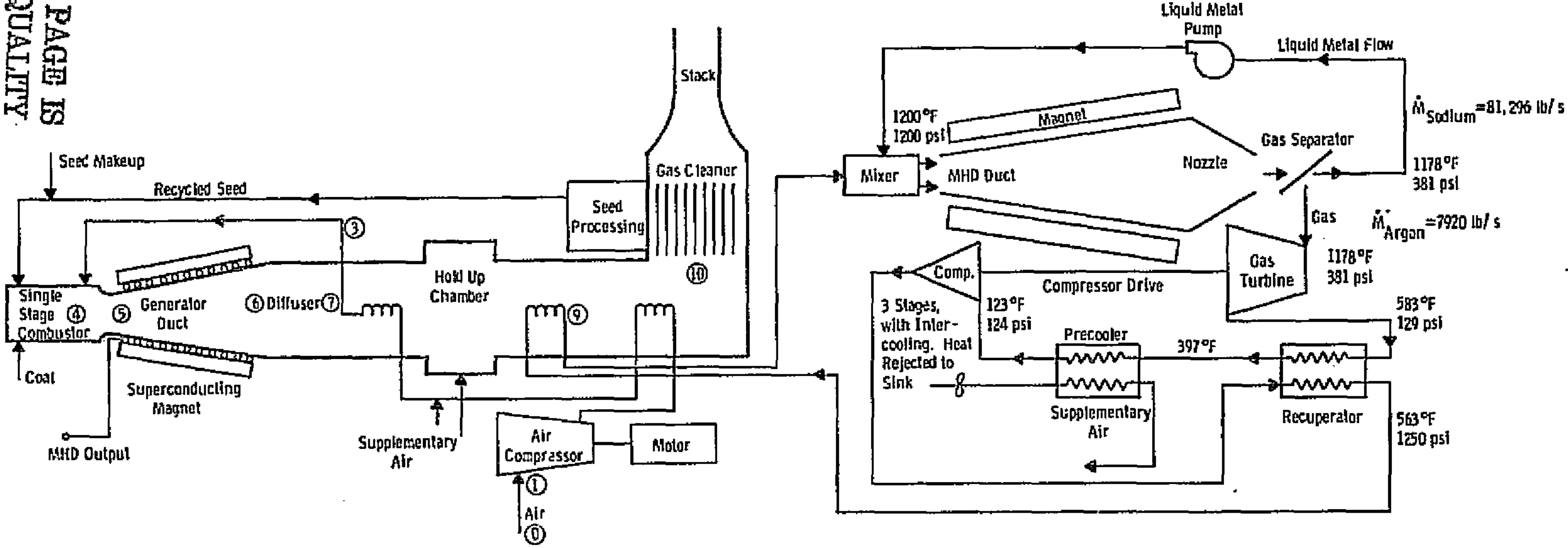

Fig. 11.4—Schematic of open cycle MHD with direct fired air preheater with a two-phase liquid-metal MHD bottom cycle (Point 4)

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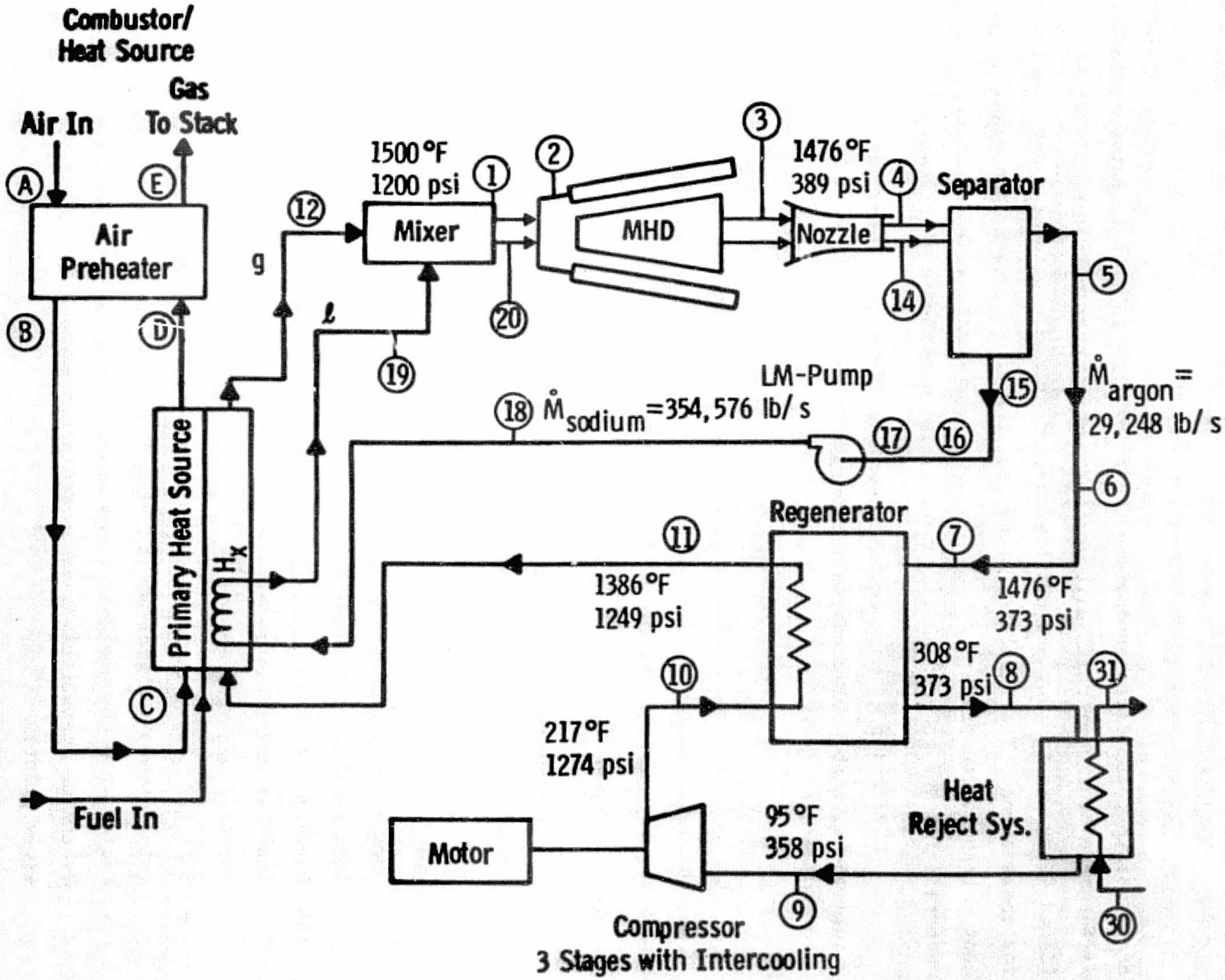

Fig. 11.5—Power plant flow schematic for all LM-MHD-Point 13

and separator, and diffuser designs had to be undertaken before the cycle performance of a commercial-size application could be calculated. Established design technology and performance, and economic data were not available for these areas. The resulting study was, therefore, based upon significant extrapolation of data for LM-MHD loop components, with resulting uncertainties and reduced ability to optimize a system realistically.

Discussion of more detailed application of the inert gas, liquid-metal, bubbly flow system and present technology as applied to this study is found in the study results in Appendix A 11.1. Calculational methods, flow models, and property data are considered sufficiently developed for argon and sodium to permit the first task of this study. Subsequent sections and appendices (as identified in the text below) deal with other aspects of the design and evaluation of the system.

11.3.2 Methodology

The methodology used in evaluating the study points in LM-MHD were as follows:

- Evaluate thermodynamic cycle for base case configuration
- Evaluate thermodynamic cycle for the parametric cases
- Conduct preliminary design and costing of major components for the base case study point
- Develop cost data information (capital and installation) based on material, temperatures, and operating conditions, for each major component
- Size and cost the major system components for each parametric point based on algorithms developed from the base case designs
- Factor into the analysis steam plant cost data where applicable
- Determine overall plant costs and performance for the required study points.

The evaluation of the LM-MHD thermodynamic cycle was done with the aid of a computer program. The purpose of the program was to identify the major system components in terms of the relevant thermodynamic and flow parameters. A description and listing of the program is given in Appendix A 11.2. The major features of the program include

- Incorporation of current analytical model(s) used for describing duct performance
- Cycle configuration flexibility to allow for system optimization, including various options for methods of heat rejection
- Appropriate iterative calculation procedures for interfacing with the bottoming plant to attain desired overall power output.

Included in Appendix A 11.2 is a sample computer output listing (base case computation) showing the calculated parameters.

Because LM-MHD is not a developed technology, the sizing and costing of the major cycle components had to be based on preliminary or conceptual designs. The approach taken was first to develop reasonable design concepts and sufficiently detailed designs for the components that comprise the base case to permit assessment, and then extrapolate these designs to the variations on the base case. This required rather generalized sizing and costing algorithms for each major component.

For instance, the configuration and arrangement of the large-scaled MHD ducts substantially affected the cost not only of the ducts and magnet systems, but of piping and pumping requirements. The initial design efforts performed in the conduct of this study contract have resulted in developing somewhat innovative design concepts that ultimately led to reduced component sizes, piping, and costs. The designs and design basis used for evaluating the base case, Point 16, are summarized in Section 11.5 as is the sizing and costing algorithm used for the MHD duct and assembly and for the major heat transfer equipment. Included are descriptions of the MHD duct assembly that include the mixer, nozzle, and separator; the MHD duct and magnet arrangement; and the preliminary plant layout that identifies the relative arrangement of the major component. The cost basis for determining installation of major components and the materials costing data that were used to establish the capital cost are, also included. Material selection for the various cases was

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TABLE 11.3 –LIQUID METAL MHD PARAMETRIC DATA–COSTED CASES

Parametric Point	BC/16	4	6	8	9	11	12	13	14
Power Output, MWe	1000	1000	1000	1000	1000	1000	1000	1000	1000
Fuel - Bituminous (1)	X	X	X	X	X	X	X	X	X
Furnace Type - Fluid Bed Cyclone	C	(3)	C	C	C	C	C	C	C
Conversion Process Parameters									
Gas Flow Rate, lb/s	11646	7922	1251	13200	9918	11341	10301	29254	11349
Liquid Metal Flow Rate, lb/s	119546	81309	85760	160118	101805	116408	105744	354584	137555
Mass Ratio								(6)	
Liquid Metal/Gas	10.26	10.26	68.5	12.12	10.2	10 3	10.3	12.1	12.1
Gas/Steam	8.30	(3)	1.11	10.2	8.30	8.30	8.30	(6)	10.2
Air/Gas	0.189	NA	1.65	0.159	0.199	0.189	0.196	0.082	0.168
MHD Conditions	A/Na	A/Na	He/Li	A/Na	A/Na	A/Na	A/Na	A/Na	A/Na
Duct Inlet Temperature, °F	1200	1200	1500	1500	1200	1200	1200	1500	1500
Duct Inlet Pressure, Atm	82.76	82.76	82.76	82.76	82.76	82.76	82.76	82.76	82.76
Duct Pressure Ratio	3.09	3.09	3.05	3.08	3.09	3.09	3.09	3.09	3.09
Magnetic Flux Density, Telsa	0.55	0.55	1.2	0.45	0.55	0.55	0.55	1.2	0.55
Duct Isentropic Eff.	0.75	0.75	0.75	0.75	0.85	0.75	0.75	0.80	0.80
Compressor Efficiency	0.85	0.85	0.85	0.85	0.875	0.85	0.85	0.85	0.875
Pump Efficiency	0.85	0.85	0.85	0.85	0.90	0.90	0.86	0.85	0.90
Compressor Inlet Temp., °F	120	123	170	175	120	120	120	95 (5)	175
Compressor Pressure Ratio	3.56	4.67	3.51	3.55	3.56	3.56	5.54	1.55 (7)	3.56
Precooler Effectiveness	0.90	0.9[illegible] (5)	0.92	0.90	0.82	0.90	0.84	0.92	0.87
Gas $\Delta P/P$ (Total-MHD Loop)	0.09	0 08	0.09	0.09	0.09	0.09	0.193	0.111	0.09
Liq. $\Delta P/P$ (Total-MHD Loop)	0.06	0.06	0.06	0.06	0.06	0.06	0.03	0.06	0.06
Duct Gross Power, MWe	1229	835 (4)	1549	1645	1155	1197	1087	3864	1498
Cycle Net Power, MWe	45.65	332	148	130.2	187.6	52.0	156	1005	254
MHD Cycle Efficiency	0.0276	0.16	0.063	0.0546	0.122	0.043	.0985	0.364	0.116
Steam Plant/3500 psi/1000°F/1000°F									
Gas Temp. Inlet, °F	1178	NA	1488	1488	1178	1178	1178	NA	1476
Steam Temp. Outlet, °F	800	NA	1000	1000	800	800	800	NA	1000
Condenser Press., in Hgabs	3.5	NA	3.5	3.5	3.5	3.5	3.5	NA	3.5
Heat to Steam Plant, MWt	1561	NA	2067	2166	1330	1526	1386	NA	1858
Direct Heat From Combustor, MWt	839.5	NA	0	0	719	825	749.3	NA	0
Net Power, MWe	256	NA	148	0	235	269	0	NA	269
Conversion Cycle Eff.	0.396	NA	0.413	0.401	0.395	0.396	0.396	NA	0.401
Combustor		(3)							
Pressure, Atm	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Stack Reject Temp., °F	337	305	370	370	337	337	337	370	370
Fuel Rate, tons/hr	465	514	422	438	424	458	435	514	404
Boiler Efficiency	0.88	NA	0.87	0.87	0.88	0.88	0.88	0.87	0.87
Thermodynamic Eff., % (1)	4[illegible].0	NA	43.4	42.0	43.9	40.6	42.9	36.4	45.7
Powerplant Eff., %	35.7	30.7	39.1	37.7	39.2	36.3	37.9	32.0	41.0
Overall Eff., %	34.3	29.6	37.5	36.2	37.3	34.5	36.4	31.0	39.4
Total Capital Costs × 10^{-6}, $	894.5	1318	1728	1118	809.2	854.5	751.1	2039	1106
Capital Costs $/kWe	942.9	1392	1817	1177	851.7	900.7	790.2	2140	1165
Cost of Elect. Mills/kWh									
Capital	29.81	44.01	57.45	37.21	26.92	28.47	25.0	67.6	36.84
Fuel (2)	8.61	9.88	7.81	8.10	7.83	8.47	8.05	9.51	7.46
Oper. & Maint.	0.94	0.90	0.90	0.92	0.90	0.93	0.91	0.88	0.90
Total	38.35	54.79	56.16	46 23	35.65	37.87	33.94	78.04	45.20
Est. Time of Construction	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0
Est. Availability Date	1983	1983	1990	1990	1983*	1983*	1985	1983	1990

*Assumes Optimistic Performance of Base Case

Notes:

(1) Where Applicable
(2) Use Base Delivered Fuel Cost
(3) MHD Open Cycle Topping
(4) Does Not Include Argon Gas Turbine
(5) Recuperator
(6) All MHD
(7) Per Stage - 3 Stages

based on the recommendations made in Subsection 3.8. The basis for sizing and costing the superconducting magnet system is given in Appendix A 11.3. The power conditioning equipment description and costs are given in Appendix A 11.4. A description of the required liquid-metal systems and subsystems are given in Appendix A 11.5. Included in this appendix is the basis for determining the appropriate sizing and cost algorithms for:

- Liquid-metal mechanical pump(s)
- EM pump (one design only)
- Liquid-metal purification sybsystem
- Liquid-metal inventory and emergency dump.

A summary of the design specifications for the steam generator and primary heat exchanger are given in Appendix A 11.6. (The theoretical basis for the designs is given in Appendix A 9.3).

The factors considered in indirect power plant costs and the subsequent basis for calculating the total plant capitalization and cost of electricity are described in Section 2.

11.4 Results of the Parametric Study

11.4.1 Summary Tables

The schematic diagram previously shown in Figure 11.1 depicts the base case and several low-temperature cases as identified in the title of the figures. The schematic diagrams shown in Figures 11.3 through 11.5 correspond to the cycle configurations for the remaining points. Tables 11.3 and 11.4 summarize the major parameter data, including flows, pressures, temperatures, and efficiencies for all the parametric cases.

The two tables, one corresponding to the required costed points and the second summarizing the noncosted parametric points, have been arranged to show the major variables associated with the topping cycle configuration; major variables associated with the steam bottoming cycle; and the parameters associated with the primary heat source (combustor). The combined-cycle thermodynamic efficiency, power plant efficiency, and

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TABLE 11.4 — LIQUID METAL MHD PARAMETRIC DATA-NON COSTED

Parametric Point	1	2	3	5	7	10	15	17
Power Output, MWe	600	3000	1000	1000	600	1000	1000	1000
Fuel - Bituminous ①	X	X	X	X	X	X	X	X
Furnace Type - Fluid Bed, Cyclone	C	C	FB	FB	C	C	C	C
Conversion Process Parameters								
Gas Flow Rate, lb/s	6962	34812	11576	12081	6834	13914	10898	27600
Liquid Metal Flow Rate, lb/s	71470	392163	118832	124022	191304	142824	132089	120710
Mass Ratio								
Liquid Metal/Gas	10.26	10.26	10.26	10 26	28	10.26	12.1	13.1 ③
Gas/Steam	8.30	8.30	8.30	8.30	8.30	8.30	10.2	10.2
Air/Gas	0.189	0.189	0.205	0.279	0.189	0.189	0.159	0.323
MHD Conditions	A/Na	A/Na	A/Na	A/Na	A/Na	A/Na	A/Na	A/Na
Duct Inlet Temp., °F	1200	1200	1200	1200	1200	1200	1500	1500
Duct Inlet Press., Atm	82	82	82	82	30	82	82	82
Duct Press. Ratio	3.08	3.08	3.08	3.08	3.08	3.08	3.08	3.08
Magnetic Flux Density, TESLA	0.55	0.55	0.55	0.55	0.55	0.55	0.55	0.55
Duct Isentropic Eff.	0.75	0.75	0.75	0.75	0 75	0.70	0.80	0.75
Compressor Efficiency	0.85	0.85	0.85	0.85	0.85	0.81	0.85	0.85
Pump Efficiency	0.85	0.85	0.85	0.85	0.85	0.75	0.85	0.85
Compressor Inlet Temp., °F	117	117	115	150	117	120	175	120
Compressor Press. Ratio	3.56	3.56	3 56	3.56	3.52	3.56	3.56	3.56 ③
Precooler Effectiveness	0.90	0.90	0.90	NA	0.90	0.90	0.90	0 90 ④
Gas ΔP/P (Total-MHD Loop)	0.09	0.09	0.09	0.09	0 09	0.09	0.09	0.09
Liq. ΔP/P (Total-MHD Loop)	0.06	0.06	0 06	0 06	0 06	0.06	0.06	0.06
Duct Gross Power, MWe	734	3670	1220	1274	716	1379	1439	1151 ③
Cycle Net Power, MWe	29.8	149	50.9	10 1	31.4	−142	188.6	405 ⑤
MHD Cycle Efficiency	0.0296	0.0296	0.0310	0.006	0.031	NA	0 092	0.118
Steam Plant/3500 psi/1000°F/1000°F								
Gas Temp. Inlet, °F	1178	1178	1178	1178	1192	1180	1476	1452
Steam Temp. Outlet, °F	1000	1000	1000	1000	1000	1000	1000	1000
Condenser Press., in Hgabs	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5
Heat to Steam Plant, MWt	937	4685	1558	1626	931.6	1875	1784	1484
Direct Heat From Combustor, MWt	506	2532	842	879	503 5	1014	0	0
Net Power, MWe	155	776	262	229	167	277	98	0 ⑥
Conversion Cycle Eff.	0.396	0.396	0.396	0.396	0.396	0.396	0.45	0.407
Combustor								
Pressure, Atm	1	1	1	100	1	1	1	1
Stack Reject Temp., °F	337	337	327	270	337	337	337	327
Fuel Rate, tons/hr								
Boiler Efficiency	0.88	0.88	0.86		0.88	0.88	0.87	0.87
Thermodynamic Eff., % ①	40.8	40 8	40 8	39.8	40 2	35.7	48.9	35.0
Power Plant Eff., %	35.4	35.4	35.4	34.6	35.6	32.0	43 9	30.4
Overall Eff., %								
Total Capital Costs × 10^{-6}, $								
Capital Costs $/kWe								
Cost of Elec. Mills/kWh								
Capital								
Fuel ②								
Oper. & Maint.								
Total								
Est. Time of Construction								
Est. Availability Date								

Notes:

① Where Applicable
② Use Base Delivered Fuel Cost
③ Per Stage - 3 MHD Stages
④ Regenerator
⑤ Total, 3-Ducts
⑥ Steam Plant Power Used for Compressor Drives

overall efficiency for each case is also shown.

A breakdown of plant costs into total capital and electrical costs (fuel costs, capital, and operating and maintenance) is given for the costed cases (Table 11.3).

11.4.2 Description of Parametric Points

The first column in Table 11.3 corresponds to the base case Point 16. This point represents a technology that was taken to be relatively near term. The MHD cycle is operated at 922°K (1200°F) and 8.27 MPa (1200 psi). The schematic of the cycle was previously shown in Figure 11.1. The power plant bottoming this MHD cycle is a 24.132 MPa/ 811°F/811°F (3500 psi/1000°F/1000°F) steam turbine plant. This plant, with no extraction feedwater heaters, has a thermodynamic cycle efficiency of about 39.5%.

The power plant efficiency for the combined cycle is about 36%. The cost of electricity for this binary power plant is estimated at 10.91 mills/MJ (39.3 mills/kWh).

The relatively low plant performance for the base case (Point 16) results from selecting relatively modest component efficiencies, assuming a MHD duct efficiency of 75% and assuming 922°K (1200°F) sodium temperature as the near term development capabilities. In this low-temperature case, an austenitic stainless steel was used as the major material for component construction.

Points 9 and 11 show that the base case plant performance increases and plant costs decrease when the efficiencies of the major loop components (compressor and pump) and duct efficiency are increased (see Table 11.3 for specific values). Point 11 uses an EM pump as prime mover for the liquid metal. Point 8 shows that raising duct inlet temperatures to 1088°K (1500°F) increases plant costs significantly. Point 14 shows the combined effect of both higher component and duct efficiencies, as well as a higher (than base case) duct inlet temperature. This plant design showed the highest energy efficiency of the costed study cases.

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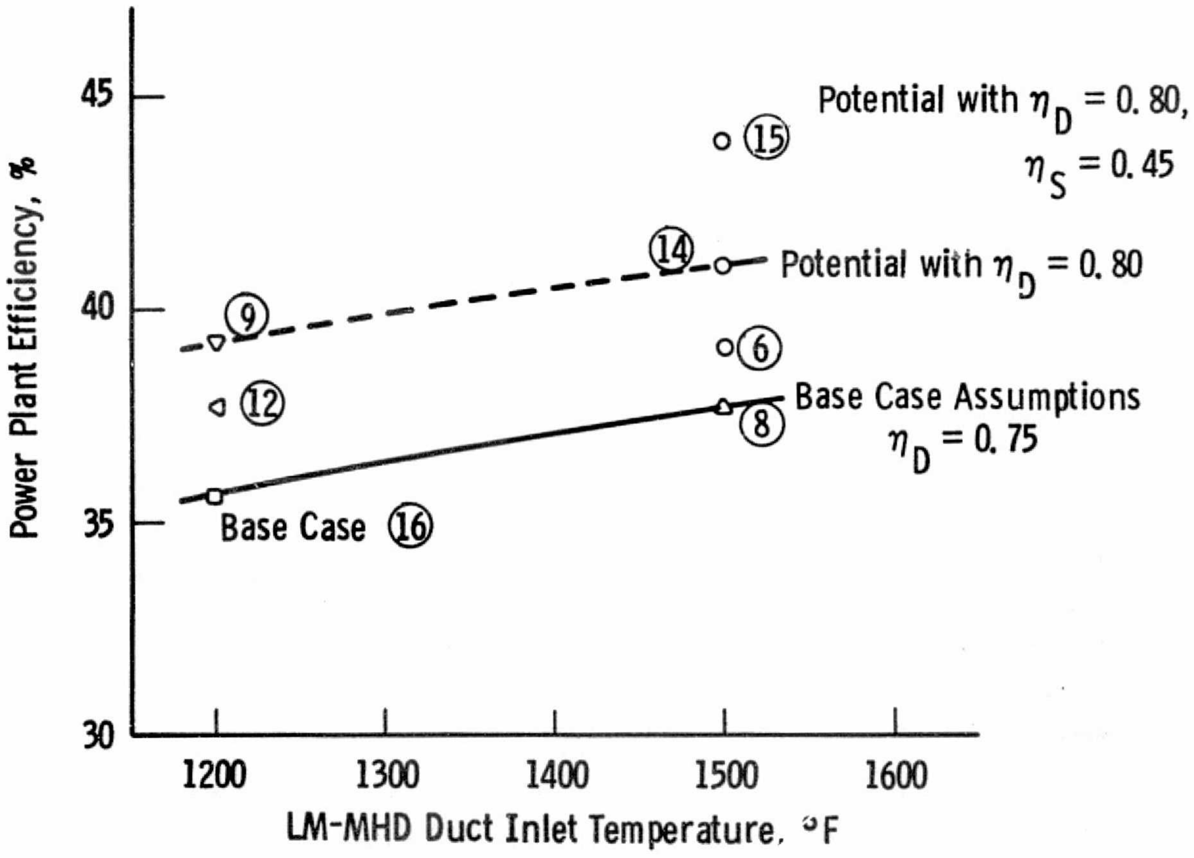

Fig 11.6—Summary and comparison of LM-MHD/ steam binary power plants

Point 12 was a plant design based on replacing the large liquid-metal pumps and drives with a two-phase nozzle diffuser pump. A power plant efficiency increase is obtained in this study case because, like any Brayton cycle, there is a net back work obtained by allowing the gas to work at the higher temperatures (i.e., pump the liquid metal) and by performing work on the gas (i.e., compressing) at the lower cycle temperature. The analysis of this parametric point was made by assuming a two-phase nozzle efficiency of 90% and a corresponding liquid diffuser efficiency of 95%. The combined component isentropic efficiency was then taken to be 86%.

Point 6 uses lithium/helium as the MHD working fluids. The relatively high cost of this plant is the result of constructing many of the loop components from a refractory metal.

Points 4 and 13 represent plant configurations that do not include a steam power plant. Point 4 is a binary plant using an open-cycle MHD power plant to top a liquid-metal MHD plant (see Figure 11.4). The efficiency of this combined cycle was about 31%. This low performance is the result of the relatively poor performance of the liquid-metal MHD bottom plant. Improved performance would be obtained by taking a higher temperature liquid-metal MHD bottom plant and better optimizing the interfacing between the two cycles. Study of this combined all-MHD plant configuration, however, was limited to only one case.

Point 13 is an all LM-MHD power plant. The system shows only marginal plant performance and relatively high plant costs. The high plant costs are due to both the larger duct size and flow requirements and the higher power conversion costs. This result is not unexpected, since the net power output of this system is small compared to the total output of the MHD generator, and parasitic losses have not been reduced.

11.4.3 Analysis of LM-MHD/Steam Binary Plant Performance

Figure 11.6 summarizes the results of the LM-MHD steam binary power plant cases and shows the potential for the system. The figure shows the combined effects of temperature and duct efficiency on power plant performance. The numbers in the figure correspond to the parametric points listed in Table 11.3. The solid line shown at the bottom represents plant performance over the range of temperatures indicated. This line shows the system potential based on relatively modest assumptions concerning MHD component efficiencies and a duct efficiency, η_D, of 75%.

The dashed line shows the potential performance of the combined cycles, assuming the more optimistic LM-MHD component efficiencies. A major effect here is the assumption of an MHD duct efficiency of 80%.

Point 15 is a noncosted study point where credit is taken for increasing the steam bottoming plant thermodynamic efficiency to 45%. Power plant efficiency of this case is 43%, which represents the highest obtained in the study. The plant costs for this case are expected to correspond approximately to those of Point 14, or about 12.5 mills/MJ (45 mills/kWh).

11.5 Capital and Installation Costs of Plant Components

11.5.1 Cost Methodology

Nine power plants were evaluated in the LM-MHD study for estimated component capital and installation costs, indirect costs, and balance-of-plant costs. The general approach taken in the evaluation of the indirect and balanced plant cost is discussed in Section 2. The following paragraphs treat the capital and installation costs of the major equipment.

Most of the major components associated with the LM-MHD cycle are not state-of-the-art designs. Preliminary designs of such equipment, therefore, had to be developed before reliable cost estimates could be made. The general methodology that was used to generate the component cost data was as follows:

- Conceptual design of the major equipment assemblies. This involved establishing the MHD duct and magnet arrangement, determining the number of flow loops, identifying the assembly interfaces, and specifying the requirements for system (or component) redundancy

- Specifications of the design requirements for each major component, such as operating temperature, pressure, flow, stress level, etc.
- Preliminary design of components to meet base case operating requirements
- Derivation of size, weight, and cost algorithms for each major component
- Development of cost data information (capital and installation) based on material selection, temperatures, and required operating conditions.

A summary is given in Table 11.5 of the algorithms that were derived to determine size, weight, and cost of each major component. The nomenclature used in Table 11.5 is defined in Table 11.6. Additional supportive information on these relationships are given in the appropriate appendices. A brief summary of the design and costing basis used for sizing and costing these components is given below.

11.5.2 MHD Duct and Magnet Costs

The MHD duct and magnet components constitute one major assembly requiring design effort to assure realism in both the structural integrity and the cost of the system. The basic assumptions from which the design evolved were:

- Conformity to limitation imposed by current theory on the electrodynamics of the duct
- Use of current liquid-metal technology, where applicable
- Minimization of magnet and duct structure costs
- Maximization of operating life and serviceability.

These considerations ultimately led to the toroidal duct assembly arrangement shown in Figure 11.7. The ducts are oriented vertically and are grouped (three or more) in a circular configuration and interconnected

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TABLE 11.5 — SUMMARY OF ALOGRITHMS USED IN SIZING AND COSTING POWER PLANT COMPONENTS

Component	Size Alogrithms	Weight Alogrithms	Cost Alogrithms
1. Superconducting Magnet	$V = (0.0397)(B)(L)(\ell_{,d})$ $\ell_{,d}$ = see below		$C_T = (28{,}571)(H)(V)$
2. Dewar	$A_1 = L_d \times \ell_{,d}$	$W_T = 284\,N\,k\,(B/S_d)\,\ell^2 A_1$	$C_T = W_T C_6$
3. Iron Poles	$\ell_{,d}$ = see below	$W_T = \frac{(n)(N)(\ell^2)(\zeta)}{2}\left(\frac{H}{2n} + \pi\right) L$	$C_T = W_T \times C_5$
4. Structural MHD Components		$K = 155 - 17.5 \cdot \ell$	
Duct	$\ell_{,d} = \frac{\ell_{o,d} + \ell_{i,d}}{2}$ $A_1 = L \times \ell$ $A_2 = \ell_{i,d} \times L$	$W_1 = K(\bar{p}/S_d)\,\ell_1^2 A_1$ $W_2 = K(\bar{p}/S_d)^{\frac{1}{2}} A_2$	$C_T = 2N(W_1 + W_2)\,C_1$
Mixer	$A_2 = \ell_{i,d}^2,\ \ell = \ell_{i,d}$	$W_T = K(\bar{p}/S_d)^{\frac{1}{2}}\,\ell_i^2 A_2$	$C_T = 4N W_T C_2$
Nozzle	$A_1 = (L)(\ell),\ A_2 = (L)(\ell)$ $L = \left[1 - \left(\frac{\zeta_i}{\zeta_o}\right)_n \left(\frac{V_i}{V_o}\right)_n\right] \frac{\ell_{o,d}}{2\tan\theta_n}$ $\ell = \frac{\ell_{o,d} + \ell_{o,n}}{2}$ $\ell_{o,n} = \left(\frac{\zeta_i}{\zeta_o}\right)_n \left(\frac{V_i}{V_o}\right)_n \ell_{o,d}$	$W_1 = K(\bar{p}/S_d)\,\ell^2 A_1$ $W_2 = K(\bar{p}/S_d)\,\ell_1^2 A_2$	$C_T = 2N(W_1 + W_2)\,C_3$
Separator/ Diffuser	$A_1 = \ell_{o,n}^2 / \tan\theta_s$ $A_2 = (\ell_{o,d})(\ell_{o,n}) / \tan\theta_s$	$W_1 = K(\bar{p}/S_d)\,\ell_{o,n}^2 A_1$ $W_2 = K(\bar{p}/S_d)\,\ell_{o,n}^2 A_2$	$C_T = 2N(W_1 + W_2)\,C_4$
Liquid Metal Return Leg Piping	$\ell = \sqrt{\frac{m}{\zeta V_p}}$ $L_T = L_m + L_d + L_n + L_s$	$W_T = K(\bar{p}/S_d)\,\ell^3 L_T N$	$C_T = W_T \times C_7$
5. Liquid Metal Pump	$n = \frac{448.8\,\dot{m}\,H}{2.5 \times 10^5 \cdot \zeta}$	$W_T = \frac{(296.2)(m)\,H}{\zeta}$	$C_T = 8 \times 10^6 \cdot n$
6. Liquid Metal Purification	$f = 448.8 \times F\left(\frac{1-p}{p+.01}\right)$		$C_T = 8572\,N\,(f)^{0.6}$
7. Liquid Metal Inventory & Dump		$W = 1.2\,m\,L_T N / V_{,p}$	$C_T = C_8 W + \left(\frac{11063}{\zeta_{LM}}\right) W^{0.7}$
8. Steam Generator	$A_S = \frac{Q}{MDT}\left[\frac{d_o^{0.4}}{V^{0.6}} / \theta_1\right] \frac{1}{N_t}$ $L = \frac{Q}{MTD} \frac{(V d_{,o})^{0.4}\, p\left(\frac{p}{d_o} - 1\right)\theta_2}{3600\,N\,m}$ $d = \sqrt{\frac{3600\,N\,m\,\rho}{N_1 V (p - d_o)\,\theta_5}}$ ρ, V, MTD } see appendix A 11.6	$W_1 = \frac{\pi d^2 \zeta_m}{2} (\bar{p}/S_d)\left(\frac{L+d}{2}\right)$ $W_2 = 0.0106 \times d_{,o} \times \zeta_g \times A_s$ $W_T = W_1 + W_2$	$C_T = (W_1 C_{14} + W_2 C_{15})\,N_1$
9. Primary Heat Exchanger	$d = \sqrt{\frac{28}{\pi} A_c}$ $L = \frac{A_s}{A_c}\left(\frac{d_i}{48}\right)$ A_s, A_c } see appendix A 11.6	$W_T = \frac{6\,L_t}{N_t}$	$C_T = N_t W_T C_{13}$
10. Recuperators Intercoolers Economizers Precoolers	$d = \sqrt{\frac{8.0\,A_c}{\pi}}$ $L = \frac{A_c}{A_s}(.011)$ A_c, A_s } see appendix A 11.6	$W_T = 0.64\,T_t$	$C_T = N_1 (L_t C_9 + N_t C_{10})$
11. Gas Compressors		$W_T = (16.2\,m\,n_1 + 10{,}000)\left(\frac{1300}{\bar{p}}\right)^{0.5}$	$C_T = 10.5\,W_T$
12. Gas Piping		$W_T = \frac{2\pi t \bar{p} \zeta_m}{\zeta_g V}\left(\frac{L_1}{S_d} + \frac{L_2}{S_c}\right)$ L_1 = Hot Leg Length L_2 = Cold Leg Length	$C_T = W_T C_{12}$

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Table 11.6—Definition of Symbols

A	= Surface area, ft^2
A_c	= Cross-sectional flow area, ft^2
A_s	= Heat transfer surface area, ft^2
B	= Magnet
C	= Cost Coefficient, \$ / lb or \$ / ft, \$ / tube
C_T	= Total capital equipment costs, \$
d	= Diameter of heat exchange vessel, ft
d_i	= Inside tube diameter, in
d_o	= Outside tube diameter, in
F	= Liquid metal flow, ft^3/s
f	= Required liquid metal flow rate, gpm
L	= Length of component, ft
ℓ	= Average width or unsupported dimension, ft
L_t	= Total tubing length, ft
m	= Mass flow rate, lb/s
MTD	= Mean temperature difference, °F
N	= Number of ducts
n	= Number of assemblies or units
N_1	= Number of heat exchanger units
N_t	= Number of tubes
p	= Required liquid metal purity, ppm, or tube pitch
$\bar{p}$	= Average pressure, psi
Q	= Total eat load, Btu/hr
S_d	= Design stress, psi
V	= Fluid velocity, ft/s
W	= Weight, lb
ζ	= Density of Material or Fluid, lb/ft^3
θ	= Angle

Subscripts

1	- Varying width plates	m	- Metal or mixer
2	- Constant width plates	n	- Nozzle
d	- Duct	o	- Out
g	- Gas	p	- Pipe
i	- In	s	- Separator
Lm	- Liquid metal		

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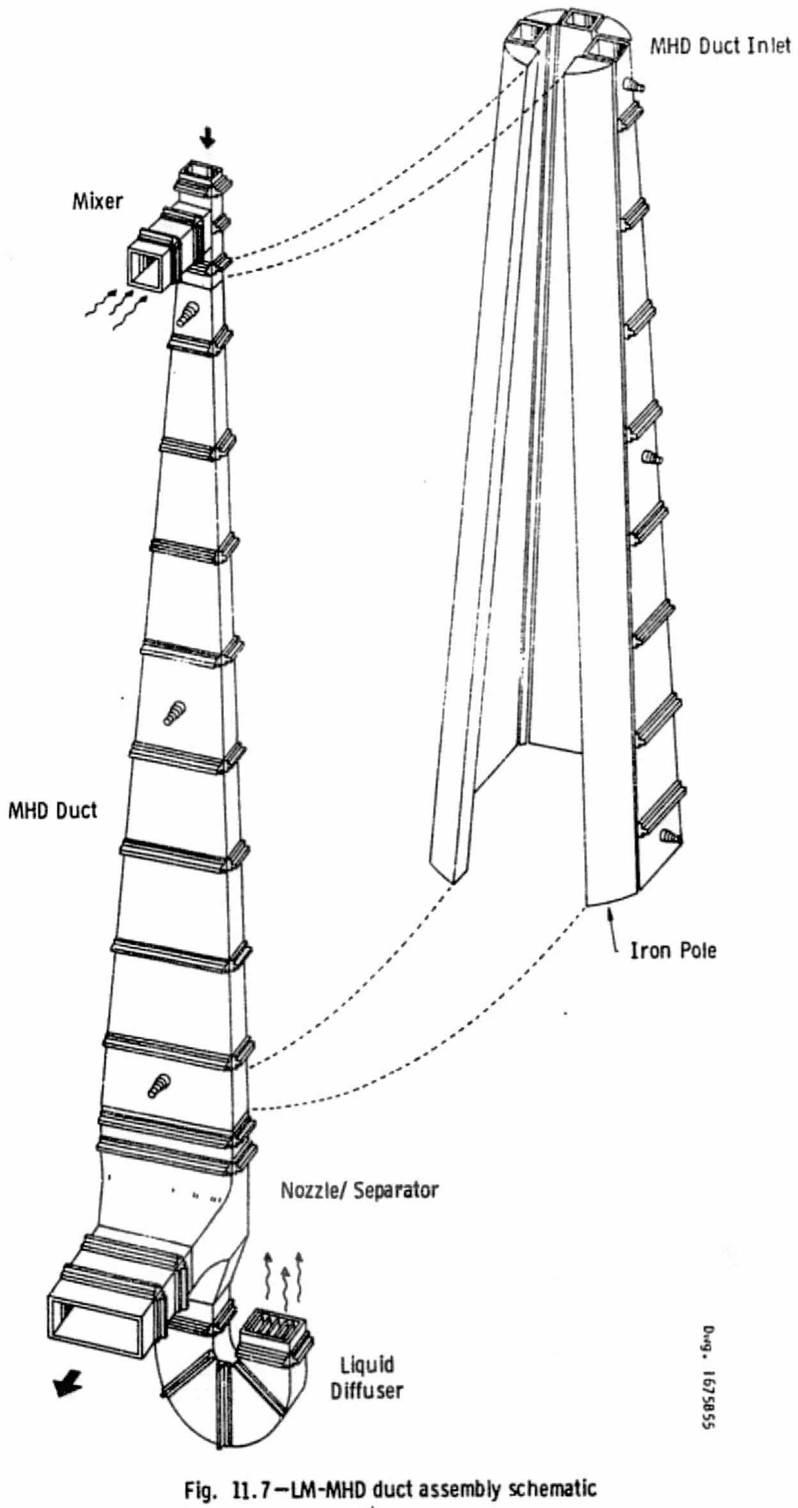

Fig. 11.7—LM-MHD duct assembly schematic

with iron pole pieces. Figure 11.8 shows further detail of the design of the ducts, as well as the design and positioning of the magnet with respect to the ducts. The superconducting magnet and dewar sets are fixed to the duct walls adjacent to the iron pole pieces. Thus, the iron pole pieces shape the magnetic field to conform to the geometry. This configuration easily meets the requirements for field uniformity and reduces stray field effects. Further detail concerning design and specification of the magnet and field requirements and the magnet and dewar designs are given in Appendix A 11.3.

The costs of the magnet system were broken into cost of the superconductor including dewar and refrigerators and cost of the iron pole pieces. Conductor costs (a low field, Nb-Ti composition) were taken as $110/kg ($50/lb). The cost of the iron pole pieces was based on the total weight of iron used in the design. Iron costs were taken as $1.58/kg ($0.72/lb) installed, (Reference 11.8). The algorithm expressing these costs was developed in terms of the MHD duct design parameters. The formulas are given in Table 11.5.

The actual MHD duct portion of the assembly was costed on the basis of the design that was previously shown in Figure 11.8. Designs and costs for the mixer, nozzle, separator-diffuser, and liquid-metal return-leg piping were based on the ribbed structual configuration used for the duct design. The major items considered in the costing of the MHD duct were the materials used for structural pressure housing, duct insulation, the electrodes, and current leads. The costing of the other components (mixer, nozzle, etc.) were based on pressure housing materials.

The basic design used for the structural housing for all pressurized components was a reinforced (ribbed) plate construction. This allowed for minimum weight designs. The design basis for the pressurized components is given in Appendix A 11.7. The costing of structural members was based on total material weights and type. The generalized form of the equations used to calculate component weights is given in Table 11.5. The specific cost factors and the criteria used for applying these costs is given in Table 11.7.

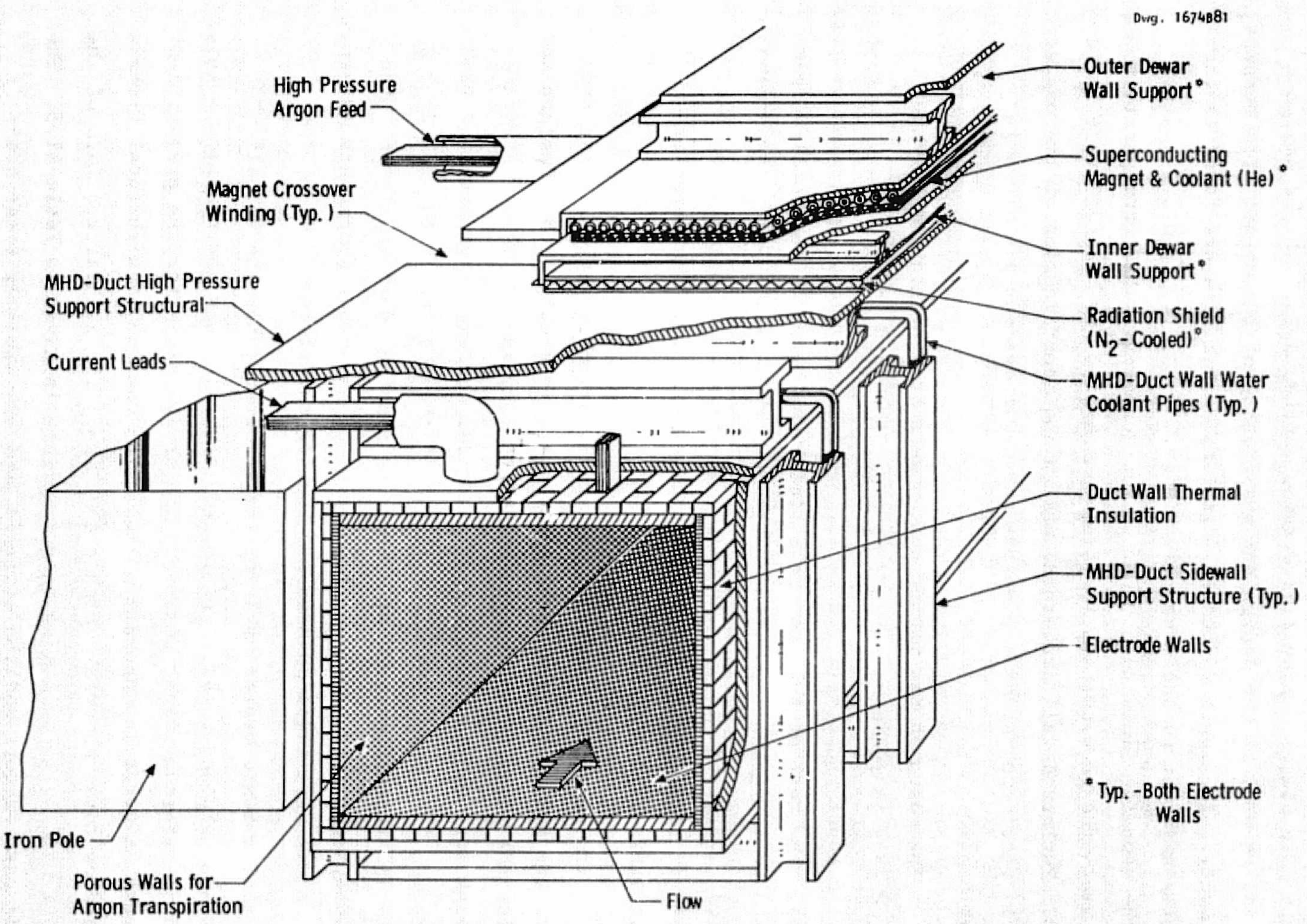

Fig. 11.8—Conceptual design for high pressure LM-MHD duct

Table 11.7 - Summary of Material Cost for Liquid Metal MHD Components

Component	Material	Total Cost $/lb[1]	Use Criteria
1. MHD duct	316 SS [2]	8.25	All cases
2. MHD duct installations	MgO Brick[3]	0.60	All cases
3. Mixer	316 SS	11.25	Na/A - only temp. ≤ 1200°F
	Haynes 25[4]	15.00	Na/A - only temp. > 1200°F
	Nb-1Zr[5]	43.80	Li/He case
4. Nozzle	316 SS	8.25	Na/A - temp. ≤ 1200°F
	Haynes 25	12.00	Na/A - temp. > 1200°F
	Nb-1Zr	43.90	Li/He case
5. Separator/ diffuser	316 SS	14.25	Na/A - temp. ≤ 1200°F
	Haynes 25	18.00	Na/A - temp. > 1200°F
	Nb-1Zr	43.90	Li/He case
6. Liquid metal[6] piping and fittings	316 SS	8.40	Na/A - temp. ≤ 1200°F
	Haynes 25	22.40	Na/A - temp. > 1200°F
	Nb-1Zr	123.00	Li/He case

(1) Includes material costs, fabrication and overhead as base, direct costs (no escalation or contingency)

(2) Material cost estimate - United States Steel - private communication, fabrication cost estimate - Ionic's Corp. - private communication; overhead taken as 50% of material and fabrication costs

(3) Cost estimate obtained from Harbison/Walker Refractories Co. - private communication

(4) Haynes Metal Alloy Data Sheets, #25, Union Carbide, Stellite Division.

(5) GEAP-14018 - UC-77, "VTHR for Process Heat," General Electric, September 1974.

(6) Costs based on CRBRP large seamless stainless steel pipe costs. Includes fittings, heat tracing, standard insulation, fabrication and erection. Piping cost for Haynes & Nb-1Zr obtained by direct ratio of material costs

The MHD duct insulation costs were based on the quantity of magnesium oxide brick required to line the two duct walls. The current leads from the duct were copper bus bars sized to handle approximately 3.7 MA of generator total current. The cost basis for these leads was flat copper bar at \$2.44/kg (\$1.107/lb). The total cost (including installation) of the electrode system was estimated for an MHD generator producing 1750 MWe (total) at \$4 million. For the parametric case in which the duct power differed appreciably from this design, electrode cost was scaled linearly with power output.

11.5.3 Liquid-Metal Pumps and Subsystem Costs

A second major set of components that required design emphasis were the liquid-metal pump and associated liquid-metal subsystems, which include the purification system and inventory and emergency dump capacities. For these systems, available liquid-metal fast breeder reactor technology was utilized to develop sizing and cost information.

The liquid-metal purification system was designed with current cold trap (oxide control) technology as developed by Mine Safety Appliance (MSA). The basic criterion for designing and sizing the system (see Appendix A 11.5) is the assumed cover gas leak rate. The value chosen for this parameter in this study was commensurate with current liquid-metal fast breeder reactor design. The algorithm developed for costing the system was based on cost estimates (made by MSA) for two different sized currently available systems.

The liquid-metal storage and emergency dump systems were sized to meet inventory requirements. The costing of the system (as given by the equation in the Table 11.5) was again based on current breeder reactor design estimates. The costing includes piping, tank, heat tracing, and valves.

11.5.4 Heat Transfer Equipment Costs

The major heat transfer equipment for which design and costing had to be established were:

- Primary heat exchanger (includes a coal combustor and the radiant and convective heat exchanger).
- Steam generator
- Compressor intercooler (if used) and
- The gas to air preheaters and recuperators.

In general, to obtain an economic and optimum heat exchanger design, a trade-off must be made between tube size, pressure loss, and heat transfer coefficients. This usually involves lengthy computer solutions. The design approach used herein, however, was to make some simplifying assumptions based on engineering experience that would avoid the iterative solution. These assumptions were to consider only counter-flow shell and tube designs, treat only the controlling-side heat transfer coefficients (i.e., neglecting water side where applicable) and, based on well-established experience, a priori select both a tube geometry (diameter and pitch) and pressure drop. In all cases, this approach led to a reasonable design but one that may not be the most economical, considering the total system.

A preliminary design was prepared for both the steam generator and primary heat exchangers for the base case conditions. These designs are summarized in Appendix A 11.6. The theoretical basis for the heat exchanger designs is the same as is given in Appendix A 9.3 of the open-cycle MHD study. For the remaining parametric cases, the heat exchange equipment was modeled from these designs. In all cases, established correlations and equations were employed to calculate heat transfer coefficients, mean temperature differences, and pressure drops. With the air-to-gas (or gas-to-gas) type exchangers, the designs were based on heat exchanger effectiveness, a concept widely applied in heat exchanger design. Once surface area requirements were determined, geometry factors (tube diameter, pitch, etc.) were employed to calculate flow area requirements and, ultimately, overall physical size.

The overall cost of the heat exchange equipment was determined from both tube and shell costs. The shell costs were based on material

Table 11.8 Summary of Cost of Heat Exchanger Component Materials

Heat Exchanger Component	Material(s)	Costs, $/lb	Use Criteria
1. Primary heat exchanger radiation tubes - 2 in id	Haynes 188-Clad 2 in i.d.	14.00[a]	Flue gas temp. < 3000°F, Na/A
2. Radiation/convection tubes-2 in id	Cb-1Zr Haynes 188	50.2[b] 14.00	Li/He case Flue gas temp.< 1800°F, Na/A
3. Convection tubes - finned - 1.8 in id	316 SS	5.83	Flue gas temp.< 1200°F, Na/A
4. Steam generator/precooler convection tubes - 1.0 in od	316 SS Haynes 188 Nb-1Zr	5.48[c] 12.1 50.2	Argon temp. < 1200°F Argon temp. < 1500°F Li/He case
5. Shell	Carbon steel, lined	0.67	All cases

[a]Cost data obtained from Reference 11.1 adjusted to 1974 dollars and corrected for cladding.

[b]GEAP-14018-uc-77 "VTHR for Process Heat."

[c]Tube material cost estimate obtained from Westinghouse, Tampa Nuclear Steam Generator Division, private communication.

type, insulation, and weight. Tube costs were broken into material and fabrication. The fabrication costs were based on the number of tube end welds required, taken at $10 per weld. This factor is approximately correct for 2.54 cm (1 in) diameter tubes. Table 11.8 summarizes the material and fabrication cost factors used for the different heat exchanger types.

11.5.5 Costs of Gas Compressors and Motor Drives

Guidelines for costing the large gas compressor were obtained from the Westinghouse Gas Turbine Division. From this information an algorithm was developed that relates costs to the required compressor flow rates and pressure ratios.

The motor drives used for the pump and/or compressor were costed at $36 per kW (installed), consistent with 1974-75 market prices (Westinghouse Large Motor Division).

11.5.6 Steam Turbine/Generator Costs

Costs for the steam plant electric generators and turbine drives (for those LM-MHD cases that used a bottoming plant) were obtained from the Westinghouse Steam Turbine Division. The costs were derived from the heat load and plant configuration that was determined to be best suited for the LM-MHD binary plant. The major steam plant costs, for the base case study point and each parametric point that involved a steam plant, were:

- Turbine/generators sets - $22.25/kW
- Turbine drives - $13.14/kW.

Since this plant did not incorporate extractive feedwater heating, there were no feedwater heaters involved. The boiler feed pump and auxiliary steam equipment costs were included in the balance of plant costs (see Section 2.0).

11.5.7 Sizing and Cost Algorithm Computer Program

To help facilitate the LM-MHD system analysis, the above described sizing, weight, and cost algorithms for each major component were programmed.

Table 11.9 Summary of Size, Weight and Cost Calculations for LM-MHD Cycle Components - Base Case

SYSTEM	MAJOR COMPONENTS	NUMBER OF COMPONENTS	TOTAL WEIGHT N LOOPS(LBS)	CHARACTERISTIC SIZE WIDTH	CHARACTERISTIC SIZE LENGTH	COST FOR N LOOPS (DOLLARS) N = 16.
LIQUID METAL LOOP (SODIUM)	MHD DUCT (STRUCT. SUPPORT	.16000+02	.15219+06	.21308+01 FT	.22775+02 FT	.12556+07
	INSULATION	.16000+02	.11400+06	.20000+00 FT	.22775+02 FT	.68399+05
	2 MIXER	.16000+02	.40226+05	.20704+01 FT	.20704+01 FT	.45255+06
	3 NOZZLE	.16000+02	.25738+04	.22534+01 FT	.33576+00 FT	.21234+05
	4 SEPARATOR AND DIFFUSER	.16000+02	.19048+04	.15023+01 FT	.67151+00 FT	.28284+05
	5PRIMARY RETURN LEG PIPING	.16000+02	.19249+06	.24498+01 FT	.30407+02 FT	.16169+07
	TOTAL WEIGHT LIQUID METAL DUCTING		.50346+06	.21308+01 FT	.30407+02 FT	.34429+07
MAGNET SYSTEM	6 IRON POLES	.16000+02	.74396+06	.20704+01 FT	.22775+02 FT	.53566+06
	7 DEWAR SET	.16000+02	.33058+04	.21308+01 FT	.22775+02 FT	.27273+05
	8 SUPERCONDUCTOR	.16000+02		.10596+01 CU-FT		.48439+06
LIQUID METAL SUB-SYSTEMS	9 LIQUID METAL PUMP	.43095+01	.71106+06	IMP. DIA.=80 INCH		.34476+08
	10 LIQUID METAL INVENTORY		.17449+06			.23904+06
	11 LIQUID METAL EMER. DUMP		.16380+04	.26208+05 GAL		.18318+07
	12 LIQUID METAL PURIFICATION			.53604+04 GPM		.44903+07
GAS LOOP ARGON	13 PRIMARY HX	.40000+01	.39961+07	.18129+02 FT	.16386+03 FT	.36364+08
	14 STM. GENERATOR	.40000+01	.69958+07	.18855+02 FT	.93450+02 F	.27778+08
	15 PREHEATER	.40000+01	.12705+07	.13353+02 FT	.12708+02 F	.55348+07
	16 INTERCOOLER	.00000	.00000	.00000 FT	.00000 FT	.00000
	17 GAS COMPRESSOR	.16000+02	.26923+06	.72789+03 LB/SEC		.28269+07
	18 GAS PIPING		.27147+04		.22500+03 FT	.16614+05

This program reduced calculation time and, in addition, permitted evaluation of the sensitivity of several independent design parameters in terms of their impact on cost. This has allowed flexibility in establishing final physical configurations that are consistent with the imposed design restrictions, as well as permitting physical sizes that conform to acceptable commercial design practice. The computer program also provided a permanent record of the data in convenient table form. Samples of such printout sheets that summarize the results of the sizing, weight, and cost calculations for the base case and for Points 14 and 8 are shown in Tables 11.9, 11.10, and 11.11, respectively.

11.5.8 Component Installation Costs

The installation costs for the major equipment were determined on the basis of the complexity of the particular piece of equipment and its capital costs. The general guidelines used are given in Table 11.12 (recommendations made by architect engineer Chas. T. Main, Inc.). Figure 11.9 shows the artist's conceptual plant arrangement prepared from plan and elevation drawings of the plant design. The plan and elevation drawings were used to estimate piping, installation, and balance of plant requirements. As Figure 11.9 illustrates, most of the plant systems have been enclosed in the protective building because of the high current requirements between the MHD duct and inverters. Figure 11.10 is the site layout prepared for the LM-MHD/steam power plant base case.

11.5.9 Summary of Component Costs for LM-MHD Study Cases

In the LM-MHD ten power plants were costed to determine component capital and installation, indirect, and balance of plant costs. The detailed accounts listing, cost of electricity summary, and input-output sheets for the base case (Point 16) and for Points 8 and 14 are given as Tables 11.13 through 11.21, respectively. A relative breakdown of the major LM-MHD component cost items for the base case is also shown graphically in Figure 11.11. The costs are shown as a percentage of the total. A review of this figure shows that the actual MHD duct assembly and magnet costs are small compared to those of other system components.

Table 11.10 Summary of Size, Weight and Cost Calculations for LM-MHD Cycle Component - Point 14

SYSTEM	MAJOR COMPONENTS	NUMBER OF COMPONENTS	TOTAL WEIGHT N LOOPS (LBS)	CHARACTERISTIC SIZE WIDTH	CHARACTERISTIC SIZE LENGTH	COST FOR N LOOPS (DOLLARS) N = 16.
LIQUID METAL LOOP (SODIUM)	MHD DUCT 1 STRUCT. SUPPORT	.16000+02	.18073+06	.22357+01 FT	.24470+02 FT	.14915+07
	INSULATION	.16000+02	.13243+06	.21000+00 FT	.24430+02 FT	.79459+05
	2 MIXER	.16000+02	.40060+05	.27209+01 FT	.22203+01 FT	.60089+06
	3 NOZZLE	.16000+02	.27592+04	.24743+01 FT	.35963+00 FT	.33230+05
	4 SEPARATOR AND DIFFUSER	.16000+02	.21967+04	.15497+01 FT	.73720+00 FT	.38691+05
	5 PRIMARY RETURN LM PIPING	.16000+02	.19074+06	.25273+01 FT	.32543+02 FT	.42725+07
	TOTAL WEIGHT LIQUID METAL DUCTING		.54893+06	.22857+01 FT	.32643+02 FT	.65163+07
MAGNET SYSTEM	6 IRON POLES	.15000+02	.91326+06	.27203+01 FT	.24470+02 FT	.66115+06
	7 DEWAR SET	.16000+02	.34986+04	.22857+01 FT	.24430+02 FT	.28863+05
	8 SUPERCONDUCTOR	.16000+02		.99755+00 CU-FT		.45602+06
LIQUID METAL SUB-SYSTEMS	9 LIQUID METAL PUMP	.49582+01	.91817+06	IMP. DIA.=30 INCH		.39669+08
	10 LIQUID METAL INVENTORY		.21553+06			.29527+06
	11 LIQUID METAL ENTR. DUMP		.20000+04	.37773+05 GAL		.21237+07
	12 LIQUID METAL PURIFICATION			.61678+04 GPM		.48847+07
GAS LOOP ARGON	13 PRIMARY HX	.40000+01	.55650+07	.29301+02 FT	.97021+02 FT	.79436+08
	14 STM. GENERATOR	.40000+01	.40742+07	.20225+02 FT	.44326+02 FT	.20918+08
	15 PREHEATER	.40000+01	.19755+07	.14743+02 FT	.15793+02 FT	.79420+07
	16 INTERCOOLER	.00000	.00000	.00000 FT	.00000 FT	.00000
	17 GAS COMPRESSOR	.15000+02	.26422+06	.70932+03 LB/SEC		.27743+07
	18 GAS PIPING		.22284+04		.20000+03 FT	.13626+05

Table 11.11 Summary of Size, Weight and Cost Calculations for LM-MHD Cycle Components - Point 8

SYSTEM	MAJOR COMPONENTS	NUMBER OF COMPONENTS	TOTAL WEIGHT N LOOPS (LBS)	CHARACTERISTIC SIZE WIDTH	CHARACTERISTIC SIZE LENGTH	COST FOR N LOOPS (DOLLARS) N = 16.
LIQUID METAL LOOP (SODIUM)	MHD DUCT 1 STRUCT. SUPPORT	.16000+02	.21835+06	.24660+01 FT	.26358+02 FT	.18019+07
	INSULATION	.16000+02	.15916+06	.21000+00 FT	.26358+02 FT	.92493+05
	2 MIXER	.16000+02	.52847+05	.23961+01 FT	.23961+01 FT	.79270+06
	3 NOZZLE	.16000+02	.37577+04	.26938+01 FT	.40137+00 FT	.45092+05
	4 SEPARATOR AND DIFFUSER	.16000+02	.29319+04	.17958+01 FT	.80273+00 FT	.52774+05
	5 PRIMARY RETURN LEG PIPING	.16000+02	.24992+06	.28352+01 FT	.35229+02 FT	.65982+07
	TOTAL WEIGHT LIQUID METAL DUCTING		.68196+06	.24660+01 FT	.35229+02 FT	.83826+07
MAGNET SYSTEM	6 IRON POLES	.16000+02	.11532+07	.23961+01 FT	.26358+02 FT	.83032+06
	7 DEWAR SET	.16000+02	.46109+04	.24660+01 FT	.26358+02 FT	.38036+05
	8 SUPERCONDUCTOR	.16000+02		.11612+01 CU-FT		.53083+06
LIQUID METAL SUB-SYSTEMS	9 LIQUID METAL PUMP	.57720+01	.95238+06	IMP. DIA.=80 INCH		.46176+08
	10 LIQUID METAL INVENTORY		.27076+06			.37094+06
	11 LIQUID METAL EMER. DUMP		.25418+04	.40669+05 GAL		.24919+07
	12 LIQUID METAL PURIFICATION			.71796+04 GPM		.53508+07
GAS LOOP ARGON	13 PRIMARY HX	.40000+01	.76428+07	.32155+02 FT	.97021+02 FT	.92478+08
	14 STM. GENERATOR	.40000+01	.47773+07	.21822+02 FT	.44249+02 FT	.24329+08
	15 PREHEATER	.40000+01	.22402+07	.15900+02 FT	.15805+02 FT	.91233+07
	16 INTERCOOLER	.00000	.00000	.00000 FT	.00000 FT	.00000
	17 GAS COMPRESSOR	.16000+02	.29561+06	.82567+03 LB/SEC		.31039+07
	18 GAS PIPING		.25941+04		.20000+03 FT	.15876+05

Table 11.12 Summary of Basis for Estimating Installation Cost of Major LM-MHD Components

Cost Basis, % of capital cost	Criteria	LM-MHD Components
10	Simple component installation on foundations	• LM pump • LM inventory • LM emergency dump • Compressors • Motors • Turbines
20	Electrical equipment and sophisticated support components	• LM auxiliary systems • Superconducting magnet • LM purification • Inverters • Transformers • Circuit breakers • Current conductors
40	Field assembly and erection	• MHD duct and component assembly • Support structure • LM piping • Gas piping • Steam generators • Primary heat exchanger • Air preheaters & gas recuperators

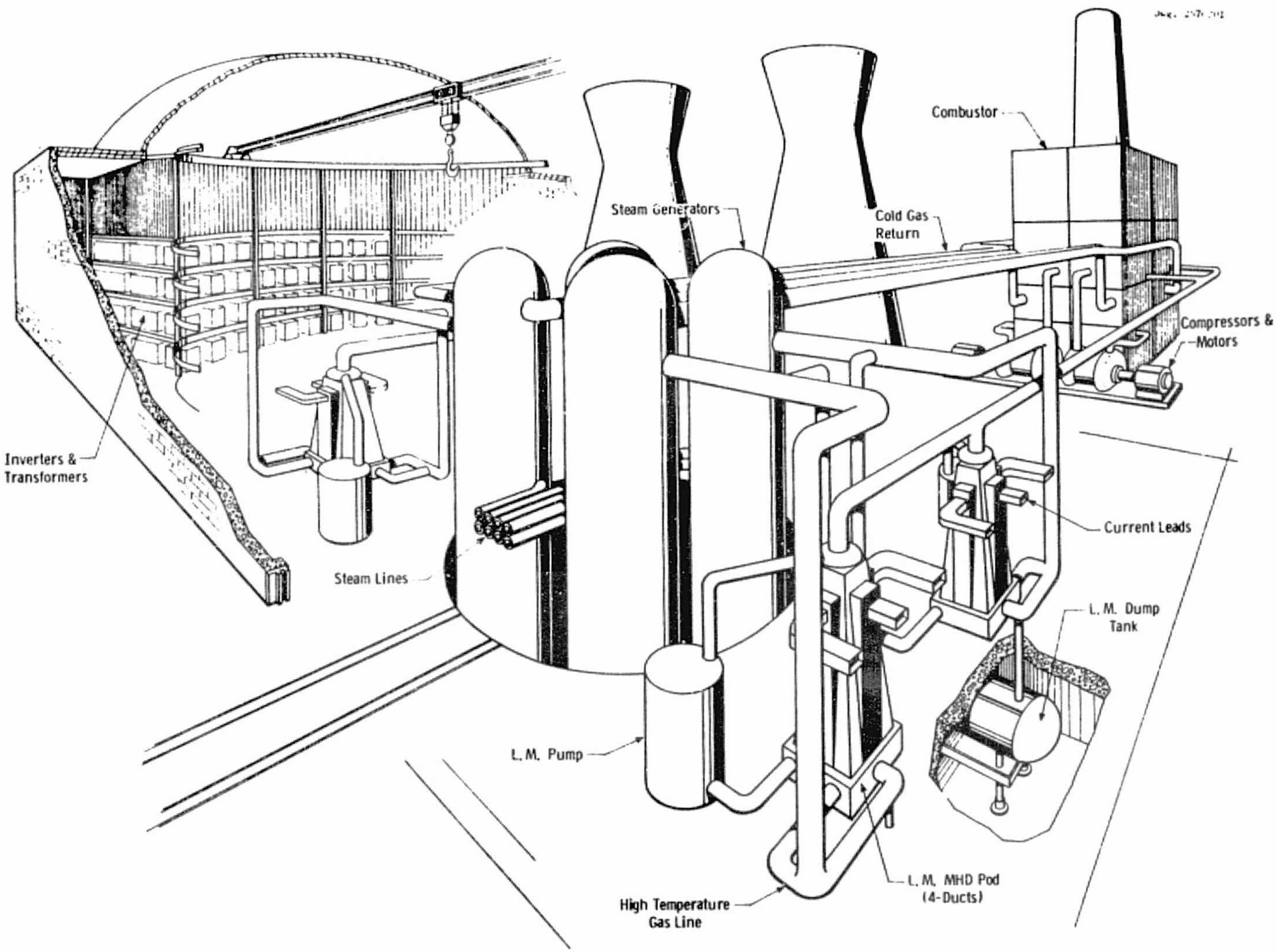

Fig. 11.9—Conceptual component arrangement for L M MHD/steam power plant

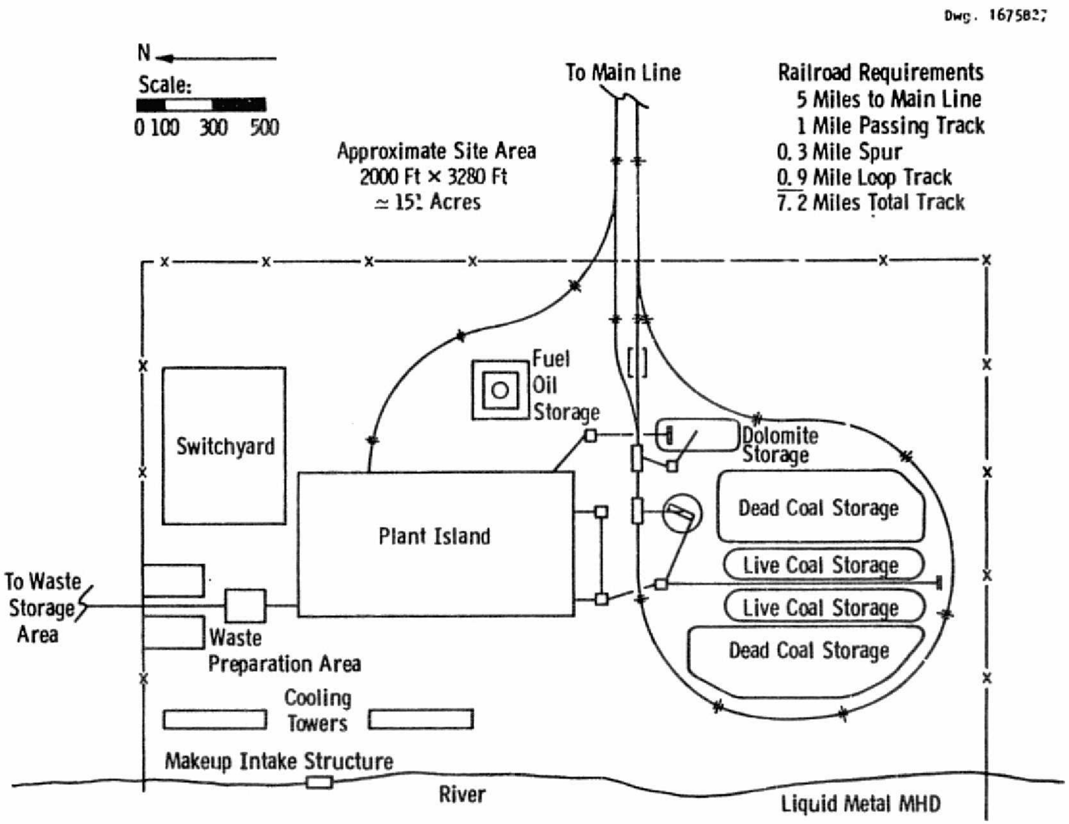

Fig. 11. 10—Plant island arrangement (LM-MHD Base Case, Point 16)

Table 11.13 CLOSE CYCLE LIQUID METAL MHD SYSTEM ACCOUNT LISTING
PARAMETRIC POINT NO.15

ACCOUNT NO. & NAME,	UNIT	AMOUNT	MAT $/UNIT	INS $/UNIT	MAT COST,$	INS COST,$
SITE DEVELOPMENT						
1. 1 LAND COST	ACRE	182.0	1000.00	.00	182000.00	.00
1. 2 CLEARING LAND	ACRE	60.7	.00	600.00	.00	36396.35
1. 3 GRADING LAND	ACRE	182.0	.00	3000.00	.00	546000.00
1. 4 ACCESS RAILROAD	MILE	5.0	115000.00	110000.00	575000.00	550000.00
1. 5 LOOP RAILROAD TRACK	MILE	2.5	120000.00	70000.00	300000.00	175000.00
1. 6 SIDING R R TRACK	MILE	.0	125000.00	90000.00	.00	.00
1. 7 OTHER SITE COSTS	ACRE	.0	.00	.00	387031.29	387031.29
PERCENT TOTAL DIRECT COST IN ACCOUNT 1 = .337			ACCOUNT TOTAL,$		1444031.29	1694427.64
EXCAVATION & PILING						
2. 1 COMMON EXCAVATION	YD3	135900.0	.00	3.00	.00	407700.00
2. 2 PILING	FT	362400.0	6.50	8.50	2355600.00	3080400.00
PERCENT TOTAL DIRECT COST IN ACCOUNT 2 = 1.559			ACCOUNT TOTAL,$		2355600.00	3488100.00
PLANT ISLAND CONCRETE						
3. 1 PLANT IS. CONCRETE	YD3	18300.0	70.00	80.00	1281000.00	1464000.00
3. 2 SPECIAL STRUCTURES	YD3	27000.0	90.00	150.00	2430000.00	4050000.00
PERCENT TOTAL DIRECT COST IN ACCOUNT 3 = 2.431			ACCOUNT TOTAL,$		3711000.00	5514000.00
HEAT REJECTION SYSTEM						
4. 1 COOLING TOWERS	EACH	17.0	.00	.00	2669500.00	1300500.00
4. 2 CIRCULATING H2O SYS	EACH	1.0	.00	.00	1431755.56	2000255.67
4. 3 SURFACE CONDENSER	FT2	502924.9	.00	.00	2029438.17	352047.46
PERCENT TOTAL DIRECT COST IN ACCOUNT 4 = 2.616			ACCOUNT TOTAL,$		6130693.69	3652803.09
STRUCTURAL FEATURES						
5. 1 STAT. STRUCTURAL ST.	TON	2875.0	650.00	175.00	1868750.00	503125.00
5. 2 SILOS & BUNKERS	TPH	443.1	1800.00	750.00	737513.69	332297.12
5. 3 CHIMNEY	FT	400.0	.00	.00	435070.92	582606.38
5. 4 STRUCTURAL FEATURES	EACH	1.0	1434000.00	435000.00	1434000.00	435000.00
PERCENT TOTAL DIRECT COST IN ACCOUNT 5 = 1.715			ACCOUNT TOTAL,$		4535333.94	1853028.50
BUILDINGS						
6. 1 STATION BUILDINGS	FT3	7340000.0	.16	.16	1174400.00	1174400.00
6. 2 ADMINSTRATION	FT2	10000.0	16.00	14.00	160000.00	140000.00
6. 3 WAREHOUSE & SHOP	FT2	20000.0	12.00	8.00	240000.00	160000.00
PERCENT TOTAL DIRECT COST IN ACCOUNT 6 = .813			ACCOUNT TOTAL,$		1574400.00	1474400.00
FUEL HANDLING & STORAGE						
7. 1 COAL HANDLING SYS	TPH	443.1	.00	.00	5140501.00	2537386.62
7. 2 DOLOMITE HAND. SYS	TPH	66.0	.00	.00	1104083.72	596144.73
7. 3 FUEL OIL HAND. SYS	GAL	5750000.0	.00	.00	79450.99	63272.91
PERCENT TOTAL DIRECT COST IN ACCOUNT 7 = 2.823			ACCOUNT TOTAL,$		7324145.62	3256804.25
FUEL PROCESSING						
8. 1 COAL DRYER & CRUSHER	TPH	443.1	.00	.00	1519709.77	1013139.84
8. 2 CARBONIZERS	TPH	.0	.00	.00	.00	.00
8. 3 GASIFIERS	TPH	.0	.00	.00	.00	.00
PERCENT TOTAL DIRECT COST IN ACCOUNT 8 = .676			ACCOUNT TOTAL,$		1519709.77	1013139.84

Table 11.13 (Continued) CLOSE CYCLE LIQUID METAL MHD SYSTEM ACCOUNT LISTING
PARAMETRIC POINT NO.16

ACCOUNT NO. & NAME,	UNIT	AMOUNT	MAT $/UNIT	INS $/UNIT	MAT COST,$	INS COST,$
FIRING SYSTEM						
9. 1		.0	.00	.00	.00	.00
PERCENT TOTAL DIRECT COST IN ACCOUNT 9 = .000 ACCOUNT TOTAL,$					.00	.00
VAPOR GENERATOR (FIRED)						
10. 1		.0	.00	.00	.00	.00
PERCENT TOTAL DIRECT COST IN ACCOUNT 10 = .000 ACCOUNT TOTAL,$					.00	.00
ENERGY CONVERTER						
11. 1 MHD DUCT STRUCT STEEL	KP	152.2	1255000.00	501000.00	1255000.00	501000.00
11. 2 DUCT INSULATION	KP	114.3	68000.00	27000.00	68000.00	27000.00
11. 3 MIXER	KP	40.2	452000.00	181000.00	452000.00	181000.00
11. 4 NOZZLE	KP	2.5	21000.00	10000.00	21000.00	10000.00
11. 5 SEPARATOR/DIFFUSER	KP	2.0	28000.00	11000.00	28000.00	11000.00
11. 6 LM PIPING/FITTING/INS	KP	192.5	1620000.00	642000.00	1620000.00	642000.00
11. 7 IRON POLES	KP	744.0	535000.00	214000.00	535000.00	214000.00
11. 8 AUX EQUIPMENT & SYSTEM		1.0	.00	.00	.00	.00
11. 9 MAGNET DEWAR	KP	3.3	30000.00	11000.00	30000.00	11000.00
11.10 SUPERCON MAG COOLANT	FT3	1.1	484000.00	97000.00	484000.00	97000.00
11.11 ASSEMBLY SUPPORT STRUCT		1.0	.00	.00	.00	.00
11.12 L M PUMPS	KP	711.1	34470000.00	3450000.00	34470000.00	3450000.00
11.13 L M INVENTORY (SODIUM)	KP	174.5	240000.00	24000.00	240000.00	24000.00
11.14 L M EMERGENCY DUMP	GAL	1.6	1832000.00	183000.00	1832000.00	183000.00
11.15 L M PURIFICATION	GPM	5.4	4490000.00	896000.00	4490000.00	896000.00
11.16 GAS COMPRESSOR	KP	263.2	2830000.00	283000.00	2830000.00	283000.00
11.17 MOTOR DRIVES	MW	405.4	1740000.00	1800000.00	1740000.00	1800000.00
11.18 GAS INVENTORY	KP	185.3	28000.00	3000.00	28000.00	3000.00
11.19 GAS PIPING	KP	2.7	16600.00	6700.00	16600.00	6700.00
11.20 STEAM TURBINE-GEN	MW	255.0	5690000.00	569000.00	5690000.00	569000.00
11.21 DRIVE TURBINES	MW	698.0	9170000.00	917000.00	9170000.00	917000.00
PERCENT TOTAL DIRECT COST IN ACCOUNT 11 =19.950 ACCOUNT TOTAL,$					54399500.00	3825700.00
COUPLING HEAT EXCHANGER						
12. 1 COMB HEAT EXCHANGER	KP	3996.1	36360000.00	14560000.00	36360000.00	14560000.00
12. 2 OPEN CYCLE MHD TOPPING		1.0	1.00	1.00	1.00	1.00
12. 3 STEAM GENERATOR	KP	6995.8	27778000.00	11120000.00	27778000.00	11120000.00
12. 4 INSULATION		1.0	3840000.00	2560000.00	3840000.00	2560000.00
PERCENT TOTAL DIRECT COST IN ACCOUNT 12 =25.667 ACCOUNT TOTAL,$					67978001.00	28240001.00
HEAT RECOVERY HEAT EXCH.						
13. 1 AIR PREHEATERS	KP	1273.5	5530000.00	553000.00	5530000.00	553000.00
13. 2 GAS RECUPERATORS	KP	1.0	1.00	1.00	1.00	1.00
13. 3 COMP INTERCOLLER	KP	1.0	1.00	1.00	1.00	1.00
13. 4 INSULATION	KP	1.0	330000.00	220000.00	330000.00	220000.00
PERCENT TOTAL DIRECT COST IN ACCOUNT 13 = 1.769 ACCOUNT TOTAL,$					5860002.00	773002.00
WATER TREATMENT						
14. 1 DEMINERALIZER	GPM	152.6	2500.00	700.00	381520.00	106825.60
14. 2 CONDENSATE POLISHING	KWE	953800.0	1.25	.30	1192250.00	286140.00
PERCENT TOTAL DIRECT COST IN ACCOUNT 14 = .525 ACCOUNT TOTAL,$					1573769.98	352965.60

Table 11.13 CLOSED CYCLE LIQUID METAL MHD SYSTEM ACCOUNT LISTING
(Continued) PARAMETRIC POINT NO.16

ACCOUNT NO. & NAME,	UNIT	AMOUNT	MAT $/UNIT	INS $/UNIT	MAT COST,$	INS COST,$
POWER CONDITIONING						
15. 1 INVERTERS		3978.3	5675000.00	7340000.00	7675000.00	7340000.00
15. 2 TRANSFORMERS	KW	3912.7	3550000.00	1990000.00	3550000.00	1930000.00
15. 3 CIRCUIT BREAKERS		144.0	[illegible]03000.00	72600.00	363000.00	72600.00
15. 4 COOLING SYSTEM		1.0	1.00	1.00	1.00	1.00
15. 5 CONDUCTORS		1.0	2800000.00	1120000.00	2800000.00	1120000.00
15. 6 STD TRANSFORMERS		312339.3	.30	.00	528934.23	10575.68
PERCENT TOTAL DIRECT COST IN ACCOUNT 15 =10.121 ACCOUNT TOTAL,$					49991835.00	10443177.62
AUXILIARY MECH EQUIPMENT						
16. 1 BOILER FEED PUMP DR.	KWE	935043.6	1.67	.10	1544931.39	92504.95
16. 2 OTHER PUMPS	KWE	290960.8	.88	.12	256041.9[illegible]	34914.81
16. 3 MISC SERVICE SYS	KWE	969955.9	1.17	.73	1134731.39	707994.90
16. 4 AUXILIARY BOILER	PPH	280000.0	4.00	.80	1120000.00	224000.00
PERCENT TOTAL DIRECT COST IN ACCOUNT 16 = 1.354 ACCOUNT TOTAL,$					4055604.91	1059414.45
PIPE & FITTINGS						
17. 1 CONVENTIONAL PIPING	TON	3800.0	3000.00	1800.00	11400000.00	6840000.00
PERCENT TOTAL DIRECT COST IN ACCOUNT 17 = 4.356 ACCOUNT TOTAL,$					11400000.00	6840000.00
AUXILIARY ELEC EQUIPMENT						
18. 1 MISC MOTERS,ETC		290956.8	1.40	.17	407339.48	49462.65
18. 2 SWITCHGEAR & MCC PAN	KWE	387942.4	1.35	.45	755497.59	174574.96
18. 3 CONDUIT,CABLES,TRAYS	FT	4390000.0	1.32	1.36	5794799.54	5970399.54
18. 4 ISOLATED PHASE BUS	FT	500.0	510.00	450.00	255000.00	225000.00
18. 5 LIGHTING & COMMUN	KWE	969855.9	.35	.43	339449.56	417038.04
PERCENT TOTAL DIRECT COST IN ACCOUNT 18 = 3.838 ACCOUNT TOTAL,$					7553075.56	6836474.52
CONTROL, INSTRUMENTATION						
19. 1 COMPUTER	EACH	1.0	660000.00	15000.00	660000.00	15000.00
19. 2 OTHER CONTROLS	EACH	1.0	1068000.00	541000.00	1068000.00	541000.00
PERCENT TOTAL DIRECT COST IN ACCOUNT 19 = .636 ACCOUNT TOTAL,$					1728000.00	656000.00
PROCESS WASTE SYSTEMS						
20. 1 BOTTOM ASH	TPH	34.2	3479071.59	863767.90	3479071.59	863767.90
20. 2 DRY ASH	TPH	9.6	613807.64	153451.91	613807.64	153451.91
20. 3 WET SLURRY	TPH	55.0	1806488.33	451622.03	1806488.33	451622.08
20. 4 ONSITE DISPOSAL	ACRE	353.6	6203.67	9282.36	2194996.09	3284281.78
20. 5 SEED TREATMENT	EACH	.0	.00	.00	.00	.00
PERCENT TOTAL DIRECT COST IN ACCOUNT 20 = 3.429 ACCOUNT TOTAL,$					8094363.56	4759123.62
STACK GAS CLEANING						
21. 1 PRECIPITATOR	EACH	.0	3000037.31	5200024.55	.00	.00
21. 2 SCRUBBER	KWE	1000000.0	21.42	5.82	21416667.75	5819194.25
21. 3 MISC STEEL & DUCTS		.0	.00	.00	.00	.00
PERCENT TOTAL DIRECT COST IN ACCOUNT 21 = 8.332 ACCOUNT TOTAL,$					21416667.75	5819194.25
TOTAL DIRECT COSTS,$					273245824.00	111631754.00

Table 11.14 CLOSE CYCLE LIQUID METAL MHD SYSTEM COST OF ELECTRICITY, MILLS/KW.HR
PARAMETRIC POINT NO.16

ACCOUNT	RATE, PERCENT	LABOR RATE, $/HR 5.00	8.50	10.50	15.00	21.50
TOTAL DIRECT COSTS,$	.0	335773225.	354742954.	374877576.	417064340.	479385696.
INDIRECT COST,$	51.0	29339977.	41563551.	51832193.	73347443.	105131335.
PROF & OWNER COSTS,$	8.0	20461859.	23379478.	29990206.	33365147.	38350055.
CONTINGENCY COST,$	11.0	35385054.	39021723.	41236533.	45877077.	52732426.
SUB TOTAL,$	.0	422959112.	463707696.	497936504.	569654000.	675600296.
ESCALATION COST,$	6.5	143093380.	152350942.	174345694.	199456600.	236552254.
INTREST DURING CONST,$	10.0	188731948.	206514656.	222198206.	254189840.	301464976.
TOTAL CAPITALIZATION,$	.0	759784432.	832983328.	894470392.	1023300440.	1213617520.
COST OF ELEC-CAPITAL	18.0	25.31874	27.75799	29.80696	34.10004	40.44209
COST OF ELEC-FUEL	.0	8.60943	8.60943	8.60943	8.60943	8.60943
COST OF ELEC-OP & MAIN	.0	.93712	.93712	.93712	.93712	.93712
TOTAL COST OF ELEC	.0	34.85529	37.30454	39.35351	43.64659	49.99863

ACCOUNT	RATE, PERCENT	CONTINGENCY, PERCENT -5.00	.00	11.00	5.00	20.00
TOTAL DIRECT COSTS,$	.0	374877576.	374877576.	374877576.	374877576.	374877576.
INDIRECT COST,$	51.0	51832193.	51832193.	51832193.	51832193.	51832193.
PROF & OWNER COSTS,$	8.0	29990206.	29990206.	29990206.	29990206.	29990206.
CONTINGENCY COST,$	20.0	-18743878.	0.	41236533.	18743878.	74975514.
SUB TOTAL,$	.0	437956096.	456699972.	497936504.	475443943.	531675484.
ESCALATION COST,$	6.5	153344370.	159907282.	174345694.	166470196.	186158938.
INTREST DURING CONST,$	10.0	195423870.	203787724.	222188206.	212151578.	237243144.
TOTAL CAPITALIZATION,$	.0	786724329.	8[illegible]0394968.	894470392.	854065616.	955077560.
COST OF ELEC-CAPITAL	18.0	25.21643	27.33350	29.80696	28.45053	31.82661
COST OF ELEC-FUEL	.0	8.60943	8.60943	8.60943	8.60943	8.60943
COST OF ELEC-OP & MAIN	.0	.93712	.93712	.93712	.93712	.93712
TOTAL COST OF ELEC	.0	35.76302	36.88505	39.35351	38.00703	41.37316

ACCOUNT	RATE, PERCENT	ESCALATION RATE, PERCENT 5.00	6.50	8.00	10.00	.00
TOTAL DIRECT COSTS,$	.0	374877576.	374877576.	374877576.	374877576.	374877576.
INDIRECT COST,$	51.0	51832193.	51832193.	51832193.	51832193.	51832193.
PROF & OWNER COSTS,$	8.0	29990206.	29990206.	29990206.	29990206.	29990206.
CONTINGENCY COST,$	11.0	41236533.	41236533.	41236533.	41236533.	41236533.
SUB TOTAL,$	.0	497936504.	497936504.	497936504.	497936504.	497936504.
ESCALATION COST,$	.0	129852135.	174345694.	221623632.	239237469.	0.
INTREST DURING CONST,$	10.0	209885628.	222188206.	235123534.	253402054.	173115218.
TOTAL CAPITALIZATION,$	.0	837684256.	894470392.	954038564.	1040626016.	671051720.
COST OF ELEC-CAPITAL	18.0	27.91484	29.80696	31.81365	34.67739	22.36185
COST OF ELEC-FUEL	.0	8.60943	8.60943	8.60943	8.60943	8.60943
COST OF ELEC-OP & MAIN	.0	.93712	.93712	.93712	.93712	.93712
TOTAL COST OF ELEC	.0	37.46119	39.35351	41.36020	44.22394	31.90840

ACCOUNT	RATE, PERCENT	INT DURING CONST, PERCENT 6.00	8.00	10.00	12.50	15.00
TOTAL DIRECT COSTS,$	.0	374877576.	374877576.	374877576.	374877576.	374877576.
INDIRECT COST,$	51.0	51832193.	51832193.	51832193.	51832193.	51832193.
PROF & OWNER COSTS,$	8.0	29990206.	29990206.	29990206.	29990206.	29990206.
CONTINGENCY COST,$	11.0	41236533.	41236533.	41236533.	41236533.	41236533.
SUB TOTAL,$	.0	497936504.	497936504.	497936504.	497936504.	497936504.
ESCALATION COST,$	6.5	174345694.	174345694.	174345694.	174345694.	174345694.
INTREST DURING CONST,$	15.0	126245985.	172962426.	222188205.	287437308.	357052232.
TOTAL CAPITALIZATION,$	.0	798528072.	845244592.	894470392.	959719496.	1029334424.
COST OF ELEC-CAPITAL	18.0	26.60982	28.16659	29.80696	31.98123	34.30111
COST OF ELEC-FUEL	.0	8.60943	8.60943	8.60943	8.60943	8.60943
COST OF ELEC-OP & MAIN	.0	.93712	.93712	.93712	.93712	.93712
TOTAL COST OF ELEC	.0	36.15637	37.71313	39.35351	41.52784	43.84766

Table 11.14 (Continued) CLOSE CYCLE LIQUID METAL MHD SYSTEM COST OF ELECTRICITY, MILLS/KW.HR
PARAMETRIC POINT NO.15

ACCOUNT	RATE, PERCENT	FIXED CHARGE RATE, PCT 13.00	14.40	18.00	21.50	25.00
TOTAL DIRECT COSTS,$	.0	374877576.	374877576.	374877576.	374877576.	374877576.
INDIRECT COST,$	51.0	51832193.	51832193.	51832193.	51832193.	51832193.
PROF & OWNER COSTS,$	8.0	29990206.	29990206.	29990206.	29990206.	29990206.
CONTINGENCY COST,$	11.0	41236533.	41236533.	41236533.	41236533.	41236533.
SUB TOTAL,$	.0	497936504.	497936504.	497936504.	497936504.	497936504.
ESCALATION COST,$	6.5	174345694.	174345694.	174345694.	174345694.	174345694.
INTREST DURING CONST,$	10.0	222188206.	222188206.	222188206.	222188206.	222188206.
TOTAL CAPITALIZATION,$	.0	894470392.	894470392.	894470392.	894470392.	894470392.
COST OF ELEC-CAPITAL	25.0	16.55942	23.84157	29.80696	35.76835	41.39856
COST OF ELEC-FUEL	.0	8.60943	8.60943	8.60943	8.60943	8.60943
COST OF ELEC-OP & MAIN	.0	.93712	.93712	.93712	.93712	.93712
TOTAL COST OF ELEC	.0	26.10597	33.39212	39.35351	45.31490	50.94510

ACCOUNT	RATE, PERCENT	FUEL COST, $/10**6 BTU .50	.85	1.50	2.50	1.02
TOTAL DIRECT COSTS,$	.0	374877576.	374877576.	374877576.	374877576.	374877576.
INDIRECT COST,$	51.0	51832193.	51832193.	51832193.	51832193.	51832193.
PROF & OWNER COSTS,$	8.0	29990206.	29990206.	29990206.	29990206.	29990206.
CONTINGENCY COST,$	11.0	41236533.	41236533.	41236533.	41236533.	41236533.
SUB TOTAL,$	.0	497936504.	497936504.	497936504.	497936504.	497936504.
ESCALATION COST,$	6.5	174345694.	174345694.	174345694.	174345694.	174345694.
INTREST DURING CONST,$	10.0	222188206.	222188206.	222188206.	222188206.	222188206.
TOTAL CAPITALIZATION,$	.0	894470392.	894470392.	894470392.	894470392.	894470392.
COST OF ELEC-CAPITAL	18.0	29.80696	29.80696	29.80696	29.80696	29.80696
COST OF ELEC-FUEL	.0	5.06437	8.60943	15.19311	25.32186	10.33132
COST OF ELEC-OP & MAIN	.0	.93712	.93712	.93712	.93712	.93712
TOTAL COST OF ELEC	.0	35.80845	39.35351	45.93719	56.06593	41.07539

ACCOUNT	RATE, PERCENT	CAPACITY FACTOR, PERCENT 12.00	45.00	50.00	65.00	80.00
TOTAL DIRECT COSTS,$	.0	374877576.	374877576.	374877576.	374877576.	374877576.
INDIRECT COST,$	51.0	51832193.	51832193.	51832193.	51832193.	51832193.
PROF & OWNER COSTS,$	8.0	29990206.	29990206.	29990206.	29990206.	29990206.
CONTINGENCY COST,$	11.0	41236533.	41236533.	41236533.	41236533.	41236533.
SUB TOTAL,$	.0	497936504.	497936504.	497936504.	497936504.	497936504.
ESCALATION COST,$	6.5	174345694.	174345694.	174345694.	174345694.	174345694.
INTREST DURING CONST,$	10.0	222188206.	222188206.	222188206.	222188206.	222188206.
TOTAL CAPITALIZATION,$	.0	894470392.	894470392.	894470392.	894470392.	894470392.
COST OF ELEC-CAPITAL	18.0	161.45437	43.05450	38.74905	29.80696	24.21816
COST OF ELEC-FUEL	.0	8.60943	8.60943	8.60943	8.60943	8.60943
COST OF ELEC-OP & MAIN	.0	.93713	.93712	.93712	.93712	.93712
TOTAL COST OF ELEC	.0	171.00093	52.60105	48.29560	39.35351	33.76470

Table 11.15 CLOSE CYCLE LIQUID METAL MHD SYSTEM

ACCOUNT NO	AUX POWER, MWE	PERC PLANT POW	OPERATION COST	MAINTENANCE COST
4	11.77790	1.24155	72.59867	16.75256
7	4.38109	.51453	353.18753	.00000
8	.57598	.06072	.00000	.00000
14	.00000	.00000	16.50640	.00000
18	6.53600	.68898	.00000	.00000
20	10.59493	1.11579	.00000	.00000
21	17.00000	1.79703	.00000	.00000
TOTALS	51.35583	5.41361	383.98706	15.75256

CLOSE CYCLE LIQUID METAL MHD SYSTEM BASE CASE INPUT

NOMINAL POWER, MWE	1000.0000	NET POWER, MWE	948.5441
NOM HEAT RATE, BTU/KW-HR	5608.5725	NET HEAT RATE, BTU/KW-HR	10128.7429
OFF DESIGN HEAT RATE	.0000		
CONDENSER			
DESIGN PRESSURE, IN HG A	3.5000	NUMBER OF SHELLS	2.0000
NUMBER OF TUBES/SHELL	13819.0457	TUBE LENGTH, FT	69.5067
U, BTU/HR-FT2-F	509.8535	TERMINAL TEMP DIFF, F	5.0000
HEAT REJECTION			
DESIGN TEMP, F	77.0000	APPROACH, F	15.6713
RANGE, F	23.0000	OFF DESIGN TEMP, F	51.4000
OFF DESIGN PRES, IN HG A	.0000	LP TURBINE BLADE LEN, IN	28.5000

1	1000.000	2	.000	3	.357	4	.000	5	8.000
6	256.000	7	3.500	8	1333.000	9	2.000	10	2.000
11	1.000	12	697.800	13	1.000	14	.000	15	.000
16	2.000	17	182.000	18	3.000	19	5.000	20	2.500
21	.000	22	18300.000	23	27000.000	24	2875.000	25	400.000
26	7340000.000	27	10000.000	28	20000.000	29	525000.000	30	.300
31	1.000	32	3800.000	33	1.000	34	.300	35	.400
36	4390000.000	37	500.000	38	1.000	39	1.000	40	1434000.000
41	405000.000	42	660000.000	43	15000.000	44	1058000.000	45	641000.000
46	5.000	47	.000	48	3.000	49	2.000	50	2.000
51	1.000	52	5.350						

1	152.130	2	114.335	3	40.225	4	2.574	5	1.985
6	192.490	7	743.980	8	1.000	9	3.306	10	1.060
11	1.000	12	711.060	13	174.490	14	1.638	15	5.360
16	269.200	17	485.400	18	185.000	19	2.710	20	256.000
21	698.000	22	1255000.000	23	591000.000	24	53000.000	25	27000.000
26	452000.000	27	181000.000	28	21000.000	29	10000.000	30	28000.000
31	11000.000	32	1620000.000	33	642000.000	34	535000.000	35	214000.000
36	.000	37	.000	38	30000.000	39	11000.000	40	484000.000
41	97000.000	42	.000	43	.000	44	3447000.000	45	3450000.000
46	240000.000	47	24000.000	48	1832000.000	49	183000.000	50	4490000.000
51	895000.000	52	2830000.000	53	283000.000	54	1740000.000	55	1800000.000
56	28000.000	57	3000.000	58	16600.000	59	6700.000	60	5690000.000
61	569000.000	62	9170000.000	63	917000.000	64	3396.100	65	1.000
66	6995.800	67	1.000	68	3636000.000	69	1458000.000	70	1.000
71	1.000	72	27773000.000	73	11120000.000	74	3340000.000	75	2560000.000
76	1270.500	77	1.000	78	1.000	79	1.000	80	5530000.000
81	553000.000	82	1.000	83	1.000	84	1.000	85	1.000
86	330000.000	87	220000.000	88	3978.800	89	3412.000	90	144.000
91	1.000	92	1.000	93	36750000.000	94	7340000.000	95	9550000.000
96	1900000.000	97	363000.000	98	72600.000	99	1.000	100	1.000
101	2800000.000	102	1120000.000	103	1.000	104	230000.000	105	1.200
106	.000	107	1.000	108	.000	109	.000	110	1.000
111	27000.000	112	90.000	113	150.000	114	.000	115	.000

Table 11.16 CLOSE CYCLE LIQUID METAL MHD SYSTEM ACCOUNT LISTING
PARAMETRIC POINT NO. 2

ACCOUNT NO. & NAME,	UNIT	AMOUNT	MAT $/UNIT	INS $/UNIT	MAT COST,$	INS COST,$
SITE DEVELOPMENT						
1. 1 LAND COST	ACRE	133.3	1000.00	.00	133300.00	.00
1. 2 CLEARING LAND	ACRE	66.7	.00	500.00	.00	33398.36
1. 3 GRADING LAND	ACRE	133.3	.00	3000.00	.00	546000.00
1. 4 ACCESS RAILROAD	MILE	5.0	115000.00	110000.00	575000.00	550000.00
1. 5 LOOP RAILROAD TRACK	MILE	2.5	120000.00	70000.00	300000.00	175000.00
1. 6 SIDING R R TRACK	MILE	.0	125000.00	80000.00	.00	.00
1. 7 OTHER SITE COSTS	ACRE	.0	.00	.00	387731.29	387731.29
PERCENT TOTAL DIRECT COST IN ACCOUNT 1 = .662 ACCOUNT TOTAL,$					1444031.29	1694427.64
EXCAVATION & PILING						
2. 1 COMMON EXCAVATION	YD3	135900.0	.00	3.00	.00	407700.00
2. 2 PILING	FT	362400.0	6.50	8.50	2355600.00	3080400.00
PERCENT TOTAL DIRECT COST IN ACCOUNT 2 = 1.213 ACCOUNT TOTAL,$					2355600.00	3488100.00
PLANT ISLAND CONCRETE						
3. 1 PLANT IS. CONCRETE	YD3	18300.0	70.00	80.00	1281000.00	1464000.00
3. 2 SPECIAL STRUCTURES	YD3	27000.0	90.00	150.00	2430000.00	4050000.00
PERCENT TOTAL DIRECT COST IN ACCOUNT 3 = 1.915 ACCOUNT TOTAL,$					3711000.00	5514000.00
HEAT REJECTION SYSTEM						
4. 1 COOLING TOWERS	EACH	13.0	.00	.00	2753500.00	1377300.00
4. 2 CIRCULATING H2O SYS	EACH	1.0	.00	.00	1618835.27	2170653.50
4. 3 SURFACE CONDENSER	FT2	545753.1	.00	.00	2179449.44	382037.69
PERCENT TOTAL DIRECT COST IN ACCOUNT 4 = 2.178 ACCOUNT TOTAL,$					6561284.69	3929691.19
STRUCTURAL FEATURES						
5. 1 STAT. STRUCTURAL ST.	TON	2875.0	550.00	175.00	1959750.00	503125.00
5. 2 SILOS & BUNKERS	TPH	419.0	1800.00	750.00	755204.70	314668.62
5. 3 CHIMNEY	FT	400.0	.00	.00	935970.32	652606.38
5. 4 STRUCTURAL FEATURES	EACH	1.0	1434000.00	405000.00	1434000.00	405000.00
PERCENT TOTAL DIRECT COST IN ACCOUNT 5 = 1.322 ACCOUNT TOTAL,$					4493025.56	1875400.00
BUILDINGS						
6. 1 STATION BUILDINGS	FT3	7340000.0	.16	.16	1174400.00	1174400.00
6. 2 ADMINSTRATION	FT2	10000.0	15.00	14.00	150000.00	140000.00
6. 3 WAREHOUSE & SHOP	FT2	20000.0	12.00	8.00	240000.00	160000.00
PERCENT TOTAL DIRECT COST IN ACCOUNT 6 = .573 ACCOUNT TOTAL,$					1574400.00	1474400.00
FUEL HANDLING & STORAGE						
7. 1 COAL HANDLING SYS	TPH	419.0	.00	.00	5840207.62	2490207.91
7. 2 DOLOMITE HAND. SYS	TPH	62.5	.00	.00	1051151.52	571545.39
7. 3 FUEL OIL HAND. SYS	GAL	573000.0	.00	.00	79460.99	63272.91
PERCENT TOTAL DIRECT COST IN ACCOUNT 7 = 2.397 ACCOUNT TOTAL,$					6976320.19	3125026.19
FUEL PROCESSING						
8. 1 COAL DRYER & CRUSHER	TPH	419.0	.00	.00	1462815.16	975210.11
8. 2 CARBONIZERS	TPH	.0	.00	.00	.00	.00
8. 3 GASIFIERS	TPH	.0	.00	.00	.00	.00
PERCENT TOTAL DIRECT COST IN ACCOUNT 8 = .505 ACCOUNT TOTAL,$					1462815.16	975210.11

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OF POOR QUALITY

Table 11.16
(Continued)

CLOSE CYCLE LIQUID METAL MHD SYSTEM ACCOUNT LISTING
PARAMETRIC POINT NO. [illegible]

ACCOUNT NO. & NAME,	UNIT	AMOUNT	MAT $/UNIT	INS $/UNIT	MAT COST,$	INS COST,$
FIRING SYSTEM						
9. 1		.0	.00	.00	.00	.00
PERCENT TOTAL DIRECT COST IN ACCOUNT 9 = .000 ACCOUNT TOTAL,$					.00	.00
VAPOR GENERATOR (FIRED)						
10. 1		.0	.00	.00	.00	.00
PERCENT TOTAL DIRECT COST IN ACCOUNT 10 = .000 ACCOUNT TOTAL,$					.00	.00
ENERGY CONVERTER						
11. 1 MHD DUCT STRUCT STEEL	KP	218.4	1801433.00	720000.00	1801433.00	720000.00
11. 2 DUCT INSULATION	KP	164.2	92493.00	37000.00	92493.00	37000.00
11. 3 MIXER	KP	52.9	792700.00	313000.00	792700.00	313000.00
11. 4 NOZZLE	KP	3.8	45092.00	18100.00	45092.00	18100.00
11. 5 SEPARATOR/DIFFUSER	KP	2.9	52774.00	21100.00	52774.00	21100.00
11. 6 LM PIPING/FITTING/INS	KP	243.9	5598200.00	2230000.00	5598200.00	2230000.00
11. 7 IRON POLES	KP	1153.2	930320.00	333000.00	930320.00	333000.00
11. 8 AUX EQUIPMENT & SYSTEM		1.0	.00	.00	.00	.00
11. 9 MAGNET DEWAR	KP	4.5	39036.00	7500.00	39036.00	7500.00
11.10 SUPERCON MAG COOLANT	FT3	1.2	530930.00	105166.00	530930.00	105166.00
11.11 ASSEMBLY SUPPORT STRUCT		1.0	.00	.00	.00	.00
11.12 L M PUMPS	KP	952.4	46176000.00	4618000.00	46176000.00	4618000.00
11.13 L M INVENTORY (SODIUM)	KP	273.9	370940.00	37100.00	370940.00	37100.00
11.14 L M EMERGENCY DUMP	GAL	2541.3	2491400.00	249100.00	2491400.00	249100.00
11.15 L M PURIFICATION	GPM	7173.6	5350800.00	1070000.00	5350800.00	1070000.00
11.16 GAS COMPRESSOR	KP	295.6	3103900.00	310390.00	3103900.00	310390.00
11.17 MOTOR DRIVES	MW	1.0	23391720.00	2300000.00	23391720.00	2300000.00
11.18 GAS INVENTORY	KP	278.0	42000.00	4000.00	42000.00	4000.00
11.19 GAS PIPING	KP	2.5	15976.00	6350.00	15976.00	6350.00
11.20 STEAM TURBINE-GEN	MW	1.0	.00	.00	.00	.00
11.21 DRIVE TURBINES	MW	955.7	11354000.00	1135400.00	11354000.00	1135400.00
PERCENT TOTAL DIRECT COST IN ACCOUNT 11 =24.003 ACCOUNT TOTAL,$					102088491.00	13522306.00
COUPLING HEAT EXCHANGER						
12. 1 COMB HEAT EXCHANGER	KP	7542.3	92479000.00	9248000.00	92479000.00	9248000.00
12. 2 OPEN CYCLE MHD TOPPING		1.0	.00	.00	.00	.00
12. 3 STEAM GENERATOR	KP	4777.3	24329000.00	2433000.00	24329000.00	2433000.00
12. 4 INSULATION		1.0	7000000.00	4670000.00	7000000.00	4670000.00
PERCENT TOTAL DIRECT COST IN ACCOUNT 12 =23.199 ACCOUNT TOTAL,$					123807000.00	16351000.00
HEAT RECOVERY HEAT EXCH.						
13. 1 AIR PREHEATERS	KP	2240.2	9123300.00	912330.00	9123300.00	912330.00
13. 2 GAS RECUPERATORS	KP	1.0	.00	.00	.00	.00
13. 3 COMP INTERCOLLER	KP	1.0	.00	.00	.00	.00
13. 4 INSULATION	KP	1.0	548300.00	364800.00	548300.00	364800.00
PERCENT TOTAL DIRECT COST IN ACCOUNT 13 = 2.273 ACCOUNT TOTAL,$					9671600.00	1277130.00
WATER TREATMENT						
14. 1 DEMINERALIZER	GPM	133.2	2600.00	700.00	348000.00	97440.00
14. 2 CONDENSATE POLISHING	KWE	870000.0	1.25	.30	1087500.00	261000.00
PERCENT TOTAL DIRECT COST IN ACCOUNT 14 = .372 ACCOUNT TOTAL,$					1435499.98	350440.00

Table 11.16 (Continued)

CLOSED CYCLE LIQUID METAL MHD SYSTEM ACCOUNT LISTING
PARAMETRIC POINT NO. [illegible]

ACCOUNT NO. & NAME,	UNIT	AMOUNT	MAT $/UNIT	INS $/UNIT	MAT COST,$	INS COST,$
POWER CONDITIONING						
15. 1 INVERTERS		3333.7	43500000.00	3900000.00	43500000.00	3900000.00
15. 2 TRANSFORMERS	KP	3511.0	11397000.00	2379000.00	11397000.00	2379000.00
15. 3 CIRCUIT BREAKERS		102.0	494000.00	96800.00	494000.00	96800.00
15. 4 COOLING SYSTEM		1.0	.00	.00	.00	.00
15. 5 CONDUCTORS		1.0	2900000.00	1130000.00	2900000.00	1130000.00
15. 6 STD TRANSFORMERS		.0	.00	.00	528892.31	10577.85
PERCENT TOTAL DIRECT COST IN ACCOUNT 15 = 15.345				ACCOUNT TOTAL,$	55209892.00	13515377.75
AUXILIARY MECH EQUIPMENT						
16. 1 BOILER FEED PUMP DDR.	KWE	843774.6	1.67	.10	1409103.62	84377.46
16. 2 OTHER PUMPS	KWE	293956.9	.87	.12	255041.96	34914.91
16. 3 MISC SERVICE SYS	KWE	969855.9	1.17	.73	1134731.39	707994.80
16. 4 AUXILIARY BOILER	PPH	280000.0	4.00	.80	1120000.00	224000.00
PERCENT TOTAL DIRECT COST IN ACCOUNT 16 = 1.032				ACCOUNT TOTAL,$	3918876.97	1051287.09
PIPE & FITTINGS						
17. 1 CONVENTIONAL PIPING	TON	3800.0	3000.00	1800.00	11400000.00	6840000.00
PERCENT TOTAL DIRECT COST IN ACCOUNT 17 = 3.737				ACCOUNT TOTAL,$	11400000.00	6840000.00
AUXILIARY ELEC EQUIPMENT						
18. 1 MISC MOTORS,ETC		[illegible]	1.43	.17	457339.48	49462.55
18. 2 SWITCHGEAR & MCC PAN	KWE	387942.4	1.95	.45	756487.59	174574.08
18. 3 CONDUIT,CABLES,TRAYS	FT	[illegible]	1.32	1.36	5734793.94	5970399.94
18. 4 ISOLATED PHASE BUS	FT	500.0	510.00	450.00	255000.00	225000.00
18. 5 LIGHTING & COMMUN	KWE	[illegible]	.35	.43	333493.56	417038.04
PERCENT TOTAL DIRECT COST IN ACCOUNT 18 = 7.958				ACCOUNT TOTAL,$	7553076.56	6836474.62
CONTROL, INSTRUMENTATION						
19. 1 COMPUTER	EACH	1.0	650000.00	15000.00	650000.00	15000.00
19. 2 OTHER CONTROLS	EACH	1.0	1080000.00	641000.00	1080000.00	641000.00
PERCENT TOTAL DIRECT COST IN ACCOUNT 19 = .495				ACCOUNT TOTAL,$	1728000.00	656000.00
PROCESS WASTE SYSTEMS						
20. 1 BOTTOM ASH	TPH	33.0	3311825.59	827956.40	3311825.59	827956.40
20. 2 DRY ASH	TPH	3.1	580343.20	145085.80	580343.20	145085.80
20. 3 WET SLURRY	TPH	62.0	1726780.09	431695.02	1726780.09	431695.02
20. 4 ONSITE DISPOSAL	ACRE	334.3	6250.39	9363.56	2095311.42	3130214.87
20. 5 SEED TREATMENT	EACH	.0	.00	.00	.00	.00
PERCENT TOTAL DIRECT COST IN ACCOUNT 20 = 2.543				ACCOUNT TOTAL,$	7714750.25	4534952.06
STACK GAS CLEANING						
21. 1 PRECIPITATOR	EACH	.0	7767027.00	4983567.50	.00	.00
21. 2 SCRUBBER	KWE	1000000.0	21.51	3.91	21512213.25	3903848.75
21. 3 MISC STEEL & DUCTS		.0	.00	.00	.00	.00
PERCENT TOTAL DIRECT COST IN ACCOUNT 21 = 5.544				ACCOUNT TOTAL,$	21512213.25	3903848.75
TOTAL DIRECT COSTS,$					394719358.00	36929068.00

Table 11.17 CLOSE CYCLE LIQUID METAL MHD SYSTEM COST OF ELECTRICITY,MILLS/KW.HR
PARAMETRIC POINT NO. 0

ACCOUNT	RATE, PERCENT	LABOR RATE, $/HR 6.00	8.50	10.80	15.00	21.50
TOTAL DIRECT COSTS,$	.0	437584375.	412445579.	481648432.	521833140.	591320776.
INDIRECT COST,$	51.0	27581910.	75640330.	49433823.	60957524.	100266718.
PROF & OWNER COSTS,$	8.0	33165790.	35095640.	38531874.	41750651.	46505662.
CONTINGENCY COST,$	11.0	48354336.	50669005.	52981327.	57407145.	63945205.
SUB TOTAL,$	.0	551087409.	579050472.	622595440.	690994456.	792038424.
ESCALATION COST,$	6.5	192555760.	206503174.	217993324.	241942310.	277321480.
INTREST DURING CONST,$	15.0	245935092.	253726433.	277813250.	309339129.	353421760.
TOTAL CAPITALIZATION,$	.0	989542056.	1059760028.	1118402016.	1241270280.	1422781664.
COST OF ELEC-CAPITAL	13.0	32.83650	35.25121	37.21023	41.29924	47.33727
COST OF ELEC-FUEL	.0	8.09826	8.09826	8.09826	8.09826	8.09826
COST OF ELEC-OP & MAIN	.0	.92090	.92090	.92090	.92090	.92090
TOTAL COST OF ELEC	.0	41.85566	44.27037	46.22944	50.31740	56.35643

ACCOUNT	RATE, PERCENT	CONTINGENCY, PERCENT -5.00	.00	11.00	5.00	20.00
TOTAL DIRECT COSTS,$	.0	481648432.	481648432.	481648432.	481648432.	481648432.
INDIRECT COST,$	51.0	49433823.	49433823.	49433823.	49433823.	49433823.
PROF & OWNER COSTS,$	8.0	38531874.	38531874.	38531874.	38531874.	38531874.
CONTINGENCY COST,$	20.0	-24082421.	0.	52981327.	24082421.	96329686.
SUB TOTAL,$	.0	545531704.	569614150.	622595440.	593696536.	665943800.
ESCALATION COST,$	6.5	131010505.	139492535.	217993324.	207874766.	233171164.
INTREST DURING CONST,$	10.0	243426035.	254172044.	277813260.	264918050.	297156076.
TOTAL CAPITALIZATION,$	.0	979968249.	1023229752.	1118402016.	1066489384.	1136271024.
COST OF ELEC-CAPITAL	18.0	32.80446	34.04277	37.21028	35.48309	39.80105
COST OF ELEC-FUEL	.0	8.09826	8.09826	8.09826	8.09826	8.09826
COST OF ELEC-OP & MAIN	.0	.92090	.92090	.92090	.92090	.92090
TOTAL COST OF ELEC	.0	41.82362	43.06294	46.22944	44.50225	48.82021

ACCOUNT	RATE, PERCENT	ESCALATION RATE, PERCENT 5.00	6.50	8.00	10.00	.00
TOTAL DIRECT COSTS,$	.0	481648432.	481648432.	481648432.	481648432.	481648432.
INDIRECT COST,$	51.0	49433823.	49433823.	49433823.	49433823.	49433823.
PROF & OWNER COSTS,$	8.0	38531874.	38531874.	38531874.	38531874.	38531874.
CONTINGENCY COST,$	11.0	52981327.	52981327.	52981327.	52981327.	52981327.
SUB TOTAL,$	.0	622595440.	622595440.	622595440.	622595440.	622595440.
ESCALATION COST,$	.0	162373258.	217993324.	277113596.	361710896.	0.
INTREST DURING CONST,$	10.0	262430720.	277813253.	293335360.	315941529.	216454798.
TOTAL CAPITALIZATION,$	.0	1047399416.	1118402016.	1193695934.	1301147856.	839050232.
COST OF ELEC-CAPITAL	18.0	34.34795	37.21028	39.71539	43.29047	27.91598
COST OF ELEC-FUEL	.0	8.09826	8.09826	8.09826	8.09826	8.09826
COST OF ELEC-OP & MAIN	.0	.92090	.92090	.92090	.92090	.92090
TOTAL COST OF ELEC	.0	43.86712	46.22944	48.73454	52.30956	36.93514

ACCOUNT	RATE, PERCENT	INT DURING CONST,PERCENT 6.00	8.00	10.00	12.50	15.00
TOTAL DIRECT COSTS,$	.0	481648432.	481648432.	481648432.	481648432.	481648432.
INDIRECT COST,$	51.0	49433823.	49433823.	49433823.	49433823.	49433823.
PROF & OWNER COSTS,$	8.0	38531874.	38531874.	38531874.	38531874.	38531874.
CONTINGENCY COST,$	11.0	52981327.	52981327.	52981327.	52981327.	52981327.
SUB TOTAL,$	.0	622595440.	622595440.	622595440.	622595440.	622595440.
ESCALATION COST,$	6.5	217993324.	217993324.	217993324.	217993324.	217993324.
INTREST DURING CONST,$	15.0	157851676.	216263770.	277813260.	359397548.	446440640.
TOTAL CAPITALIZATION,$	.0	998440432.	1056852433.	1118402016.	1199936304.	1287029392.
COST OF ELEC-CAPITAL	18.0	33.21904	35.16347	37.21028	39.92460	42.82067
COST OF ELEC-FUEL	.0	8.09826	8.09826	8.09826	8.09826	8.09826
COST OF ELEC-OP & MAIN	.0	.92090	.92090	.92090	.92090	.92090
TOTAL COST OF ELEC	.0	42.23820	44.18153	46.22944	48.94387	51.83983

Table 11.17 (Continued)

CLOSE CYCLE LIQUID METAL MHD SYSTEM COST OF ELECTRICITY,MILLS/KW.HR
PARAMETRIC POINT NO.

ACCOUNT	RATE, PERCENT	FIXED CHARGE RATE, PCT 10.00	14.40	18.00	21.60	25.00
TOTAL DIRECT COSTS,$	.0	431649432.	4 1649432.	431649432.	431649432.	431649432.
INDIRECT COST,$	51.0	49433923.	49433923.	49433923.	49433923.	49433923.
PROF & OWNER COSTS,$	9.0	38531874.	38531874.	38531874.	38531874.	38531874.
CONTINGENCY COST,$	11.0	52981327.	52981327.	52981327.	52981327.	52981327.
SUB TOTAL,$	.0	522595440.	522595440.	522595440.	522595440.	522595440.
ESCALATION COST,$	6.5	217993324.	217993324.	217993324.	217993324.	217993324.
INTREST DURING CONST,$	10.0	277813260.	277813260.	277813260.	277813260.	277813260.
TOTAL CAPITALIZATION,$	.0	1118402016.	1118402016.	1118402016.	1118402016.	1118402016.
COST OF ELEC-CAPITAL	25.0	20.67238	29.76817	37.21028	44.65233	51.68094
COST OF ELEC-FUEL	.0	8.09826	8.09826	8.09826	8.09826	8.09826
COST OF ELEC-OP & MAIN	.0	.92090	.92090	.92090	.92090	.92090
TOTAL COST OF ELEC	.0	29.69154	38.78733	46.22944	53.67149	60.70010

ACCOUNT	RATE, PERCENT	FUEL COST, $/10**6 BTU .50	.95	1.50	2.50	1.02
TOTAL DIRECT COSTS,$	.0	431649432.	4 1649432.	431649432.	431649432.	431649432.
INDIRECT COST,$	51.0	49433923.	49433923.	49433923.	49433923.	49433923.
PROF & OWNER COSTS,$	8.0	38531874.	38531874.	38531874.	38531874.	38531874.
CONTINGENCY COST,$	11.0	52981327.	52981327.	52981327.	52981327.	52981327.
SUB TOTAL,$	.0	522595440.	522595440.	522595440.	522595440.	522595440.
ESCALATION COST,$	5.5	217993324.	217993324.	217993324.	217993324.	217993324.
INTREST DURING CONST,$	10.0	277813260.	277813260.	277813260.	277813260.	277813260.
TOTAL CAPITALIZATION,$	.0	1118402015.	1118402015.	1118402015.	1118402015.	1118402016.
COST OF ELEC-CAPITAL	13.0	37.21028	37.21028	37.21028	37.21028	37.21028
COST OF ELEC-FUEL	.0	4.75339	9.09925	14.29105	23.81842	9.71792
COST OF ELEC-OP & MAIN	.0	.92090	.92090	.92090	.92090	.92090
TOTAL COST OF ELEC	.0	42.88436	45.22944	52.42223	61.94960	47.84909

ACCOUNT	RATE, PERCENT	CAPACITY FACTOR, PERCENT 12.00	45.00	56.00	65.00	80.00
TOTAL DIRECT COSTS,$	.0	431649432.	4 1649432.	431649432.	431649432.	431649432.
INDIRECT COST,$	51.0	49433923.	49433923.	49433923.	49433923.	49433923.
PROF & OWNER COSTS,$	8.0	38531874.	38531874.	38531874.	38531874.	38531874.
CONTINGENCY COST,$	11.0	52981327.	52981327.	52981327.	52981327.	52981327.
SUB TOTAL,$	.0	522595440.	522595440.	522595440.	522595440.	522595440.
ESCALATION COST,$	6.5	217993324.	217993324.	217993324.	217993324.	217993324.
INTREST DURING CONST,$	10.0	277813260.	277813260.	277813260.	277813260.	277813260.
TOTAL CAPITALIZATION,$	.0	1118402016.	1118402016.	1118402016.	1118402016.	1118402016.
COST OF ELEC-CAPITAL	13.0	201.55556	53.74913	48.37335	37.21029	30.23335
COST OF ELEC-FUEL	.0	8.09826	8.09826	8.09826	8.09826	8.09826
COST OF ELEC-OP & MAIN	.0	.92091	.92090	.92090	.92090	.92090
TOTAL COST OF ELEC	.0	210.57484	62.76734	57.39252	46.22944	39.25251

Table 11.18 CLOSE CYCLE LIQUID METAL MHD SYSTEM

ACCOUNT NO	AUX POWER,MWE	PERC PLANT POW	OPERATION COST	MAINTENANCE COST
4	12.77956	1.33754	79.78321	17.35400
7	4.60160	.48430	334.45079	.00000
9	.54543	.05745	.00000	.00000
14	.00000	.00000	15.05616	.00000
18	5.00000	.52574	.00000	.00000
20	9.99890	1.05226	.00000	.00000
21	17.00000	1.73370	.00000	.00000
TOTALS	49.85456	5.24705	274.99462	17.36400

CLOSE CYCLE LIQUID METAL MHD SYSTEM CASE CASE INPUT

NOMINAL POWER, MWE	1000.0000	NET POWER, MWE	950.1454
NOM HEAT RATE, BTU/KW-HR	9052.3358	NET HEAT RATE, BTU/KW-HR	9527.3694
OFF DESIGN HEAT RATE	.0000		
CONDENSER			
DESIGN PRESSURE, IN HG A	3.5500	NUMBER OF SHELLS	2.0000
NUMBER OF TUBES/SHELL	14395.2629	TUBE LENGTH, FT	53.5067
U, BTU/HR-FT2-F	608.8535	TERMINAL TEMP DIFF, F	5.0000
HEAT REJECTION			
DESIGN TEMP, F	77.0000	APPROACH, F	15.6713
RANGE, F	23.0000	OFF DESIGN TEMP, F	51.4000
OFF DESIGN PRES, IN HG A	.0000	LP TURBINE BLADE LEN, IN	28.5000

1	1000.000	2	.505	3	.377	4	.000	5	3.000
6	.000	7	3.500	8	1414.000	9	2.000	10	2.000
11	1.000	12	370.500	13	1.000	14	.300	15	.000
16	2.000	17	182.000	18	3.000	19	5.000	20	2.500
21	.000	22	13300.000	23	27000.000	24	2375.000	25	400.000
26	7340000.000	27	10000.000	28	20000.000	29	575000.000	30	.300
31	1.000	32	3300.000	33	1.000	34	.300	35	.400
36	4390000.000	37	500.000	38	1.000	39	1.000	40	1434000.000
41	405000.000	42	550000.000	43	15000.000	44	1030000.000	45	641000.000
46	6.000	47	.000	48	3.000	49	2.000	50	2.000
51	.600	52	5.350						

1	218.350	2	154.100	3	52.347	4	3.750	5	2.932
6	249.920	7	1153.230	8	1.000	9	4.610	10	1.161
11	1.000	12	952.360	13	270.760	14	2541.800	15	7179.600
16	295.610	17	1.000	18	278.000	19	2.594	20	1.000
21	665.000	22	1001400.000	23	720000.000	24	52493.000	25	37000.000
26	792700.000	27	313000.000	28	45092.000	29	13100.000	30	52774.000
31	21100.000	32	5598200.000	33	2230000.000	34	830320.000	35	333000.000
36	.000	37	.000	38	38035.000	39	7590.000	40	530830.000
41	106166.000	42	.000	43	.000	44	4617000.000	45	4618000.000
46	370940.000	47	37100.000	48	2491400.000	49	249100.000	50	5350800.000
51	1070000.000	52	3103900.000	53	310390.000	54	23391720.000	55	2300000.000
56	42000.000	57	4000.000	58	15875.000	59	6350.000	60	.000
61	.000	62	1136400.000	63	1136400.000	64	7642.800	65	1.000
66	4777.300	67	1.000	68	22478000.000	69	9240030.000	70	.000
71	.000	72	24329000.000	73	2433000.000	74	7000000.000	75	4670000.000
76	2240.200	77	1.000	78	1.000	79	1.000	80	9123300.000
81	912330.000	82	.000	83	.000	84	.000	85	.000
86	549300.000	87	354900.000	88	5339.712	89	3511.900	90	192.000
91	1.000	92	1.000	93	4950000.000	94	9900000.000	95	11897000.000
96	2379000.000	97	494000.000	98	96800.000	99	.000	100	.000
101	2800000.000	102	1130000.000	103	1.000	104	290000.000	105	1.200
106	.000	107	1.000	108	.000	109	.000	110	1.000
111	27000.000	112	90.000	113	150.000	114	.000	115	.000

Table 11.19 CLOSE CYCLE LIQUID METAL MHD SYSTEM ACCOUNT LISTING
PARAMETRIC POINT NO.14

ACCOUNT NO. & NAME,	UNIT	AMOUNT	MAT $/UNIT	INS $/UNIT	MAT COST,$	INS COST,$
SITE DEVELOPMENT						
1. 1 LAND COST	ACRE	132.0	1000.00	.00	132000.00	.00
1. 2 CLEARING LAND	ACRE	60.7	.00	600.00	.00	35396.36
1. 3 GRADING LAND	ACRE	132.0	.00	3000.00	.00	540000.00
1. 4 ACCESS RAILROAD	MILE	5.0	115000.00	110000.00	575000.00	550000.00
1. 5 LOOP RAILROAD TRACK	MILE	2.5	132000.00	70000.00	330000.00	175000.00
1. 6 SIDING R R TRACK	MILE	.0	125000.00	80000.00	.00	.00
1. 7 OTHER SITE COSTS	ACRE	.0	.00	.00	397331.29	397331.29
PERCENT TOTAL DIRECT COST IN ACCOUNT 1 = .674 ACCOUNT TOTAL,$					1444031.28	1654427.64
EXCAVATION & PILING						
2. 1 COMMON EXCAVATION	YD3	135900.0	.00	3.00	.00	407700.00
2. 2 PILING	FT	362400.0	6.50	8.50	2355600.00	3080400.00
PERCENT TOTAL DIRECT COST IN ACCOUNT 2 = 1.255 ACCOUNT TOTAL,$					2355600.00	3488100.00
PLANT ISLAND CONCRETE						
3. 1 PLANT IS. CONCRETE	YD3	18300.0	70.00	80.00	1281000.00	1464000.00
3. 2 SPECIAL STRUCTURES	YD3	27000.0	90.00	150.00	2430000.00	4050000.00
PERCENT TOTAL DIRECT COST IN ACCOUNT 3 = 1.981 ACCOUNT TOTAL,$					3711000.00	5514000.00
HEAT REJECTION SYSTEM						
4. 1 COOLING TOWERS	EACH	21.0	.00	.00	3223500.00	1606500.00
4. 2 CIRCULATING H2O SYS	EACH	1.0	.00	.00	1835214.25	2460790.34
4. 3 SURFACE CONDENSER	FT2	313717.3	.00	.00	2434874.12	433102.13
PERCENT TOTAL DIRECT COST IN ACCOUNT 4 = 2.576 ACCOUNT TOTAL,$					7493588.37	4500392.44
STRUCTURAL FEATURES						
5. 1 STAT. STRUCTURAL ST.	TON	2975.0	653.00	175.00	1959750.00	593125.00
5. 2 SILOS & BUNKERS	TPH	385.8	1800.00	750.00	694419.94	285341.64
5. 3 CHIMNEY	FT	450.0	.00	.00	435070.32	552506.38
5. 4 STRUCTURAL FEATURES	EACH	1.0	1434000.00	405000.00	1434000.00	405000.00
PERCENT TOTAL DIRECT COST IN ACCOUNT 5 = 1.349 ACCOUNT TOTAL,$					4432240.81	1835973.02
BUILDINGS						
6. 1 STATION BUILDINGS	FT2	734000.0	1.60	1.60	1174400.00	1174400.00
6. 2 ADMINISTRATION	FT2	10000.0	15.00	14.00	150000.00	140000.00
6. 3 WAREHOUSE & SHOP	FT2	20000.0	12.00	8.00	240000.00	160000.00
PERCENT TOTAL DIRECT COST IN ACCOUNT 6 = .555 ACCOUNT TOTAL,$					1564400.00	1474400.00
FUEL HANDLING & STORAGE						
7. 1 COAL HANDLING SYS	TPH	385.5	.00	.00	5420365.06	2333796.62
7. 2 DOLOMITE HAND. SYS	TPH	57.5	.00	.00	974584.89	535646.30
7. 3 FUEL OIL HAND. SYS	GAL	525000.0	.00	.00	79460.99	63272.91
PERCENT TOTAL DIRECT COST IN ACCOUNT 7 = 2.023 ACCOUNT TOTAL,$					6474410.87	2932715.81
FUEL PROCESSING						
8. 1 COAL DRYER & CRUSHER	TPH	385.5	.00	.00	1375366.59	919577.73
8. 2 CARBONIZERS	TPH	.0	.00	.00	.00	.00
8. 3 GASIFIERS	TPH	.0	.00	.00	.00	.00
PERCENT TOTAL DIRECT COST IN ACCOUNT 8 = .494 ACCOUNT TOTAL,$					1375366.59	919577.73

Table 11.19 (Continued) CLOSED CYCLE LIQUID METAL MHD SYSTEM ACCOUNT LISTING
PARAMETRIC POINT NO.19

ACCOUNT NO. & NAME,	UNIT	AMOUNT	MAT $/UNIT	INS $/UNIT	MAT COST,$	INS COST,$
FIRING SYSTEM						
9. 1		.0	.00	.00	.00	.00
PERCENT TOTAL DIRECT COST IN ACCOUNT 9 = .000 ACCOUNT TOTAL,$					.00	.00
VAPOR GENERATOR (FIRED)						
10. 1		.0	.00	.00	.00	.00
PERCENT TOTAL DIRECT COST IN ACCOUNT 10 = .000 ACCOUNT TOTAL,$					.00	.00
ENERGY CONVERTER						
11. 1 MHD DUCT STRUCT STEEL	KP	191.0	1430000.00	595000.00	1430000.00	595000.00
11. 2 DUCT INSULATION	KP	132.0	79000.00	20000.00	79000.00	20000.00
11. 3 MIXER	KP	43.0	530000.00	240000.00	530000.00	240000.00
11. 4 NOZZLE	KP	2.6	33000.00	13000.00	33000.00	13000.00
11. 5 SEPARATOR/DIFFUSER	KP	2.1	39000.00	15000.00	39000.00	15000.00
11. 6 LM PIPING/FITTING/INS	KP	190.7	4270000.00	1710000.00	4270000.00	1710000.00
11. 7 IRON POLES	KP	313.0	651000.00	260000.00	651000.00	260000.00
11. 8 AUX EQUIPMENT & SYSTEM		1.0	.00	.00	.00	.00
11. 9 MAGNET DEWAR	KP	3.5	28300.00	12000.00	28300.00	12000.00
11.10 SUPERCON MAG COOLANT	FT3	1.0	456000.00	182000.00	456000.00	182000.00
11.11 ASSEMBLY SUPPORT STRUCT		1.0	.00	.00	.00	.00
11.12 L M PUMPS	KP	813.0	3970000.00	4000000.00	3970000.00	4000000.00
11.13 L M INVENTORY (SODIUM)	KP	215.5	235000.00	39000.00	235000.00	39000.00
11.14 L M EMERGENCY DUMP	GAL	32373.0	2124000.00	210000.00	2124000.00	210000.00
11.15 L M PURIFICATION	GPM	6137.0	4990000.00	490000.00	4990000.00	490000.00
11.16 GAS COMPRESSOR	KP	264.2	2770000.00	280000.00	2770000.00	280000.00
11.17 MOTOR DRIVES	MW	527.0	18970000.00	1900000.00	18970000.00	1900000.00
11.18 GAS INVENTORY	KP	195000.0	28000.00	3000.00	28000.00	3000.00
11.19 GAS PIPING	KP	22.2	13600.00	6000.00	13600.00	6000.00
11.20 STEAM TURBINE-GEN	MW	30.0	670000.00	70000.00	670000.00	70000.00
11.21 DRIVE TURBINES	MW	715.0	3410000.00	340000.00	3410000.00	340000.00
PERCENT TOTAL DIRECT COST IN ACCOUNT 11 =20.336 ACCOUNT TOTAL,$					26517400.00	10370000.00
COUPLING HEAT EXCHANGER						
12. 1 COMB HEAT EXCHANGER	KP	5550.1	73440000.00	31790000.00	73440000.00	31790000.00
12. 2 OPEN CYCLE MHD TOPPING		1.0	.00	.00	.00	.00
12. 3 STEAM GENERATOR	KP	4374.2	20900000.00	8400000.00	20900000.00	8400000.00
12. 4 INSULATION		1.0	6000000.00	4000000.00	6000000.00	4000000.00
PERCENT TOTAL DIRECT COST IN ACCOUNT 12 =32.323 ACCOUNT TOTAL,$					100340000.00	44190000.00
HEAT RECOVERY HEAT EXCH.						
13. 1 AIR PREHEATERS	KP	1925.0	7840000.00	800000.00	7840000.00	800000.00
13. 2 GAS RECUPERATORS	KP	1.0	.00	.00	.00	.00
13. 3 COMP INTERCOLLER	KP	1.0	.00	.00	.00	.00
13. 4 INSULATION	KP	1.0	470000.00	310000.00	470000.00	310000.00
PERCENT TOTAL DIRECT COST IN ACCOUNT 13 = 2.073 ACCOUNT TOTAL,$					8310000.00	1110000.00
WATER TREATMENT						
14. 1 DEMINERALIZER	GPM	119.4	2500.00	700.00	298400.00	83552.00
14. 2 CONDENSATE POLISHING	KWE	746000.0	1.25	.30	932500.00	223800.00
PERCENT TOTAL DIRECT COST IN ACCOUNT 14 = .330 ACCOUNT TOTAL,$					1230899.99	307352.00

Table 11.19 (Continued) CLOSE CYCLE LIQUID METAL MHD SYSTEM ACCOUNT LISTING
PARAMETRIC POINT NO.14

ACCOUNT NO. & NAME,	UNIT	AMOUNT	MAT $/UNIT	INS $/UNIT	MAT COST,$	INS COST,$
POWER CONDITIONING						
15. 1 INVERTERS		4873.3	45000000.00	3000000.00	45000000.00	3000000.00
15. 2 TRANSFORMERS	KF	3297.4	10557000.00	2200000.00	10557000.00	2200000.00
15. 3 CIRCUIT BREAKERS		172.3	430000.00	20000.00	430000.00	20000.00
15. 4 COOLING SYSTEM		1.0	.00	.00	.00	.00
15. 5 CONDUCTORS		1.0	2800000.00	1100000.00	2800000.00	1100000.00
15. 6 STD TRANSFORMERS		36666.7	.00	.00	528868.11	10577.36
PERCENT TOTAL DIRECT COST IN ACCOUNT 15 =15.471 ACCOUNT TOTAL,$					53715363.00	12330577.25
AUXILIARY MECH EQUIPMENT						
16. 1 BOILER FEED PUMP &DR.	KWE	723512.5	1.67	.10	1208265.87	72351.25
16. 2 OTHER PUMPS	KWE	290955.8	.88	.12	256041.36	34914.81
16. 3 MISC SERVICE SYS	KWE	969855.9	1.17	.73	1134731.39	707994.80
16. 4 AUXILIARY BOILER	PPH	280000.0	4.00	.80	1120000.00	224000.00
PERCENT TOTAL DIRECT COST IN ACCOUNT 16 = 1.072 ACCOUNT TOTAL,$					3719039.22	1039260.84
PIPE & FITTINGS						
17. 1 CONVENTIONAL PIPING	TON	3800.0	3000.00	1800.00	11400000.00	6840000.00
PERCENT TOTAL DIRECT COST IN ACCOUNT 17 = 3.317 ACCOUNT TOTAL,$					11400000.00	6840000.00
AUXILIARY ELEC EQUIPMENT						
18. 1 MISC MOTORS,ETC		290955.8	1.40	.17	407339.49	49462.55
18. 2 SWITCHGEAR & MCC PAN	KWE	387942.4	1.95	.45	756487.59	174574.06
18. 3 CONDUIT,CABLES,TRAYS	FT	4345000.0	1.32	1.35	5734739.94	5870393.94
18. 4 ISOLATED PHASE BUS	FT	500.0	510.00	450.00	255000.00	225000.00
18. 5 LIGHTING & COMMUN	KWE	969855.9	.35	.43	339449.56	417338.04
PERCENT TOTAL DIRECT COST IN ACCOUNT 18 = 7.050 ACCOUNT TOTAL,$					7553076.56	6838474.62
CONTROL, INSTRUMENTATION						
19. 1 COMPUTER	EACH	1.0	660000.00	15000.00	660000.00	15000.00
19. 2 OTHER CONTROLS	EACH	1.0	1068000.00	641000.00	1068000.00	641000.00
PERCENT TOTAL DIRECT COST IN ACCOUNT 19 = .512 ACCOUNT TOTAL,$					1728000.00	656000.00
PROCESS WASTE SYSTEMS						
20. 1 BOTTOM ASH	TPH	25.6	3080995.34	772748.84	3080995.34	772748.84
20. 2 DRY ASH	TPH	7.4	535490.12	134122.53	535490.12	134122.53
20. 3 WET SLURRY	TPH	57.5	1610680.62	402671.66	1610680.62	402671.66
20. 4 ONSITE DISPOSAL	ACRE	307.5	6352.49	9473.47	1956337.72	2914479.34
20. 5 SEED TREATMENT	EACH	.0	.00	.00	.00	.00
PERCENT TOTAL DIRECT COST IN ACCOUNT 20 = 2.452 ACCOUNT TOTAL,$					7184503.75	4224022.81
STACK GAS CLEANING						
21. 1 PRECIPITATOR	EACH	.0	7161279.69	4667831.75	.00	.00
21. 2 SCRUBBER	KWE	1000000.0	22.10	10.13	22036270.75	10130781.12
21. 3 MISC STEEL & DUCTS		.0	.00	.00	.00	.00
PERCENT TOTAL DIRECT COST IN ACCOUNT 21 = 6.329 ACCOUNT TOTAL,$					22036270.75	10130781.12
TOTAL DIRECT COSTS,$					344539538.00	121006151.00

Table 11.20 CLOSE CYCLE LIQUID METAL MHD SYSTEM COST OF ELECTRICITY, MILLS/KW.HR
PARAMETRIC POINT NO.14

ACCOUNT	RATE, PERCENT	LABOR RATE, $/HR				
		6.00	8.50	10.60	15.00	21.50
TOTAL DIRECT COSTS,$	.0	413163732.	441702923.	465675835.	515904804.	590106698.
INDIRECT COST,$	51.0	34931963.	49406940.	61713136.	87329909.	125172869.
PROF & OWNER COSTS,$	8.0	33053099.	35336233.	37254055.	41272384.	47208535.
CONTINGENCY COST,$	11.0	45448010.	48587320.	51224341.	56749528.	64911735.
SUB TOTAL,$	.0	526596795.	575113415.	615857368.	701256624.	827399808.
ESCALATION COST,$	6.5	184380706.	201368140.	215637582.	245535468.	289702788.
INTREST DURING CONST,$	10.0	234976342.	256625923.	274811072.	312913292.	359200644.
TOTAL CAPITALIZATION,$	.0	945954432.	1033107490.	1106316016.	1259705376.	1486303232.
COST OF ELEC-CAPITAL	18.0	31.49303	34.40302	36.83769	41.94519	49.49036
COST OF ELEC-FUEL	.0	7.45757	7.45757	7.45757	7.45757	7.45757
COST OF ELEC-OP & MAIN	.0	.90212	.90212	.90212	.90212	.90212
TOTAL COST OF ELEC	.0	39.85772	42.75970	45.19737	50.30487	57.85004

ACCOUNT	RATE, PERCENT	CONTINGENCY, PERCENT				
		-5.00	.00	11.00	5.00	20.00
TOTAL DIRECT COSTS,$	.0	465675836.	465675836.	465675836.	465675836.	465675836.
INDIRECT COST,$	51.0	61713136.	61713136.	61713136.	61713136.	61713136.
PROF & OWNER COSTS,$	8.0	37254066.	37254066.	37254066.	37254066.	37254066.
CONTINGENCY COST,$	20.0	-23283791.	0.	51224341.	23283791.	93135166.
SUB TOTAL,$	.0	541359248.	564643032.	615867368.	567926816.	657778192.
ESCALATION COST,$	6.5	189549576.	197702079.	215637582.	205854579.	230312086.
INTREST DURING CONST,$	10.0	241564214.	251953856.	274811072.	252343498.	253512436.
TOTAL CAPITALIZATION,$	.0	972473032.	1014298953.	1106316016.	1056124993.	1181602704.
COST OF ELEC-CAPITAL	18.0	32.38103	33.77374	36.83769	35.16644	39.34455
COST OF ELEC-FUEL	.0	7.45757	7.45757	7.45757	7.45757	7.45757
COST OF ELEC-OP & MAIN	.0	.90212	.90212	.90212	.90212	.90212
TOTAL COST OF ELEC	.0	40.74072	42.13343	45.19737	43.52613	47.70424

ACCOUNT	RATE, PERCENT	ESCALATION RATE, PERCENT				
		5.00	6.50	8.00	10.00	.00
TOTAL DIRECT COSTS,$	.0	465675835.	465675835.	465675835.	465675835.	465675835.
INDIRECT COST,$	51.0	61713136.	61713136.	61713136.	61713136.	61713136.
PROF & OWNER COSTS,$	8.0	37254065.	37254065.	37254066.	37254066.	37254066.
CONTINGENCY COST,$	11.0	51224341.	51224341.	51224341.	51224341.	51224341.
SUB TOTAL,$	.0	615867363.	615867368.	615867368.	615867368.	615867368.
ESCALATION COST,$	.0	160618574.	215637582.	274118968.	357862072.	0.
INTREST DURING CONST,$	10.0	259594764.	274811072.	290809996.	313417594.	214115582.
TOTAL CAPITALIZATION,$	.0	1036080696.	1106316016.	1180796320.	1287087024.	829983048.
COST OF ELEC-CAPITAL	18.0	34.49902	36.83769	39.31770	42.85693	27.63646
COST OF ELEC-FUEL	.0	7.45757	7.45757	7.45757	7.45757	7.45757
COST OF ELEC-OP & MAIN	.0	.90212	.90212	.90212	.90212	.90212
TOTAL COST OF ELEC	.0	42.85871	45.19737	47.67739	51.21662	35.99614

ACCOUNT	RATE, PERCENT	INT DURING CONST, PERCENT				
		6.00	8.00	10.00	12.50	15.00
TOTAL DIRECT COSTS,$	.0	465675835.	465675836.	465675836.	465675836.	465675836.
INDIRECT COST,$	51.0	61713135.	61713135.	61713136.	61713135.	61713136.
PROF & OWNER COSTS,$	8.0	37254066.	37254066.	37254066.	37254066.	37254066.
CONTINGENCY COST,$	11.0	51224341.	51224341.	51224341.	51224341.	51224341.
SUB TOTAL,$	.0	615867368.	615867368.	615867368.	615867368.	615867368.
ESCALATION COST,$	6.5	215637582.	215637582.	215637582.	215637582.	215637582.
INTREST DURING CONST,$	15.0	156145054.	213926678.	274811072.	355513720.	441616184.
TOTAL CAPITALIZATION,$	.0	987650792.	1045431616.	1106316015.	1187018656.	1273121120.
COST OF ELEC-CAPITAL	10.0	32.88642	34.81038	36.83769	39.52489	42.39190
COST OF ELEC-FUEL	.0	7.45757	7.45757	7.45757	7.45757	7.45757
COST OF ELEC-OP & MAIN	.0	.90212	.90212	.90212	.90212	.90212
TOTAL COST OF ELEC	.0	41.24610	43.17007	45.19737	47.88458	50.75159

Table 11.20 (Continued) CLOSE CYCLE LIQUID METAL MHD SYSTEM COST OF ELECTRICITY, MILLS/KW.HR
PARAMETRIC POINT NO.14

ACCOUNT	RATE, PERCENT	FIXED CHARGE RATE, PCT 10.00	14.40	18.00	21.60	25.00
TOTAL DIRECT COSTS,$	.0	455675836.	455675836.	455675836.	455675836.	455675836.
INDIRECT COST,$	51.0	61713136.	61713136.	61713136.	61713136.	61713136.
PROF & OWNER COSTS,$	8.0	37254066.	37254066.	37254066.	37254066.	37254066.
CONTINGENCY COST,$	11.0	51224341.	51224341.	51224341.	51224341.	51224341.
SUB TOTAL,$	.0	615867368.	615867368.	615867368.	615867368.	615867368.
ESCALATION COST,$	6.5	215637582.	215637582.	215637582.	215637582.	215637582.
INTREST DURING CONST,$	10.0	274911072.	274911072.	274911072.	274911072.	274911072.
TOTAL CAPITALIZATION,$	.0	1106316016.	1106316016.	1106316016.	1106316016.	1106316016.
COST OF ELEC-CAPITAL	25.0	22.45533	29.47015	36.83769	44.20527	51.15346
COST OF ELEC-FUEL	.0	7.45757	7.45757	7.45757	7.45757	7.45757
COST OF ELEC-OP & MAIN	.0	.90212	.90212	.90212	.90212	.90212
TOTAL COST OF ELEC	.0	29.82507	37.82984	45.19737	52.56491	59.57314

ACCOUNT	RATE, PERCENT	FUEL COST, $/10**6 BTU .60	.95	1.55	2.50	1.37
TOTAL DIRECT COSTS,$	.0	455675836.	455675836.	455675836.	455675836.	455675836.
INDIRECT COST,$	51.0	61713136.	61713136.	61713136.	61713136.	61713136.
PROF & OWNER COSTS,$	8.0	37254066.	37254066.	37254066.	37254066.	37254066.
CONTINGENCY COST,$	11.0	51224341.	51224341.	51224341.	51224341.	51224341.
SUB TOTAL,$	.0	615867368.	615867368.	615867368.	615867368.	615867368.
ESCALATION COST,$	6.5	215637582.	215637582.	215637582.	215637582.	215637582.
INTREST DURING CONST,$	10.0	274911072.	274911072.	274911072.	274911072.	274911072.
TOTAL CAPITALIZATION,$	.0	1106316016.	1106316016.	1106316016.	1106316016.	1106316016.
COST OF ELEC-CAPITAL	15.0	36.83769	36.83769	36.83769	36.83769	36.83769
COST OF ELEC-FUEL	.0	4.39631	7.45757	13.16042	21.93403	9.34909
COST OF ELEC-OP & MAIN	.0	.90212	.90212	.90212	.90212	.90212
TOTAL COST OF ELEC	.0	42.12651	45.19737	50.90022	59.67384	45.68889

ACCOUNT	RATE, PERCENT	CAPACITY FACTOR, PERCENT 12.00	45.00	50.00	65.00	80.00
TOTAL DIRECT COSTS,$	.0	455675836.	455675836.	455675836.	455675836.	455675836.
INDIRECT COST,$	51.0	61713136.	61713136.	61713136.	61713136.	61713136.
PROF & OWNER COSTS,$	8.0	37254066.	37254066.	37254066.	37254066.	37254066.
CONTINGENCY COST,$	11.0	51224341.	51224341.	51224341.	51224341.	51224341.
SUB TOTAL,$	.0	615867368.	615867368.	615867368.	615867368.	615867368.
ESCALATION COST,$	6.5	215637582.	215637582.	215637582.	215637582.	215637582.
INTREST DURING CONST,$	10.0	274911072.	274911072.	274911072.	274911072.	274911072.
TOTAL CAPITALIZATION,$	.0	1106316016.	1106316016.	1106316016.	1106316016.	1106316016.
COST OF ELEC-CAPITAL	18.0	193.53747	53.20999	47.88839	36.83769	29.93062
COST OF ELEC-FUEL	.0	7.45757	7.45757	7.45757	7.45757	7.45757
COST OF ELEC-OP & MAIN	.0	.97213	.90212	.90212	.90212	.90211
TOTAL COST OF ELEC	.0	207.83717	61.56968	56.24866	45.19737	38.29031

Table 11.21 CLOSE CYCLE LIQUID METAL MHD SYSTEM

ACCOUNT NO	AUX POWER, MWE	PERC PLANT POW	OPERATION COST	MAINTENANCE COST
4	14.57355	1.52778	89.31364	20.53764
7	4.23377	.44545	307.53159	.00000
8	.50153	.05283	.00000	.00000
14	.00000	.00000	12.91023	.00000
19	5.19000	.54532	.00000	.00000
20	9.19720	.96375	.00000	.00000
21	17.00000	1.75953	.00000	.00000
TOTALS	50.61606	5.33146	556.44991	20.53764

CLOSE CYCLE LIQUID METAL MHD SYSTEM BASE CASE INPUT

NOMINAL POWER, MWE	1000.0000	NET POWER, MWE	949.3839
NOM HEAT RATE, BTU/KW-HR	8329.5231	NET HEAT RATE, BTU/KW-HR	8773.6133
OFF DESIGN HEAT RATE	.0000		
CONDENSER			
DESIGN PRESSURE, IN HG A	3.5000	NUMBER OF SHELLS	2.0000
NUMBER OF TUBES/SHELL	17000.7139	TUBE LENGTH, FT	59.5067
U, BTU/HR-FT2-F	609.8535	TERMINAL TEMP DIFF, F	5.0000
HEAT REJECTION			
DESIGN TEMP, F	77.0000	APPROACH, F	15.6713
RANGE, F	23.0000	OFF DESIGN TEMP, F	51.4000
OFF DESIGN PRES, IN HG A	.0000	LP TURBINE BLADE LEN, IN	28.5000

1	1000.000	2	.000	3	.410	4	.000	5	8.000
6	30.000	7	3.500	8	1603.000	9	2.000	10	2.000
11	1.000	12	716.000	13	1.000	14	.000	15	.000
16	2.000	17	182.000	18	3.000	19	5.000	20	2.500
21	.000	22	19300.000	23	27000.000	24	2975.000	25	400.000
26	7340000.000	27	10000.000	28	20000.000	29	525000.000	30	.300
31	1.000	32	3800.000	33	1.000	34	.300	35	.400
36	4390000.000	37	500.000	38	1.000	39	1.000	40	1434000.000
41	405000.000	42	550000.000	43	15000.000	44	1056000.000	45	641000.000
46	6.000	47	.000	48	7.000	49	2.000	50	2.000
51	1.000	52	5.350						

1	181.000	2	132.000	3	40.000	4	2.769	5	2.146
6	190.740	7	913.000	8	1.000	9	3.499	10	.990
11	1.000	12	918.000	13	215.500	14	32373.000	15	6167.000
16	264.220	17	527.000	18	185000.000	19	22.204	20	30.000
21	716.000	22	1490000.000	23	590000.000	24	73000.000	25	20000.000
26	500000.000	27	240000.000	28	33000.000	29	13000.000	30	39000.000
31	16000.000	32	4270000.000	33	1710000.000	34	601000.000	35	260000.000
36	.000	37	.000	38	29800.000	39	12000.000	40	456000.000
41	182000.000	42	.000	43	.000	44	3970000.000	45	4000000.000
46	295000.000	47	30000.000	48	2124000.000	49	210000.000	50	4880000.000
51	490000.000	52	2770000.000	53	280000.000	54	1397000.000	55	1900000.000
56	23000.000	57	3000.000	58	13600.000	59	5000.000	60	670000.000
61	70000.000	62	9410000.000	63	940000.000	64	6560.000	65	1.000
66	4074.200	67	1.000	68	7944000.000	69	3173000.000	70	.000
71	.000	72	20900000.000	73	8400000.000	74	6000000.000	75	4000000.000
76	1925.000	77	1.000	78	1.000	79	1.000	80	7840000.000
81	800000.000	82	.000	83	.000	84	.000	85	.000
86	470000.000	87	310000.000	88	4870.000	89	3293.400	90	172.000
91	1.000	92	1.000	93	4500000.000	94	9000000.000	95	10957000.000
96	2200000.000	97	430000.000	98	20000.000	99	.000	100	.000
101	2800000.000	102	1100000.000	103	1.000	104	280000.000	105	1.200
106	.000	107	1.200	108	.000	109	.000	110	1.000
111	27000.000	112	90.000	113	150.000	114	.000	115	.000

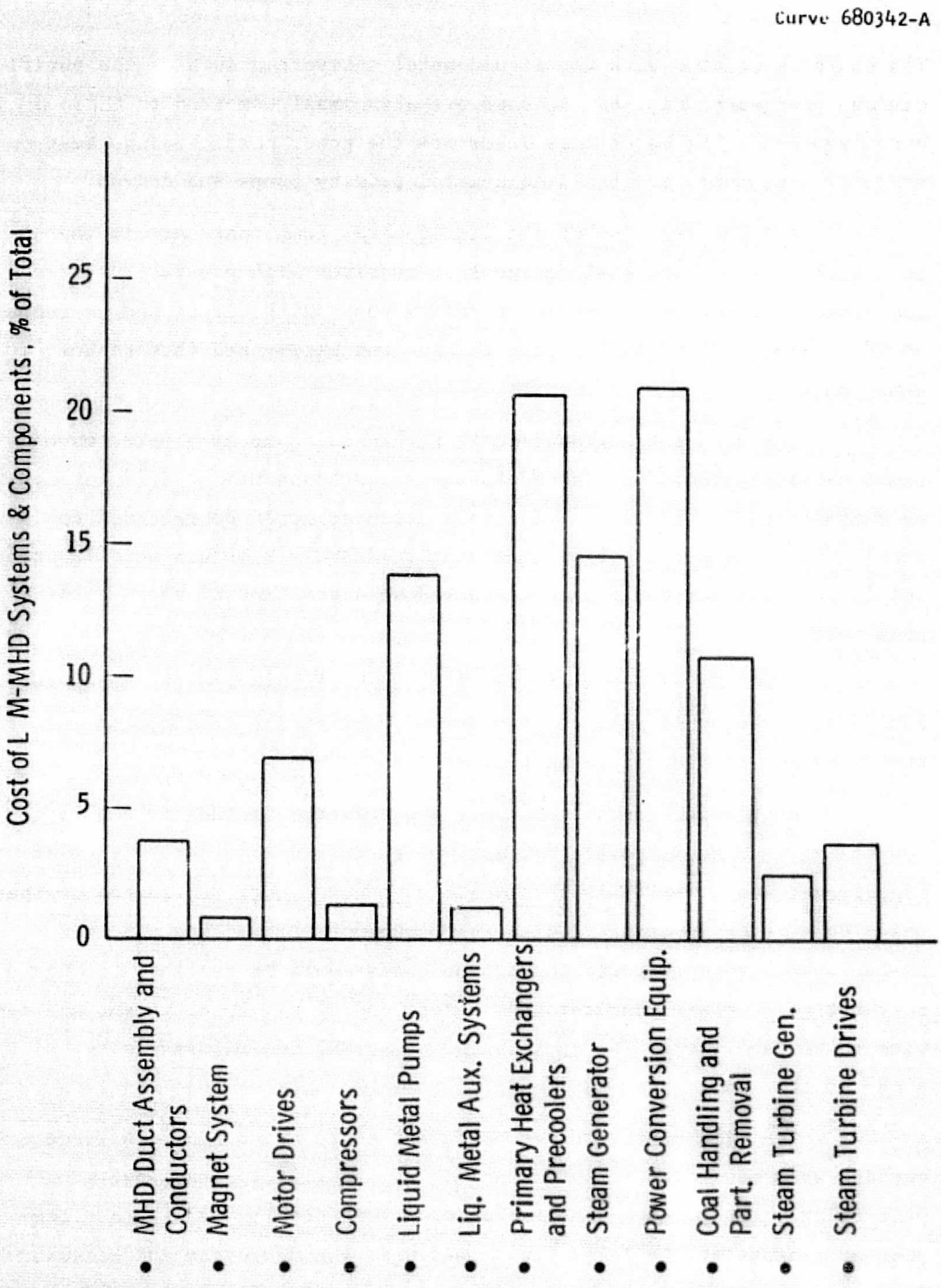

Fig. 11.11—Comparison of LM-MHD major component costs-base case

The costs associated with the liquid-metal subsystems such as the purification, emergency dump, and storage are also small compared to those of other systems. The major cost items are the power conditioning, heat transfer equipment, and the liquid-metal primary pumps and drives.

A large fraction of the liquid-metal pump costs are in the so-called free surface seal design that requires high-pressure tankage and cross-over piping. Developing sodium pumps with direct sodium seals would eliminate the need for this tankage and piping and thus reduce pump costs.

The need for a liquid-metal mechanical pump as a prime mover could be eliminated if a high-performance two-phase nozzle diffuser could be demonstrated. The two-phase nozzle diffuser would be required to operate for long periods efficiently at relatively high gas void fractions and large flows but could be constructed at a fraction of the mechanical pump costs.

Both the direct sodium seal mechanical pump and the two-phase nozzle diffuser would require significant engineering development and, therefore, are not considered as near term.

High power conversion costs are incurred because of the large low-voltage MHD gross power that must be generated in order to produce significant net power. All the low-voltage power must be treated by the power conversion equipment. With the homogenous flow, two-component LM-MHD system,reduced power conversion costs could be realized through more cost-effective power conversion equipment and if highly efficient MHD ducts were to be developed. The application of ac-MHD generators was beyond the scope of this work.

The high heat transfer equipment costs arise from the large surface area needed to transfer heat in gas-to-gas type exchangers, particularly the primary heat exchanger. This problem was further compounded because of the large flows needed in the MHD cycle and because argon gas is not a particularly effective heat transfer medium. Thus, a trade-off must be made between the thermodynamics of the cycle and heat transfer characteristics of the MHD working fluids. Development of improved high-temperature metals technology should also lead to reduced heat exchanger costs.

11.6 Analysis of Overall Cost of Electricity

11.6.1 Cost Accounts

Included in the costing of each parametric point were some 21 accounts plus summations and additions leading to the cost of electricity for various capacity factors, fixed charges, labor rates, interest during construction, escalation rate, and fuel costs. A breakdown of these accounts was provided as computer printout for each case. Tables 11.13, 11.16, and 11.19 show these printouts for the base case (Point 16), Points 8 and 14, respectively. Summary sheets for all costed points are shown in Tables 11.22, 11.23, and 11.24. The LM-MHD natural resource requirements for each costed study point are given in Table 11.25. These resource tables give a quantitative breakdown of the water and land usage and ultimate fuel requirements. The major environmental intrusions are associated with the coal ash handling and disposal and with the stack-gas desulfurization, as itemized in Accounts 20 and 21 of Tables 11.13, 11.16, and 11.19. Cleanup of these power plants is not expected to present formidable problems or costs that exceed current coal-fired steam plant technology.

11.6.2 Comparison of the Cost of Electricity for LM-MHD Steam Binary Power Plant

The cost of electricity for each costed parametric point are given in Table 11.22. A bar chart comparison is shown in Figure 11.12 of these costs for five representative binary plant study cases. Capital, fuel, operating and maintenance, and total costs are shown. For the cases shown, the costs vary from a low of about 9.44 mills/MJ (34 mills/kWh) to slightly over 12.78 mills/MJ (46 mills/kWh). The higher cost cases correspond to the 1088°K (1500°F) duct inlet temperature. The lowest cost was Point 12, a parametric variation of the base case that utilized the two-phase nozzle diffuser as the prime mover for the liquid metal. The

Table 11.22 CLOSE CYCLE LIQUID METAL MHD SYSTEM SUMMARY PLANT RESULTS

PARAMETRIC POINT	1	2	3	4	5	6	7	8
THERMODYNAMIC EFF	.000	.000	.000	.000	.000	.000	.000	.000
POWER PLANT EFF	.000	.000	.000	.294	.000	.371	.000	.358
OVERALL ENERGY EFF	.000	.000	.000	.294	.000	.371	.000	.358
CAP COST MILLION $	.000	.000	.000	1315.205	.000	1728.430	.000	1118.402
CAPITAL COST,$/KWE	.000	.000	.000	1372.159	.000	1917.202	.000	1177.095
COE CAPITAL	.000	.000	.000	44.010	.000	57.446	.000	37.210
COE FUEL	.000	.000	.000	9.833	.000	7.810	.000	8.098
COE OP & MAIN	.000	.000	.000	.901	.000	.901	.000	.921
COST OF ELECTRIC	.000	.000	.000	54.793	.000	55.157	.000	46.223
EST TIME OF CONST	.000	.000	.000	8.000	.000	8.000	.000	8.000

PARAMETRIC POINT	9	10	11	12	13	14	15	16
THERMODYNAMIC EFF	.000	.000	.000	.000	.000	.000	.000	.000
POWER PLANT EFF	.371	.000	.342	.360	.305	.389	.000	.337
OVERALL ENERGY EFF	.371	.000	.342	.350	.305	.389	.000	.337
CAP COST MILLION $	809.194	.000	854.464	731.121	2039.277	1106.316	.000	884.470
CAPITAL COST,$/KWE	851.719	.000	933.735	793.193	2133.735	1155.293	.000	942.834
COE CAPITAL	26.925	.000	28.473	24.980	67.644	36.838	.000	29.807
COE FUEL	7.829	.000	8.470	8.352	8.512	7.458	.000	8.609
COE OP & MAIN	.901	.000	.932	.915	.822	.902	.000	.937
COST OF ELECTRIC	35.555	.000	37.875	33.947	73.038	45.197	.000	33.354
EST TIME OF CONST	8.000	.000	8.000	9.000	6.000	8.000	.000	6.000

PARAMETRIC POINT	17	18	19	20	21	22	23	24
THERMODYNAMIC EFF	.000	.000	.000	.000	.000	.000	.000	.000
POWER PLANT EFF	.000	.347	.000	.000	.000	.000	.000	.000
OVERALL ENERGY EFF	.000	.347	.000	.000	.000	.000	.000	.000
CAP COST MILLION $	.000	1118.849	.000	.000	.000	.000	.000	.000
CAPITAL COST,$/KWE	.000	1151.243	.000	.000	.000	.000	.000	.000
COE CAPITAL	.000	36.393	.000	.000	.000	.000	.000	.000
COE FUEL	.000	9.351	.000	.000	.000	.000	.000	.000
COE OP & MAIN	.000	1.842	.000	.000	.000	.000	.000	.000
COST OF ELECTRIC	.000	45.595	.000	.000	.000	.000	.000	.000
EST TIME OF CONST	.000	8.000	.000	.000	.000	.000	.000	.000

Table 11.23 CLOSE CYCLE LIQUID METAL MHD SYSTEM SUMMARY PLANT RESULTS

	PARAMETRIC POINT	1	2	3	4	5	6	7	8
	TOTAL CAPITAL COST ,M$	.00	.00	.00	1318.21	.00	1728.43	.00	1118.40
P	LIQ MET DUCT ASSEMBLY ,M$	.000	.000	.000	1.656	.000	9.714	.000	8.383
L	SUPERCONDUCTING MAGNET ASSY,M$	.000	.000	.000	.643	.000	3.354	.000	1.399
A	LIQ MET SUBSYSTEMS ,M$	.000	.000	.000	20.366	.000	54.820	.000	54.389
N	LIQ MET PUMP MOTOR DRIVE ,M$	.000	.000	.000	18.100	.000	21.359	.000	23.392
T	COMPRESSOR TURBINE DRIVES ,M$	.000	.000	.000	.020	.000	10.433	.000	11.364
	STEAM TURBINE GENERATOR ,M$	.000	.000	.000	.000	.000	1.290	.000	.000
	COUPLING HEAT EXCHANGERS ,M$	.000	.000	.000	265.360	.000	289.592	.000	133.479
	POWER CONDITION EQUIPMENT ,M$	.000	.000	.000	33.018	.000	58.919	.000	55.210
R	TOT MAJOR COMPONENT COST ,M$	.000	.000	.000	347.171	.000	450.580	.000	297.615
E	TOT MAJOR COMPONENT COST,$/KWE	.000	.000	.000	365.549	.000	473.721	.000	313.231
S	BALANCE OF PLANT COST ,$/KWE	.000	.000	.000	93.355	.000	88.910	.000	91.675
U	SITE LABOR ,$/KWE	.000	.000	.000	133.377	.000	201.216	.000	102.015
L	TOTAL DIRECT COST ,$/KWE	.000	.000	.000	593.881	.000	763.853	.000	506.921
T	INDIRECT COSTS ,$/KWE	.000	.000	.000	58.277	.000	102.620	.000	52.028
	PROF & OWNER COSTS ,$/KWE	.000	.000	.000	47.511	.000	61.108	.000	40.554
B	CONTINGENCY COST ,$/KWE	.000	.000	.000	65.327	.000	84.024	.000	55.761
R	ESCALATION COST ,$/KWE	.000	.000	.000	271.354	.000	354.200	.000	229.432
E	INT DURING CONSTRUCTION ,$/KWE	.000	.000	.000	345.817	.000	451.337	.000	292.390
A	TOTAL CAPITALIZATION ,$/KWE	.000	.000	.000	1392.166	.000	1817.202	.000	1177.085
K	COST OF ELEC-CAPITAL,MILLS/KWE	.000	.000	.000	44.010	.000	57.446	.000	37.210
D	COST OF ELEC-FUEL ,MILLS/KWE	.000	.000	.000	9.893	.000	7.810	.000	8.098
O	COST OF ELEC-OP&MAIN,MILLS/KWE	.000	.000	.000	.901	.000	.901	.000	.921
W	TOTAL COST OF ELEC ,MILLS/KWE	.000	.000	.000	54.793	.000	66.157	.000	46.229
N	COE 0.5 CAP. FACTOR ,MILLS/KWE	.000	.000	.000	67.396	.000	83.391	.000	57.393
	COE 0.8 CAP. FACTOR ,MILLS/KWE	.000	.000	.000	46.542	.000	55.388	.000	39.253
	COE 1.2XCAP. COST ,MILLS/KWE	.000	.000	.000	63.595	.000	77.646	.000	53.671
	COE 1.2XFUEL COST ,MILLS/KWE	.000	.000	.000	56.770	.000	67.719	.000	47.849
	COE (CONTINGENCY=0) ,MILLS/KWE	.000	.000	.000	51.084	.000	61.396	.000	43.063
	COE (ESCALATION=0) ,MILLS/KWE	.000	.000	.000	43.801	.000	51.809	.000	36.935

	PARAMETRIC POINT	9	10	11	12	13	14	15	16
	TOTAL CAPITAL COST ,M$	333.19	.00	354.49	751.12	2339.29	1106.32	.00	394.47
P	LIQ MET DUCT ASSEMBLY ,M$	2.671	.000	7.012	3.155	30.092	6.511	.000	3.444
L	SUPERCONDUCTING MAGNET ASSY,M$	.354	.000	.928	.895	5.273	1.146	.000	1.049
A	LIQ MET SUBSYSTEMS ,M$	35.172	.000	29.211	5.980	117.650	46.959	.000	41.032
N	LIQ MET PUMP MOTOR DRIVE ,M$	14.059	.000	.000	3.132	52.135	18.970	.000	1.740
T	COMPRESSOR TURBINE DRIVES ,M$	7.582	.000	6.926	11.090	.000	9.410	.000	9.170
	STEAM TURBINE GENERATOR ,M$	5.229	.000	5.010	.000	.000	.670	.000	5.690
	COUPLING HEAT EXCHANGERS ,M$	55.551	.000	71.030	65.556	339.717	114.650	.000	73.838
	POWER CONDITION EQUIPMENT ,M$	47.245	.000	48.145	44.305	155.339	59.715	.000	49.992
R	TOT MAJOR COMPONENT COST ,M$	168.372	.000	167.314	134.716	693.016	258.072	.000	185.955
E	TOT MAJOR COMPONENT COST,$/KWE	177.213	.000	175.354	141.723	733.471	271.331	.000	196.022
S	BALANCE OF PLANT COST ,$/KWE	87.287	.000	91.765	90.795	78.402	91.215	.000	92.017
U	SITE LABOR ,$/KWE	93.749	.000	107.255	95.993	132.387	127.459	.000	107.134
L	TOTAL DIRECT COST ,$/KWE	358.254	.000	375.384	328.512	944.261	490.503	.000	395.172
T	INDIRECT COSTS ,$/KWE	47.312	.000	54.700	48.357	67.517	65.003	.000	54.638
	PROF & OWNER COSTS ,$/KWE	25.660	.000	30.031	26.281	75.541	39.240	.000	31.614
B	CONTINGENCY COST ,$/KWE	39.403	.000	41.292	35.135	103.869	53.955	.000	43.469
R	ESCALATION COST ,$/KWE	166.012	.000	175.561	154.020	417.078	227.134	.000	183.784
E	INT DURING CONSTRUCTION ,$/KWE	211.557	.000	223.737	136.295	531.529	289.463	.000	234.217
A	TOTAL CAPITALIZATION ,$/KWE	851.714	.000	900.705	790.190	2139.795	1165.299	.000	942.894
K	COST OF ELEC-CAPITAL,MILLS/KWE	25.925	.000	28.473	24.930	67.644	36.833	.000	29.307
D	COST OF ELEC-FUEL ,MILLS/KWE	7.820	.000	8.470	8.052	2.512	7.458	.000	8.609
O	COST OF ELEC-OP&MAIN,MILLS/KWE	.931	.000	.932	.315	.832	.932	.000	.937
W	TOTAL COST OF ELEC ,MILLS/KWE	[illegible]	.000	37.875	33.347	78.038	45.197	.000	39.354
N	COE 0.5 CAP. FACTOR ,MILLS/KWE	43.732	.000	45.417	41.441	99.331	56.249	.000	48.295
	COE 0.8 CAP. FACTOR ,MILLS/KWE	30.606	.000	32.536	29.263	65.355	38.290	.000	33.765
	COE 1.2XCAP. COST ,MILLS/KWE	41.040	.000	43.570	38.943	91.557	52.555	.000	45.315
	COE 1.2XFUEL COST ,MILLS/KWE	37.221	.000	39.569	35.557	79.940	46.689	.000	41.075
	COE (CONTINGENCY=0) ,MILLS/KWE	33.417	.000	35.530	31.895	72.139	42.133	.000	36.895
	COE (ESCALATION=0) ,MILLS/KWE	28.930	.000	30.763	27.700	61.142	35.996	.000	31.908

Table 11.23 (Continued) CLOSE CYCLE LIQUID METAL MHD SYSTEM SUMMARY PLANT RESULTS

PARAMETRIC POINT		17	18	19	20	21	22	23	24
TOTAL CAPITAL COST	,M$	.00	1119.35	.00	.00	.00	.00	.00	.00
P LIQ MET DUCT ASSEMBLY	,M$	.000	3.444	.000	.000	.000	.000	.000	.000
L SUPERCONDUCTING MAGNET ASSY	,M$	.000	1.049	.000	.000	.000	.000	.000	.000
A LIQ MET SUBSYSTEMS	,M$	.000	41.032	.000	.000	.000	.000	.000	.000
N LIQ MET PUMP MOTOR DRIVE	,M$	.000	1.790	.000	.000	.000	.000	.000	.000
T COMPRESSOR TURBINE DRIVES	,M$	.000	9.170	.000	.000	.000	.000	.000	.000
STEAM TURBINE GENERATOR	,M$	.000	5.599	.000	.000	.000	.000	.000	.000
COUPLING HEAT EXCHANGERS	,M$	.000	1 3.470	.000	.000	.000	.000	.000	.000
POWER CONDITION EQUIPMENT	,M$	.000	39.992	.000	.000	.000	.000	.000	.000
R TOT MAJOR COMPONENT COST	,M$	.000	275.555	.000	.000	.000	.000	.000	.000
E TOT MAJOR COMPONENT COST	,$/KWE	.000	293.415	.000	.000	.000	.000	.000	.000
S BALANCE OF PLANT COST	,$/KWE	.000	72.965	.000	.000	.000	.000	.000	.000
U SITE LABOR	,$/KWE	.000	143.222	.000	.000	.000	.000	.000	.000
L TOTAL DIRECT COST	,$/KWE	.000	474.600	.000	.000	.000	.000	.000	.000
T INDIRECT COSTS	,$/KWE	.000	75.133	.000	.000	.000	.000	.000	.000
PROF & OWNER COSTS	,$/KWE	.000	37.968	.000	.000	.000	.000	.000	.000
B CONTINGENCY COST	,$/KWE	.000	52.236	.000	.000	.000	.000	.000	.000
R ESCALATION COST	,$/KWE	.000	274.394	.000	.000	.000	.000	.000	.000
E INT DURING CONSTRUCTION	,$/KWE	.000	335.971	.000	.000	.000	.000	.000	.000
A TOTAL CAPITALIZATION	,$/KWE	.000	1151.243	.000	.000	.000	.000	.000	.000
K COST OF ELEC-CAPITAL	,MILLS/KWE	.000	35.393	.000	.000	.000	.000	.000	.000
D COST OF ELEC-FUEL	,MILLS/KWE	.000	3.361	.000	.000	.000	.000	.000	.000
O COST OF ELEC-OP&MAIN	,MILLS/KWE	.000	1.842	.000	.000	.000	.000	.000	.000
W TOTAL COST OF ELEC	,MILLS/KWE	.000	46.596	.000	.000	.000	.000	.000	.000
N COE 0.5 CAP. FACTOR	,MILLS/KWE	.000	57.514	.000	.000	.000	.000	.000	.000
COE 0.8 CAP. FACTOR	,MILLS/KWE	.000	39.772	.000	.000	.000	.000	.000	.000
COE 1.2XCAP. COST	,MILLS/KWE	.000	73.975	.000	.000	.000	.000	.000	.000
COE 1.2XFUEL COST	,MILLS/KWE	.000	40.268	.000	.000	.000	.000	.000	.000
COE (CONTINGENCY=0)	,MILLS/KWE	.000	43.631	.000	.000	.000	.000	.000	.000
COE (ESCALATION=0)	,MILLS/KWE	.000	37.506	.000	.000	.000	.000	.000	.000

Table 11.24 CLOSE CYCLE LIQUID METAL MHD SYSTEM NATURAL RESOURCE REQUIREMENTS

PARAMETRIC POINT	1	2	3	4	5	6	7	8
COAL, LB/KW-HR	.00000	.00000	.00000	1.07773	.00000	.35171	.00000	.38315
SORBANT OR SEED, LB/KW-HR	.00000	.00000	.00000	.16058	.00000	.12674	.00000	.13159
TOTAL WATER, GAL/KW-HR	.000	.000	.000	.065	.000	1.025	.000	1.098
COOLING WATER	.000	.000	.000	.000	.000	.966	.000	1.036
GASIFIER PROCESS H2O	.00000	.00000	.00000	.00000	.00000	.00000	.00000	.00000
CONDENSATE MAKE UP ,	.00000	.00000	.00000	.00000	.00000	.00860	.00000	.00879
WASTE HANDLING SLURRY	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000
SCRUBBER WASTE WATER	.00000	.00000	.00000	.06466	.00000	.05104	.00000	.05299
NOX SUPPRESSION	.00000	.00000	.00000	.00000	.00000	.00000	.00000	.00000
TOTAL LAND ACRES/1000MWE	.00	.00	.00	130.80	.00	85.54	.00	88.78
MAIN PLANT	.00	.00	.00	24.53	.00	19.13	.00	19.15
DISPOSAL LAND	.00	.00	.00	42.94	.00	33.91	.00	35.18
LAND FOR ACCESS RR	.00	.00	.00	63.37	.00	32.50	.00	34.44

PARAMETRIC POINT	9	10	11	12	13	14	15	16
COAL, LB/KW-HR	.85331	.00000	.92367	.87810	1.03731	.81328	.00000	.93689
SORBANT OR SEED, LB/KW-HR	.12556	.00000	.17597	.13039	.15456	.12109	.00000	.13918
TOTAL WATER, GAL/KW-HR	1.028	.000	1.036	1.062	.062	1.232	.000	1.022
COOLING WATER	.968	.000	.971	1.006	.000	1.175	.000	.957
GASIFIER PROCESS H2O	.00000	.00000	.00000	.00000	.00000	.00000	.00000	.00000
CONDENSATE MAKE UP ,	.00825	.00000	.00950	.00352	.00999	.00754	.00000	.00965
WASTE HANDLING SLURRY	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000
SCRUBBER WASTE WATER	.05295	.00000	.05512	.05259	.05224	.04976	.00000	.05605
NOX SUPPRESSION	.00000	.00000	.00000	.00000	.00000	.00000	.00000	.00000
TOTAL LAND ACRES/1000MWE	85.61	.00	89.45	89.55	60.42	91.78	.00	89.07
MAIN PLANT	19.16	.00	19.18	19.15	19.10	19.17	.00	19.19
DISPOSAL LAND	33.92	.00	37.69	39.38	41.33	32.39	.00	37.30
LAND FOR ACCESS RR	32.53	.00	32.58	24.43	.00	40.22	.00	32.58

PARAMETRIC POINT	17	18	19	20	21	22	23	24
COAL, LB/KW-HR	.00000	.31178	.00000	.00000	.00000	.00000	.00000	.00000
SORBANT OR SEED, LB/KW-HR	.00000	.48242	.00000	.00000	.00000	.00000	.00000	.00000
TOTAL WATER, GAL/KW-HR	.000	.943	.000	.000	.000	.000	.000	.000
COOLING WATER	.000	.934	.000	.000	.000	.000	.000	.000
GASIFIER PROCESS H2O	.00000	.00000	.00000	.00000	.00000	.00000	.00000	.00000
CONDENSATE MAKE UP ,	.00000	.00942	.00000	.00000	.00000	.00000	.00000	.00000
WASTE HANDLING SLURRY	.0000	.0036	.0000	.0000	.0000	.0000	.0000	.0000
SCRUBBER WASTE WATER	.00000	.00000	.00000	.00000	.00000	.00000	.00000	.00000
NOX SUPPRESSION	.00000	.00000	.00000	.00000	.00000	.00000	.00000	.00000
TOTAL LAND ACRES/1000MWE	.00	130.45	.00	.00	.00	.00	.00	.00
MAIN PLANT	.00	18.73	.00	.00	.00	.00	.00	.00
DISPOSAL LAND	.00	79.92	.00	.00	.00	.00	.00	.00
LAND FOR ACCESS RR	.00	31.80	.00	.00	.00	.00	.00	.00

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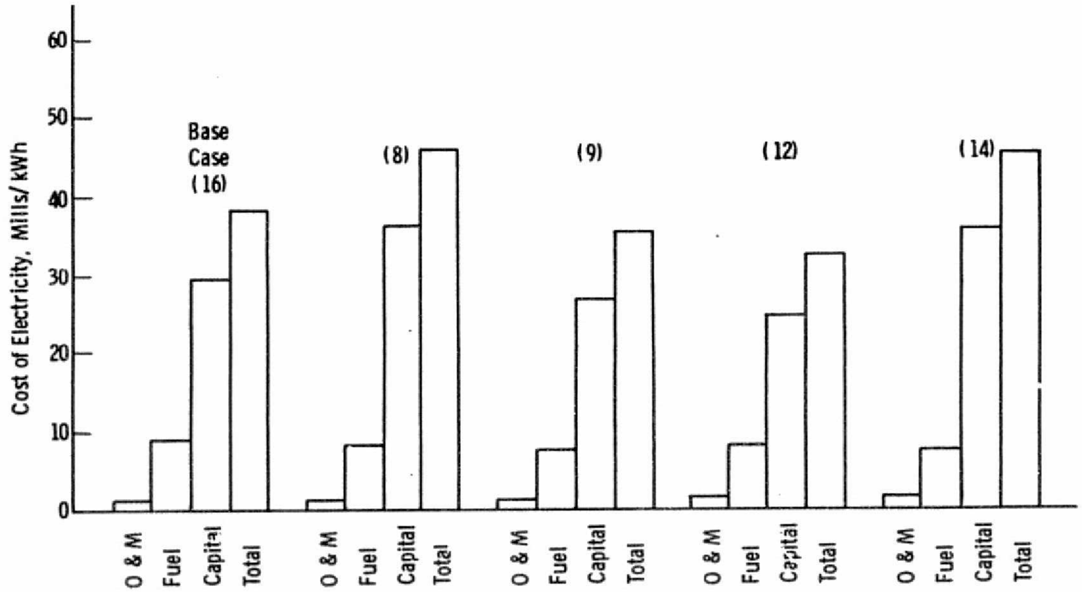

Fig. 11.12—Comparison of electrical costs of LM-MHD/steam binary plants

operating and maintenance costs are relatively small for all cases, compared to either the capital equipment costs or fuel costs. The fuel costs range from about 1/4 to 1/3 of the capital costs. For the comparisons shown, fuel costs were taken at \$0.805/GJ (\$0.85/10^6 Btu).

The effect of the fuel costs on the total costs of electricity is shown in Figure 11.13 for the five plants. A comparison of these fuel cost curves indicates a difference in the slope of the cost line for various parametric cases. This difference in the slopes is due to differences in power plant efficiency. The higher the power plant efficiency, the less dependent is the cost of electricity on fuel cost.

The effect of power plant efficiency on relative fuel costs is shown in Figure 11.14. In this figure the fuel costs relative to the base case are plotted with respect to power plant efficiency for the six LM-MHD steam binary plants. Each of these power plants represents a different aspect of LM-MHD technology that requires development. Developments in duct and component efficiencies as well as higher duct inlet temperatures are indicated, and both effects are seen to act to reduce fuel costs. The combined effect of the most optimistic component performance with the high duct inlet temperature would be about a 14% reduction in the base case fuel costs, i.e., from 2.39 to 2.87 mills/MJ (8.61 to 7.46 mills/kWh).

Fuel conservation is an important consideration in today's economy, but fuel costs are only one aspect that must be considered. The total cost of electricity is still the deciding criterion. As such, a comparison of total costs of electricity for the various LM-MHD power plants as a function of power plant efficiency is shown in Figure 11.15. The numbers in the circles in the figure correspond to the respective parametric points. Also indicated beside the points are the technology achievements assumed in developing each of the study points. Thus, in assessing this figure, it can be seen, for example, that increasing the duct inlet temperature over the base case (Point 16 compared to Point 8) results in increased plant efficiency but at significantly increased plant costs. Some of this cost increase is recoverable if higher duct efficiencies are assumed (i.e.,

Curve 681473-A

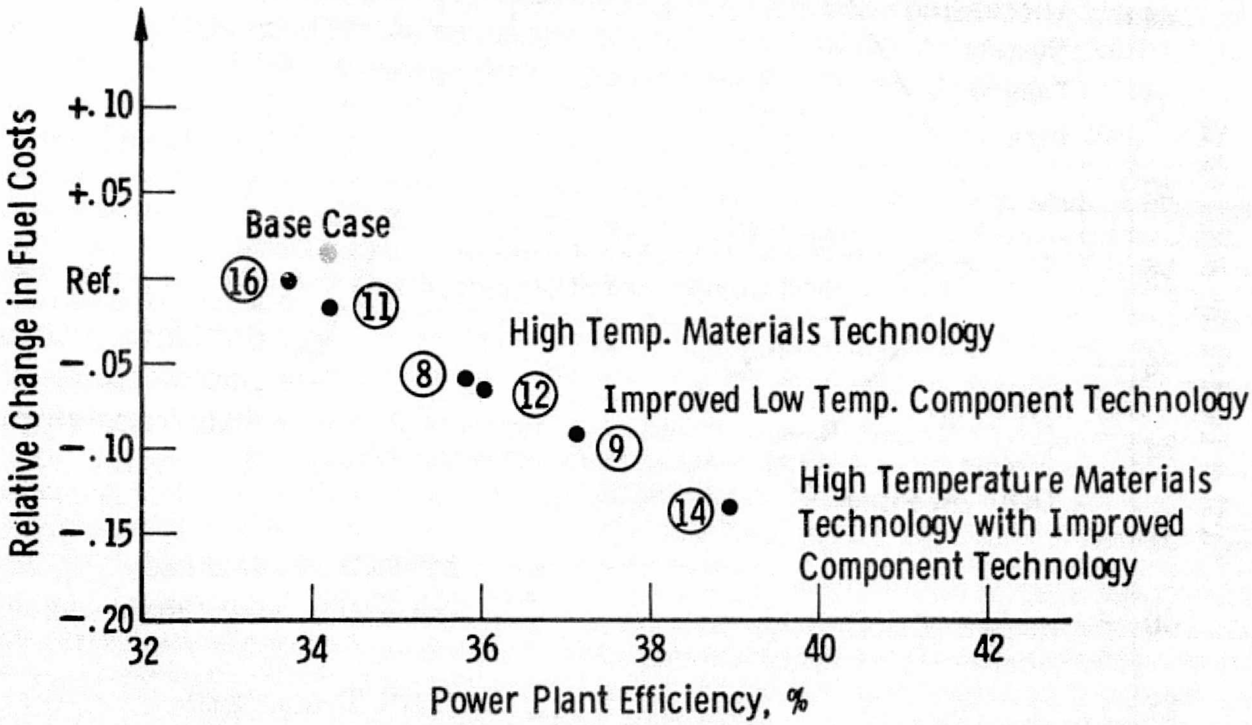

Fig. 11.14 — Comparison of fuel cost and power plant efficiency for different LM MHD/ steam binary plants

Curve 681472-A

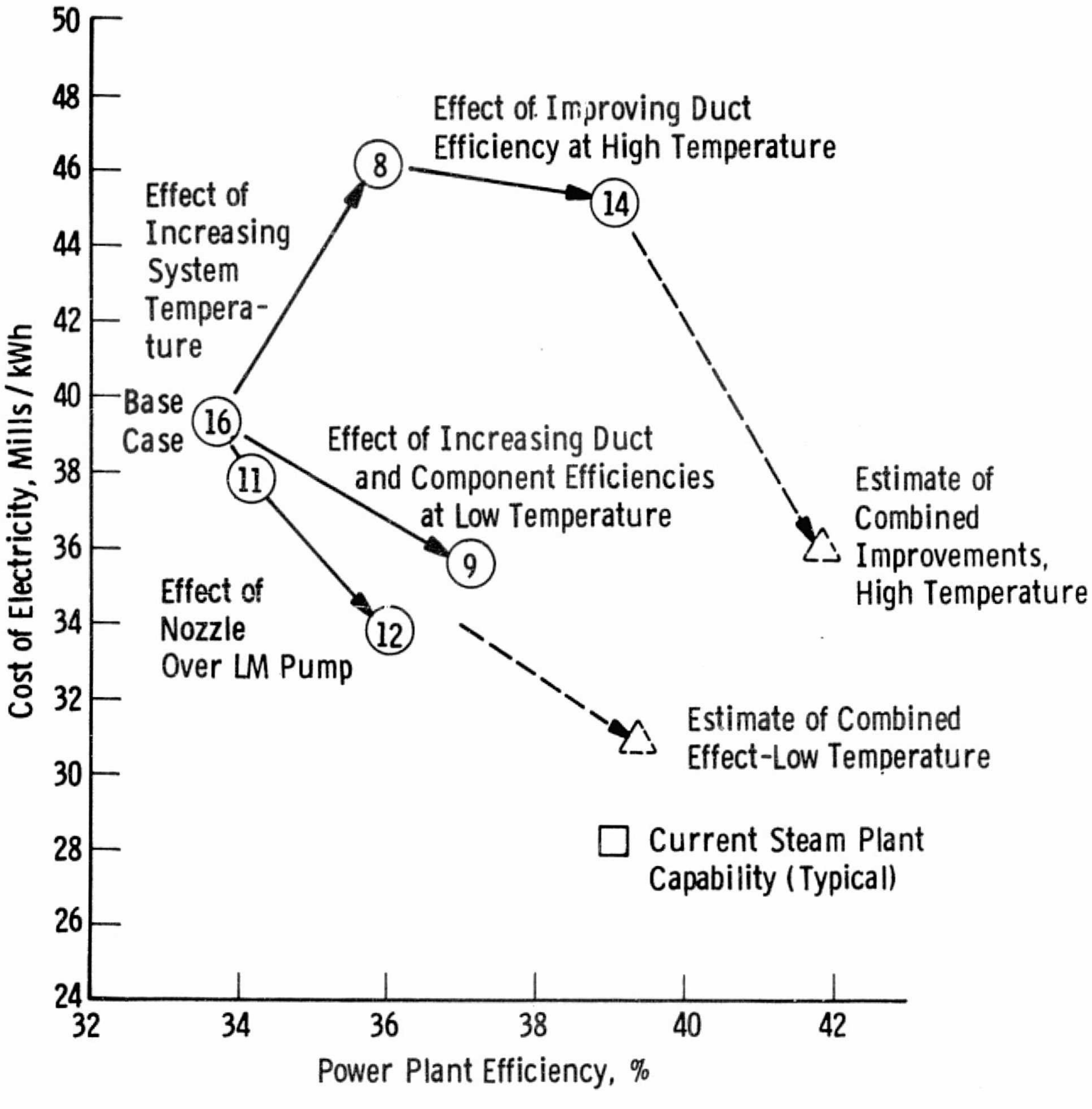

Fig. 11.15—The effect of technology advancement on LM-MHD/ steam binary power plant performance and cost

in going from Point 8 to Point 14). In a similar manner, if we assume only improved duct and component efficiency over the base case (no increase in temperature) the results are increased plant efficiencies and decreased costs. The most predominant effect here is to replace the costly liquid-metal mechanical pumps with a highly efficient two-phase nozzle diffuser.

The dotted lines in the figure show how the trends in this analysis might be extrapolated to account for the combined effects of both higher component and duct efficiencies and the utilization of a liquid-metal two-phase nozzle diffuser. These combined effects are shown for both the low and high duct inlet temperatures. Comparing these two cases then, would suggest that the high-temperature duct does not lead to the most cost effective power plant. The cost and performance for the high-temperature duct with combined improvements are 10.0 mills/MJ (36 mills/kWh) at about 42%, respectively. The low-temperature case is 8.61 mills/MJ (31 mills/kWh) at 39%. A typical value for current steam power plants is shown for comparison.

The major conclusion that could be inferred from this figure is that any near term LM-MHD development effort might best be spent improving and demonstrating the duct and component efficiencies for the low-temperature application. Development of a highly efficient, two-phase nozzle diffuser would impact significantly on the economic viability of the plant.

It should be noted that the comparison made in Figure 11.15 is based on a fuel cost of \$0.805/GJ (\$0.85/10^6 Btu). Should significantly higher fuel costs be incurred, the difference between the costs of the low- and high-temperature case diminishes. For example, at the upper range of coal costs considered in this study [\$2.37/GJ (\$2.50/10^6 Btu)], the cost of electricity for the two cases would become comparable, but the high-temperature case would hold an efficiency advantage. Care must be exercised. therefore, in evaluating plant costs when both temperature-dependent material costs as well as fuel costs are involved.

11.6.3 All MHD Power Plants

Two parametric cases were studied that represent all MHD power plants. Point 4 involved an open-cycle MHD topping the LM-MHD. The

Curve 680350-A

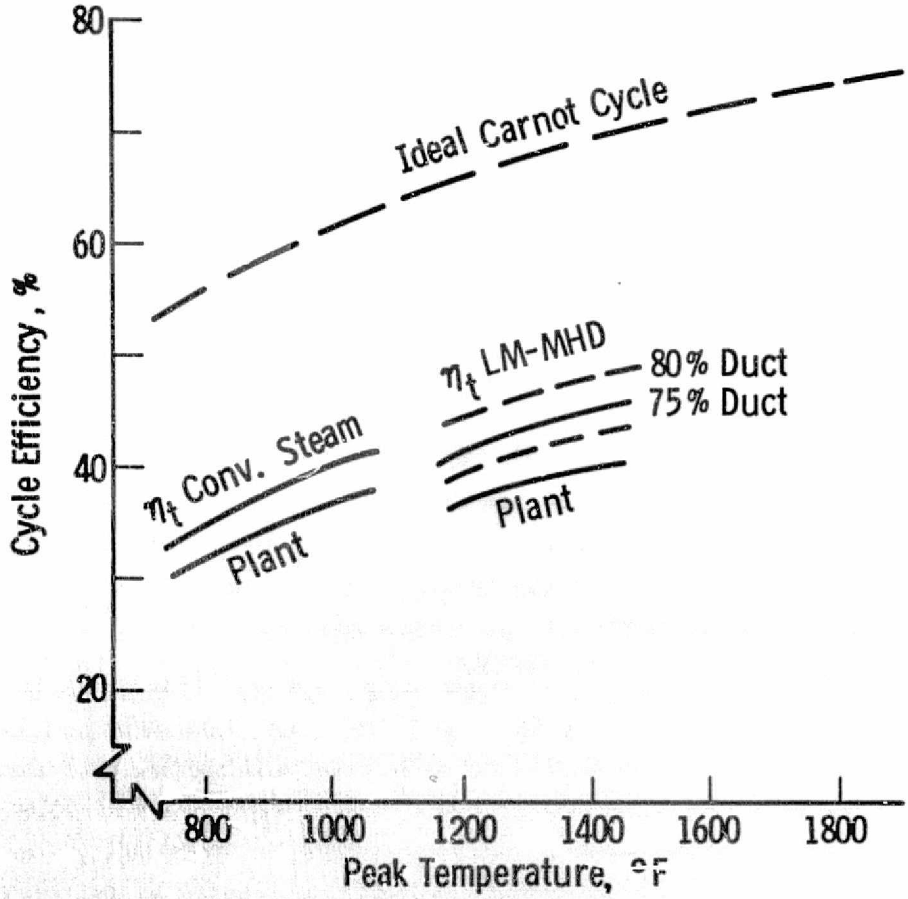

Fig. 11.16—Efficiency overview LM-MHD system

cost of electricity was about 15.28 mills/MJ (55 mills/kWh), with the major cost factor again being the capital equipment associated with the LM-MHD system.

The second all-MHD plant, Point 13, was an all LM-MHD system producing 1005 MWe net but requiring over 3800 MWe gross. The power costs associated with converting 3800 MWe from dc to ac and the high system flow rates resulted in prohibitive power generation costs. The cost of electricity was nearly 22.2 mills/MJ (80 mills/kWh).

11.7 Conclusions and Recommendations

Results of the study show that of the near term cases studied [near term being dictated by the lower temperature sodium technology - 922°K (1200°F)], none would appear to offer attractive plant performance. The potential of the direct coal-fired LM-MHD steam binary system exists with the further development of liquid-metal component technology and demonstration of high MHD duct efficiencies. Higher duct inlet temperatures, 1088°K (1500°F) lead to higher plant efficiency but not necessarily to lower electrical costs. At 1088°K (1500°F), power plant efficiencies of about 43% are attainable contingent on achieving MHD generator efficiencies of 80% and assuming marginal improvements in steam plant technology. Further studies are recommended to define and evaluate the duct variables and trade-off that lead to high duct efficiencies.

An overview of the potential performance of the LM-MHD binary systems is depicted in Figure 11.16. The operating regime of the LM-MHD system is compared to conventional steam plants and the ideal Carnot cycle as a function of peak conversion temperature. The purpose of the LM-MHD topping cycle is to extend the operating temperature range and efficiency of the power plant in a manner predicted by the ideal Carnot cycle. Real effects, however, can limit the attainment of this increased efficiency. As noted, no penalty on plant performance appears to exist for the LM-MHD binary plant with an 80% MHD duct efficiency. At 75% duct efficiency, however, an approximate 373°K (671°F) temperature penalty is incurred in order to obtain increased system performance over the conventional steam plant. In other words, a 978°K (1300°F) LM-MHD system appears to be the threshold for improved plant performance for this case.

Since the conventional steam plant operation is currently in the range of 811°K (1000°F), the conclusion inferred from Figure 11.16 is that there is a potential gain in plant performance by going to a LM-MHD steam binary system with peak temperatures above 922°K (1200°F) if the LM-MHD system components can be made to meet the assumed performance levels. The major cost factors that limit the economic potential of the LM-MHD/steam binary plant are the large costs for power conversion, heat transfer equipment, and liquid-metal pumping. The lowest range of electrical costs determined for the cases studied was about 9.44 mills/MJ (34 mills/kWh), which could be reduced to about 8.33 mills/MJ (30 mills/kWh) with improvements in LM-MHD components. In all cases studied, however, the costing was largely uncertain, since experience in design and fabrication of LM-MHD components is not available.

It is expected that through innovative design and with the demonstration of improved high-temperature metals technology, heat transfer equipment costs could be reduced. Reduced power conversion costs are associated with still higher duct efficiencies. Development of a high performance direct ac generator (i.e., slug-flow type) would eliminate the need for much of the expensive inverter equipment. The demonstration of a large-scale, high-performance, two-phase flow nozzle diffuser would both reduce costs and improve cycle performance. A cost advantage is achieved in both the liquid-metal pump hardware and in the power conversion equipment.

The results of this study are believed to be adequate for the needed system assessments on a relative basis, but specific conclusions on performance and cost should be revised with increased understanding of large-scale LM-MHD component design, performance, and costs. Because of the complexity in interfacing LM-MHD cycles with Rankine-type cycles, further studies are required to optimize plant performance with respect to various cost factors. Of particular importance are the trade-offs between the MHD duct operating temperatures with respect to material cost considerations and fuel cost.

The studies made on the two all-MHD systems must be considered preliminary and were not adequate to determine the potential for this power plant. Both plants showed low efficiency and high cost, in part due to the modest assumptions made with respect to the LM-MHD component and duct efficiencies. These studies, however, should provide a guide for identifying major cost considerations and determining cycle configurations that could lead to improved plant performance.

It is recommended that no full-scale commercial plant design study of the LM-MHD system be undertaken in Task II of the ECAS program. Other advanced conversion systems under study in Task I would appear to offer the potential for higher performance and lower costs with less uncertainty associated with the results. Efforts on LM-MHD should, however, be encouraged in order to develop sufficient data to predict reliably full-scale MHD generator efficiencies as well as associated component performance.

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Appendix A 11.1

LIQUID-METAL MHD TWO-PHASE FLOW AND PRESSURE LOSS CONSIDERATIONS

The two-phase flow components of the LM-MHD System are the mixer, the MHD duct, the nozzle, and the separator.

A 11.1.1 Mixer

The mixer provides a homogeneous (bubbly) flow into the MHD duct. Within the mixer, the two fluids (argon and sodium) are brought together and mixed to form the desired flow. The problems associated with the mixer are the evaluation of the pressure loss incurred and the design of a system for minimum pressure loss. Although a significant technology base exists for fluid mixer designs, the two-phase (gas-liquid metal) systems of the component size required for this study makes it a development item. Indeed, the need for homogeneous (bubbly) flow with low pressure loss has led to the need for a preliminary conceptual design.

Preliminary analysis shows that, based on the desired MHD duct inlet flow void fraction (65%), the two-phase flow would naturally tend toward a dispersed-type flow pattern (liquid droplets entrained in the gas). This observation is based on established correlations for adiabatic, horizontal, two-phase, two-component flow for air-water systems. Thus, initiating and maintaining a bubbly flow will be difficult. Factors to be considered in establishing bubbly flow include the mechanism of bubble generation, bubble size, and bubble influence on the dynamics of the mixture.

The usual method for introducing a gas into a liquid medium is through an orifice or porous plate. Depending on the gas velocity, the gas can be introduced as discrete bubbles that are formed at the orifice and subsequently break off or as a gas jet which eventually breaks into individual bubbles. When discrete bubbles are formed at the orifice, the equilibrium bubble size (break-off size) is determined by balancing buoyance, surface tension, inertia, and viscous forces.

The pressure drop across an orifice where bubbles are being formed is given approximately by

$$\Delta p = \frac{2\sigma}{R}$$

where R is the bubble radius at break-off and σ is the surface tension. For sodium/argon, where $\sigma \approx 0.191$ N/m (0.0131 lb/ft), the following table is constructed.

Table A 11.1.1

Bubble Radius vs. Orifice Pressure Drop

Bubble Radius, in	Δp psi	
0.0001	22	Range for porous plates
0.001	2.2	
0.01	0.22	
0.10	0.022	Range for orifices
0.25	0.0087	
0.50	0.0044	

Assuming that bubble size is on the same order of magnitude as the orifice radius, the above table indicates the range of pressure drops that could be expected under ideal conditions where dynamic and interference effects are neglected.

The criteria of a jet issuing from an orifice (as opposed to discrete bubble formation) are given by the dimensional Equation A 11.1.1 (Reference 11.9).

$$\frac{V_g \sqrt{\rho_g}}{[g_c g\ \sigma(\rho_f - \rho_g)]^{1/4}} = 1.25\ [\frac{\sigma}{(\rho_f - \rho_g)\ R_o^2}] \qquad \text{(A 11.1.1)}$$

where V_g is the gas jet velocity, ρ_f and g_c are the liquid and gaseous component densities, R_o is the orifice diameter, and g is the gravitational constant, or, for the sodium-argon system, for example,

$$0.317\ V_g \geq \frac{0.035 \times 10^{-2}}{R_o}$$

Where R_o is in ft and V_g is in ft/s.

Assuming V_g = 100 ft/s.

$$0.325\ V_g \geq \frac{0.0208}{R_o}$$

$$R_o \geq 0.0077 \text{ in}$$

Thus, for an orifice radius of 0.195 mm (0.0077 in) or larger the argon gas will enter as a jet stream; below this orifice, discrete bubbles will form.

The pressure loss in the mixer can be determined from a momentum balance across the system. The gas-side pressure requirement is obtained by considering the details of the method of injection. If the bubbles are injected so that discrete bubbles form at the wall of the mixer, the gas-side pressure drop is given as

$$\Delta p = \frac{2\sigma}{R_o}$$

where R_o is the radius of the orifice. Pressure losses for various orifice sizes are given in Table A 11.1.1. If, on the other hand, the

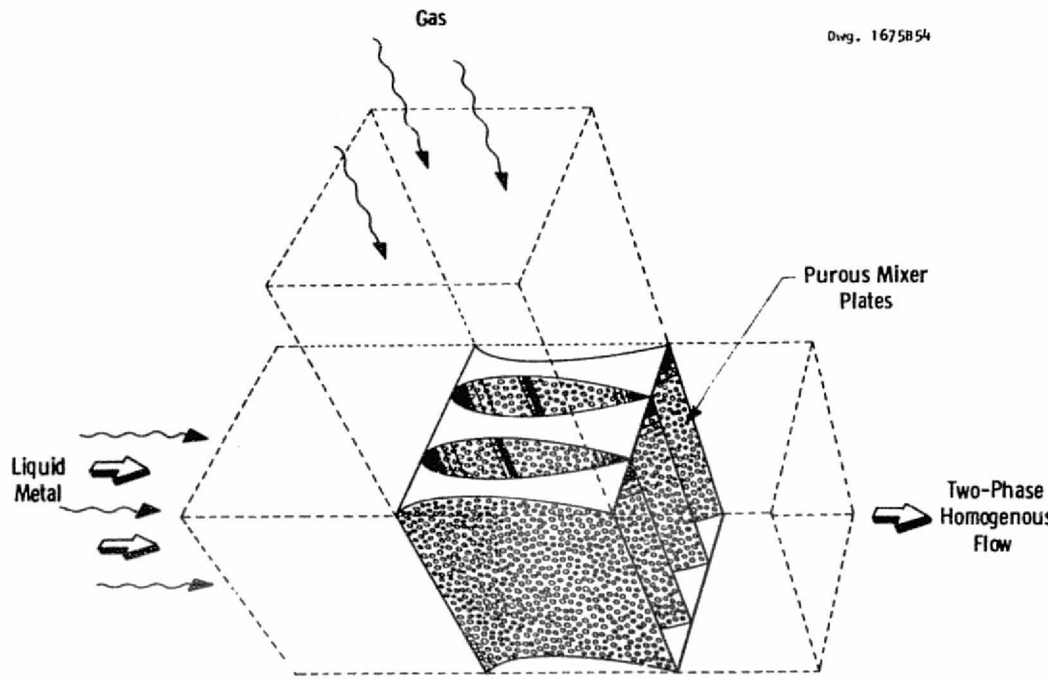

Fig. A 11. 1. 1—Low pressure loss-L. M. MHD liquid-gas mixer, conceptual design

design is such that the gas enter the liquid as a jet stream (subsequently breaking into bubbles), the pressure loss is given by the usual orifice equation:

$$(P_g - P_{mix}) = \frac{1}{2}\frac{\rho_g V_g^2}{g_c} + K\frac{\rho_g V_g^2}{2\,g_c} \qquad \text{(A 11.1.2)}$$

For worst case conditions, K can be taken as 1. Taking V_g at 30.48 m/s (100 ft/s), the pressure loss across the orifice is 40.06 kPa (5.81 psi) ($\Delta p/p = 0.0048$). The preferred method of mixing the gas and liquid would be by formation of a gas jet stream that sufficiently penetrates the liquid stream. With the cases where discrete bubbles form at the wall, there would be a high likelihood of bubbles agglomerating within the liquid-wall boundary layer which could lead to an undesirable slug flow development.

The design of the mixer can be based on two cases:

- Accelerating the liquid metal prior to its entry into the mixer to the required duct velocity and designing the mixer to maintain a constant mixture velocity
- Designing the mixer for constant area so that the gas-liquid mixture is accelerated to the desired duct velocity at the exit of the mixer.

An advantage may exist with the first approach, since this design may enhance the stability of the bubbly flow. Figure A 11.1.2 shows a conceptual design of one-mixer system where gas is injected into the liquid through air-foil shaped plates. This design leads to low friction losses in the mixer (approximately 2 psi assumes an effective $\frac{L}{D}$ of 20); and, accordingly, this friction loss was neglected compared to the losses associated with other major components.

A 11.1.2 MHD Duct

Two-phase, two-component LM-MHD generators have been tested at low temperatures in small-scale models by several groups using NaK and nitrogen. Duct efficiencies of about 50% have been reported (References 11.1, 11.2, and 11.3) with recent developments in identifying and controlling boundary layer, shunt losses, and end-loss attenuation two-phase theory and experimental data have been brought into closer agreement. When applied to large-scale systems, these models predict MHD duct conversion efficiencies of around 75%.

Additional experiments in the USSR and West Germany (References 11.10 and 11.11) have shown good performance without degradation at higher temperature [∿ 800°K (980°F)]. The principal performance parameters appear to indicate as good or better performance on large-scale systems and would lead one to propose maximizing duct size and plant power levels. These performance parameters do not, however, reflect the real-life limitations imposed by structural and physical system requirements. These include structural designs capable of operation at temperature and high pressures [10.13 MPa (100 atm)] and the transmission by conductors of large amperage currents at low voltages from the ducts to inverter systems. Such limitations as these result in size and arrangement constraints on the MHD ducts.

The nature of the two-phase flow within the MHD duct has been described as churn turbulent-bubble flow. Because of the complex nature of this flow, in part due to the uncertain effects of the interaction between slip and electrodynamic forces, an analysis of this flow field cannot be made in closed form. Empirical expressions have been developed, however, that attempt to account for the major flow phenomena. As indicated above, collaboration of these models on small systems have been successful to the extent that experimental MHD duct performances can be predicted over limited operation conditions. The stability of the bubble regime within the MHD duct in a large system remains uncertain. The electrodynamic force retarding the motion of the liquid, coupled with a gas transpiration (gas injection to circumvent electrical shunting) along the duct walls may act to retard formation of the stable, dispersed annular flow regime. Details of the calculational model used to predict MHD duct performance in this study are described in detail in Appendix A 11-2.

A 11.1.3 Nozzle

After passing through the MHD duct, the flows are separated into two fluid streams (sodium/argon), and the liquid pumped back to the inlet pressure conditions. The technical complexity and practicability of these requirements are severe. The large volume of liquid metal that must be pumped [63.09 m^3/s (10^6 gpm)] far exceed current state of the art in liquid-metal pump sizes. Projected mechanical pump sizes for commerical fast-breeder reactor plants are on the order of 3.785 m^3/s (60,000 gpm).

An alternative to using a liquid-metal mechanical pump would be to impart sufficient dynamic head to the flowing liquid metal (from the gases) through the two-phase nozzle that is connected to the exit of the MHD duct. The objective then would be to recover this dynamic heat (after the two fluids are separated) in a liquid diffuser. The hydrodynamics of such an approach are complex. The requirements on the acceleration of the liquid phase by the gas in the nozzle section would be highly dependent on flow regime. The flow tends toward annular or dispersed annular regime. In annular flow, the liquid metal flows along the containing walls, and viscous effects and phase slip would severely limit liquid flow velocity. With dispersed flow, the liquid exists as droplets entrained in the gas phase. Although the phases are close coupled so that the required dynamic head could be imparted in the nozzle, the losses that would be incurred in separating the phases would be greatly increased. The problem is further complicated, since the required velocities in the nozzle are such that sonic flow conditions in the two-phase system could result. The required liquid velocity corresponding to an 8.274 MPa (1200 psi) dynamic head is 143.2 m/s (470 ft/s). Sonic flow conditions correspond to about 152 m/s (500 ft/s).

The affect on the flow of achieving sonic and near sonic flow conditions is to increase system pressure losses, increase erosion of materials (because of high velocity), and enhance structural problems resulting from vibrations and "water hammer" effects.

A second alternative to conventional liquid-metal pumps is an electromagnetic (EM) pump. The concept would employ a return duct within the same magnetic field developed for the MHD duct. The power required to drive the EM pump could be shunted from one or more of the adjacent MHD power ducts. The practicability of building such a pump and its resulting performance are uncertain. State of the art on such systems is for comparatively small scale, 0.00012 to 0.315 m^3/s (2 to 5,000 gpm). Developmental costs for large EM pump systems, however, would not be expected to be as exhorbitant as the LM pumps, since the required magnet and ducting are scalable. A preliminary design and cost of one 15.77 m^3/s (250,000 gpm) EM pump is described in Appendix A 11.5.

A 11.1.4 Separator

The gas/liquid separator system must effectively separate the two fluids with minimum pressure loss. Should the separation be ineffective, carry-over of liquid metal with the gas will occur. This may be in the form of an oxidized aerosol that could carry for some distance in the piping system. Such aerosols may present problems with rotary seals and blade erosion in the gas compressor system. Experimental data on small-scale impingement-type, liquid metal-gas separator systems indicate 95 to 99% effectiveness.

Large pressure losses in the separator degrade system performance. This is particularly true where high velocity heads are imparted to the liquid metal by the gas and subsequently recovered in a liquid-metal diffuser. Again, with small-scale systems, 10% pressure losses are common.

The plate-separator system considered here is to impart sufficient momentum to the liquid metal so that it will not follow the gas through the turning angle or bend. The liquid impinges on the plate surface and forms a fully liquid system entering the diffuser slots. Plate angle and flow surface length are design parameters, as are also slot sizes for entry to the diffuser section. Figure A 11.1.2 shows a conceptual design of a gas-liquid metal separator and diffuser that utilizes the above described method.

Flow regime (bubble, annular, or dispersed) will greatly affect the effectiveness of this separation method. Other separation schemes include decelerating the flow to allow gravity separation or direct impingement of the liquid-metal droplets in a radial-type turbine. The major disadvantage with these systems is that the dynamic pressure head will be lost and erosion could be severe.

A 11.1.5 Evaluation for System Pressure Losses

Because of the sensitivity of Brayton-type cycles to pressure losses on cycle performance, care was taken to assure a fair (and probably optimistic) evaluation of this factor. To evaluate these losses, simplifying assumptions were made (namely, one-dimensional homogeneous flow) because of the complexity of treating two-phase flows and the uncertainty about which two-phase region would actually be encountered. In some cases—for example, the MHD duct—friction losses were neglected. Most of the system losses were incurred in the heat exchanger components (single-phase flow). With these components pressure losses were generally assumed (based on experience), and heat exchanger designs were developed that would satisfy the constraints.

Table A 11.1.2 summarizes the basis for evaluation and pressure loss values that were used in evaluating the LM-MHD cycle.

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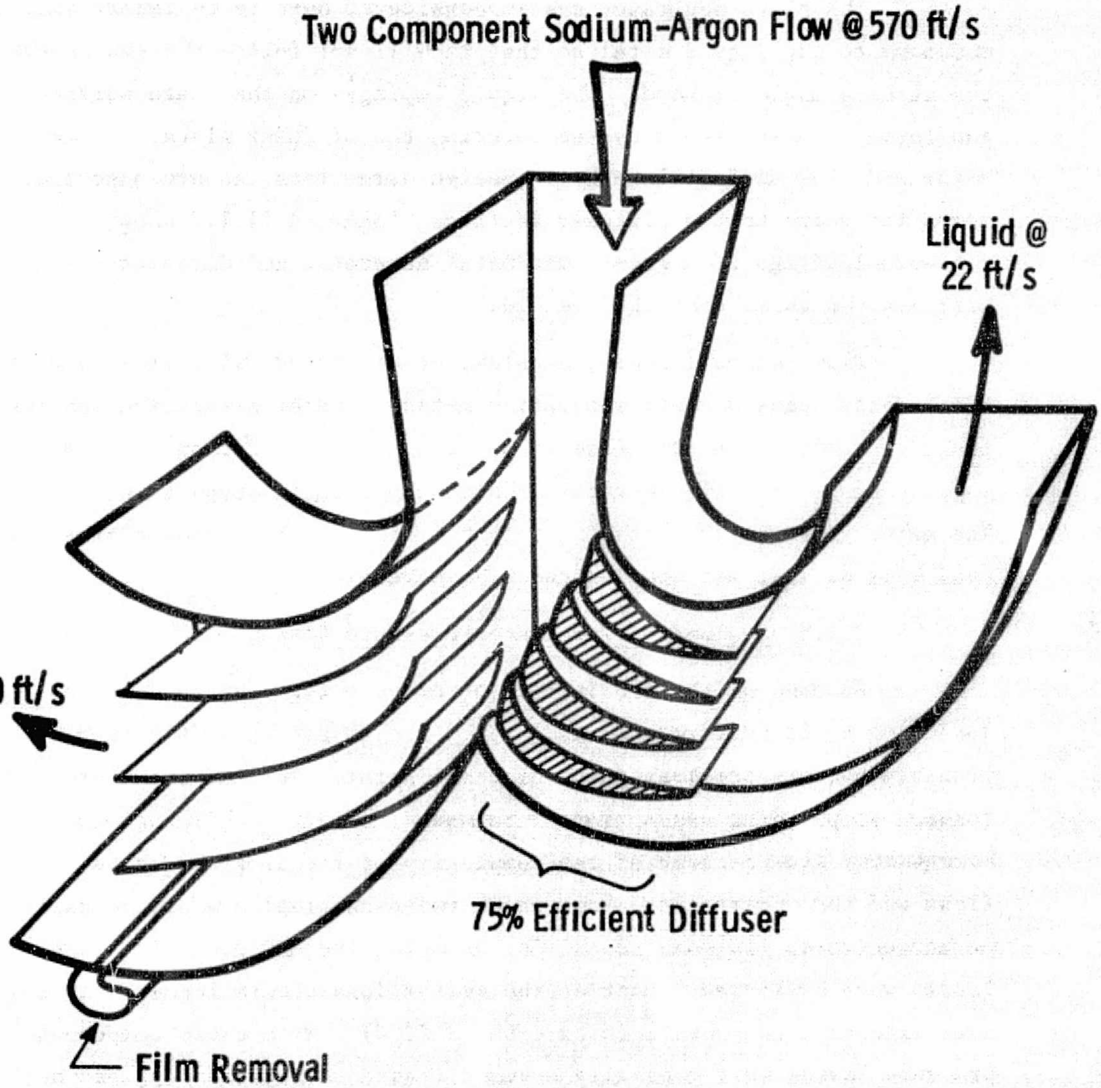

Separator/Diffuser Concept (Side Removed)

Fig. A 11.1.2—Conceptual design of nozzle

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Table A 11.1.2

Summary of the LM-MHD Component Pressure Losses

Component	Basis for Evaluation	Loss, psi	Pressure Loss as Fraction of Duct Inlet Pressure
Mixer			
Gas	Orifice pressure loss	5.5	0.0046
Mixture	Homogenous 2 Ø flow friction loss	4.5	0.0075
MHD Duct	Friction losses neglected	-	
Nozzle - Mixture	95% efficiency	19.4	0.016
Separator			
Gas & Diffuser	Friction loss	6	0.005
Liquid	Loss of the velocity component corresponding to deflection angle	15	0.012
Steam Generator	Designed	20	0.017
Primary Heat Exchanger			
Gas	Single-phase friction loss	50	0.042
Liquid	Single-phase friction loss	65	0.054
Recuperators/ Intercoolers and Air Preheaters	2% of component inlet pressure	As required	0.02

Appendix A 11.2

DESCRIPTION OF THE LM MHD DUCT AND CYCLE COMPUTER MODEL

A computer program was written for rapid evaluation of LM-MHD cycles. This report describes the basic assumptions and analytical methods incorporated.

In the cycle discussed here a gaseous phase is dispersed in a liquid metal at high pressure and temperature. This mixture expands through an MHD duct in which the liquid metal provides the electrical conduction path. The two components are separated downstream of the duct, and the reject heat is removed from the gas stream. The two phases are separately pumped back to duct inlet pressure and heat added to one or both streams prior to remixing.

A 11.2.1 Continuity Relations

Three different measures of gas fraction in the mixture are used which we define as follows:

w_g = fraction of total mass flow rate as gas

w_ℓ = fraction of total mass flow rate as liquid

ϕ_g = fraction of total volume flow as gas

ϕ_ℓ = fraction of total volume flow as liquid

β_g = fraction of cross-sectional area occupied by gas

β_ℓ = fraction of cross-sectional occupied by liquid.

In addition, we let

U_g = gas velocity

U_ℓ = liquid velocity

v_g = gas specific volume

v_ℓ = liquid specific volume.

Continuity demands the following identities:

$$w_g = \frac{\frac{\phi_g}{v_g}}{\frac{\phi_g}{v_g} + \frac{\phi_\ell}{v_\ell}} \qquad \text{(A 11.2.1)}$$

$$\phi_g = \frac{w_g v_g}{w_g v_g + w_\ell v_\ell} \qquad \text{(A 11.2.2)}$$

$$\phi_g = \frac{\beta_g U_g}{\beta_g U_g + \beta_\ell U_\ell} \qquad \text{(A 11.2.3)}$$

$$\beta_g = \frac{\frac{\phi_g}{U_g}}{\frac{\phi_g}{U_g} + \frac{\phi_\ell}{U_\ell}} \qquad \text{(A 11.2.4)}$$

A 11.2.2 Thermodynamic Relations

The ideal adiabatic expansion (or compression) of a gas and liquid mixture in thermal equilibrium obeys the same laws as does a pure gas phase, with slight modification. Assuming, in addition, that the gas is a perfect gas, and that the liquid has constant properties and negligible vapor pressure, then the following relations hold:

$$Pv_g = RT \tag{A 11.2.5}$$

$$w_g P dV_g + w_g C_{vg} dT + w_\ell C_\ell dT = 0 \tag{A 11.2.6}$$

$$C_{pg} = C_{vg} + R \tag{A 11.2.7}$$

If we define

$$\gamma = \frac{C_{vg} w_g + R w_g + C_\ell w_\ell}{C_{vg} w_g + C_\ell w_\ell} \tag{A 11.2.8}$$

as the ratio of weighted mean specific heats of the mixture, then the integral expression becomes:

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} \tag{A 11.2.9}$$

$$\frac{v_{g2}}{v_{g1}} = \left(\frac{P_2}{P_1}\right)^{-\frac{1}{\gamma}} \tag{A 11.2.10}$$

These expressions must be modified to account for entropy changes that will occur in a real situation. Thus, as in gas turbine practice, we may define isentropic or polytropic expansion efficiencies such that:

$$T_1 - T_2 = T_1 \eta_i \left[1 - \left(\frac{P_2}{P_1} \right)^{\frac{\gamma-1}{\gamma}} \right] \qquad \text{(A 11.2.11)}$$

$$T_1 - T_2 = T_1 \left[1 - \left(\frac{P_2}{P_1} \right)^{\frac{(\gamma-1)\eta_p}{\gamma}} \right] \qquad \text{(A 11.2.12)}$$

The small stage efficiency in the MHD duct, however, will normally vary significantly during the expansion. This fact requires a numerical integration of the differential form of the above equations. This may take the form:

$$dT = \frac{(\gamma-1)\eta_p}{\gamma} \frac{T}{P} dP, \qquad \text{(A 11.2.13)}$$

$$dP = \frac{P}{T} \frac{\gamma}{(\gamma-1)\eta_p} dT, \text{ or} \qquad \text{(A 11.2.14)}$$

$$dP = \frac{\gamma}{\gamma(\eta_p-1)-\eta_p} \frac{P}{v_g} dv_g, \qquad \text{(A 11.2.15)}$$

depending on whether one wished to integrate between pressure, temperature, or specific volume (void fraction) limits.

A 11.2.3 Efficiency Estimates

The performance of the LM-MHD two-component, two-phase cycle, as with any Brayton-like cycle is acutely sensitive to irreversibilities in the individual components. The expansion efficiency is of particular concern. The following sections are thought to include the most significant expansion losses.

A 11.2.3.1 Drag Losses Due to Slip between the Liquid and Gas

The liquid and gas are equally subject to forces arising from a pressure gradient in the direction of flow. These forces are countered in the liquid metal by body forces of electromagnetic origin implicit in the conversion to electrical energy. Since the pressure forces on the gas are resisted only by drag between the liquid and gas, it necessarily follows that the gas velocity will be greater than the liquid velocity and that pressure and kinetic energy will be degraded back into thermal energy by effects of drag forces and relative velocity.

The momentum equations for the gas and liquid components are

$$-\frac{dP}{dx} + D_g - \frac{d}{dx}(\rho_g U_g^2) = 0 \qquad \text{(A 11.2.16)}$$

$$-\frac{dP}{dx} + D_\ell + f_\ell - \frac{d}{dx}(\rho_\ell U_\ell^2) = 0 \ , \qquad \text{(A 11.2.17)}$$

where D_g and D_ℓ are respectively the drag in units of force per unit volume in gas and liquid, all quantities taken as positive in the direction of flow.

Note:

$$D_g\beta_g = -D_\ell(1 - \beta_g). \qquad \text{(A 11.2.18)}$$

For brevity let

$$R_g = \frac{d}{dx}(\rho_g U_g^2) \qquad \text{(A 11.2.19)}$$

$$R_\ell = \frac{d}{dx}(\rho_\ell U_\ell^2). \qquad \text{(A 11.2.20)}$$

Then

$$D_g = \frac{dP}{dx} + R_g \tag{A 11.2.21}$$

$$f_\ell = \frac{dP}{dx} - D_\ell + R_\ell = \frac{dp}{dx} + \frac{\beta_g}{1-\beta_g}\left(\frac{dP}{dx} + R_g\right) + R_\ell$$

$$f_\ell = \frac{\frac{dP}{dx} + \beta_g R_g + (1 - \beta_g)\ R_\ell}{1 - \beta_g} \tag{A 11.2.22}$$

The mechanical energy converted to electrical (other losses omitted) per unit volume of mixture per unit time is

$$\varepsilon_c = - f_\ell U_\ell\ (1 - \beta_g) \tag{A 11.2.23}$$

This mechanical energy reconverted to thermal is:

$$\varepsilon_d = - D_g \beta_g\ (U_g - U_\ell) \tag{A 11.2.24}$$

The efficiency reduction factor for slip is then

$$\eta_s = \frac{\varepsilon_c}{\varepsilon_c + \varepsilon_d} = \frac{-f_\ell U_\ell (1 - \beta_g)}{-f_\ell U_\ell (1 - \beta_g) - D_g \beta_g\ (U_g - U_\ell)} \tag{A 11.2.25}$$

$$\eta_s = \frac{-U_\ell\ [R_\ell (1 - \beta_g) + R_g \beta_g + \frac{dP}{dx}]}{-U_\ell R_\ell (1 - \beta_g) - U_g R_g \beta_g - U_g (1 - \beta_g)\ \frac{dP}{dx} - U_g \beta_g\ \frac{dP}{dx}}$$

$$\eta_s = \frac{[R_\ell\ (1 - \beta_g) + R_g \beta_g + \frac{dP}{dx}\ ]}{R_\ell (1 - \beta_g) + (1 - \beta_g)\ \frac{dP}{dx} + S(R_g \beta_g + \beta_g\ \frac{dP}{dx}\ )} \tag{A 11.2.26}$$

where

$$S = \frac{U_g}{U_\ell}$$

It is noted that quantities S, β, and dP/dx dominate this expression. In order to evaluate η_s the slip ratio, S, must be determined, depending in turn on the relationship between drag force and relative velocity. Argonne National Laboratory personnel have suggested the formula

$$D_g = -C_D \rho_\ell (U_g - U_\ell)^2 (1 - \beta_g)^3 \qquad \text{(A 11.2.28)}$$

based on experimental data by Zuber et al. (References 11.12 and 11.13).

It is now assumed that for a Faraday generator, the magnetic flux, the duct width normal to the magnetic field, and the liquid velocity will be held constant, as far as is possible. This will tend to hold a uniform, open-circuit voltage.

From Equation A 11.2.16

$$-\frac{dP}{dx} - C_D\rho_\ell (U_g - U_\ell)^2 (1 - \beta_g)^3 - U_g^2 \frac{d\rho_g}{dx} - 2\rho_g U_g \frac{dU_g}{dx} = 0$$

$$2\rho_g S \frac{dS}{dx} + C_D \rho_\ell (S - 1)^2 (1 - \beta_g)^3 + S^2 \frac{d\rho_g}{dx} + \frac{1}{U_\ell^2}\frac{dP}{dx} = 0 \qquad \text{(A 11.2.29)}$$

An examination of the numerical values of the terms of this equation show that the drag force and pressure gradient terms are highly dominating. This justifies omitting the term involving the gradient in slip and calculating slip, on a quasi steady-state basis, from the local gradients in pressure and density.

This slip value may be substituted into Equation A 11.2.26 to estimate the slip contribution to local duct efficiency losses. As applied here

$$R_{\ell} = 0$$

consistent with axially uniform liquid velocity.

A 11.2.3.2 Ohmic Losses from Nonuniform Induced EMF and Fluid Shear Losses

These losses are closely related, and it does not seem possible in the general case to decouple the two contributors except for end losses.

In ordinary pipe flow the total pressure gradient along the length of the pipe acts primarily to overcome fluid shear stresses. In an MHD generator it is intended that the pressure gradient react primarily against electromagnetic body forces, thereby resulting in useful energy conversion, with fluid shear stresses kept reasonably small. It is, thus, not expected that the velocity distribution in an MHD duct will closely resemble that usually encountered in pipe flow. Any nonuniformity in the magnetic field -- in the magnetic field direction -- will, for example, result in a corresponding nonuniformity in the electric field that will tend to increase the ohmic losses. It will also result in velocity gradients that will increase fluid friction losses and feedback into the electric field distribution. Velocity gradients at the boundary resulting from wall drag will similarly interact with the voltage and current fields.

This fairly complex source of efficiency loss has not been treated in detail. It has simply been assumed that the voltage and velocity fields are uniform. The result is an efficiency factor of E/E_0 that is the working voltage over the open-circuit voltage, as applied to the MHD duct proper.

At each end of the duct the induced voltage drops with the magnetic field and no longer counters the applied voltage. This results in reverse current flow and loss of electrical energy in ohmic heating. The effective resistance of an infinitely long approach with a sharp magnetic field drop was calculated by Sutton (Reference 11.13) as

$$R_e = \frac{\pi\delta}{2W\ell n(2)} \qquad \text{(A 11.2.30)}$$

The ohmic losses can then be calculated as E^2/R_e for each end of the duct. It has been shown experimentally at Argon that these losses can be reduced by approximately an order of magnitude by appropriately tapering the magnetic field.

A 11.2.3.3 Departure from Thermal Equilibrium

As noted above, the ideal cycle is predicted on thermal equilibrium between the liquid and gas. In actuality, the expansion work performed by the gas component results, for the most part, from the thermal energy of the liquid. Thus, there will necessarily be a temperature drop across the liquid-gas interface, whose value depends on the required rate of heat transfer and the thermal resistance. It is expected that the gass will be dispersed into a large number of small bubbles with sufficient surface area that the temperature difference will be small. For present purposes this source of irreversibility is not studied.

A 11.2.3.4 Thermal Losses through the Duct Wall

These constitute a direct source of energy loss and may be estimated from the overall thermal resistance from the inside of the duct wall. For large MHD ducts these are expected to be small and have not been studied.

A 11.2.4 Electromagnetic Relationships

It is assumed that the current through the duct does not affect the magnetic field. This can be approximated by proper arrangement of the conduction path outside the duct so that no net magnetic flux is contributed by the duct current. Then the open-circuit voltage is

$$E_o = B\, U_\ell t \qquad \text{(A 11.2.31)}$$

where E_o is the volts
B is magnetic flux, T
U_ℓ is the liquid velocity, m/s
t is duct thickness, m.

The current density, j, is related to the working voltage, E, by Equation A 11.2.32:

$$j = \frac{E_o - E}{\delta t} \qquad \text{(A 11.2.32)}$$

where δ is the mixture resistivit,.

Mixture resistivity is estimated as

$$\delta = \frac{\varepsilon^{(3.8\,\beta_g)}}{\kappa} \qquad \text{(A 11.2.33)}$$

where κ is the pure liquid conductivity (Reference 11.12).

The linear electrical power density is given by

$$\frac{dp}{dX} = E\, j\, W \qquad \text{(A 11.2.34)}$$

By equating the electrical power density to the gradient in enthalpy flow rate we can relate the physical length of the duct to the electrical and thermodynamic parameters by

$$\frac{dX}{dH} = -\delta U_\ell \left[\frac{S\beta_g}{v_g} + \frac{(1 - \beta_g)}{v_\ell}\right] = \frac{\left(\frac{t}{E_o}\right)^2}{\frac{E}{E_o}\,(1 - \frac{E}{E_o})} \qquad \text{(A 11.2.35)}$$

A 11.2.5 Steam Bottom Cycle

The steam bottom cycle is calculated in somewhat less detail than the MHD top cycle. The procedure amounts to assigning portions of the thermal energy rejected from the top cycle to

- Steam generation and superheat (if used)
- Steam reheat
- Combustion air preheat
- Rejected heat.

Internal reversibility factors are assigned to the bottom cycle for each component heat source used directly in the steam cycle, and a stack loss efficiency factor is assigned to the combustor-primary heat exchanger combination. The overall thermodynamic efficiency is calculated for each heat source component from the appropriate temperature profile according to the equation

$$\eta_{th} = 1 - T_0\ \ell n\ (\frac{T_1}{T_2})/(T_1 - T_2) \qquad \text{(A 11.2.36)}$$

Here T_0 is the steam cycle sink temperature, and T_1 and T_2 are the upper and lower values along the top cycle gas temperature profile.

These components are combined to calculate overall bottom cycle power and efficiency and combined-cycle power and efficiency.

A 11.2.6 Input Data for Numerical Calculations

The following information is read as input into the program.

- Cycle configuration
  - The number of compressor stages each with a pre(inter) cooler ahead (up to four stages)
  - The number of regenerative heat exchangers (as either zero or one)
- Fluid properties
  - Gas molecular weight
  - Gas specific heat at constant pressure
  - Liquid density
  - Liquid specific heat
  - Liquid electrical resistivity
- Calculational options
  - Overall combined-cycle power output may be specified together with instructions to iterate on duct inlet cross-section size (constant aspect ratio maintained).
  - The duct efficiency estimate internal to the program may be overridden by input of a constant duct efficiency.
  - Thermodynamic calculations may be followed by an additional routine that estimates component costs.
- Component characteristics
  - Separator efficiency as a fraction of gas and fraction of liquid channeled into the gas stream. Ideally these fractions would be 1.0 and 0.0, respectively.

- Polytropic efficiency of the compressor and efficiency of the liquid-metal pump
- Pressure loss, as $\Delta P/P$, through each of the heat exchangers, the separator, and the mixer. Piping pressure losses may be lumped into these.
- The duct loading as a ratio of working voltage to open-circuit voltage
- Initial slip ratio at the duct inlet
- The temperature difference across the regenerator. This difference is constant since the heat exchanger is linear.
- Reduction factors to be applied to duct inlet and exit values from Sutton's formula of ohmic end losses

- Magnitude parameters
  - The inlet duct width, in the direction of the magnetic field, and the duct thickness in the direction of the electric field. The former is allowed to vary along the length to maintain constant liquid velocity, while the latter is held constant.
  - Output power may be specified. If iteration to this power is desired, the inlet duct dimensions will change, in the same ratio, to the size required for that power.
  - Inlet liquid velocity
  - Either the open-circuit voltage or the magnetic flux may be specified.
- Fluid conditions
  - Mixture temperature and pressure, and gas volumetric flow fraction, are specified at the outlet of the mixer.
  - Any one of the above parameters is specified at the duct outlet.

- Temperature is specified at the gas stream outlet of the steam generator (the first heat exchanger after expansion in the duct), and a common gas temperature is given at each of the compressor inlets.
- The steam cycle bottom temperature is specified.

- Bottom and overall cycle characteristics
  - Reversibility index for each source and use of thermal energy into the steam cycle
  - Stack efficiency
  - Fraction of thermal energy from the steam generator (between Points 6 and 7) assigned to steam reheat and the temperature limits over which this is taken.

A 11.2.7 Calculational Procedures

A 11.2.7.1 MHD Cycle

The starting point for cycle analysis is the mixer exit (Point 1 in Figure A 11.2.1). The changes in temperature and enthalpy are determined from the ohmic heating as the mixture approaches the duct inlet (Point 2).

Depending on which duct outlet parameter is specified, the change in value over the duct length is divided into increments and a numerical integration carried out to determine conditions along the duct, making use of Equations A 11.2.13, A 11.2.14, or A 11.2.15. At each mesh point the slip ratio and the efficiency are calculated for use in the numerical integration. Also, the duct length integral and the duct cross-sectional area are calculated.

Again, ohmic heating at the duct outlet is estimated to give conditions at the separator inlet. The enthalpy change from Point 1 to Point 4 is the work performed by the duct.

Dwg. 6354A87

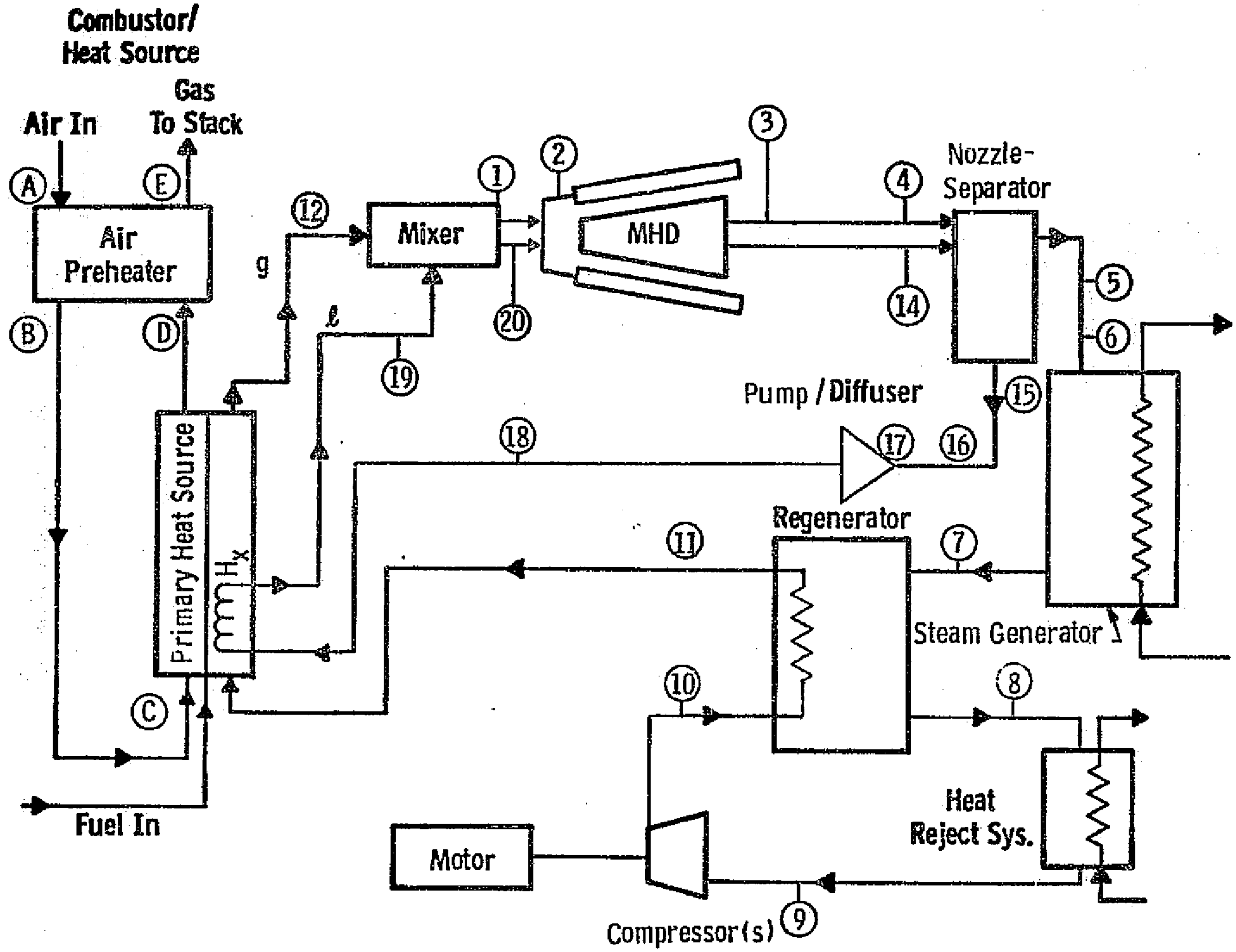

Fig. A 11. 2. 1 – Schematic arrangement of MHD cycle

The system component pressure losses allow the compressor pressure ratio to be calculated, which, combined with the compressor inlet temperature input, permits estimation of conditions at the exit of each compressor stage using the compression analogue of Equation A.2.12 with the input polytropic efficiency. Equal pressure ratios are assumed for each stage.

Temperatures are given at Points 7 and 9; thus the input approach temperature difference allows temperatures at Points 8 and 11 to be determined.

Proceeding along similar lines, we can calculate the outlet conditions for the liquid-metal pump. Here the pump work is increased by the reciprocal of pump efficiency, with the excess work appearing as thermal energy in the liquid metal.

To close the cycle it is only necessary to add enthalpy to one or both streams between Points 11 and 12 or Points 18 and 19 to return to mixer outlet enthalpy. The program calculates temperatures at the mixer inlet for various splits between heat addition to the two streams.

A 11.2.8 The Program

The listings of the program and subroutines are given in Subappendix AA 11.2.1. The input data are as follows:

ATWT	Molecular weight of the gas component
CP (1)	Specific heat at constant pressure of the gas component, Btu/lb-°F
DENS	Density of the liquid, lb/ft^3
CP(2)	Specific heat of the liquid, Btu/lb-°F
RESIS	Resistivity of the liquid, ohm-cm
VEL	Liquid-metal duct velocity, ft/s
WIDE(1)	Duct inlet width in magnetic field direction, ft
THICK	Duct thickness in the electric field direction, dt
VLØ	Duct open-circuit potential, V

FLØ	Duct magnetic flux, T
VLØAD	Duct loading, V/V
SL	Duct inlet slip ratio
FACT(1), FACT(2)	Reduction factors for Sutton's formula for inlet
EFC	Compressor polytropic efficiency
EFP	Pump efficiency
PI(1,1)	Duct inlet pressure, psi
TF(1,1)	Duct inlet temperature, °F
F(1,1)	Duct inlet void fraction
PIØUT	Duct exit pressure, psi
TFØUT	Duct exit temperature, °F
FØUT	Duct exit void fraction
TF(1,9)	Compressor inlet temperature, °F
TSINK	Steam cycle sink temperature, °F
NCØMP	Number of compressor stages - 1, 2, 3, or 4
NREG	Number of regenerator stages - 0 or 1
THETA	Regenerator approach temperature difference, °F
TGEN	Gas stream temperature leaving steam generator at Point 7, °F
TFFD	Lowest temperature usable for feedwater heat, °F
FSEP(1), FSEP(2)	Fraction of gas and liquid entering the gas
DELP(4), DELP(6), DELP(7)	Fractional pressure losses in the gas stream through the separator, steam generator, and regenerator hot side, respectively
DELP(28), DELP(38), DELP(48), DELP(58)	Fractional pressure losses through the compressor precoolers
DELP(10), DELP(11), DELP(12)	Fractional gas stream pressure losses through the regenerator cold side, source heat exchanger, and mixer, respectively

DELP(14)	Fractional pressure loss in liquid-metal stream through the separator
DELP(16)	Pressure loss through any additional components in liquid-metal stream between the separator and pump
DELP(18), DELP(19)	Fractional pressure loss in liquid stream through source heat exchanger and mixer
ETAS(6)	Internal reversibility index of the steam cycle applicable to thermal energy fed from the steam generator
ETAS(28), ETAS(38), ETAS(48), ETAS(58)	Internal reversibility indices of steam cycle for thermal energy entering the cycle through the compressor precoolers, combined with the fraction of the heat used in this way
EFSTCK	Stack efficiency
ETAPRE(28), ETAPRE(38), ETAPRE(48), ETAPRE(58)	Fraction of the thermal energy from the compressor precoolers used for combustion air preheat. Note ETAPRE(N) + ETAS(N) < 1
REHEAT	Fraction of thermal energy from the steam generator (between Points 6 and 7) used for steam reheat
TFUP, TFDØWN	Upper and lower limits (bottom cycle hole) over which thermal energy is used as steam reheat
EFRHH	Internal reversibility index for thermal energy used as steam reheat
NCØST	Index for cost routine option 1 if cost routine is to be used, 0 otherwise
NITER	Index for option to iterate on power. 1 if iteration is desired, 0 otherwise

PØWER	Overall combined-cycle power for which component sizes will be chosen, MW
EFDUCT	MHD duct efficiency to be taken as fixed if nonzero value is entered.

A sample output is given in Subappendix AA 11.2.2.

A 11.2.9 Nomenclature

B	Magnetic flux density
C_D	Interphase drag coefficient
C_ℓ	Specific heat of liquid metal
C_{pg}	Specific heat of gas at constant pressure
C_{vg}	Specific heat of gas at constant volume
D_g	Interphase drag force acting on gas component per unit volume gas
D_ℓ	Interphase drag force acting on liquid component per unit volume gas
E	Working potential across duct thickness
E_0	Open-circuit potential across duct thickness
ε_c	Volumetric energy conversion rate
ε_d	Volumetric energy degradation rate
f_ℓ	Electromagnetic body force acting on liquid metal
g	Gravitational constant
H	Mixture enthalpy
j	Current density
P	Pressure
p	Power
R	Gas law constant
R_ε	Effective and electrical resistance
R_g	Gas momentum velocity gradient
R_ℓ	Liquid momentum velocity gradient
S	Slip ratio, U_g/U_ℓ
T	Temperature
t	Duct thickness normal to the magnetic field
U_g	Gas-phase velocity
U_ℓ	Liquid velocity

v_g	Gas specific volume
v_ℓ	Liquid specific volume
W	Width of duct parallel to magnetic field
w_g	Fraction of total mass flow as gas
w_ℓ	Fraction of total mass flow as liquid
X	Coordinate along duct length direction
β_g	Fraction of cross-sectional area occupied by gas
β_ℓ	Fraction of cross-sectional area occupied by liquid
γ	Weighted mean specific heat ratio of the mixture
η_i	Isentropic expansion efficiency
η_p	Polytropic expansion efficiency
η_s	Slip efficiency factor
η_{th}	Ideal thermodynamic efficiency
κ	Electrical conductivity of the pure liquid metal
ρ_g	Gas density
ρ_ℓ	Liquid density
δ	Electrical resistivity of the mixture
ϕ_g	Fraction of total volume flow as gas
ϕ_ℓ	Fraction of total volume flow as liquid

Subappendix AA 11.2.1

COMPUTER PROGRAM LISTING

```
@RUN,N/RNPT MHDTOP,D9E96ECAS6D,GRIMBLE,1,25

@SYM    PRINT$,,PR7

@ASG,A  GRIMBLE*MHD.

@FOR,IS        MHD.MHDTOP
FOR OT28-06/10/75-11:05:08 (,0)
```

MAIN PROGRAM

STORAGE USED: CODE(1) 002145; DATA(0) 002656; BLANK COMMON(2) 010165

EXTERNAL REFERENCES (BLOCK, NAME)

```
0003    VALUE
0004    SHUNT
0005    FIXP
0006    FIXV
0007    FIXT
0010    SKIP
0011    SEPER
0012    THROT
0013    SINK
0014    REPORT
0015    HEAT
0016    COST
0017    NINTR$
0020    NIOCB$
0021    NSCR$
0022    NNRFU$
0023    NNWFU$
0024    ALOG
0025    XPRR
0026    SQRT
0027    NSTOP$
0030    NBFO$
```

STORAGE ASSIGNMENT (BLOCK, TYPE, RELATIVE LOCATION, NAME)

0000	000267 1F	0000	000421 10F	0001	000006 100L	0001	001121 1005G	0001	001234 1042G
0001	001240 1046G	0001	001273 1055G	0001	000322 107L	0001	001322 1070G	0001	000521 108L
0000	000434 11F	0001	000530 112L	0000	002313 1120D	0000	002317 1124D	0000	002323 1127D
0000	002327 1135D	0000	002334 1144D	0000	002341 1150D	0000	002346 1154D	0001	001541 1157G
0001	000536 116L	0000	002352 1161D	0000	002366 1174D	0000	002372 1177D	0000	000447 12F
0000	002376 1202D	0000	002402 1205D	0000	002406 1210D	0000	002412 1216D	0001	001627 1223G
0000	002416 1232D	0000	002423 1236D	0000	002430 1242D	0000	002435 1247D	0000	002442 1253D
0000	002446 1256D	0000	002452 1261D	0000	002456 1264D	0000	002462 1270D	0000	002467 1273D
0000	002474 1276D	0000	002501 1301D	0000	002506 1304D	0000	002513 1310D	0000	002524 1317D
0000	002531 1324D	0000	002536 1327D	0000	002543 1332D	0000	002550 1335D	0000	002554 1337D
0001	002062 1343G	0000	002560 1356D	0000	002567 1366D	0001	001102 137L	0001	001126 139L
0000	001644 143D	0001	001174 146L	0000	000457 15F	0000	000467 16F	0000	000477 17F
0000	000506 18F	0000	000516 19F	0001	002141 199L	0000	000276 2F	0001	000260 202L
0001	000343 203L	0001	000350 204L	0001	001516 208L	0001	001527 212L	0000	001653 214D
0001	001533 216L	0000	001665 223D	0001	001620 228L	0000	001674 230D	0000	001704 236D
0000	001714 244D	0000	000526 25F	0000	001723 251D	0000	000612 254F	0000	001732 256D
0000	001740 262D	0000	000770 266F	0000	001751 271D	0000	001060 271F	0000	001757 275D
0000	001217 283F	0000	001430 290F	0000	001473 291F	0000	001561 295F	0000	000305 3F
0000	001767 303D	0000	000344 307F	0000	000376 308F	0000	001777 311D	0000	002006 316D
0000	002016 324D	0000	002030 334D	0000	002041 343D	0000	002051 351D	0000	000631 354F
0000	002061 362D	0000	002065 364D	0000	002071 366D	0000	002077 372D	0000	002106 377D
0000	001243 383F	0000	000314 4F	0000	002114 403D	0000	002122 407D	0000	002131 414D
0000	002137 420D	0000	002146 425D	0000	002152 427D	0000	002162 435D	0000	002172 443D
0000	002201 450D	0000	002205 452D	0000	000650 454F	0000	002215 460D	0000	002227 470D
0000	002240 477D	0000	001267 483F	0000	001564 495F	0000	000324 5F	0000	002250 515D
0000	000551 52F	0000	002257 522D	0000	002266 527D	0000	002274 533D	0000	000601 54F
0000	002304 541D	0001	000366 567G	0001	000367 572G	0000	000334 6F	0000	000673 60F
0001	000402 602G	0000	000704 61F	0001	000424 613G	0000	000717 62F	0000	000721 64F
0000	000740 65F	0000	000757 66F	0000	001001 68F	0000	001020 69F	0000	000354 7F
0000	001034 70F	0001	000654 703G	0001	000661 706G	0000	001052 71F	0000	001064 72F
0001	000706 721G	0001	000750 731G	0001	000757 734G	0000	001107 74F	0001	001031 747G

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0000      001126 75F        0001      001107 776G       0000      000365 8F         0000      001137 80F        0000      001147 81F
0000      001163 82F        0000      001175 83F        0000      001306 84F        0000      001321 86F        0000      001333 87F
0000      001355 88F        0000      001370 89F        0000      000406 9F         0000      001410 90F        0000      001451 91F
0000      001506 92F        0000      001517 93F        0000      001542 94F        0000      001557 95F        0000      001610 96F
0000      001621 97F        0000      001637 98F        0000      001641 99F        0000 R 000167 ATWT       0002      004160 B
0002 R 010011 BETA       0000 R 000230 CAPP       0002 R 010157 COND       0002 R 007715 CP         0002 R 007721 CV
0002 R 006535 DELH       0002 R 006251 DELP       0002      006403 DELT       0000 R 000170 DENS       0000 R 000265 DH
0002 R 007545 DIST       0000 R 000232 DP         0000 R 000174 EFC        0002 R 010164 EFDUCT     0002 R 007627 EFF
0000 R 000175 EFP        0000 R 000213 EFRHT      0000 R 000207 EFSTCK     0000 R 000234 ENER       0000 R 000260 ETAC
0000 R 000231 ETAM       0000 R 000261 ETAMHD     0000 R 000032 ETAPRE     0002 R 007021 ETAS       0000 R 000254 ETAST
0002 R 006667 ETATH      0000 R 000221 ETATHR     0000 R 000262 ETATOT     0000 R 000263 ETA1       0000 R 000264 ETA2
0002 R 002506 F          0000 R 000002 FACT       0002 R 007401 FGAS       0002      005214 FLM        0002 R 006250 FLMO
0000 R 000214 FLUX       0002      005632 FLV        0000 R 000173 FLO        0000 R 000200 FOUT       0000 R 000000 FSEP
0002 R 003124 H          0000 R 000247 HIN        0000 R 000233 HOUT       0000 R 000253 HREHT      0000 R 000252 HSTM
0000 I 000257 I          0000 I 000226 J          0000 I 000241 KAP        0000 I 000222 KOUNT      0000 I 000225 L
0000 I 000240 LC         0000 I 000006 LCOMP      0000 I 000244 LC10       0000 I 000242 LC8        0000 I 000243 LC9
0000 I 000245 LT         0000 I 000237 N          0000 I 000202 NCOMP      0000 I 000164 NCOST      0000 I 000165 NITER
0000 I 000246 NOT        0000 I 000203 NREG       0002      007726 PCOEF      0002 R 001452 PF         0002 R 001034 PI
0000 R 000224 PIE        0000 R 000176 PIOUT      0000 R 000255 POW        0000 R 000166 POWER      0000 R 000236 PRAT
0000 R 000251 PREHT      0002 R 007153 PRES       0000 R 000266 PROP       0000 R 000256 RAT        0000 R 000210 REHEAT
0000 R 000171 RESIS      0002      010073 RG         0002 R 007723 RHEAT      0002 R 007722 RWORK      0002      003542 S
0002 R 010163 SL         0002 R 007727 SLIP       0000 R 000215 TAB        0002 R 007235 TEMP       0002 R 000000 TF
0000 R 000212 TFDOWN     0000 R 000206 TFFD       0000 R 000177 TFOUT      0000 R 000211 TFUP       0000 R 000205 TGEN
0000 R 000204 THETA      0002 R 010155 THICK      0000 R 000235 THIN       0002 R 000416 TR         0000 R 000220 TRDOWN
0002 R 007725 TREF       0000 R 000216 TRFD       0000 R 000217 TRUP       0000 R 000201 TSINK      0002 R 002070 V
0002 R 010160 VEL        0002 R 010156 VLOAD      0000 R 000172 VLD        0002      007317 VOL        0002 R 010161 VOLT
0000 R 000227 VRAT       0002 R 007711 WIDE       0002 R 007463 WIDTH      0000 R 000250 WORK       0002      010162 WRAT
0002 R 004576 WT         0000 R 000223 WVOLT      0002 R 007724 Y
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00101        COMMON TF(3,90),TR(3,90),PI(3,90),PF(3,90),V(3,90),F(3,90),               000000
00101       1       H(3,90),S(3,90),B(3,90),WT(3,90),FLM(3,90),FLV(3,90),FLMO,          000000
00101       2       DELP(90),DELT(90),DELH(90),ETATH(90),ETAS(90),                      000000
00101       3       PRES(50),TEMP(50),VOL(50),FGAS(50),WIDTH(50),DIST(50),              000000
00101       4       EFF(50),WIDE(4),CP(4),CV,RWORK,RHEAT,Y,TREF,PCOEF,                  000000
00101       5       SLIP(50),BETA(50),RG(50),THICK,VLOAD,COND,VEL,VOLT,WRAT,SL,         000000
00101       6       EFDUCT                                                              000000
00103        DIMENSION FSEP(2),FACT(4),LCOMP(20)                                        000001
00104        DIMENSION ETAPRE(90)                                                       000001
00105      1 FORMAT('0',T5,'****OUTLET FROM MIXER****')                                 000001
00106      2 FORMAT('0',T5,'****INLET TO MHD DUCT****')                                 000001
00107      3 FORMAT('0',T5,'****OUTLET FROM MHD DUCT*')                                 000001
00110      4 FORMAT('0',T5,'****INLET TO NOZZLE-SEPERATOR*')                            000001
00111      5 FORMAT('0',T5,'****GAS OUTLET FROM SEPERATOR*')                            000001
00112      6 FORMAT('0',T5,'****INLET TSTEAM GENERATOR***')                             000001
00113    307 FORMAT('0',T5,'****OUTLET TSTEAM GENERATOR***')                            000001
00114      7 FORMAT(     T5,'****INLET TO REGENERATER LOW PRESS SIDE***')               000001
00115      8 FORMAT('0',T5,'****INLET TO WASTE COOLER NUMBER ',I2)                      000001
00116    308 FORMAT('0',T5,'****INLET TO FEED WATER HEATER***')                         000001
00117      9 FORMAT('0',T5,'****INLET TO GAS COMPRESSOR NUMBER ',I2,'****')             000001
00120     10 FORMAT('0',T5,'****OUTLET FROM GAS COMPRESSOR NUMBER ',I2, '****')         000001
00121     11 FORMAT('0',T5,'****OUTLET FROM REGENERATER HIGH PRESS SIDE***')            000001
00122     12 FORMAT('0',T5,'****OUTLET FROM SECOND GAS HEATER')                         000001
00123     15 FORMAT('0',T5,'*** LIQUID OUTLET FROM SEPERATOR')                          000001
00124     16 FORMAT('0',T5,'****INLET TO LIQUID COOLER******')                          000001
00125     17 FORMAT('0',T5,'****INLET TO LIQUID PUMP***')                               000001
00126     18 FORMAT('0',T5,'****OUTLET FROM LIQUID PUMP**')                             000001
00127     19 FORMAT('0',T5,'****LIQUID INLET TO MIXER****')                             000001
00130     25 FORMAT('0','NO.COMP.STAGES=',I2,' *NO.REGEN.=',I2,' *REG.APP=',            000001
00130       1       F6.2,' DEG.F *REG.CUTOFF=',F6.2,' DEG.F')                           000001
00131     52 FORMAT('0',T2,'IN DUCT*****DIST.-FT*****WIDTH-FT****TEMP-DEG.R',           000001
00131       1       '-*PRES-LB/SQFT*AREA FRAC.GAS*VOL.FRAC.GAS****SLIP RATIO',          000001
00131       2       '***LOCAL EFFIC')                                                   000001
00132     54 FORMAT('0',T2,'MHD DUCT ISENTROPIC EFFICIENCY=',F6.4)                      000001
00133    254 FORMAT('0','OVERALL COMB. CYCLE EFFICIENCY INCLUDING ',                    000001
00133       1       ' COMBUSTER-PRIMARY HT.X=',F6.4)                                    000001
00134    354 FORMAT('0','OVERALL COMB. CYCLE EFFICIENCY FOR IDEAL ',                    000001
00134       1       ' COMBUSTER-PRIMARY HT.X=',F6.4)                                    000001
00135    454 FORMAT('0','OVERALL COMB. CYCLE EFFICIENCY EXCLUDING ',                    000001
00135       1       ' COMBUSTER-PRIMARY HT.X AND PREHEAT ADVANTAGE=',F6.4)              000001
00136     60 FORMAT('0',T2,'COMPRESSOR ISENTROPIC EFFICIENCY=',F6.4)                    000001
00137     61 FORMAT('0',T2,'ENTHALPY ADDED AT TOP OF CYCLE=',F8.2,'BTU/LB')             000001
00140     62 FORMAT(T9,8F14.4)                                                          000001
00141     64 FORMAT('0',T2,'ENTHALPY REJECTED AT BOTTOM OF MHD CYCLE=',                 000001
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00141          1      F8.2,'BTU/LB OF ILET MIXTURE')                                          000001
00142     65 FORMAT('0','COMB.CYC.POWER PER DUCT=',F8.2,'MW, ITERATION INDEX=',                000001
00142          1      I2,' COST INDEX=',I2)                                                   000001
00143        READ(5,295)NCOST,NITER,POWER                                                     000001
00150     66 FORMAT('0',T2,'MHD TOPPING CYCLE EFFICIENCY=',F6.4)                              000006
00151    266 FORMAT('0',T2,'STEAM BOTT. CYCLE EFFICIENCY=',F6.4)                              000006
00152     68 FORMAT('0',T2,'TOP TEMPERATURES WITH VARIOUS SPLITS BETWEEN',                    000006
00152          1      ' GAS AND LIQUID HEATING')                                              000006
00153     69 FORMAT(T2,'FRACTION HEAT ADDED TO GAS***GAS TEMP. F*LIQUID',                     000006
00153          1      ' TEMP. F')                                                             000006
00154     70 FORMAT('1',T2,'******OUTPUT DATA-BASED ON ONE POUND MIXTURE AT',                 000006
00154          1      ' MHD DUCT INLET')                                                      000006
00155     71 FORMAT('1',T2,'******INPUT DATA')                                                000006
00156    271 FORMAT('0','******FINAL PARAMETERS')                                             000006
00157     72 FORMAT('0',T2,'DUCT INLET SHUNT LOSS REDUCTION=',F6.4,                           000006
00157          1      '****DUCT OUTLET SHUNT LOSS REDUCTION=',F6.4)                           000006
00160     74 FORMAT('0',T2,'COMPRESSOR POLYTROPIC EFFICIENCY=',F6.4,                          000006
00160          1      '****LIQUID PUMP EFFICIENCY=',F6.4)                                     000006
00161     75 FORMAT('0',T2,'NET WORK=',F8.2,' BTU PER LB INLET')                              000006
00162     80 FORMAT('0',T2,'SPECIFIED MHD INLET CONDITIONS')                                  000006
00163     81 FORMAT(T2,'TEMP=',F8.2,' DEG.F****PRES=',F8.2,' PSI****VOID VOL=',               000006
00163          1      F6.4)                                                                   000006
00164     82 FORMAT('0',T2,'SPECIFIED MHD OUTLET PRESSURE=',F8.2,' PSI')                      000006
00165     83 FORMAT(      T2,'1ST WST. HT. X=',F6.4,'  2ND WST.HT. X=',F6.4,                  000006
00165          1      ' 3RD WST.HT. X=',F6.4,' 4TH WST.HT. X=',F6.4,)                         000006
00166    283 FORMAT('0','ASSUMED ST.CYC.INT.EFFIC.FOR ST.GEN.=',F6.4,                         000006
00166          1      '  FOR FEED WATER HEATER',F6.4,                                         000006
00166          2      'AND FOR PRECOOLERS',5F8.4)                                             000006
00167    383 FORMAT('0','MAX. THERMODYNAMIC EFFIC.FOR ST.GEN.=',F6.4,                         000006
00167          1      '  FOR FEED WATER HEATER',F6.4,                                         000006
00167          2      'AND FOR PRECOOLERS',5F8.4)                                             000006
00170    483 FORMAT('0','STACK EFF.=',F6.4,                                                   000006
00170          1      ,'FRACT. OF PRECOOLER HEAT USED FOR AIR PREHEAT=',4F7.4)                000006
00171     84 FORMAT('0',T2,'SPECIFIED MHD OUTLET TEMPERATURE=',F8.2,' DEG.F')                 000006
00172     86 FORMAT('0',T2,'SPECIFIED MHD OUTLET VOID FRACTION=',F6.4)                        000006
00173     87 FORMAT('0',T2,'FRACT.OF TOTAL GAS SEPERATED IN GAS STREAM=',F6.4,                000006
00173          1      '****FRACT.LIQUID IN GAS STREAM=',F6.4)                                 000006
00174     88 FORMAT('0','GAS MOL.WT=',F7.2,'****GAS CP=',F7.4,' BTU/LB')                      000006
00175     89 FORMAT(T2,'LIQ.DENS=',F7.2,' LB/CU FT****LIQ.CP=',F7.4,                          000006
00175          1      ' BTU/LB****LIQ.RESIS=',E9.4,' OHM-CM')                                 000006
00176     90 FORMAT('0',T2,'MIX.VEL=',F7.2,' FT/SEC***INLET WIDTH=',F6.2,                     000006
00176          1      ' FT***THICKNESS=',F6.2,' FT')                                          000006
00177    290 FORMAT('0',T2,'MAG.FLUX DEN=',F6.2,' TESLA***LOADING=',F6.4,                     000006
00177          1      ' VOLT/VOLT***INLET SLIP RATIO=',F4.2)                                  000006
00200     91 FORMAT('0',T2,'SPEC.COMP.IN.TEMP=',F8.2,' DEG.F***COMP.EF=',F6.4,                000006
00200          1      '****CYCLE REJECT TEMP=',F8.2,' DEG.F')                                 000006
00201    291 FORMAT('0',T2,'OPEN CIR.VOLT=',F6.2,' WORKING VOLTAGE=',F6.2)                    000006
00202     92 FORMAT('0',T2,'GAS STREAM PRESSURE LOSSES AS DP/P')                              000006
00203     93 FORMAT(T2,'NOZZLE-SEP=',F6.4,'***STEAM GEN.=',F6.4,                              000006
00203          1      '***REGEN.LO PR SIDE=',F6.4,'***FEED WATER HEATER',F6.4)                000006
00204     94 FORMAT(T2,'REGEN.HI.SIDE=',F6.4,'***PRIMARY HEATER=',F6.4,                       000006
00204          1      '***MIXER=',F6.4)                                                       000006
00205     95 FORMAT(I12,5F12.4)                                                               000006
00206    295 FORMAT(2I12,4F12.2)                                                              000006
00207    495 FORMAT('0','FRACT. OF STEAM HEAT FOR DIRECT ST. REHEAT=',F6.4,                   000006
00207          1      'FROM',F7.1,' TO',F7.1,' DEG.F.AT INTERNAL EFF.',F6.4)                  000006
00210     96 FORMAT('0',T2,'LIQUID STREAM PRESSURE LOSSES AS DP/P')                           000006
00211     97 FORMAT(T2,'NOZZLE-SEP=',F6.4,'***COOLER=',F6.4,'***HEATER=',F6.4,                000006
00211          1      '***MIXER=',F6.4)                                                       000006
00212     98 FORMAT(6F12.4)                                                                   000006
00213     99 FORMAT(4F12.4,2E12.4)                                                            000006
00214    100 READ(5,99,END=199)ATWT,CP(1),DENS,CP(2),RESIS                                    000006
00223        READ(5,98)VEL,WIDE(1),THICK
00230        READ(5,98)VLO,FLO,VLOAD,SL
00236        READ(5,98)FACT(1),FACT(2),EFC,EFP
00244        READ(5,98)PI(1,1),TF(1,1),F(1,1)
00251        READ(5,98)PIOUT,TFOUT,FOUT
00256        READ(5,98)TF(1,9),TSINK
00262        READ(5,295)NCOMP,NREG,THETA,TGEN,TFFD
00271        READ(5,98)FSEP(1),FSEP(2)
00275        READ(5,98)DELP(4),DELP(6),DELP(7) ,DELP(26)
00303        READ(5,98)DELP(28),DELP(38),DELP(48),DELP(58)
00311        READ(5,98)DELP(10),DELP(11),DELP(12)
00316        READ(5,98)DELP(14),DELP(16),DELP(18),DELP(19)
00324        READ(5,98)ETAS(6),ETAS(26),ETAS(28),ETAS(38),ETAS(48),ETAS(58)
00334        READ(5,98) EFSTCK,ETAPRE(28),ETAPRE(38),ETAPRE(48),ETAPRE(58)
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00343              READ(5,98) REHEAT,TFUP,TFDOWN,EFRHT
00351              READ(5,295)NCOST,NITER,POWER ,EFDUCT
00357              VOLT=VLO
00360              FLUX=FLO                                                          000113
00361              ETAS(8)=ETAS(28)                                                  000115
00362              WRITE(6,71)                                                       000117
00364              WRITE(6,80)
00366              WRITE(6,88)ATWT,CP(1)
00372              WRITE(6,89)DENS,CP(2),RESIS
00377              WRITE(6,72)FACT(1),FACT(2)
00403              WRITE(6,74)EFC,EFP
00407              WRITE(6,81)TF(1,1),PI(1,1),F(1,1)
00414              WRITE(6,87)FSEP(1),FSEP(2)
00420              WRITE(6,91)TF(1,9),EFC,TSINK
00425              WRITE(6,92)
00427              WRITE(6,93)DELP(4),DELP(6),DELP(7),DELP(26)
00435              WRITE(6,83)DELP(28),DELP(38),DELP(48),DELP(58)
00443              WRITE(6,94)DELP(10),DELP(11),DELP(12)
00450              WRITE(6,96)
00452              WRITE(6,97)DELP(14),DELP(16),DELP(18),DELP(19)
00460              WRITE(6,283)ETAS(6),ETAS(26),ETAS(28),ETAS(38),ETAS(48),ETAS(5)
00470              WRITE(6,483) EFSTCK,ETAPRE(28),ETAPRE(38),ETAPRE(48),ETAPRE(58)
00477              WRITE(6,495) REHEAT,TFUP,TFDOWN,EFRHT
00505              TAB=459.69
00506              THFD=TFFD+TAB                                                     000231
00507              TREF=TSINK+TAB                                                    000233
00510              TRUP = TFUP + TAB + 0.0001                                        000236
00511              TRDOWN = TFDOWN + TAB                                             000242
00512              ETATHR = 1.-TREF* ALOG(TRUP/TRDOWN)/(TRUP-TRDOWN)                 000245
00513              KOUNT=0                                                           000256
00514          202 KOUNT=KOUNT+1                                                     000260
00515              WRITE(6,90)VEL,WIDE(1),THICK                                      000262
00522              WRITE(6,290)FLUX,VLOAD,SL
00527              WRITE(6,291)VOLT,WVOLT
00533              WRITE(6,25)NCOMP,NREG,THETA,TGEN
00541              WRITE(6,65)POWER,NITER,NCOST
00546              IF(KOUNT.GE.2)GO TO 100
00550              RHEAT=1.987/ATWT                                                  000312
00551              RWORK=RHEAT/.001248                                               000315
00552              PIE=3.14159                                                       000317
00553          107 PI(1,3)=PIOUT                                                     000322
00554              TF(1,3)=TFOUT                                                     000323
00555              F(1,3)=FOUT                                                       000325
00556              IF(VLO.LE.0.001)GO TO 203                                         000327
00560              FLUX=VOLT/(VEL*THICK*.0929)                                       000333
00561              GO TO 204                                                         000341
00562          203 VOLT=VEL*THICK*FLUX*.0929                                         000343
00563          204 CONTINUE                                                          000350
00564              WVOLT=VOLT*VLOAD                                                  000350
00565              COND=30.48/RESIS                                                  000352
00566              DO 104 L=1,3,2                                                    000367
00571              DO 102 J=2,3,1                                                    000367
00574              TF(J,L)=TF(1,L)                                                   000367
00575          102 PI(J,L)=PI(1,L)                                                   000370
00577              F(2,L)=1.-F(1,L)                                                  000373
00600              F(3,L)=1.                                                         000376
00601              DO 104 J=1,3,1                                                    000402
00604              PF(J,L)=PI(J,L)*144                                               000402
00605              TR(J,L)=TF(J,L)+TAB                                               000404
00606          104 CONTINUE                                                          000415
00611              V(1,1)=RWORK*TR(1,1)/PF(1,1)                                      000415
00612              DO 105 L=1,90,1                                                   000424
00615          105 V(2,L)=1./DENS                                                    000424
00617              VRAT=V(1,1)/V(2,1)                                                000426
00620              F(2,1)=1-F(1,1)                                                   000431
00621              F(3,1)=1.                                                         000434
00622              WT(1,1)=1/(1+VRAT*F(2,1)/F(1,1))                                  000436
00623              WT(2,1)=1-WT(1,1)                                                 000444
00624              WT(3,1)=1.                                                        000446
00625              V(3,1)=(V(1,1)*WT(1,1)+V(2,1)*WT(2,1))/WT(3,1)                    000450
00626              CV=CP(1)-RHEAT                                                    000457
00627              CAPP=CP(1)*WT(1,1)+CP(2)*WT(2,1)                                  000462
00630              Y=RHEAT*WT(1,1)/CAPP                                              000470
00631              FLHD=WIDE(1)*THICK*VEL/V(3,1)                                     000474
00632              CALL VALUE(1)                                                     000501
00633              CALL SHUNT(1,WIDE(1),FACT(1))                                     000503
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00634        CALL VALUE(2)                                                        000507
00635        IF(PF(1,3)-.001)108,108,106                                          000511
00640    106 CALL FIXP(2)                                                         000515
00641        GO TO 116                                                            000517
00642    108 IF(F(1,3)-.001)112,112,110                                           000521
00645    110 CALL FIXV(2)                                                         000524
00646        GO TO 116                                                            000526
00647    112 IF(TR(1,3)-.1)116,116,114                                            000530
00652    114 CALL FIXT(2)                                                         000533
00653    116 CONTINUE                                                             000536
00654        CALL VALUE(3)                                                        000536
00655        CALL SHUNT(3,            WIDE(2),FACT(2))                            000537
00656        CALL VALUE(4)                                                        000543
00657        ETAM=(TR(1,1)-TR(1,4))/(TR(1,1)*(1-(PF(1,4)/PF(1,1))**(   Y)))      000545
00660        CALL SKIP(4,14)                                                      000561
00661        CALL VALUE(14)                                                       000564
00662        CALL SEPER(4,FSEP(1),FSEP(2))                                        000566
00663        CALL VALUE(5)                                                        000572
00664        CALL VALUE(15)                                                       000574
00665        DP=-DELP(4)                                                          000576
00666        CALL THROT(5,6,DP)                                                   000600
00667        CALL VALUE(6)                                                        000604
00670        TR(1,7)=TGEN+TAB                                                     000606
00671        DP=-DELP(6)                                                          000613
00672        CALL SINK(6,7,TR(1,7),DP)                                            000615
00673        CALL VALUE(7)                                                        000623
00674        DP=-DELP(7)                                                          000625
00675        CALL THROT(7,8,DP)                                                   000627
00676        HOUT=H(3,6)-H(3,7)                                                   000633
00677        ENER=ETATH(6)*ETAS(6)*(H(3,6)-H(3,7))                                000636
00700        THIN=TF(1,9)+459.69                                                  000642
00701        CALL SKIP(1,13)                                                      000645
00702        DO 120 L=12,10,-1                                                    000654
00705        DO 120 J=1,3,1                                                       000661
00710        WT(J,L )=WT(J,8)                                                     000661
00711        PF(J,L)=PF(J,L+1)/(1-DELP(L))                                        000662
00712    120 CONTINUE                                                             000673
00715        CALL SKIP(8,28)                                                      000673
00716        CALL VALUE(28)                                                       000676
00717        PRAT=PF(1,10)/PF(1,8)                                                000700
007          DO 121 N=1,NCOMP,1                                                   000706
00723        LC=(N+1)*10+8                                                        000706
00724    121 PRAT=PRAT/(1.-DELP(LC))                                              000713
00726        PRAT=PRAT**(1./NCOMP)                                                000723
00727        Y=WT(1,8)*RHEAT/(WT(1,8)*CP(1)+WT(2,8)*CP(2))                        000734
00730        DO 134 N=1,NCOMP,1                                                   000750
00733        DO 130 KAP=8,10,1                                                    000757
00736    130 LCOMP(KAP)=(N+1)*10+KAP                                              000757
00740        LC8=LCOMP(8)                                                         000764
00741        LC9=LCOMP(9)                                                         000767
00742        LC10=LCOMP(10)                                                       000775
00743        DP=-DELP(LC8)                                                        001001
00744        CALL SINK(LCOMP(8),LCOMP(9),THIN,DP)                                 001003
00745        CALL VALUE(LCOMP(9))                                                 001011
00746        DO 132 J=1,3,1                                                       001013
00751        TR(J,LC10      )=TR(1,LC9       )*PRAT**(Y/EFC)                      001031
00752        PF(J,LC10      )=PF(1,LC9       )*PRAT                               001033
00753    132 WT(J,LC10      )=WT(J,LC9       )                                    001036
00755        CALL VALUE(LCOMP(10))                                                001041
00756        LT=LCOMP(10)+8                                                       001043
00757        CALL SKIP(LCOMP(10),LT)                                              001046
00760        CALL VALUE(LT)                                                       001051
00761    134 CONTINUE                                                             001055
00763        CALL SKIP(LCOMP(10),10)                                              001055
00764        CALL VALUE(10)                                                       001060
00765        NOT=NREG                                                             001062
00766        IF((TR(1,10)+THETA).GE.TR(1,7))NOT=0                                 001064
00770        IF(NOT )135,135,137                                                  001072
00773    135 CALL SKIP(10,11)                                                     001075
00774        GO TO 139                                                            001100
00775    137 DO 136 J=1,3,1                                                       001102
01000        TR(J,8)=TR(1,10)+THETA                                               001107
01001        TR(J,7)=TGEN+TAB                                                     001111
01002    136 TR(J,11)=TR(J,7)-THETA                                               001113
01004        DO 138 L=7,8,1                                                       001121
01007    138 CALL VALUE(L)                                                        001121
```

```
01011        139 CALL VALUE(11)                                                         001126
01012            CALL VALUE(8)                                                          001127
01013            IF(TFFD-.0001)146,146,142                                              001131
01016        142 CALL SKIP(8,26)                                                        001135
01017            CALL VALUE(26)                                                         001140
01020            DP=-DELP(26)                                                           001142
01021            CALL SINK(26,8,TRFD,DP)                                                001144
01022            CALL VALUE(8)                                                          001151
01023            ENER=ENER+ETATH(26)*ETAS(26)*(H(3,26)-H(3,8))                          001153
01024            HOUT=HOUT+H(3,26)-H(3,8)                                               001162
01025            CALL SKIP(8,28)                                                        001166
01026            CALL VALUE(28)                                                         001171
01027        146 CONTINUE                                                               001174
01030            DP=-DELP(28)                                                           001174
01031            CALL SINK(8,29,TMIN,DP)                                                001175
01032            DP=-DELP(14)                                                           001202
01033            CALL THROT(15,16,DP)                                                   001204
01034            CALL VALUE(16)                                                         001210
01035            DP=-DELP(16)                                                           001212
01036            CALL THROT(16,17,DP)                                                   001214
01037            CALL VALUE(17)                                                         001220
01040            CALL SKIP(1,20)                                                        001222
01041            DO 122 J=1,3,1                                                         001234
01044            WT(J,18)=WT(J,17)                                                      001234
01045            DO 122 L=19,18,-1                                                      001240
01050            PF(J,L)=PF(J,L+1)/(1-DELP(L))                                          001240
01051        122 CONTINUE                                                               001250
01054            DO 123 J=1,3,1                                                         001250
01057        123 TR(J,18)=TR(J,17)+(PF(2,18)-PF(2,17))*V(3,17)*.001284*(1/EFP-1)*       001273
01057          1          WT(3,17)/(CP(1)*WT(1,17)+CP(2)*WT(2,17))                      001273
01061            CALL VALUE(18)                                                         001276
01062            HIN=H(3,1)-H(3,18)-H(3,11)                                             001300
01063            WORK=H(3,1)-H(3,4)-(H(3,18)-H(3,17))                                   001304
01064            ETAPRE(8) = ETAPRE(28)                                                 001312
01065            PREHT = 0                                                              001314
01066            HSTM=HOUT                                                              001315
01067            DO 226 N=1,NCOMP,1                                                     001322
01072            LC8=(N+1)*10+8                                                         001325
01073            IF(N.EQ.1)LC8=8                                                        001330
01075            LC9=(N+1)*10+9                                                         001335
01076            LC10=(N+2)*10                                                          001340
01077            WORK=WORK-(H(3,LC10      )-H(3,LC9))                                   001344
01100            ENER=ENER+ETATH(LC8)*(H(3,LC8)-H(3,LC9))*ETAS(LC8)                     001352
01101            PREHT=PREHT+             (H(3,LC8)-H(3,LC9))*ETAPRE(LC8)               001364
01102            HSTM=HSTM+     (H(3,LC8)-H(3,LC9))* ETAS(LC8)/(ETAS(LC8)+.00001)       001370
01103        226 HOUT=HOUT+(H(3,LC8       )-H(3,LC9))                                   001377
01105            HREHT = REHEAT * HSTM  /(1.0-REHEAT)                                   001404
01106            ENER = ENER + HREHT * ETATHR * EFRHT                                   001411
01107            ETAST=ENER/(HSTM+HREHT)                                                001415
01110            ENER=ENER+WORK                                                         001421
01111            POW=WIDE(1)*THICK*VEL*3.6*ENER/(V(3,2)*3412)                           001423
01112            RAT=SQRT(POWER/POW)                                                    001434
01113            WIDE(1)=WIDE(1)*RAT                                                    001442
01114            THICK=THICK*RAT                                                        001444
01115            IF(ABS(NITER*(RAT-1))-.0001)127,127,107                                001447
01120        127 WRITE(6,70)                                                            001460
01122            NREG=HOT
01123            POWER=POW                                                              001466
01124            WRITE(6,1)                                                             001470
01126            CALL REPORT(1)
01127            WRITE(6,2)                                                             001476
01131            CALL REPORT(2)
01132            IF(PIOUT-.001)208,208,206                                              001504
01135        206 WRITE(6,82)PIOUT                                                       001510
01140            GO TO 216
01141        208 IF(FOUT-.001)212,212,210                                               001516
01144        210 WRITE(6,86)FOUT                                                        001521
01147            GO TO 216
01150        212 WRITE(6,84)TFOUT                                                       001527
01153        216 CONTINUE                                                               001533
01154            WRITE(6,52)                                                            001533
01156            DO 124 I=1,40,1                                                        001541
01161        124 WRITE(6,62)DIST(I),WIDTH(I),TEMP(I),PRES(I),BETA(I),FGAS(I),           001541
01161          1          SLIP(I),EFF(I)                                                001541
01174            WRITE(6,3)                                                             001545
01176            CALL REPORT(3)
```

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01177              WRITE(6,4)                                                                  001553
01201              CALL REPORT(4)
01202              WRITE(6,5)                                                                  001561
01204              CALL REPORT(6)
01205              WRITE(6,307)                                                                001567
01207              IF(NREG.GE.1)WRITE(6,7)
01212              CALL REPORT(7)
01213              IF(TFFD-.001)226,228,227                                                    001605
01216         227  WRITE(6,308)                                                                001611
01220              CALL REPORT(26)
01221         228  CONTINUE                                                                    001620
01222              DO 126 N=1,NCOMP,1                                                          001620
01225              LC8=(N+1)*10+8                                                              001632
01226              IF(N.EQ.1)LC8=8                                                             001635
01230              LC9=(N+1)*10+9                                                              001642
01231              LC10=(N+2)*10                                                               001645
01232              WRITE(6,8)N                                                                 001651
01235              CALL REPORT(LC8)
01236              WRITE(6,9)N                                                                 001657
01241              CALL REPORT(LC9)
01242              WRITE(6,10)N                                                                001665
01245              CALL REPORT(LC10)
01246              ETAC=TR(1,LC9      )*(PRAT**Y-1)/(TR(1,LC10      )-TR(1,LC9))           001673
01247         126  WRITE(6,60)ETAC                                                             001713
01253              WRITE(6,11)                                                                 001721
01255              CALL REPORT(11)
01256              WRITE(6,15)                                                                 001727
01260              CALL REPORT(16)
01261              WRITE(6,17)                                                                 001735
01263              CALL REPORT(17)
01264              WRITE(6,18)                                                                 001743
01266              CALL REPORT(18)
01267              ETAHHD=WORK/HIN                                                             001751
01270              WRITE(6,61)HIN                                                              001754
01273              WRITE(6,64)HOUT
01276              WRITE(6,75)WORK
01301              WRITE(6,54),ETAH
01304              WRITE(6,66)ETAHHD
01307              ETATOT = ENER * EFSTCK / (HIN + HREHT - EFSTCK  * PREHT)
01310              WRITE(6,383)ETATH(6),ETATH(28),ETATH(38),ETATH(48),ETATH(58)                002007
01317              WRITE(6,266)ETAST
01322              ETA1=ENER/(HIN+HREHT-PREHT)
01323              ETA2=ENER/(HIN+HREHT)                                                       002024
01324              WRITE(6,354)ETA1                                                            002027
01327              WRITE(6,454)ETA2
01332              WRITE(6,254)ETATOT
01335              WRITE(6,68)
01337              WRITE(6,69)
01341              DH=H(3,1)-H(3,11)-H(3,18)
01342              DO 128 I=0,10,1                                                             002062
01345              DELH(11)=DH*I/10.                                                           002064
01346              DELH(18)=DH-DELH(11)                                                        002071
01347              DP=-DELP(11)                                                                002073
01350              CALL HEAT(11,12,DELH(11),DP)                                                002075
01351              CALL VALUE(12)                                                              002102
01352              DP=-DELP(18)                                                                002104
01353              CALL HEAT(10,19,DELH(18),DP)                                                002106
01354              CALL VALUE(19)                                                              002113
01355              PROP=I/10.                                                                  002115
01356         128  WRITE(6,62)PROP,TF(1,12),TF(2,19)                                           002120
01364              IF(NCOST.GE.1)CALL COST                                                     002126
01366              WRITE(6,271)                                                                002134
01370              GO TO 202
01371         199  CONTINUE                                                                    002141
01372              STOP                                                                        002141
01373              END                                                                         002144

     END OF COMPILATION:        NO  DIAGNOSTICS.

@FIN
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@FOR,IS          MHD.EFIZNC
FOR 0126-04/17/75-13:15:51 (,0)

   SUBROUTINE EFIZNC     ENTRY POINT 000375

   STORAGE USED: CODE(1) 000406; DATA(0) 000075; BLANK COMMON(2) 010165

   EXTERNAL REFERENCES (BLOCK, NAME)

    0003    EXP
    0004    SQRT

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0001     000024 340L       0001     000170 350L       0001     000345 370L       0000     000040 62F        0000 R 000022 AA
    0002     004160 B          0000 R 000023 BB         0002 R 010011 BETA       0000 R 000036 BOT        0000 R 000024 CC
    0002 R 010157 COND       0002 R 007715 CP         0002     007721 CV         0002     006535 DELH       0002     006251 DELP
    0002     006403 DELT       0000 R 000020 DISDEL     0002 R 007545 DIST       0000 R 000037 DPC        0000 R 000031 DS
    0000     000042 DTHS       0002 R 010164 EFDUCT     0002 R 007627 EFF        0000 R 000004 EFFI       0002     007021 ETAS
    0002     006667 ETATH      0002     002506 F          0000 R 000021 FAVE       0002 R 007401 FGAS       0002     005214 FLM
    0002     006256 FLMO       0002     005632 FLV        0002     003124 H          0000 R 000013 HDEL       0000 I 000011 J
    0000 I 000010 K          0000 I 000012 KAP        0000 R 000027 ORD1       0000 R 000030 ORD2       0000 R 000034 PAVE
    0000 R 000000 PC         0002 R 007726 PCOEF      0000 R 000015 PDEL       0002     001462 PF         0002     001034 PI
    0002 R 007153 PRES       0000 R 000014 RESIS      0002 R 010073 RG         0002     007723 RHEAT      0002     007722 RWORK
    0002     003542 S          0002     010163 SL         0000 R 000032 SLAVE      0002 R 007727 SLIP       0000 R 000026 SL1
    0000 R 000025 SL2        0000 R 000033 TAVE       0002 R 007235 TEMP       0002     000000 TF         0002 R 010155 THICK
    0000 R 000035 TOP        0002     000416 TR         0002     007725 TREF       0002 R 002070 V          0000 R 000016 VAVE
    0002 R 010160 VEL        0002 R 010156 VLOAD      0002 R 007317 VOL        0000 R 000017 VOLDEL     0002 R 010161 VOLT
    0002 R 007711 WIDE       0002 R 007463 WIDTH      0002 R 010162 WRAT       0002     004576 WT         0002     007724 Y


00101            SUBROUTINE EFIZNC(I,L)                                                          000003
00103            COMMON TF(3,90),TR(3,90),PI(3,90),PF(3,90),V(3,90),F(3,90),                     000003
00103           1       H(3,90),S(3,90),B(3,90),WT(3,90),FLM(3,90),FLV(3,90),FLMO,               000003
00103           2       DELP(90),DELT(90),DELH(90),ETATH(90),ETAS(90),                           000003
00103           3       PRES(50),TEMP(50),VOL(50),FGAS(50),WIDTH(50),DIST(50),                   000003
00103           4       EFF(50),WIDE(4),CP(4),CV,RWORK,RHEAT,Y,TREF,PCOEF,                       000003
00103           5       SLIP(50),BETA(50),RG(50),THICK,VLOAD,COND,VEL,VOLT,WRAT,SL,              000003
00103           6       EFDUCT                                                                   000003
00104            DIMENSION PC(4),EFFI(4)                                                         000003
00105         62 FORMAT(I9,0E14.4)                                                               000003
00106            PCOEF=    300.*.3048 /V(2,L)                                                    000003
00107            K=0                                                                             000006
00110            IF(EFDUCT.GE.0.0001) K=1                                                        000007
00112            PC(1)=PCOEF                                                                     000015
00113            PC(2)=PCOEF*1.4                                                                 000017
00114            J=0                                                                             000021
00115            KAP=0                                                                           000022
00116        340 J=J+1                                                                           000024
00117            HDEL=(TEMP(I)-TEMP(I-1))*(WRAT*CP(1)+(1-WRAT)*CP(2))                            000026
00117           1       +(1-WRAT)*(PRES(I)-PRES(I-1))*V(2,L)*.001284                             000026
00120            RESIS=EXP(3.6*BETA(I-1))/COND                                                   000050
00121            DIST(I)=DIST(I-1)-((THICK/VOLT)**2)*RESIS*VEL*HDEL*                             000057
00121           1       (SLIP(I-1)*BETA(I-1)/VOL(I-1)+(1-BETA(I-1)))/V(2,L))/                    000057
00121           2       (VLOAD*(1-VLOAD)*.060948)                                                000057
00122            PDEL=(PRES(I)-PRES(I-1))*32.16                                                  000104
00123            VAVE=(VOL(I)+VOL(I-1))/2.                                                       000107
00124            VOLDEL=VOL(I)-VOL(I-1)                                                          000113
00125            DISDEL=DIST(I)-DIST(I-1)                                                        000116
00126            FAVE=(FGAS(I)+FGAS(I-1))/2                                                      000120
00127            AA=FAVE/(1.-FAVE)                                                               000124
00130            BB=-PDEL/(VEL*VEL*PC(J)*DISDEL)                                                 000130
00131            CC=VOLDEL/(VAVE*VAVE*PC(J)*DISDEL)                                              000137
00132            SL2=SLIP(I-1)                                                                   000144
00133            SL1=SL2*1.2                                                                     000146
00134            ORD1=1.-SQRT(((SL1+AA)/SL1)**3)*(BB+CC*SL1*SL1))-SL1                            000150
00135        350 ORD2=1.+SQRT(((SL2+AA)/SL2)**3)*(BB+CC*SL2*SL2))-SL2                            000170
00136            DS=-ORD2*(SL2-SL1)/(ORD2-ORD1)                                                  000210
00137            ORD1=ORD2                                                                       000216
00140            SL1=SL2                                                                         000220
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00141      SL2=SL2+DS                                                        000222
00142      IF(ABS(DS/SL2).GT.0.00005)GO TO 350                               000224
00144      SLIP(I)=SL2                                                       000231
00145      SLAVE=(SLIP(I)+SLIP(I-1))/2                                       000232
00146      TAVE=(TEMP(I)+TEMP(I-1))/2                                        000235
00147      PAVE=(PRES(I)+PRES(I-1))*32.16/2                                  000241
00150      RG(I)=VEL*VEL*SLAVE*(SLAVE*VOLDEL)/DISDEL                         000246
00151      BETA(I)=FGAS(I)/(FGAS(I)+SLIP(I)*(1-FGAS(I)))                     000255
00152      TOP=RG(I)*BETA(I)+PDEL/DISDEL                                     000264
00153      BOT=(RG(I)+PDEL/DISDEL)*BETA(I)*SLIP(I)                           000272
00154      EFFI(J)=TOP/(BOT+        PDEL*(1-BETA(I))/DISDEL)                 000276
00155      IF(KAP*K-1)370,340,344                                            000306
00160  344 DPC=-(PC(J)-PC(J-1))*(EFFI(J)-EFDUCT)/(EFFI(J)-EFFI(J-1))         000313
00161      PC(1)=PC(2)                                                       000323
00162      PC(2)=PC(2)+DPC                                                   000325
00163      EFFI(1)=EFFI(2)                                                   000327
00164      J=J-1                                                             000331
00165      IF(ABS((EFFI(J)-EFDUCT)/EFDUCT).GT.0.001)GO TO 340                000334
00167  370 EFF(I)=EFFI(1)                                                    000345
00170      IF(K.EQ.1)EFF(I)=EFDUCT                                           000346
00172      WIDTH(I)=WIDE(I)*(1-BETA(1))/(1-BETA(I))                          000353
00173      RETURN                                                            000362
00174      END                                                               000405

END OF COMPILATION:        NO  DIAGNOSTICS.
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WFOR,IS          MOD.EQUATE
FOR 0T26-04/17/75-13:16:02 (,0)

   SUBROUTINE EQUATE     ENTRY POINT 000061

   STORAGE USED: CODE(1) 000071; DATA(0) 000016; BLANK COMMON(2) 010164

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0001      000032 105G        0001      000036 121G        0002      004160 G         0002      010011 BETA        0002      010157 COND
    0002      007715 CP          0002      007721 CV          0002      006535 DELH      0002      006251 DELP        0002      006403 DELT
    0002      007545 DIST        0000      000001 DTHS        0002      007627 EFF       0002      007021 ETAS        0002      006667 ETATH
    0002  R   002506 F           0002  R   007401 FGAS        0002      005214 FLH       0002      006250 FLMO        0002      005632 FLV
    0002      003124 H           0000  I   000000 J           0002      007726 PCOEF     0002  R   001452 PF          0002      001034 PI
    0002  R   007153 PRES        0002      010073 RG          0002      007723 RHEAT     0002      007722 RWORK       0002      003542 S
    0002      010163 SL          0002      007727 SLIP        0002  R   007235 TEMP      0002      000000 TF          0002      010155 THICK
    0002  R   000416 TR          0002      007725 TREF        0002  R   002070 V         0002      010160 VEL         0002      010156 VLOAD
    0002  R   007317 VOL         0002      010161 VOLT        0002  R   007711 WIDE      0002  R   007463 WIDTH       0002      010162 WRAT
    0002  R   004576 WT          0002      007724 Y


 00101      1.           SUBROUTINE EQUATE(L)                                                          000012
 00103      2.           COMMON TF(3,90),TR(3,90),PI(3,90),PF(3,90),V(3,90),F(3,90),                   000012
 00103      3.          1      H(3,90),S(3,90),G(3,90),WT(3,90),FLH(3,90),FLV(3,90),FLMO,              000012
 00103      4.          2      DELP(90),DELT(90),DELH(90),ETATH(90),ETAS(90),                          000012
 00103      5.          3      PRES(50),TEMP(50),VOL(50),FGAS(50),WIDTH(50),DIST(50),                  000012
 00103      6.          4      EFF(50),WIDE(4),CP(4),CV,RWORK,RHEAT,Y,TREF,PCOEF,                      000012
 00103      7.          5      SLIP(50),BETA(50),RG(50),THICK,VLOAD,COND,VEL,VOLT,WRAT,SL               000012
 00104      8.           DO 804 J=1,3,1                                                                000012
 00107      9.           TR(J,L+1)=TEMP(40)                                                            000012
 00110     10.       804 PF(J,L+1)=PRES(40)                                                            000013
 00112     11.           WIDE(2)=WIDTH(40)                                                             000016
 00113     12.           F(1,L+1)=FGAS(40)                                                             000020
 00114     13.           F(2,L+1)=1-FGAS(40)                                                           000022
 00115     14.           F(3,L+1)=1.                                                                   000024
 00116     15.           V(1,L+1)=VOL(40)                                                              000026
 00117     16.           V(2,L+1)=V(2,L)                                                               000030
 00120     17.           DO 806 J=1,3,1                                                                000036
 00123     18.       806 WT(J,L+1)=WT(J,L)                                                             000036
 00125     19.           V(3,L+1)=(V(1,L+1)*WT(1,L+1)+V(2,L+1)*WT(2,L+1))/WT(3,L+1)                   000040
 00126     20.           RETURN                                                                        000047
 00127     21.           END                                                                           000070

     END OF COMPILATION:        NO  DIAGNOSTICS.
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WFOR,IS        MHD.FIXP
FOR UT28-04/17/75-13:17:49 (,0)

    SUBROUTINE FIXP       ENTRY POINT 000130

    STORAGE USED: CODE(1) 000146; DATA(0) 000026; BLANK COMMON(2) 010164

    EXTERNAL REFERENCES (BLOCK, NAME)

     0003    EF1ZNC
     0004    EQUATE
     0005    XPRR

    STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

     0001     000050 1216       0002     004160 B         0002 R 010011 BETA     0002     010157 CONO     0002     007715 CW
     0002     007721 CV         0002     006535 DELH      0002     006251 DELP     0002     006403 DELT     0002 R 007545 DIST
     0000 R 000000 DP          0000     000004 DYNS      0002 R 007627 EFF      0002     007021 ETAS     0002     006667 ETATH
     0002 R 002506 F           0002 R 007401 FGAS      0002     005219 FLM      0002     006250 FLMO     0002     005632 FLV
     0002     003124 H          0000 I 000002 I         0000 I 000001 L        0002     007726 PCOEF    0002 R 001452 PF
     0002     001034 PI         0002 R 007153 PRES      0002 R 010073 RG       0002     007723 RHEAT    0002 R 007722 RWORK
     0002     003542 S          0002 R 010163 SL        0002 R 007727 SLIP     0002 R 007235 TEMP     0002     000000 TE
     0002     010155 THICK      0002 R 000416 TR        0002     007725 TREF     0002 R 002070 V        0002     010160 VEL
     0002 R 010156 VLOAD       0002 R 007317 VOL       0002     010161 VOLT     0000 R 000003 VRAT     0002 R 007711 WIDE
     0002 R 007463 WIDTH       0002 R 010162 WRAT      0002 R 004576 WT       0002 R 007724 Y


00101     1*            SUBROUTINE FIXP(LOCAT)                                                 000000
00103     2*            COMMON TF(3,90),TR(3,90),PI(3,90),PF(3,90),V(3,90),F(3,90),            000000
00103     3*           1      H(3,90),S(3,90),B(3,90),WT(3,90),FLM(3,90),FLV(3,90),FLMO,      000000
00103     4*           2      DELP(90),DELT(90),DELH(90),ETATH(90),ETAS(90),                  000000
00103     5*           3      PRES(50),TEMP(50),VOL(50),FGAS(50),WIDTH(50),DIST(50),          000000
00103     6*           4      EFF(50),WIDE(4),CP(4),CV,RWORK,RHEAT,Y,TREF,PCOEF,              000000
00103     7*           5      SLIP(50),BETA(50),RG(50),THICK,VLOAD,COND,VEL,VOLT,WRAT,SL      000000
00104     8*            DP=(PF(1,LOCAT+1)/PF(1,LOCAT))**(1./39.)                             000000
00105     9*            EFF(1)=VLOAD                                                           000011
00106    10*            SLIP(1)=SL                                                             000013
00107    11*            L=LOCAT                                                                000015
00110    12*            BETA(1)=F(1,L)/(F(1,L)+SL*(1-F(1,L)))                                  000017
00111    13*            RG(1)=0                                                                000030
00112    14*            PRES(1)=PF(1,LOCAT)                                                    000031
00113    15*            TEMP(1)=TR(1,LOCAT)                                                    000034
00114    16*            FGAS(1)=F(1,LOCAT)                                                     000036
00115    17*            VOL(1)=V(1,LOCAT)                                                      000040
00116    18*            WIDTH(1)=WIDE(1)                                                       000042
00117    19*            DIST(1)=0.                                                             000044
00120    20*            DO 622 I=2,40,1                                                        000050
00123    21*            TEMP(I)=TEMP(I-1)-TEMP(I-1)*(1-DP**Y)*EFF(I-1)                         000050
00124    22*            PRES(I)=PRES(I-1)*DP                                                   000060
00125    23*            VOL(I)=RWORK*TEMP(I)/PRES(I)                                           000063
00126    24*            VRAT=VOL(I)/V(2,LOCAT)                                                 000066
00127    25*            WRAT=WT(1,LOCAT)/WT(3,LOCAT)                                           000070
00130    26*            FGAS(I)=      WRAT   *VRAT/(1+(VRAT-1)*WRAT)                           000073
00131    27*            CALL EF1ZNC(I,L)                                                       000102
00132    28*        622 EFF(I)=VLOAD*EFF(I)                                                    000105
00134    29*            CALL EQUATE(LOCAT)                                                     000112
00135    30*            RETURN                                                                 000114
00136    31*            END                                                                    000145

    END OF COMPILATION:        NO  DIAGNOSTICS.
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WFOR,IS      MHD.FIXT
FOR 0T28-09/17/75-13:17:52 (,0)

SUBROUTINE FIXT        ENTRY POINT 000117

STORAGE USED: CODE(1) 000135; DATA(0) 000022; BLANK COMMON(2) 010164

EXTERNAL REFERENCES (BLOCK, NAME)

 0003    EFIZNC
 0004    EQUATE

STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

 0001     000041 1216     0002     004160 B       0002 R 010011 BETA     0002     010157 COND     0002     007715 CP
 0002     007721 CV       0002     006535 DELH    0002     006251 DELP     0002     006403 DELT     0002 R 007595 DIST
 0000 R 000000 DT       0000     000003 DYNS    0002 R 007627 EFF      0002     007021 ETAS     0002     006667 ETATH
 0002 R 002506 F        0002 R 007401 FGAS    0002     005214 FLM      0002     006250 FLMC     0002     005632 FLV
 0002     003124 H        0000 I 000001 I       0002     007726 PCOEF    0002 R 001452 PF       0002     001034 PI
 0002 R 007153 PRES     0002 R 010073 RG      0002     007723 RHEAT    0002 R 007722 RWORK    0002     003542 S
 0002 R 010163 SL       0002 R 007727 SLIP    0002 R 007235 TEMP     0002     000000 TF       0002     010155 THICK
 0002 R 004416 TR       0002     007725 TREF    0002 R 002070 V        0002     010160 VEL      0002 R 010156 VLOAD
 0002 R 007317 VOL      0002     010161 VOLT    0000 R 000002 VRAT     0002 R 007711 WIDE     0002 R 007463 WIDTH
 0002 R 010162 WRAT     0002 R 004576 WT      0002 R 007724 Y

00101          SUBROUTINE FIXT(L)                                                              000000
00103          COMMON TF(3,90),TR(3,90),PI(3,90),PF(3,90),V(3,90),F(3,90),                    000000
00103        1       H(3,90),S(3,90),B(3,90),WT(3,90),FLM(3,90),FLV(3,90),FLMC,               000000
00103        2       DELP(90),DELT(90),DELH(90),ETATH(90),ETAS(90),                           000000
00103        3       PRES(50),TEMP(50),VOL(50),FGAS(50),WIDTH(50),DIST(50),                   000000
00103        4       EFF(50),WIDE(4),CP(4),CV,RWORK,RHEAT,Y,TREF,PCOEF,                       000000
00103        5       SLIP(50),BETA(50),RG(50),THICK,VLOAD,COND,VEL,VOLT,WRAT,SL               000000
00104          DT=(TR(1,L+1)-TR(1,L))/39.                                                      000000
00105          PRES(1)=PF(1,L)                                                                 000005
00106          TEMP(1)=TR(1,L)                                                                 000007
00107          VOL(1)=V(1,L)                                                                   000011
00110          WIDTH(1)=WIDE(1)                                                                000013
00111          DIST(1)=0                                                                       000015
00112          FGAS(1)=F(1,L)                                                                  000016
00113          EFF(1)=VLOAD                                                                    000020
00114          SLIP(1)=SL                                                                      000022
00115          BETA(1)=F(1,L)/(F(1,L)+SL*(1-F(1,L)))                                           000024
00116          RG(1)=B                                                                         000032
00117          WRAT=WT(1,L)/WT(3,L)                                                            000033
00120          DO 802 I=2,40,1                                                                 000041
00123          PRES(I)=PRES(I-1)*(1+(DT/Y)/(TEMP(I-1)*EFF(I-1)))                               000043
00124          TEMP(I)=TEMP(I-1)+DT                                                            000053
00125          VOL(I)=RWORK*TEMP(I)/PRES(I)                                                    000056
00126          VRAT=VOL(I)/V(2,L)                                                              000061
00127          FGAS(I)=WRAT*VRAT/(1+(VRAT-1)*WRAT)                                             000063
00130          CALL EFIZNC(I,L)                                                                000072
00131      802 EFF(I)=VLOAD*EFF(I)                                                             000075
00133          CALL EQUATE(L)                                                                  000102
00134          RETURN                                                                          000104
00135          END                                                                             000134

    END OF COMPILATION:        NO  DIAGNOSTICS.
```

```
@FOR,IS         MHD.FIXV
FOR UT28-04/17/75-13:17:55 (,0)

SUBROUTINE FIXV       ENTRY POINT 000045

STORAGE USED: CODE(1) 000055; DATA(0) 000010; BLANK COMMON(2) 010164

EXTERNAL REFERENCES (BLOCK, NAME)

  0003    FIXP

STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

 0001     000017 832L      0002     004160 B        0002     010011 BETA     0002     010157 COND     0002     007715 CP
 0002     007721 CV        0002     006535 DELH     0002     006251 DELP     0002     006403 DELT     0002     007545 DIST
 0000     000003 DYNS      0002     007627 EFF      0002     007021 ETAS     0002     006667 ETATH    0002 R   002506 F
 0000 R   000001 FF        0002     007401 FGAS     0002     005214 FLH      0002     006250 FLMO     0002     005632 FLV
 0002     003124 H         0002     007726 PCOEF    0002 R   001452 PF       0002     001034 PI       0002     007153 PRES
 0002     010073 RG        0002     007723 RHEAT    0002 R   007722 RWORK    0002     003542 S        0002     010163 SL
 0002     007727 SLIP      0000 R   000002 TEM      0002 R   007235 TEMP     0002     000000 TF       0002     010155 THICK
 0002 R   000416 TR        0002     007725 TREF     0002 R   002070 V        0002     010160 VEL      0002     010156 VLOAD
 0002     007317 VOL       0002     010161 VOLT     0000 R   000000 VV       0002     007711 WIDE     0002     007463 WIDTH
 0002     010162 WRAT      0002 R   004576 WT       0002     007724 Y

00101           SUBROUTINE FIXV(LOCAT)                                                000000
00103           COMMON (F(3,90),TR(3,90),PI(3,90),PF(3,90),V(3,90),F(3,90),           000000
00103          1       H(3,90),S(3,90),B(3,90),WT(3,90),FLH(3,90),FLV(3,90),FLMO,     000000
00103          2       DELP(90),DELT(90),DELH(90),ETATH(90),ETAS(90),                 000000
00103          3       PRES(50),TEMP(50),VOL(50),FGAS(50),WIDTH(50),DIST(50),         000000
00103          4       EFF(50),WIDE(4),CP(4),CV,RWORK,RHEAT,Y,TREF,PCOEF,             000000
00103          5       SLIP(50),BETA(50),RG(50),THICK,VLOAD,COND,VEL,VOLT,WRAT,SL     000000
00104           VV      =V(2,LOCAT)*(1-WT(1,LOCAT))*F(1,LOCAT+1)/((1-F(1,LOCAT+1))    000000
00104          1        *WT(1,LOCAT))                                                 000000
00105           FF=F(1,LOCAT+1)                                                       000012
00106           TEMP(40)=TR(1,LOCAT)                                                  000014
00107       832 TEM=TEMP(40)                                                          000017
00110           PF(1,LOCAT+1)=RWORK*TEM/VV                                            000020
00111           CALL FIXP(LOCAT)                                                      000025
00112           IF(ABS((FF-F(1,LOCAT+1))/FF)-.001)834,834,832                         000027
00115       834 CONTINUE                                                              000040
00116           RETURN                                                                000050
00117           END                                                                   000054

     END OF COMPILATION:        NO  DIAGNOSTICS.
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```
WFOR,IS          MHD,HEAT
FOR 0126-04/17/75-13:17:59 (,0)

   SUBROUTINE HEAT        ENTRY POINT 000056

   STORAGE USED: CODE(1) 000073; DATA(0) 000012; BLANK COMMON(2) 010164

   EXTERNAL REFERENCES (BLOCK, NAME)

    0003     VOLUM

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0001     000034 1L76          0002     004160 B          0002     010011 BETA         0002     010157 COND          0002 R 007715 CP
    0002     007721 CV            0002     006535 DELH       0002     006251 DELP         0002     006403 DELT          0002   007545 DIST
    0000 R  000000 DT             0000     000002 DYN$       0002     007627 EFF          0002     007021 ETAS          0002   006667 ETATH
    0002     002506 F             0002     007401 FGAS       0002     005214 FLH          0002     006250 FLHO          0002   005632 FLV
    0002     003124 H             0000 I  000001 J           0002     007726 FCOEF        0002 R  001952 PF            0002   001034 PI
    0002     007153 PRES          0002     010073 RG         0002     007723 RHEAT        0002     007722 RWORK         0002   003542 S
    0002     010163 SL            0002     007727 SLIP       0002     007235 TEMP         0002     000000 TF            0002   010155 THICK
    0002 R  000416 TR             0002     007725 TREF       0002 R  002070 V            0002     010160 VEL           0002   010156 VLOAD
    0002     007317 VOL           0002     010161 VOLT       0002     007711 WIDE         0002     007463 WIDTH         0002   010162 WRAT
    0002 R  004576 WT             0002     007724 Y


00101      1*              SUBROUTINE HEAT(L1,L2,DH,DP)                                              000004
00103      2*              COMMON TF(3,90),TR(3,90),PI(3,90),PF(3,90),V(3,90),F(3,90),               000004
00103      3*             1     H(3,90),S(3,90),B(3,90),WT(3,90),FLH(3,90),FLV(3,90),FLHO,           000004
00103      4*             2     DELP(90),DELT(90),DELH(90),ETATH(90),ETAS(90),                       000004
00103      5*             3     PRES(50),TEMP(50),VOL(50),FGAS(50),WIDTH(50),DIST(50),               000004
00103      6*             4     EFF(50),WIDE(4),CP(4),CV,RWORK,RHEAT,Y,TREF,PCOEF,                   000004
00103      7*             5     SLIP(50),BETA(50),RG(50),THICK,VLOAD,COND,VEL,VOLT,WRAT,SL           000004
00104      8*              DP=DP*PF(3,L1)*.001284                                                    000004
00105      9*              DT=(DH-V(2,L1)*WT(2,L1)*DP)/(WT(1,L1)*CP(1)+WT(2,L1)*CP(2))               000010
00106     10*              DO 880 J=1,3,1                                                            000034
00111     11*              TR(J,L2)=TR(J,L1)+DT                                                      000034
00112     12*              PF(J,L2)=PF(J,L1)+DP                                                      000036
00113     13*          880 WT(J,L2)=WT(J,L1)                                                         000041
00115     14*              CALL VOLUM(L2)                                                            000044
00116     15*              RETURN                                                                    000046
00117     16*              END                                                                       000072

      END OF COMPILATION:        NO  DIAGNOSTICS.
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```
WFOR,IS        MHD-REPORT
FOR 0T2B-04/17/75-13:16:03 (,0)

   SUBROUTINE REPORT      ENTRY POINT 000067

   STORAGE USED: CODE(1) 000072; DATA(0) 000257; BLANK COMMON(2) 007726

   EXTERNAL REFERENCES (BLOCK, NAME)

    0003     NIOCLS
    0004     NSCKS
    0005     NNWFUS
    0006     NOFUS

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0000     000135 120D     0000     000141 122D     0000     000150 127D     0000     000157 134D     0000     000166 141D
    0000     000175 146D     0000     000204 153D     0000     000213 160D     0000     000222 165D     0000     000231 172D
    0000     000240 177D     0000     000247 204D     0000     000000 502F     0000     000002 504F     0000     000011 506F
    0000     000021 508F     0000     000027 510F     0000     000041 512F     0000     000054 514F     0000     000064 516F
    0000     000075 518F     0000     000104 520F     0000     000116 522F     0000     000125 524F     0002 R 004160 B
    0002     007715 CP       0002     007721 CV       0002     006535 DELH     0002     006251 DELP     0002     006403 DELT
    0002     007645 DIST     0000     000253 DYN$     0002     007627 EFF      0002     007021 ETAS     0002     006667 ETATH
    0002 R 002506 F          0002     007401 FGAS     0002 R 005214 FLM       0002     006250 FLMO     0002 R 005632 FLV
    0002 R 003124 H          0002     001452 PF       0002 R 001034 PI        0002     007153 PRES     0002     007723 RHEAT
    0002     007722 RWORK    0002 R 003542 S          0002     007235 TEMP     0002 R 000000 TF        0002     000416 TR
    0002     007725 TREF     0002 R 002070 V          0002     007317 VOL      0002     007711 WIDE     0002     007465 WIDTH
    0002 R 004576 WT         0002     007724 Y


00101              SUBROUTINE REPORT(L)                                                         000002
00103              COMMON TF(3,90),TR(3,90),PI(3,90),PF(3,90),V(3,90),F(3,90),                  000002
00103             1     H(3,90),S(3,90),B(3,90),WT(3,90),FLM(3,90),FLV(3,90),FLMO,              000002
00103             2     DELP(90),DELT(90),DELH(90),ETATH(90),ETAS(90),                          000002
00103             3     PRES(50),TEMP(50),VOL(50),FGAS(50),WIDTH(50),DIST(50),                  000002
00103             4     EFF(50),WIDE(4),CP(4),CV,RWORK,RHEAT,Y,TREF                             000002
00104          502 FORMAT('0')                                                                  000002
00105          504 FORMAT(T55,'GAS',T66,'LIQUID',T78,'TOTAL')                                   000002
00106          506 FORMAT('0',T2,'TEMPERATURE,DEG.F',T51,3F12.2)                                000002
00107          508 FORMAT(T2,'PRESSURE,PSI',T51,3F12.2)                                         000002
00110          510 FORMAT(T2,'MASS FRACTION,REFERRED TO MHD DUCT INLET',T51,3F12.6)             000002
00111          512 FORMAT(T2,'ENTHALPY,BTU PER POUND TOTAL AT MHD DUCT INLET',                  000002
00111             1     T51,3F12.3)                                                             000002
00112          514 FORMAT(T2,'ENTROPY,BTU/R-LB(INLET MASS)',T51,3F12.4)                         000002
00113          516 FORMAT(T2,'AVAILABILITY,BTU/LB(INLET MASS)',T51,3F12.4)                      000002
00114          518 FORMAT(T2,'VOLUME FRACTION,LOCAL',T51,3F12.6)                                000002
00115          520 FORMAT(T2,'SPECIFIC VOLUME,CUBIC FEET PER POUND',T51,3F12.4)                 000002
00116          522 FORMAT(T2,'MASS FLOW RATE, LB/SEC',T51,3F12.2)                               000002
00117          524 FORMAT(T2,'VOLUME FLOW RATE,CU.FT/SEC',T51,3F12.1)                           000002
00120              WRITE(6,504)                                                                 000002
00122              WRITE(6,506)TF(1,L),TF(2,L),TF(3,L)
00127              WRITE(6,508)PI(1,L),PI(2,L),PI(3,L)
00134              WRITE(6,510)WT(1,L),WT(2,L),WT(3,L)
00141              WRITE(6,512)H(1,L),H(2,L),H(3,L)
00146              WRITE(6,514)S(1,L),S(2,L),S(3,L)
00153              WRITE(6,516)B(1,L),B(2,L),B(3,L)
00160              WRITE(6,518)F(1,L),F(2,L),F(3,L)
00165              WRITE(6,520)V(1,L),V(2,L),V(3,L)
00172              WRITE(6,522)FLM(1,L),FLM(2,L),FLM(3,L)
00177              WRITE(6,524)FLV(1,L),FLV(2,L),FLV(3,L)
00204              WRITE(6,502)
00206              RETURN
00207              END                                                                          000071

     END OF COMPILATION:         NO  DIAGNOSTICS.
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```
WFOR,IS        MHD.SEPER
FOR 0T28-04/17/75-13:18:08 (,0)

  SUBROUTINE SEPER      ENTRY POINT 000106

  STORAGE USED: CODE(1) 000120; DATA(0) 000041; BLANK COMMON(2) 010164

  EXTERNAL REFERENCES (BLOCK, NAME)

   0003   VOLUM

  STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

   0001     000007 116G     0001     000037 114G     0001     000050 122G     0002    004160 B         0002    010011 BETA
   0002     010157 COND     0002     007715 CP       0002     007721 CV       0002    006535 DELH      0002    006251 DELP
   0002     006403 DELT     0002     007545 DIST     0000     000020 DYN$     0002    007627 EFF       0002    007021 ETAS
   0002     006667 ETATH    0002     002506 F        0000 R   000003 FC       0002    007401 FGAS      0002    005214 FLH
   0002     006250 FLHD     0002     005632 FLV      0000 R   000000 FS       0002    003124 H         0000 I  000016 J
   0000 I   000014 L        0000 I   000015 LL       0000 I   000017 LLL      0002    007726 PCOEF     0002 R  001452 PF
   0002     001034 PI       0002     007153 PRES     0002     010073 RG       0002    007723 RHEAT     0002    007722 RWORK
   0002     003542 S        0002     010163 SL       0002     007727 SLIP     0002    007235 TEMP      0002    000000 TE
   0002     010155 THICK    0002 R   000416 TR       0002     007725 TREF     0002    002070 V         0002    010160 VEL
   0002     010156 VLOAD    0002     007317 VOL      0002     010161 VOLT     0002    007711 WIDE      0002    007463 WIDTH
   0002     010162 WRAT     0002 R   004576 WT       0002     007724 Y

 00101      1*           SUBROUTINE SEPER(LOCAT,FS1,FS2)                                          000000
 00103      2*           COMMON TF(3,90),TR(3,90),PI(3,90),PF(3,90),V(3,90),F(3,90),              000000
 00103      3*          1      H(3,90),S(3,90),B(3,90),WT(3,90),FLH(3,90),FLV(3,90),FLHD,          000000
 00103      4*          2      DELP(90),DELT(90),DELH(90),ETATH(90),ETAS(90),                      000000
 00103      5*          3      PRES(50),TEMP(50),VOL(50),FGAS(50),WIDTH(50),DIST(50),              000000
 00103      6*          4      EFF(50),WIDE(4),CP(4),CV,RWORK,RHEAT,Y,TREF,PCOEF,                  000000
 00103      7*          5      SLIP(50),BETA(50),RG(50),THICK,VLOAD,COND,VEL,VOLT,WRAT,SL         000000
 00104      8*           DIMENSION FS(3),FC(3,3)                                                  000000
 00105      9*           FS(1)=FS1                                                                000000
 00106     10*           FS(2)=FS2                                                                000001
 00107     11*           DO 406 L=1,2,1                                                           000007
 00112     12*           LL=LOCAT+(L-1)*10                                                        000020
 00113     13*           DO 402 J=1,3,1                                                           000025
 00116     14*           TR(J,LL+1)=TR(J,LL)                                                      000037
 00117     15*       402 PF(J,LL+1)=PF(J,LL)                                                      000040
 00121     16*           DO 404 J=1,2,1                                                           000050
 00124     17*           FC(J,L)=FS(J)*(3-2*L)+L-1                                                000050
 00125     18*       404 WT(J,LL+1)=WT(J,LL)*FC(J,L)                                              000054
 00127     19*           WT(3,LL+1)=WT(1,LL+1)+WT(2,LL+1)                                         000060
 00130     20*           LLL=LL+1                                                                 000064
 00131     21*       406 CALL VOLUM(LLL)                                                          000067
 00133     22*           RETURN                                                                   000074
 00134     23*           END                                                                      000117

      END OF COMPILATION:        NO DIAGNOSTICS.
```

```
@FOR,IS          HHD.SHUNT
FOR UT28-04/17/75-13:16:13 (,0)

   SUBROUTINE SHUNT      ENTRY POINT 000077

   STORAGE USED: CODE(1) 000114; DATA(0) 000024; BLANK COMMON(2) 010164

   EXTERNAL REFERENCES (BLOCK, NAME)

    0003   VOLUM
    0004   EXP
    0005   ALOG

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0001     000052 111G      0002     004160 B         0002     010011 BETA      0002 R 010157 COND      0002 R 007715 CP
    0002     007721 CV        0002 R 006535 DELH      0002     006251 DELP      0002 R 006403 DELT      0002   007545 DIST
    0000     000003 DYNS      0002     007627 EFF       0002     007021 ETAS      0002   006667 ETATH     0002 R 002506 F
    0002     007401 FGAS      0002     005214 FLH       0002     006250 FLMU      0002   005632 FLV       0002   003124 H
    0000 I 000002 J         0002     007726 FCOEF     0002 R 001452 PF        0002   001034 PI        0000 R 000000 PIE
    0002     007153 PRES      0000 R 000001 RESIS     0002     010073 RG        0002   007723 RHEAT     0002   007722 RWORK
    0002     003542 S         0002     010163 SL        0002     007727 SLIP      0002   007235 TEMP      0002   000000 TF
    0002     010155 THICK     0002 R 000416 TR        0002     007725 TREF      0002 R 002070 V         0002 R 010160 VEL
    0002 R 010156 VLOAD     0002     007317 VOL       0002 R 010161 VOLT      0002   007711 WIDE      0002   007463 WIDTH
    0002     010162 WRAT      0002 R 004576 WT        0002     007724 Y


 00101      1*             SUBROUTINE SHUNT(L,             WTH,FCT)                                        000007
 00103      2*             COMMON TF(3,90),TR(3,90),PI(3,90),PF(3,90),V(3,90),F(3,90),                     000007
 00103      3*            1      H(3,90),S(3,90),B(3,90),WT(3,90),FLH(3,90),FLV(3,90),FLMU,               000007
 00103      4*            2      DELP(90),DELT(90),DELH(90),ETATH(90),ETAS(90),                             000007
 00103      5*            3      PRES(50),TEMP(50),VOL(50),FGAS(50),WIDTH(50),DIST(50),                     000007
 00103      6*            4      EFF(50),WIDE(4),CP(4),CV,RWORK,RHEAT,Y,TREF,PCOEF,                         000007
 00103      7*            5      SLIP(50),BETA(50),RG(50),THICK,VLOAD,COND,VEL,VOLT,WRAT,SL                 000007
 00104      8*             PIE=3.14159                                                                     000007
 00105      9*             RESIS=EXP(3.8*F(1,L))/COND                                                      000011
 00106     10*             DELH(L)=ALOG(2)*VOLT*VOLT*V(3,L)*FCT*.000946*VLOAD*VLOAD/                       000020
 00106     11*            1      (PIE*RESIS*WTH*VEL)                                                       000020
 00107     12*             DELT(L)=DELH(L)/(WT(1,L)*CP(1)+WT(2,L)*CP(2))                                   000037
 00110     13*             DO 602 J=1,3,1                                                                  000052
 00113     14*             TR(J,L+1)=TR(J,L)+DELT(L)                                                       000052
 00114     15*             PF(J,L+1)=PF(J,L)                                                               000054
 00115     16*         602 WT(J,L+1)=WT(J,L)                                                               000056
 00117     17*             CALL VOLUM(L+1)                                                                 000061
 00120     18*             RETURN                                                                          000066
 00121     19*             END                                                                             000113

      END OF COMPILATION:        NO  DIAGNOSTICS.
```

```
@FOR,IS          MHD.SINK
FOR CT2B-04/17/75-13:16:17 (,0)

   SUBROUTINE SINK        ENTRY POINT 000065

   STORAGE USED: CODE(1) 000102; DATA(0) 000017; BLANK COMMON(2) 010164

   EXTERNAL REFERENCES (BLOCK, NAME)

    0003    VOLUM
    0004    ALOG

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0001     000023 1656      0002     004166 B        0002     010011 BETA     0002     010157 CONU     0002     007715 CP
    0002     007721 CV        0002     006535 DELH     0002     006261 DELP     0002     006403 DELT     0002     007545 DIST
    0000     000002 DYNS      0002     007627 EFF      0002     007021 ETAS     0002 R   006667 ETATH    0002     002506 F
    0002     007401 FGAS      0002     005214 FLH      0002     006250 FLMO     0002     005632 FLV      0002     003124 H
    0000 I   000000 J         0002     007726 PCOEF    0002 R   001452 PF       0002     001034 PI       0002     007153 PRES
    0002     010073 RG        0002     007723 RHEAT    0002     007722 RWORK    0002     003542 S        0002     010163 SL
    0002     007727 SLIP      0002     007235 TEMP     0002     000000 TF       0002     010155 THICK    0002 R   000416 TR
    0002 R   007725 TREF      0000 R   000001 TXX      0002     002070 V        0002     010160 VEL      0002     010156 VLOAD
    0002     007317 VOL       0002     010161 VOLT     0002     007711 WIDE     0002     007463 WIDTH    0002     010162 WRAT
    0002 R   004576 WT        0002     007724 Y


 00101              SUBROUTINE SINK(L1,L2,T2,DP)                                                000007
 00103              COMMON TF(3,90),TR(3,90),PI(3,90),PF(3,90),V(3,90),F(3,90),                000007
 00103             1       H(3,90),S(3,90),B(3,90),WT(3,90),FLH(3,90),FLV(3,90),FLMO,           000007
 00103             2       DELP(90),DELT(90),DELH(90),ETATH(90),ETAS(90),                       000007
 00103             3       PRES(50),TEMP(50),VOL(50),FGAS(50),WIDTH(50),DIST(50),               000007
 00103             4       EFF(50),WIDE(4),CP(4),CV,RWORK,RHEAT,Y,TREF,PCOEF,                   000007
 00103             5       SLIP(50),BETA(50),RG(50),THICK,VLOAD,COND,VEL,VOLT,WRAT,SL           000007
 00104              DO 902 J=1,3,1                                                              000007
 00107              TR(J,L2)=T2                                                                 000023
 00110              PF(J,L2)=PF(J,L1)*(1+DP)                                                    000024
 00111          902 WT(J,L2)=WT(J,L1)                                                           000027
 00113              CALL VOLUM(L2)                                                              000032
 00114              TXX=TR(1,L1)+.0001                                                          000036
 00115              ETATH(L1)=1-TREF*ALOG(TXX     /TR(1,L2))/(TXX     -TR(1,L2))                000041
 00116              RETURN                                                                      000054
 00117              END                                                                         000103

      END OF COMPILATION:        NO  DIAGNOSTICS.
```

```
@FOR,IS        MHD.SKIP
FOR UT20-04/17/75-13:18:21 (,0)

    SUBROUTINE SKIP        ENTRY POINT 000040

    STORAGE USED: CODE(1) 000047; DATA(0) 000014; BLANK COMMON(2) 010164

    STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

     0001     000015 1056      0002     004160 B          0002     010011 BETA       0002     010157 COND       0002     007715 CP
     0002     007721 CV        0002     006535 DELH       0002     006251 DELP       0002     006403 DELT       0002     007545 DIST
     0000     000001 DYNS      0002     007627 EFF        0002     007021 ETAS       0002     006667 ETATH      0002 R   002506 F
     0002     007401 FGAS      0002     005214 FLH        0002     006250 FLMU       0002     005632 FLV        0002     003124 H
     0000     000000 J         0002     007726 PCOEF      0002 R   001452 PF         0002     001034 PI         0002     007153 PRES
     0002     010073 RG        0002     007723 RHEAT      0002     007722 RWORK      0002     003542 S          0002     010163 SL
     0002     007727 SLIP      0002     007235 TEMP       0002     000000 TF         0002     010155 THICK      0002 R   000416 TR
     0002     007725 TREF      0002 R   002070 V          0002     010160 VEL        0002     010156 VLOAD      0002     007317 VOL
     0002     010161 VOLT      0002     007711 WIDE       0002     007463 WIDTH      0002     010162 WRAT       0002 R   004576 WT
     0002     007724 Y

00101          SUBROUTINE SKIP(L1,L2)                                                        000015
00103          COMMON TF(3,90),TR(3,90),PI(3,90),PF(3,90),V(3,90),F(3,90),                   000015
00103         1     H(3,90),S(3,90),B(3,90),WT(3,90),FLH(3,90),FLV(3,90),FLMO,               000015
00103         2     DELP(90),DELT(90),DELH(90),ETATH(90),ETAS(90),                           000015
00103         3     PRES(50),TEMP(50),VOL(50),FGAS(50),WIDTH(50),DIST(50),                   000015
00103         4     EFF(50),WIDE(4),CP(4),CV,RWORK,RHEAT,Y,TREF,PCOEF,                       000015
00103         5     SLIP(50),BETA(50),RG(50),THICK,VLOAD,COND,VEL,VOLT,WRAT,SL               000015
00104          DO 302 J=1,3,1                                                                000015
00107          TR(J,L2)=TR(J,L1)                                                             000015
00110          PF(J,L2)=PF(J,L1)                                                             000016
00111          V(J,L2)=V(J,L1)                                                               000020
00112          WT(J,L2)=WT(J,L1)                                                             000022
00113      302 F(J,L2)=F(J,L1)                                                               000024
00115          RETURN                                                                        000027
00116          END                                                                           000046

     END OF COMPILATION:          NO  DIAGNOSTICS.
```

```
WFGR.IS        MHD.THROT
FOR 0I2E-04/17/75-13:16:25 (,0)

    SUBROUTINE THROT      ENTRY POINT 000054

    STORAGE USED: CODE(1) 000073; DATA(0) 000013; BLANK COMMON(2) 010164

    EXTERNAL REFERENCES (BLOCK, NAME)

     0003    VOLUM

    STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

     0001     000020 1066       0002     004160 B          0002     010011 BETA       0002     010157 COND       0002 R 007715 CP
     0002     007721 CV         0002     006555 DELH       0002     006251 DELP       0002     006403 DELT       0002   007545 DIST
     0000     000001 DYNS       0002     007627 EFF        0002     007071 ETAS       0002     006667 ETATH      0002   002506 F
     0002     007401 FGAS       0002     005214 FLH        0002     006250 FLHO       0002     005632 FLV        0002   003124 H
     0000 I   000000 J          0002     007726 PCOEF      0002 R   001452 PF         0002     001034 PI         0002   007153 PRES
     0002     010073 RG         0002     007723 RHEAT      0002     007722 RWORK      0002     003542 S          0002   010163 SL
     0002     007727 SLIP       0002     007236 TEMP       0002     000000 TF         0002     010155 THICK      0002 R 000416 TR
     0002     007725 TREF       0002 R   002070 V          0002     010160 VEL        0002     010156 VLOAD      0002   007317 VOL
     0002     010161 VOLT       0002     007711 WIDE       0002     007463 WIDTH      0002     010162 WRAT       0002 R 004576 WT
     0002     007724 Y

 00101      1*           SUBROUTINE THROT(L1,L2,DP)                                                         000004
 00103      2*           COMMON TF(3,90),TR(3,90),PI(3,90),PF(3,90),V(3,90),F(3,90),                        000004
 00103      3*          1       H(3,90),S(3,90),B(3,90),WT(3,90),FLH(3,90),FLV(3,90),FLHO,                  000004
 00103      4*          2       DELP(90),DELT(90),DELH(90),ETATH(90),ETAS(90),                              000004
 00103      5*          3       PRES(50),TEMP(50),VOL(50),FGAS(50),WIDTH(50),DIST(50),                      000004
 00103      6*          4       EFF(50),WIDE(4),CP(4),CV,RWORK,RHEAT,Y,TREF,PCOEF,                          000004
 00103      7*          5       SLIP(50),BETA(50),RG(50),THICK,VLOAD,COND,VEL,VOLT,WRAT,SL                  000004
 00104      8*           DP=DP*PF(1,L1)                                                                     000004
 00105      9*           DO 862 J=1,3,1                                                                     000007
 00110     10*           WT(J,L2)=WT(J,L1)                                                                  000020
 00111     11*           PF(J,L2)=PF(J,L1)+DP                                                               000021
 00112     12*       862 TR(J,L2)=TR(J,L1)-WT(2,L1)*V(2,L1)*DP*.0012847/                                    000024
 00112     13*          1       (WT(2,L1)*CP(2)+WT(1,L1)*CP(1))                                             000024
 00114     14*           CALL VOLUM(L2)                                                                     000041
 00115     15*           RETURN                                                                             000043
 00116     16*           END                                                                                000072

        END OF COMPILATION:         NO  DIAGNOSTICS.
```

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@FOR,IS        MHD.VALUE
FOR U72B-04/17/75-13:18:30 (,0)

   SUBROUTINE VALUE       ENTRY POINT 000152

   STORAGE USED: CODE(1) 000165; DATA(0) 000024; BLANK COMMON(2) 010164

   EXTERNAL REFERENCES (BLOCK, NAME)

    0003    VOLUM
    0004    ALOG

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0001     000013 106G      0001     000104 125G      0001     000133 136G      0002 R 004160 B         0002     010011 BETA
    0002     010157 COND      0002 R 007715 CP        0002     007721 CV        0002   006535 DELH      0002     006251 DELP
    0002     006403 DELT      0002     007545 DIST      0000     000003 DYNS      0002     007627 EFF       0002     007021 ETAS
    0002     006607 ETATH     0002     002506 F         0002     007401 FGAS      0002     005214 FLM       0002     006250 FLMO
    0002     005632 FLV       0002 R 003124 H         0000 I 000001 J         0002     007726 PCOEF     0002 R 001452 PF
    0002 R 001034 PI        0000 R 000000 PREF      0002     007153 PRES      0002     010073 RG        0002 R 007723 RHEAT
    0002     007722 RWORK     0002 R 003542 S         0002     010163 SL        0002     007727 SLIP      0000 R 000002 TAB
    0002     007235 TEMP      0002 R 000000 TF        0002     010155 THICK     0002 R 000416 TR        0002 R 007725 TREF
    0002 R 002070 V         0002     010160 VEL       0002     010156 VLOAD     0002     007317 VOL       0002     010161 VOLT
    0002     007711 WIDE      0002     007463 WIDTH     0002     010162 WRAT      0002 R 004576 WT        0002     007724 Y


 00101          SUBROUTINE VALUE(L)                                                    000000
 00103          COMMON TF(3,90),TR(3,90),PI(3,90),PF(3,90),V(3,90),F(3,90),            000000
 00103         1       H(3,90),S(3,90),B(3,90),WT(3,90),FLM(3,90),FLV(3,90),FLMO,      000000
 00103         2       DELP(90),DELT(90),DELH(90),ETATH(90),ETAS(90),                  000000
 00103         3       PRES(50),TEMP(50),VOL(50),FGAS(50),WIDTH(50),DIST(50),          000000
 00103         4       EFF(50),WIDE(4),CP(4),CV,RWORK,RHEAT,Y,TREF,PCOEF,              000000
 00103         5       SLIP(50),BETA(50),RG(50),THICK,VLOAD,COND,VEL,VOLT,WRAT,SL      000000
 00104          PREF=14.7*144.                                                         000000
 00105          DO 742 J=2,3,1                                                         000001
 00110          TR(J,L)=TR(1,L)                                                        000013
 00111      742 PF(J,L)=PF(1,L)                                                        000014
 00113          CALL VOLUM(L)                                                          000017
 00114          S(3,L)=0                                                               000021
 00115          B(3,L)=0                                                               000025
 00116          H(3,L)=0                                                               000026
 00117          H(2,L)=WT(2,L)*V(2,L)*(PF(2,L)        )*.001284                        000027
 00120          H(1,L)=0                                                               000034
 00121          TAB=459.69                                                             000035
 00122          S(1,L)=WT(1,L)*(CP(1)*ALOG(TR(1,L)/TAB) -RHEAT*ALOG(PF(1,L)/PREF))     000037
 00123          S(2,L)=WT(2,L)*WT(2,L)*CP(2)*ALOG(TR(2,L)/TAB)                         000061
 00124          DO 744 J=1,2,1                                                         000104
 00127          H(J,L)=WT(J,L)*CP(J)*(TR(J,L)-TREF)+H(J,L)                             000104
 00130          B(J,L)=H(J,L)-TREF *S(J,L)                                             000112
 00131          S(3,L)=S(3,L)+S(J,L)                                                   000116
 00132          H(3,L)=H(3,L)+H(J,L)                                                   000121
 00133      744 B(3,L)=B(3,L)+B(J,L)                                                   000123
 00135          DO 746 J=1,3,1                                                         000133
 00140          PI(J,L)=PF(J,L)/144                                                    000133
 00141      746 TF(J,L)=TR(J,L)-459.69                                                 000135
 00143          RETURN                                                                 000141
 00144          END                                                                    000164

   END OF COMPILATION:        NO  DIAGNOSTICS.
```

```
@FOR,IS        MHD.VOLUM
FOR 0T28-04/17/75-13:18:36 (,0)

   SUBROUTINE VOLUM      ENTRY POINT 000062

   STORAGE USED: CODE(1) 000070; DATA(0) 000014; BLANK COMMON(2) 010164

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0001     000045 1140      0002     004160 B        0002     010011 BETA     0002     010157 COND     0002     007715 CR
    0002     007721 CV        0002     006535 DELH     0002     006251 DELP     0002     006403 DELT     0002     007545 DIST
    0000     000002 DTHS      0002     007627 EFF      0002     007021 ETAS     0002     006667 ETATH    0002 R   002506 F
    0002     007401 FGAS      0002 R   005214 FLM      0002 R   006250 FLMO     0002 R   005632 FLV      0002     003124 H
    0000 I   000001 J         0002     007726 PCOEF    0002 R   001452 PF       0002     001034 PI       0002     007153 PRES
    0002     010073 RG        0002     007723 RHEAT    0002 R   007722 RWORK    0002     003542 S        0002     010163 SL
    0002     007727 SLIP      0002     007235 TEMP     0002     000000 TF       0002     010155 THICK    0002 R   000916 TR
    0002     007725 TREF      0002 R   002070 V        0002     010160 VEL      0002     010156 VLOAD    0002     007317 VOL
    0002     010161 VOLT      0000 R   000000 VRAT     0002     007711 WIDE     0002     007463 WIDTH    0002 R   010162 WRAT
    0002 R   004576 WT        0002     007724 Y

00101            SUBROUTINE VOLUM(LOCAT)                                              000006
00103            COMMON TF(3,90),TR(3,90),PI(3,90),PF(3,90),V(3,90),F(3,90),          000006
00103           1       H(3,90),S(3,90),B(3,90),WT(3,90),FLM(3,90),FLV(3,90),FLMO,    000006
00103           2       DELP(90),DELT(90),DELH(90),ETATH(90),ETAS(90),                000006
00103           3       PRES(50),TEMP(50),VOL(50),FGAS(50),WIDTH(50),DIST(50),        000006
00103           4       EFF(50),WIDE(4),CP(4),CV,RWORK,RHEAT,Y,TREF,PCOEF,            000006
00103           5       SLIP(50),BETA(50),RG(50),THICK,VLOAD,COND,VEL,VOLT,WRAT,SL    000006
00104            V(1,LOCAT)=RWORK*TR(1,LOCAT)/PF(1,LOCAT)                              000006
00105            V(3,LOCAT)=(V(1,LOCAT)*WT(1,LOCAT)+V(2,LOCAT)*WT(2,LOCAT))            000012
00105           1       /WT(3,LOCAT)                                                   000012
00106            VRAT=V(1,LOCAT)/V(2,LOCAT)                                            000020
00107            WRAT=WT(1,LOCAT)/WT(3,LOCAT)                                          000023
00110            F(1,LOCAT)=VRAT*WRAT/(1+VRAT*WRAT-WRAT)                               000026
00111            F(2,LOCAT)=1.-F(1,LOCAT)                                              000035
00112            F(3,LOCAT)=1.                                                         000037
00113            DO 750 J=1,3,1                                                        000045
00116            FLM(J,LOCAT)=FLMO*WT(J,LOCAT)                                         000045
00117        750 FLV(J,LOCAT)=FLM(J,LOCAT)*V(J,LOCAT)                                  000047
00121            RETURN                                                                000052
00122            END                                                                   000067

      END OF COMPILATION:        NO  DIAGNOSTICS.

@FIN
```

Subappendix AA 11.2.2

SAMPLE OUTPUT

```
******INPUT DATA

SPECIFIED MHD INLET CONDITIONS

GAS MOL.WT=  39.95****GAS CP=  .1290 BTU/LB
LIQ.DENS=  49.80 LB/CU FT****LIQ.CP=  .3000 BTU/LB****LIQ.RESIS= .9660-05 OHM-CM

DUCT INLET SHUNT LOSS REDUCTION= .0000****DUCT OUTLET SHUNT LOSS REDUCTION= .0000

COMPRESSOR POLYTROPIC EFFICIENCY= .8750****LIQUID PUMP EFFICIENCY= .8500
TEMP= 1200.00 DEG.F****PRES= 1200.00 PSI****VOID VOL= .6500

FRACT.OF TOTAL GAS SEPERATED IN GAS STREAM=1.0000****FRACT.LIQUID IN GAS STREAM= .0000

SPEC.COMP.IN.TEMP=  120.00 DEG.F***COMP.EF= .8750****CYCLE REJECT TEMP=  100.00 DEG.F

GAS STREAM PRESSURE LOSSES AS DP/P
NOZZLE-SEP= .0200***STEAM GEN.= .0200***REGEN.LO PR SIDE= .0200***FEED WATER HEATER .0000
1ST WST. HT. X= .0200  2ND WST.HT. X= .0200 3RD WST.HT. X= .0200 4TH WST.HT. X= .0200
REGEN.HI.SIDE= .0200***PRIMARY HEATER= .0200***MIXER= .0200

LIQUID STREAM PRESSURE LOSSES AS DP/P
NOZZLE-SEP= .0500***COOLER= .0000***HEATER= .0400***MIXER= .0000

ASSUMED ST.CYC.INT.EFFIC.FOR ST.GEN.= .7700  FOR FEED WATER HEATER .0000AND FOR PRECOOLERS   .0000   .0000   .0000   .0000

STACK EFF.= .8800FRACT. OF PRECOOLER HEAT USED FOR AIR PREHEAT= 1.0000  .0000  .0000  .0000

FRACT. OF STEAM HEAT FOR DIRECT ST. REHEAT= .3500FROM 1000.0 TO  600.0 DEG.F.AT INTERNAL EFF. .8000

MIX.VEL= 100.00 FT/SEC***INLET WIDTH=  5.85 FT***THICKNESS=  5.85 FT

MAG.FLUX DEN=   .00 TESLA***LOADING= .9500 VOLT/VOLT***INLET SLIP RATIO=1.00

OPEN CIR.VOLT= 33.00 WORKING VOLTAGE=   .00

NO.COMP.STAGES= 1 *NO.REGEN.= 0 *REG.APP=   .00 DEG.F *REG.CUTOFF=150.00 DEG.F

COMB.CYC.POWER PER DUCT=   62.50MW, ITERATION INDEX= 1 COST INDEX= 1
```

******OUTPUT DATA-BASED ON ONE POUND MIXTURE AT MHD DUCT INLET

****OUTLET FROM MIXER**** Point 1 of Fig. A 11.2.1

	GAS	LIQUID	TOTAL
TEMPERATURE,DEG.F	1200.00	1200.00	1200.00
PRESSURE,PSI	1200.00	1200.00	1200.00
MASS FRACTION,REFERRED TO MHD DUCT INLET	.088771	.911229	1.000000
ENTHALPY,BTU PER POUND TOTAL AT MHD DUCT INLET	12.108	304.765	316.874
ENTROPY,BTU/R-LB(INLET MASS)	-.0053	.3198	.3145
AVAILABILITY,BTU/LB(INLET MASS)	15.0780	125.7738	140.8518
VOLUME FRACTION,LOCAL	.650000	.350000	1.000000
SPECIFIC VOLUME,CUBIC FEET PER POUND	.3828	.0201	.0523
MASS FLOW RATE, LB/SEC	727.89	7471.68	8199.57
VOLUME FLOW RATE,CU.FT/SEC	278.6	150.0	426.7

****INLET TO MHD DUCT**** Point 2 of Fig. A 11.2.1

	GAS	LIQUID	TOTAL
TEMPERATURE,DEG.F	1200.00	1200.00	1200.00
PRESSURE,PSI	1200.00	1200.00	1200.00
MASS FRACTION,REFERRED TO MHD DUCT INLET	.088771	.911229	1.000000
ENTHALPY,BTU PER POUND TOTAL AT MHD DUCT INLET	12.108	304.765	316.874
ENTROPY,BTU/R-LB(INLET MASS)	-.0053	.3198	.3145
AVAILABILITY,BTU/LB(INLET MASS)	15.0780	125.7738	140.8518
VOLUME FRACTION,LOCAL	.650000	.350000	1.000000
SPECIFIC VOLUME,CUBIC FEET PER POUND	.3828	.0201	.0523
MASS FLOW RATE, LB/SEC	727.89	7471.68	8199.57
VOLUME FLOW RATE,CU.FT/SEC	278.6	150.0	426.7

SPECIFIED MHD OUTLET VOID FRACTION= .8500

IN DUCT******

DIST.-FT	WIDTH-FT	TEMP-DEG.R	PRES-LB/SQFT	AREA FRAC.GAS	VOL.FRAC.GAS	SLIP RATIO	LOCAL EFFIC
.0000	2.0704	1659.6900	172800.0000	.6500	.6500	1.0000	.9500
.1987	1.6726	1658.9816	167871.5723	.5667	.6565	1.4608	.7410
.3511	1.6649	1658.4296	163083.7090	.5646	.6629	1.5154	.7410
.5011	1.6878	1657.8776	158432.4004	.5706	.6692	1.5223	.7410
.6507	1.7127	1657.3258	153913.7520	.5769	.6755	1.5271	.7410
.7998	1.7382	1656.7742	149523.9785	.5831	.6818	1.5318	.7410
.9486	1.7643	1656.2227	145259.4062	.5893	.6880	1.5367	.7410
1.0969	1.7909	1655.6715	141116.4629	.5954	.6941	1.5418	.7410
1.2448	1.8182	1655.1204	137091.6816	.6014	.7001	1.5470	.7410
1.3922	1.8460	1654.5695	133181.6914	.6075	.7061	1.5523	.7410
1.5391	1.8745	1654.0188	129383.2178	.6134	.7120	1.5579	.7410
1.6856	1.9035	1653.4683	125693.0801	.6193	.7178	1.5636	.7410
1.8316	1.9332	1652.9180	122108.1885	.6252	.7236	1.5694	.7410
1.9771	1.9635	1652.3678	118625.5420	.6309	.7292	1.5754	.7410
2.1220	1.9944	1651.8178	115242.2236	.6367	.7349	1.5817	.7410
2.2664	2.0260	1651.2681	111955.4014	.6423	.7404	1.5880	.7410
2.4103	2.0583	1650.7184	108762.3223	.6479	.7458	1.5946	.7410
2.5535	2.0912	1650.1690	105660.3135	.6535	.7512	1.6013	.7410
2.6962	2.1248	1649.6198	102646.7764	.6590	.7565	1.6083	.7410
2.8383	2.1591	1649.0707	99719.1685	.6644	.7618	1.6154	.7410
2.9797	2.1941	1648.5219	96875.0986	.6697	.7669	1.6227	.7410
3.1205	2.2298	1647.9732	94112.1250	.6750	.7720	1.6302	.7410
3.2606	2.2662	1647.4247	91427.9541	.6802	.7770	1.6378	.7410
3.4001	2.3033	1646.8763	88820.3379	.6854	.7819	1.6457	.7410
3.5389	2.3412	1646.3282	86287.0937	.6905	.7867	1.6538	.7410
3.6769	2.3798	1645.7802	83826.1006	.6955	.7915	1.6621	.7410
3.8142	2.4191	1645.2325	81435.2969	.7005	.7962	1.6706	.7410
3.9508	2.4593	1644.6849	79112.6816	.7053	.8008	1.6793	.7410
4.0867	2.5002	1644.1375	76856.3096	.7102	.8053	1.6882	.7410
4.2217	2.5417	1643.5902	74664.2910	.7149	.8098	1.6973	.7410
4.3560	2.5844	1643.0432	72534.7910	.7196	.8141	1.7066	.7410
4.4895	2.6277	1642.4963	70466.0264	.7242	.8184	1.7162	.7410
4.6221	2.6718	1641.9496	68456.2656	.7288	.8226	1.7260	.7410
4.7540	2.7168	1641.4031	66503.8252	.7333	.8268	1.7360	.7410
4.8849	2.7626	1640.8568	64607.0703	.7377	.8308	1.7462	.7410
5.0151	2.8092	1640.3106	62764.4126	.7420	.8348	1.7566	.7410
5.1443	2.8567	1639.7647	60974.3076	.7463	.8387	1.7673	.7410
5.2727	2.9051	1639.2189	59235.2617	.7506	.8425	1.7783	.7410
5.4002	2.9544	1638.6733	57545.6135	.7547	.8463	1.7894	.7410

5.5260	3.0046	1638.1274	55909.5498	.7588	.8500	1.8006	.7410

****OUTLET FROM MHD DUCT* Point 3 of Fig. A 11.2.1

	GAS	LIQUID	TOTAL
TEMPERATURE,DEG.F	1178.44	1178.44	1178.44
PRESSURE,PSI	388.23	388.23	388.23
MASS FRACTION,REFERRED TO MHD DUCT INLET	.088771	.911229	1.000000
ENTHALPY,BTU PER POUND TOTAL AT MHD DUCT INLET	11.871	296.125	307.996
ENTROPY,BTU/R-LB(INLET MASS)	-.0005	.3165	.3161
AVAILABILITY,BTU/LB(INLET MASS)	12.1324	118.9562	131.0886
VOLUME FRACTION,LOCAL	.849981	.150019	1.000000
SPECIFIC VOLUME,CUBIC FEET PER POUND	1.1679	.0201	.1220
MASS FLOW RATE, LB/SEC	727.89	7471.68	8199.57
VOLUME FLOW RATE,CU.FT/SEC	850.1	150.0	1000.1

****INLET TO NOZZLE-SEPERATOR* Point 4 of Fig. A 11.2.1

	GAS	LIQUID	TOTAL
TEMPERATURE,DEG.F	1178.44	1178.44	1178.44
PRESSURE,PSI	388.23	388.23	388.23
MASS FRACTION,REFERRED TO MHD DUCT INLET	.088771	.911229	1.000000
ENTHALPY,BTU PER POUND TOTAL AT MHD DUCT INLET	11.871	296.125	307.996
ENTROPY,BTU/R-LB(INLET MASS)	-.0005	.3165	.3161
AVAILABILITY,BTU/LB(INLET MASS)	12.1329	118.9562	131.0886
VOLUME FRACTION,LOCAL	.849981	.150019	1.000000
SPECIFIC VOLUME,CUBIC FEET PER POUND	1.1679	.0201	.1220
MASS FLOW RATE, LB/SEC	727.89	7471.68	8199.57
VOLUME FLOW RATE,CU.FT/SEC	850.1	150.0	1000.1

****GAS OUTLET FROM SEPERATOR* Point 5 of Fig. A 11.2.1

	GAS	LIQUID	TOTAL
TEMPERATURE,DEG.F	1178.44	1178.44	1178.44
PRESSURE,PSI	380.46	380.46	380.46
MASS FRACTION,REFERRED TO MHD DUCT INLET	.088771	.000000	.088771
ENTHALPY,BTU PER POUND TOTAL AT MHD DUCT INLET	11.871	.000	11.871
ENTROPY,BTU/R-LB(INLET MASS)	-.0004	.0000	-.0004
AVAILABILITY,BTU/LB(INLET MASS)	12.0825	.0000	12.0825
VOLUME FRACTION,LOCAL	1.000000	.000000	1.000000
SPECIFIC VOLUME,CUBIC FEET PER POUND	1.1917	.0201	1.1917
MASS FLOW RATE, LB/SEC	727.89	.00	727.89
VOLUME FLOW RATE,CU.FT/SEC	867.4	.0	867.4

****INLET TO REGENERATER LOW PRESS SIDE***
Point 6/7 of Fig. A 11.2.1

	GAS	LIQUID	TOTAL
TEMPERATURE,DEG.F	150.00	150.00	150.00
PRESSURE,PSI	372.85	372.85	372.85
MASS FRACTION,REFERRED TO MHD DUCT INLET	.088771	.000000	.088771
ENTHALPY,BTU PER POUND TOTAL AT MHD DUCT INLET	.550	.000	.550
ENTROPY,BTU/R-LB(INLET MASS)	-.0112	.0000	-.0112
AVAILABILITY,BTU/LB(INLET MASS)	6.8010	.0000	6.8010
VOLUME FRACTION,LOCAL	1.000000	.000000	1.000000
SPECIFIC VOLUME,CUBIC FEET PER POUND	.4526	.0201	.4526
MASS FLOW RATE, LB/SEC	727.89	.00	727.89
VOLUME FLOW RATE,CU.FT/SEC	329.4	.0	329.4

****INLET TO WASTE COOLER NUMBER 1 Point 8 of Fig. A 11.2.1

	GAS	LIQUID	TOTAL
TEMPERATURE,DEG.F	150.00	150.00	150.00
PRESSURE,PSI	365.40	365.40	365.40
MASS FRACTION,REFERRED TO MHD DUCT INLET	.088771	.000000	.088771
ENTHALPY,BTU PER POUND TOTAL AT MHD DUCT INLET	.550	.000	.550
ENTROPY,BTU/R-LB(INLET MASS)	-.0111	.0000	-.0111
AVAILABILITY,BTU/LB(INLET MASS)	6.7511	.0000	6.7511
VOLUME FRACTION,LOCAL	1.000000	.000000	1.000000

	GAS	LIQUID	TOTAL
SPECIFIC VOLUME,CUBIC FEET PER POUND	.4618	.0201	.4618
MASS FLOW RATE, LB/SEC	727.89	.00	727.89
VOLUME FLOW RATE,CU.FT/SEC	336.2	.0	336.2

****INLET TO GAS COMPRESSOR NUMBER 1***
Point 9 of Fig. A 11.2.1

	GAS	LIQUID	TOTAL
TEMPERATURE,DEG.F	120.00	120.00	120.00
PRESSURE,PSI	358.09	358.09	358.09
MASS FRACTION,REFERRED TO MHD DUCT INLET	.088771	.000000	.088771
ENTHALPY,BTU PER POUND TOTAL AT MHD DUCT INLET	.220	.000	.220
ENTROPY,BTU/R-LB(INLET MASS)	-.0115	.0000	-.0115
AVAILABILITY,BTU/LB(INLET MASS)	6.6818	.0000	6.6818
VOLUME FRACTION,LOCAL	1.000000	.000000	1.000000
SPECIFIC VOLUME,CUBIC FEET PER POUND	.4481	.0201	.4481
MASS FLOW RATE, LB/SEC	727.89	.00	727.89
VOLUME FLOW RATE,CU.FT/SEC	326.1	.0	326.1

****OUTLET FROM GAS COMPRESSOR NUMBER 1***
Point 10 of Fig. A 11.2.1

	GAS	LIQUID	TOTAL
TEMPERATURE,DEG.F	577.90	577.90	577.90
PRESSURE,PSI	1274.98	1274.98	1274.98
MASS FRACTION,REFERRED TO MHD DUCT INLET	.088771	.000000	.088771
ENTHALPY,BTU PER POUND TOTAL AT MHD DUCT INLET	5.261	.000	5.261
ENTROPY,BTU/R-LB(INLET MASS)	-.0107	.0000	-.0107
AVAILABILITY,BTU/LB(INLET MASS)	11.2739	.0000	11.2739
VOLUME FRACTION,LOCAL	1.000000	.000000	1.000000
SPECIFIC VOLUME,CUBIC FEET PER POUND	.2252	.0201	.2252
MASS FLOW RATE, LB/SEC	727.89	.00	727.89
VOLUME FLOW RATE,CU.FT/SEC	164.0	.0	164.0

COMPRESSOR ISENTROPIC EFFICIENCY= .8410

****OUTLET FROM REGENERATER HIGH PRESS SIDE***
Point 11 of Fig. A 11.2.1

	GAS	LIQUID	TOTAL
TEMPERATURE,DEG.F	577.90	577.90	577.90
PRESSURE,PSI	1274.98	1274.98	1274.98
MASS FRACTION,REFERRED TO MHD DUCT INLET	.088771	.000000	.088771
ENTHALPY,BTU PER POUND TOTAL AT MHD DUCT INLET	5.261	.000	5.261
ENTROPY,BTU/R-LB(INLET MASS)	-.0107	.0000	-.0107
AVAILABILITY,BTU/LB(INLET MASS)	11.2739	.0000	11.2739
VOLUME FRACTION,LOCAL	1.000000	.000000	1.000000
SPECIFIC VOLUME,CUBIC FEET PER POUND	.2252	.0201	.2252
MASS FLOW RATE, LB/SEC	727.89	.00	727.89
VOLUME FLOW RATE,CU.FT/SEC	164.0	.0	164.0

****LIQUID OUTLET FROM SEPERATOR *** Point 15 of Fig. A 11.2.1

	GAS	LIQUID	TOTAL
TEMPERATURE,DEG.F	1178.68	1178.68	1178.68
PRESSURE,PSI	368.81	368.81	368.81
MASS FRACTION,REFERRED TO MHD DUCT INLET	.000000	.911229	.911229
ENTHALPY,BTU PER POUND TOTAL AT MHD DUCT INLET	.000	296.125	296.125
ENTROPY,BTU/R-LB(INLET MASS)	.0000	.3166	.3166
AVAILABILITY,BTU/LB(INLET MASS)	.0000	118.9357	118.9357
VOLUME FRACTION,LOCAL	.000000	1.000000	1.000000
SPECIFIC VOLUME,CUBIC FEET PER POUND	1.2295	.0201	.0201
MASS FLOW RATE, LB/SEC	.00	7471.68	7471.68
VOLUME FLOW RATE,CU.FT/SEC	.0	150.0	150.0

****INLET TO LIQUID PUMP***
Point 16/17 of Fig. A 11.2.1

	GAS	LIQUID	TOTAL
TEMPERATURE,DEG.F	1178.68	1178.68	1178.68

	GAS	LIQUID	TOTAL
PRESSURE,PSI	368.81	368.81	368.81
MASS FRACTION,REFERRED TO MHD DUCT INLET	.000000	.911229	.911229
ENTHALPY,BTU PER POUND TOTAL AT MHD DUCT INLET	.000	296.125	296.125
ENTROPY,BTU/R-LB(INLET MASS)	.0000	.3166	.3166
AVAILABILITY,BTU/LB(INLET MASS)	.0000	118.9357	118.9357
VOLUME FRACTION,LOCAL	.000000	1.000000	1.000000
SPECIFIC VOLUME,CUBIC FEET PER POUND	1.2295	.0201	.0201
MASS FLOW RATE, LB/SEC	.00	7471.68	7471.68
VOLUME FLOW RATE,CU.FT/SEC	.0	150.0	150.0

****OUTLET FROM LIQUID PUMP** Point 18 of Fig. A 11.2.1

	GAS	LIQUID	TOTAL
TEMPERATURE,DEG.F	1180.60	1180.60	1180.60
PRESSURE,PSI	1250.00	1250.00	1250.00
MASS FRACTION,REFERRED TO MHD DUCT INLET	.000000	.911229	.911229
ENTHALPY,BTU PER POUND TOTAL AT MHD DUCT INLET	.000	299.632	299.632
ENTROPY,BTU/R-LB(INLET MASS)	.0000	.3169	.3169
AVAILABILITY,BTU/LB(INLET MASS)	.0000	122.2794	122.2794
VOLUME FRACTION,LOCAL	.000000	1.000000	1.000000
SPECIFIC VOLUME,CUBIC FEET PER POUND	.3632	.0201	.0201
MASS FLOW RATE, LB/SEC	.00	7471.68	7471.68
VOLUME FLOW RATE,CU.FT/SEC	.0	150.0	150.0

ENTHALPY ADDED AT TOP OF CYCLE= 11.98BTU/LB

ENTHALPY REJECTED AT BOTTOM OF MHD CYCLE= 11.65BTU/LB OF ILET MIXTURE

NET WORK= .33 BTU PER LB INLET

MHD DUCT ISENTROPIC EFFICIENCY= .7480

MHD TOPPING CYCLE EFFICIENCY= .0276

MAX. THERMODYNAMIC EFFIC.FOR ST.GEN.= .4621 FOR FEED WATER HEATER .0587AND FOR PRECOOLERS .0000 .0000 .0000

STEAM BOTT. CYCLE EFFICIENCY= .3958

OVERALL COMB. CYCLE EFFICIENCY FOR IDEAL COMBUSTER-PRIMARY HT.X= .4071

OVERALL COMB. CYCLE EFFICIENCY EXCLUDING COMBUSTER-PRIMARY HT.X AND PREHEAT ADVANTAGE= .3996

OVERALL COMB. CYCLE EFFICIENCY INCLUDING COMBUSTER-PRIMARY HT.X= .3574

TOP TEMPERATURES WITH VARIOUS SPLITS BETWEEN GAS AND LIQUID HEATING

FRACTION HEAT ADDED TO GAS	GAS TEMP. F	LIQUID TEMP. F
.0000	577.9015	1225.0498
.1000	686.7471	1220.6676
.2000	795.5926	1216.2841
.3000	904.4381	1211.9013
.4000	1013.2837	1207.5184
.5000	1122.1292	1203.1356
.6000	1230.9747	1198.7528
.7000	1339.8203	1194.3699
.8000	1448.6658	1189.9871
.9000	1557.5113	1185.6042
1.0000	1666.3569	1181.2214

Appendix A 11.3

SUPERCONDUCTING MAGNET DESIGN FOR LIQUID-METAL MHD GENERATORS

A 11.3.1 General Magnet Requirement

The liquid-metal MHD generator is rather different from the open- and closed-cycle MHD generators. The major difference in the magnet design arises from the fact that the magnetic field in the duct is relatively small - below 2.0 T. The requirement for field uniformity is easily met by using iron poles to shape the magnetic fields. Hence, the base case magnet design was selected to have four ducts which were interconnected magnetically by iron, as previously shown in Figures 11.7 and 11.8 of the text. This method of construction reduced the stray fields, which is important from two aspects. The stray fields represent an environmental problem because magnetic objects tend to be pulled toward the magnet; and secondly, the stray field from one duct magnet will tend to affect the uniformity of the nearby magnets of the other MHD ducts. By minimizing the stray fields through the use of iron flux shunting paths, the above problems have been eliminated.

As with the open- and closed-cycle plasma MHD generators, the design of a superconducting magnet for LM-MHD application does not require any new technological developments with respect to the superconductor. Since the magnetic field is below 2 T at the wire, presently available multifilament niobium-titanium superconductors operating at 4.2°K (-452.13°F) were determined to be sufficient for this application.

Accordingly, the base case design herein described has been determined,utilizing the following design boundary conditions:

- A niobium-titanium filamentary conductor would be employed as the source of the magnetic field.
- The magnet winding would be forced cooled and operate at 4.2°K ± 0.2°K (-452.13°F ± 0.36°F).
- The magnet structure would be designed to be self-supporting against magnetic loading.
- The structure would be designed for an overall minimum cost.
- Iron poles between ducts would be used to shunt the magnetic field between the ducts and to provide a field uniformity within the duct to 8%.

A 11.3.2 Magnetic Field Analysis

The principal features of the electrical design for the base case LM-MHD generator are shown in Figures A 11.3.1 and A 11.3.2. Magnetic field calculations for this design were carried out using an existing computer program (References 11.15, 11.16, and 11.17) that is based on a numerical evaluation of a Fredholm-type integral for solving two-dimensional magnetostatics problems in rectangular coordinates. The uniformity of the field along the entire length of the generator ducts were determined by computing separately the fields for the generator entrance and exit cross sections.

The linear current sources were assumed constant and having a value of 1.1875 MA/m throughout the calculations. The total winding current required to achieve this is 1.202×10^7 ampere-turns (At) at the generator entrance and 2.649×10^7 At at the generator exit. The field calculations also assume that the iron pole width is 2.225 m (7.3 ft), that it is located 0.3048 m (1 ft) from the duct wall, and that it extends 0.3048 m (1 ft) beyond the duct corners.

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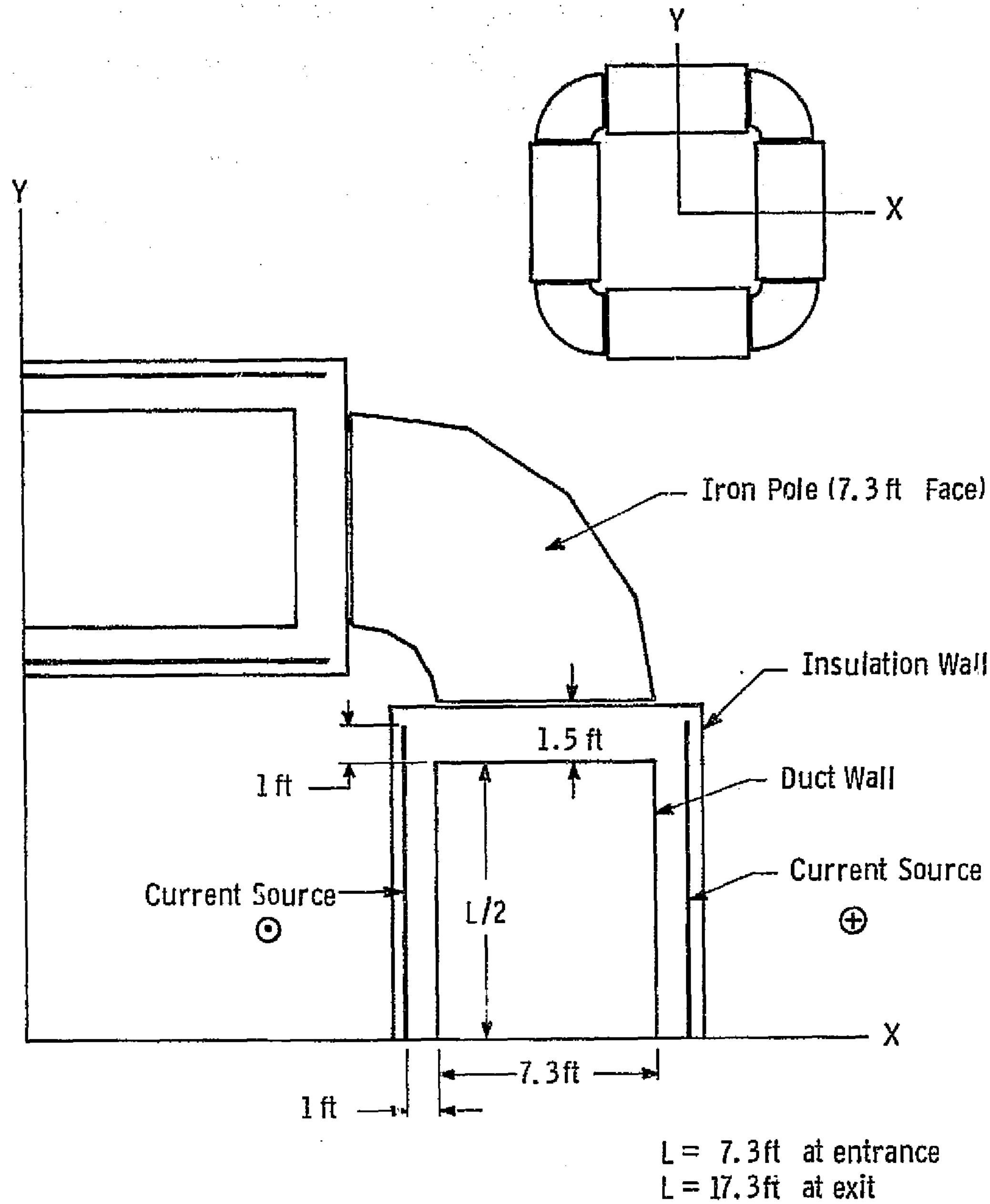

Fig. A 11.3.1 — The liquid-metal MHD generator magnet design employed in magnetic field calculations

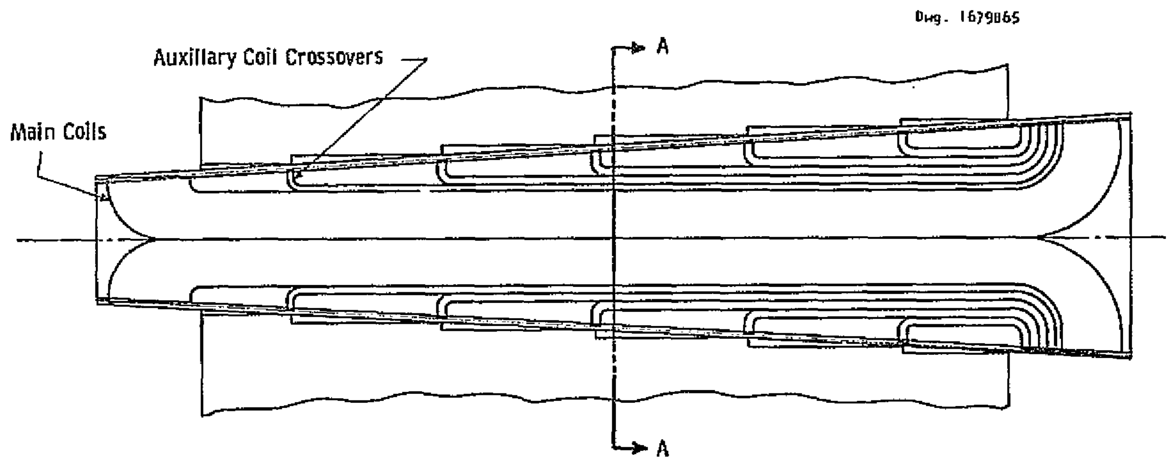

Fig. A 11.3.2—Winding configuration for liquid metal MHD design

Curve 682867-A

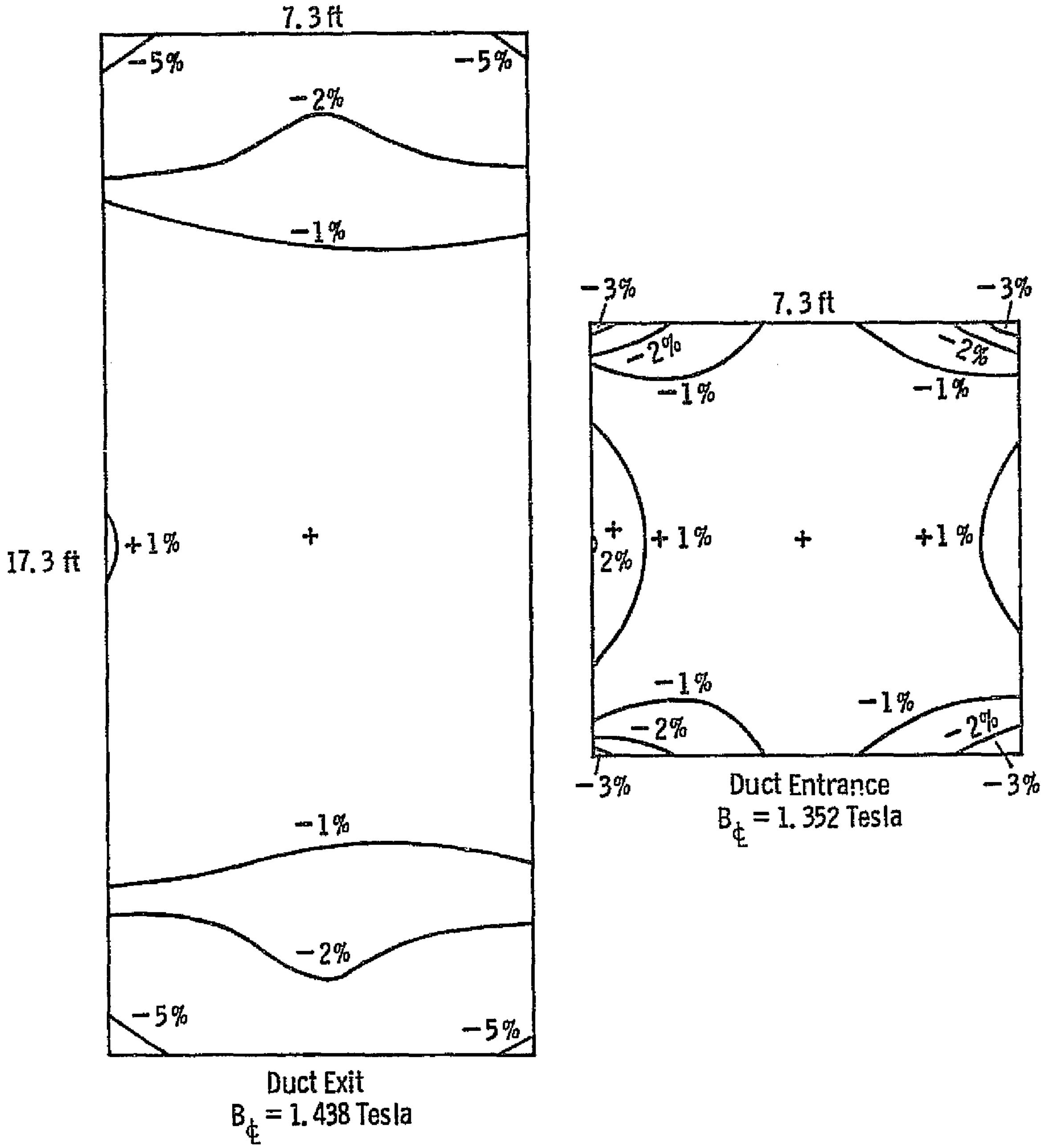

Fig. A11.3.3—Magnetic field uniformity for the exit and entrance faces of the liquid metal MHD generator duct

The calculated magnetic field uniformity across the entrance and exit duct faces is shown on Figure A 11.3.3, where lines of constant percent deviation from the value of the field at the duct centerline are given. The field uniformity is better than 4% at the entrance and 6% at the exit of the generator, where the centerline fields are 1.352 and 1.438 T, respectively. Based on the maximum and minimum fields in the generator ducts the overall field for the electrical design can be expressed as 1.373 T $\pm$ 5.6%.

If the iron pole width was increased from 2.225 to 2.53 m (7.3 to 8.3 ft) then the overall field was found to be 1.387 T $\pm$ 4.8%. This is an 0.8 point improvement in the spread of the field determined for the 2.225 m (7.3 ft) pole.

A 11.3.3 Conductor Design

The environment of a LM-MHD magnet system does not require the selection of sophisticated superconductors, primarily because there are no ac or transient magnetic fields present. Furthermore, the magnetic field distribution cannot accommodate graded winding designs because of the presence of cross-over turns linking the magnetic field.

Since the peak field seen by the duct for the LM-MHD concept is approximately 1.5 T or less, a filamentary niobium-titanium conductor has been selected for the base case design.

The most important aspect to the conductor design is selecting a reasonable operating current density for the winding. Illustrated in Figure A 11.3.4 is a normalized plot of the critical current density, jc, for niobium-titanium wires as a function of the peak field on the wire ($jc(5T) \approx 10^9$ A/m^2). An operating current of 5000 A was arbitrarily selected for this magnet. A conductor with filaments of 100 μm (0.00394 in) or less, which is twisted approximately 39.4 twists per meter (1 twist per inch) was selected to inhibit the possibility of flux jump instability in the wire when the magnet is either being charged or discharged. A winding packing factor of 0.7 and a conductor aspect ratio of 2 to 1 were established as sufficient to accommodate liquid

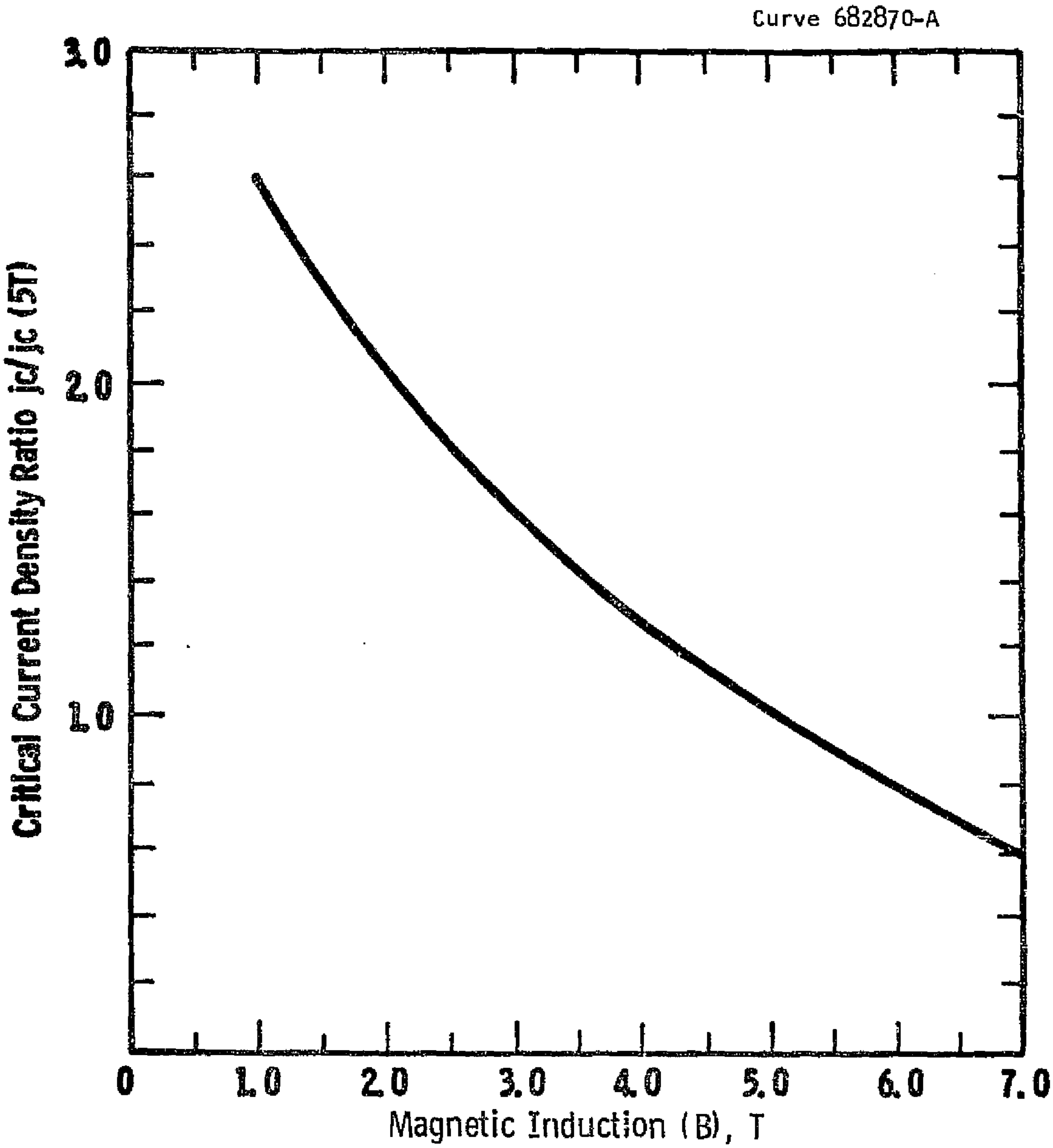

Fig. A 11.3.4—Normalized J_c-B curve for NbTI superconductors helium cooling and the necessary distributed support structure. To ensure stable operation, a 3 to 1 copper-to-superconductor ratio was selected, which is not a sufficient amount of copper to crystabilize the winding but should be sufficient to dynamically stabilize the winding. Although the MHD magnet is a dc device, provision for operation margin must be made. If one has temperature excursions of between 0.1 to 0.2°K (0.18 to 0.36°F) from the nominal 4.2°K (-452.13°F) in the windings, an operational current density j of about 0.5 jc at 4.2°K (-452.13°F) affords a reasonable compromise between high current density and thermal margin and was selected as the design poi..t for the peak field region in the winding. Accordingly, a winding current density of 2×10^8 A/m^2 was selected for the electrical design of the liquid-metal base case magnet design.

A 11.3.4 Stored Energy and Inductance Considerations

The stored energy of the system, E_s, can be calculated if we consider the iron to have infinite permeability in comparison to air from

$$E_s = \frac{B^2 V}{2\mu_o}$$

where B is the average magnetic interaction in the duct, μ_o is the permeability of free space = $4\pi \times 10^{-7}$ H/m and V is the total volume between the iron poles.

Since the typical magnets considered have large inductances, it is advised that the winding be subdivided and powered by separate power supplies to ensure reliable operation.

A 11.3.5 Mechanical Design

The major structural problem in the design of the dewars is the provision of a lightweight wall structure to minimize construction costs, that is compatible with the bending moments generated by the electromagnetic forces on the coils. Because of the necessity of

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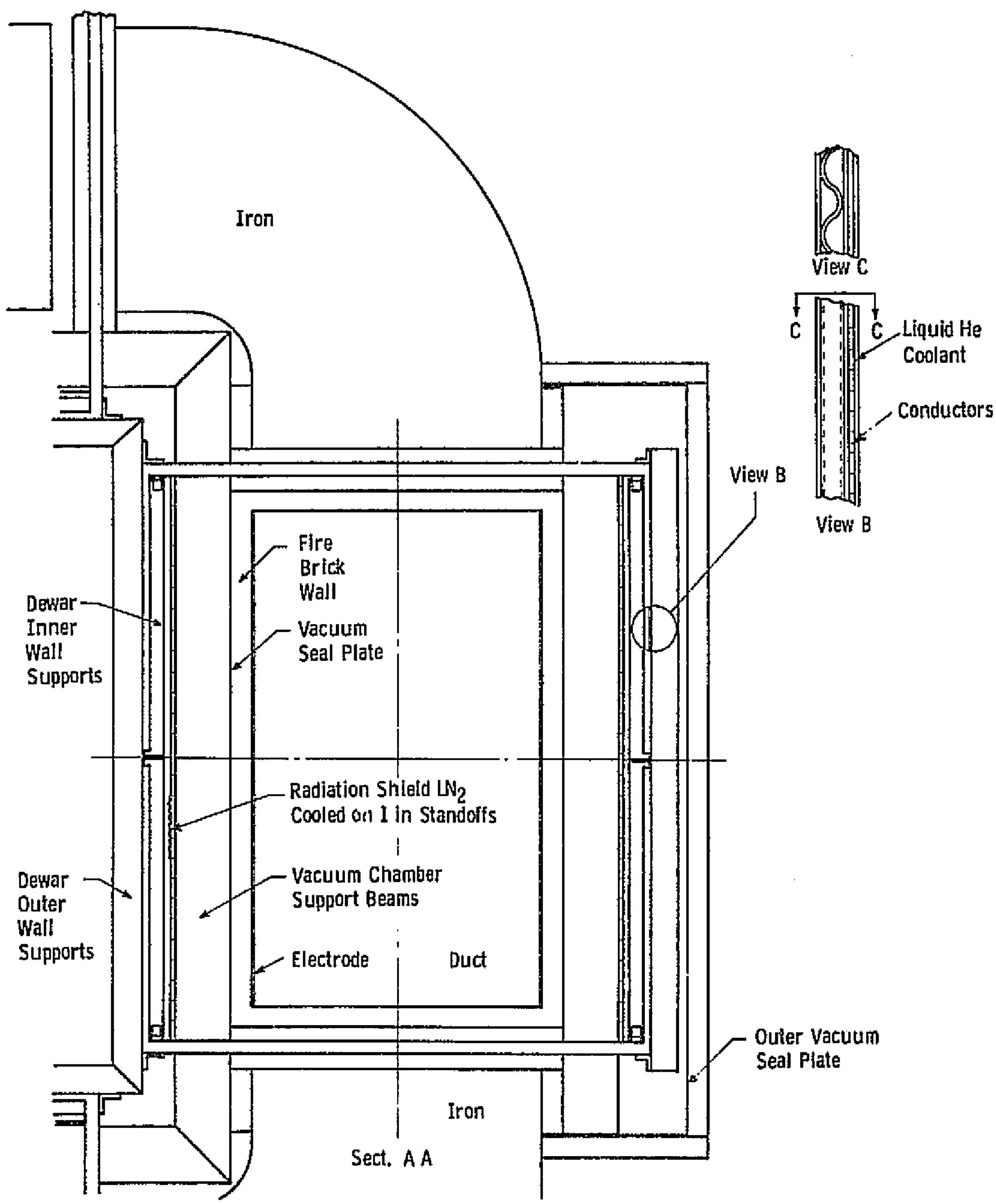

Fig. A 11.3.5—Sectional view of liquid metal MHD magnet design

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enclosing liqui. helium in the dewar, it is impratical from a heat transfer standpoint to provide supporting struts to the warmer structural elements. The dewars are to be essentially self-supporting, except for the provision of support columns at the base to sustain the dead weight of the structure.

For maximum economy and minimum weight the dewar walls subjected to bending loads were designed in plate-girder form. The spacing height and thickness of the webs were optimized with the thickness of the plates to produce a minimum weight structure consistent with the restriction of design stresses and buckling. In some cases, where other design considerations were dominant, a nonoptimal (in terms of weight) structure was used.

Figure A 11.3.5 shows the essential elements of the dewar design as discussed above.

A 11.3.6 <u>Heat Transfer Analysis</u>

The requirement of maintaining a superconducting magnet at 4.2°K (-452.13°F) within a tolerance of 0.2°K (0.36°F) can be achieved with existing technology. Liquid helium and nitrogen systems can be operated continuously for a year or more. In the past, the limiting factor in system endurance was clogging of the flow passages due to the freezing out of impurities. The major impurity source was compressor oil. Presently, dry compressors, tube expanders, and reduntant compressors in a closed-loop, cryogenic refrigeration system can be operated continuously for several years. Cryogenic refrigeration equipment with sufficient reliability to support the superconducting magnets for the MHD generators, therefore, are available.

A survey of the manufacturers of refrigeration equipment was performed several years ago, and these results have been applied in estimating the electrical requirements of the refrigeration equipment. No allowance has been made for technological improvements that may be made to increase the percent of Carnot efficiency of these machines. It is expected, however, that the continued emphasis on utilizing

Table A 11.3.1

Summary of Cooling Requirements for Liquid-Metal MHD Design

Load	Heat Input, W	Mass Flow, lb/hr	Electrical Load, kW
	(a) Helium Refrigeration		
Radiation	18	20	10.8
Electrical Leads	100	113	180.0
Support Structure	40	45	24.0
Totals	158	178	214.8
	(b) Nitrogen Refrigeration		
Helium Refrigerator	761	30.3	6.1
Radiation	7500	298.5	60.0
Conduction	325	12.9	2.6
Totals	8586	341.7	68.7

superconducting magnets in power generation systems will encourage innovation in the heat exchanger design and improvements in the reliability.

Liquid helium refrigeration systems can be obtained wich specific power requirements (watts of electrical power required to produce one watt refrigeration) as low as 300 W/W and helium liquefaction systems with as low as 400 W/W. These types of specific powers are generally obtained only in very large capacity devices. For a total system load of 160 W, 600 W/W are required for liquefaction.

Liquid nitrogen refrigeration systems can be obtained with specific power requirements as low as 6.8 W/W. For a 9 kW load specific power of 8 W/W is required.

A cursory examination of the use of foam insulation around the periphery of the liquid nitrogen shield showed that the liquid nitrogen requirements for the radiation shield would be one-sixth of the requirements for the foam-insulated liquid nitrogen vacuum vessel.

Since the most economical system for a magnet operating in a power system is usually the one with the highest efficiency, the down loss shielding system was selected; although if accessibility is an important requirement, the foam insulation will not severely affect the overall efficiency.

Illustrated in Table A 11.3.1 is a summary of the cooling requirements for the LM-MHD magnet.

A 11.3.7 Summary of Magnet Cost Basis

The cost of the magnet system including refrigerators for LM-MHD magnets can be roughly estimated by multiplying the cost of the conductor by a factor of approximately four. Hence, the following parametric expression applies for a four-duct magnet system:

$$C = \frac{32\ B\ L\ 10^6}{\mu_o\ J_{av}} \left(\frac{D_1 + D_2}{2} + 2R' \right)$$

Table A 11.3.2 - Summary of the Liquid-Metal MHD Magnet Design

Nominal Rating	
Inlet Cross-sectional Area	2.2 m x 2.2 m
Exit Cross-sectional Area	5.2 m x 2.2 m
Length of Duct	22 m
Field on Axis of Duct	1.37 T
Number of Ducts	4
Average Ampere Turns Required	1.93×10^{7} At
Current per Turn	5000 A
Average Winding Current Density	2×10^{8} A/m^{2}
Winding Peaking Factor	0.7
Conductor Aspect Ratio	2:1
Fraction of Superconductor in Conductor	0.25
Inductance	145 h
Stored Energy	1817 MJ
Number of Turns	5298
Conductor Operating Temperature	4.2°K
Liquid Helium Refrigerator Thermal Load	158 W
Liquid Helium Refrigerator Electrical Load	215 kW
Liquid Nitrogen Refrigerator Thermal Load	8.6 kW
Liquid Nitrogen Refrigerator Electrical Load	69 kW
Total Electrical Load	284 kW
Total Estimated Cost	$15,400,000
$/kVA	

where C = cost of magnet system, \$

B = magnet field, T

L = length of duct, m

$\mu_o = 4\pi \times 10^{-7}$ H/m

J_{av} = average winding current density

D_1 = inlet duct width, m

D_2 = exit duct width, m

R' = insulation thickness, m.

Utilizing this information and the information presented earlier, a summary of the results for the base case liquid-metal design is illustrated in Table A 11.3.2. The unit cost is approximately \$116/kVA, and there are some economies with scaling to even larger magnet systems implicit to the cost expression presented.

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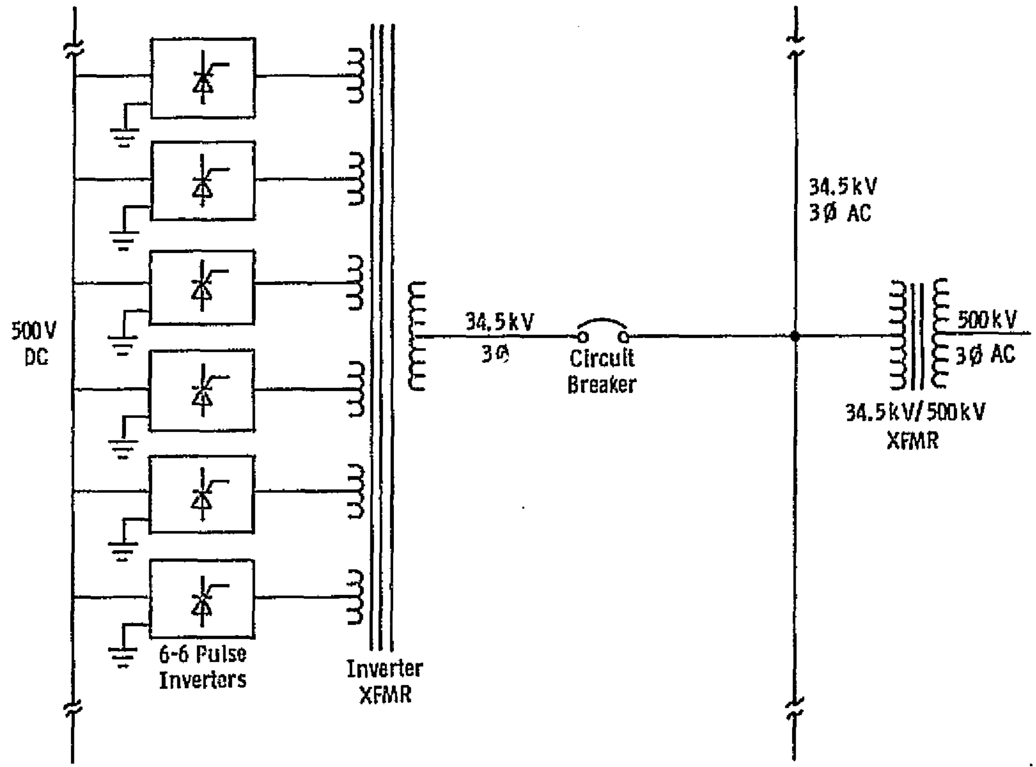

Fig. A 11.4.1 — One-line diagram of dc to ac power conditioning circuit. One of 24 such 500 V d.c. - 34.5 kV converter circuit is shown

Appendix A 11.4

DC TO AC POWER CONDITIONING SYSTEM FOR LM MHD

A 11.4.1 General Requirements

A power conditioning system is needed to convert the dc power from the output of the liquid-metal MHD generator to ac power. the MHD electrical power output for this specific case is 1800 MW, of which 1000 MW is to be fed to the mains having a line-line voltage of 500 kV; and the remaining 800 MW will be used to drive the pumps and auxiliary equipment. The output voltage and current from the MHD generator are:

- Voltage - 500 V
- Current - 3.6 MA.

A one-line diagram of the power conditioning system is shown in Figure A 11.4.1. The dc power from the MHD busses is fed into 144 solid-state six-pulse inverter sets, each having a dc input voltage and current of 500 V and 25 kA. The output from each inverter set is fed to one of the six primary windings of the inverter transformer. It is proposed that 24 inverter transformers will be used. Each transformer will have six 350 V - 17.6 kA, three-phase primary windings; and a 34.5 kV, three-phase secondary winding. Fourteen of these inverter transformers will be connected to the primaries of the 500 kV power transformers. A 34.5 kV 2500 MVA, three-phase circuit breaker will be inserted between each inverter transformer and the power transformer. Three 500 kV, 333 MVA, single-phase power transformers are used in a three-phase connection. Power from output of the other ten inverter transformers will be employed to run pumps and other auxiliaries.

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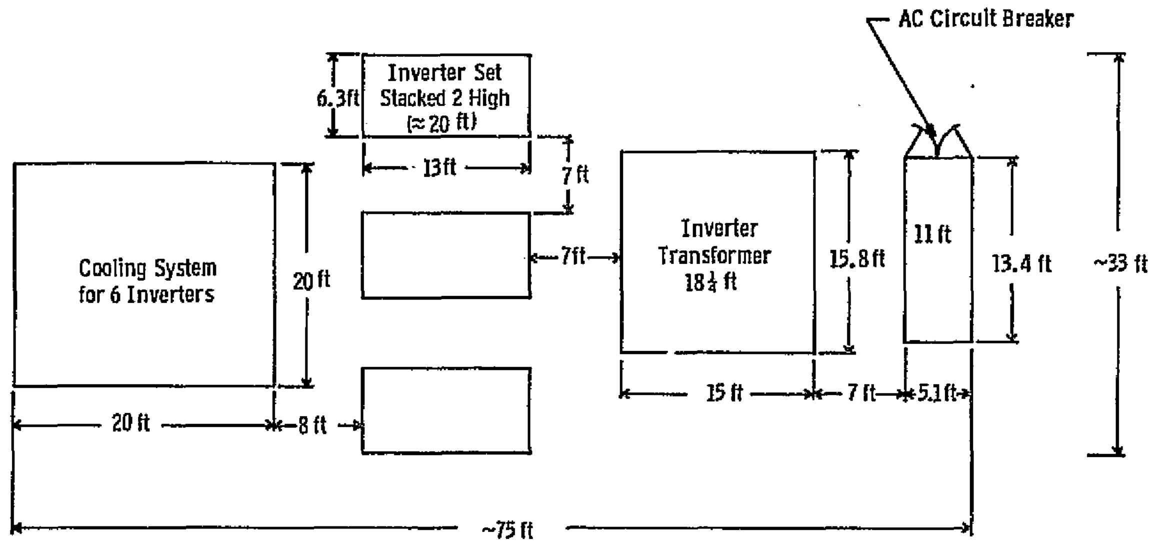

Fig. A 11.4.2—Layout of dc to ac converter circuit components. Twenty-four such circuits are arranged in parallel with each other

Each inverter set produces a three-phase output voltage with six current pulses. Since the inverter transformer has six three-phase primary windings, each primary receives six current pulses from the respective inverter. The inverters can be synchronized with each other so that the inverter transformer receives a total of 36 pulses. By proper timing of these inverters, the harmonic content of the output of the inverter transformer would be negligible. A filter across the output of the dc to ac converter system, therefore, is not necessary. This would represent a cost reduction of approximately $6/kW to the converter system.

A 11.4.2 Size and Weights of the DC to AC Converter Components and Power Transformers

The dimensions and the weights of the inverter sets, inverter transformer, ac circuit breaker, and power transformer are given in Table A 11.4.1. The total weight of the system is 7159.4 Mg (7,890 tons). The dimensions of the pad necessary to house these components is approximately 36.57 by 304.8 m (120 by 1000 ft). Figure A 11.4.2 shows a suggested layout of one of the 24,500 V dc to 34.5 kV ac converter circuits.

A 11.4.3 Cost of Dc to Ac Converter Components

The cost of the components for the converter having an input power of 1800 MW dc and output power of 800 MVA at 34.5 kV and 1000 MVA at 500 kV are given as follows:

• 12.5 MW inverter set at $30/kW is	$ 375,000
For 144 inverter sets is	54,000,000
• 83 MVA 350 V/34.5 kV inverter transformer is	470,000
For 24 inverter transformer is	11,280,000
• 34.5 kV, 2000 A, 2500 MVA circuit breaker is	24,200
For 24 circuit breakers is	581,000
• 34.5 kV/500 kV, 333 MVA power transformer is	832,000
For three power transformers is	2,497,000

The total cost at FOB is $68,358,000 which represents a cost of $37.9/kW. These costs do not include delivery and installation.

Table A 11.4.1 - Size and Weights of DC and AC Power Conditioning Components

Item	Dimensions, in	Weight, lb
Inverter Set (144)	120 x 151 x 75.6	40,600
Inverter Transformer (24)	219 x 180 x 190	180,800
ac Circuit Breaker (24)	131.7 x 61.0 x 160.4	9,620
Cooling System for 6 Inverters (24)	146 x 240 x 240	240,000
Power Transformer (3)	465 x 260 x 210	445,000
Total Weight		15,783,500

Appendix A 11.5

LIQUID-METAL SYSTEM AND SUBSYSTEMS

A 11.5.1 General Requirements

The liquid-metal system and subsystems consist of the following major items:

- Liquid-metal pump
- Liquid-metal piping
- Liquid-metal purification
- Liquid-metal dump systems.

Much of the liquid-metal (sodium) technology that exists today has been developed in conjunction with the liquid-metal fast breeder reactor (LMFBR). Current sodium technology is reflected in both the fast flux test facility (FFTF) and Clinch River Breeder Reactor Program (CRBRP) demonstration plant. Table A 11.5.1 summarizes the key design parameters.

A 11.5.2 Liquid-Metal Mechanical Pumps

The basis for determining the MHD liquid-metal pump cost was current state-of-the-art design practice for the breeder reactor programs. The sodium pumps presently being considered for the CRBRP are on the order of 1.8927 m^3/s (30,000 gpm) each and based on single-stage, low-head [1.063 MPa (450 ft) sodium] hydraulic design. Figure A 11.5.1 shows a schematic diagram of one such pump design. Costs for this type of sodium pump are estimated at $3.4 million per pump.

The liquid-metal pump for the MHD system under study requires pumps to handle flows in the range of 15.77 to 31.545 m^3/s (250,000 to

Table A 11.5.1 - Construction Seismic Class 1

Liquid-Metal System	FFTF	Clinch River
LM pump	Mechanical, single-stage 15,000 gpm, 450 ft Na	Mechanical, single-stage 30,000 gpm, 450 ft Na
Pumping and Valves	Piping and valving 28-36 in diameter T = 1200°F V = 20-40 ft/s p = 200 psi	Piping and valving 36-50 in diameter T = 1200°F V = 20-40 ft/s p = 200 psi
Purification (Na)	2 ppm O_2 level cold trap O_2, H_2 monitoring 0.1% of total volume per day; cover gas leak rate (max)	2 ppm O_2 level cold trap O_2, H_2 monitoring
Safety-Emergency	Sodium-dump - gravity smoke and sodium vapor leak detectors	Sodium dump

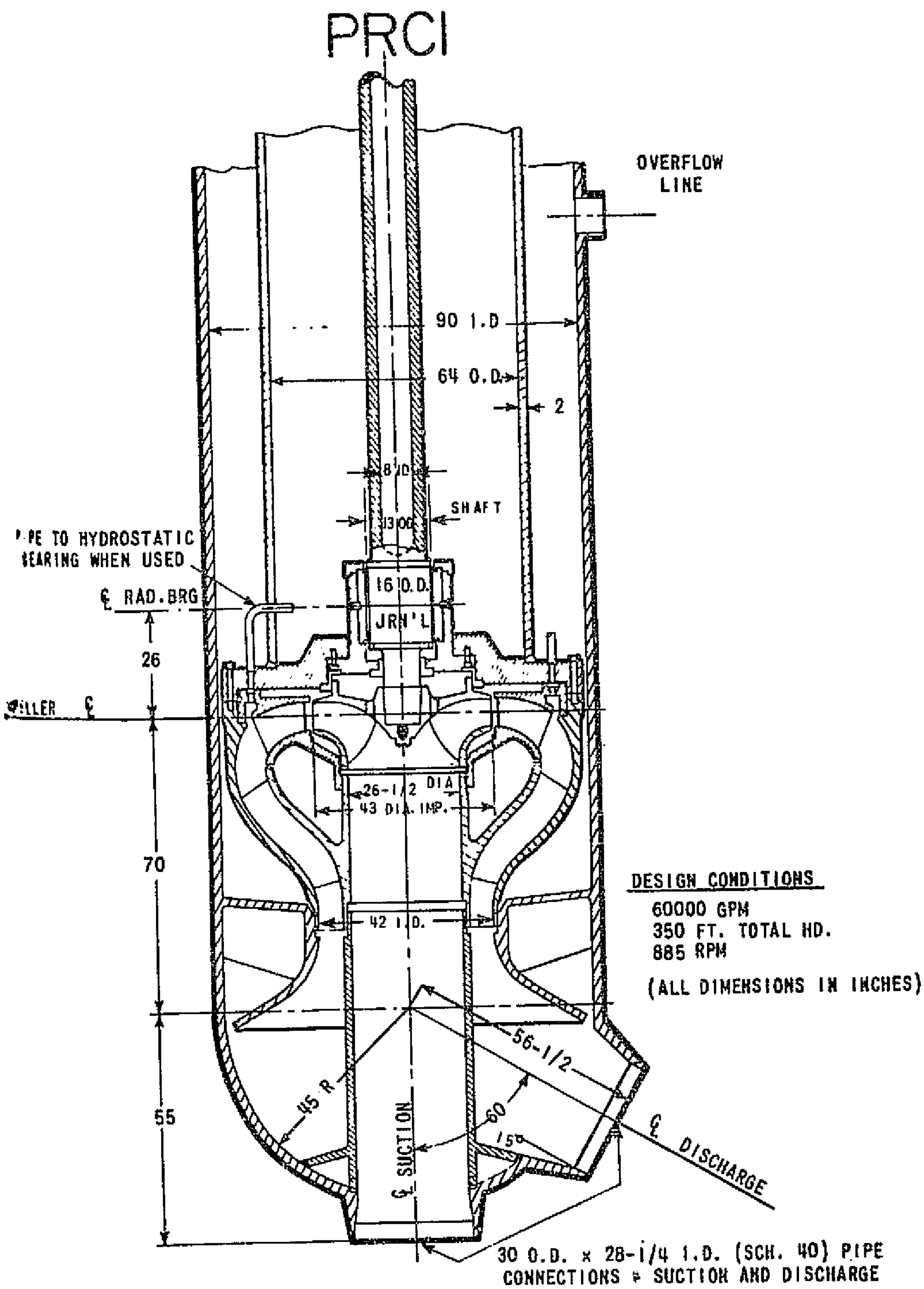

Fig. A 11.5.1—Single-suction pump (Removable concentric casing)

500,000 gpm) at high system heads [5.472 MPa (54 atm)]. A preliminary design of a sodium pump to meet these requirements was prepared by the Westinghouse Cheswick Large Pump Division. The design was based on current sodium pump technology as embodied in the CRBRP design shown previously in Figure A 11.5.1. The basic and essential hydraulic features of the LM-MHD sodium pump design are summarized in Table A 11.5.2.

The cost for this pump was developed on the basis of material requirements. This cost, however, was subsequently judged to be excessive, and substantial reduction in the material usage could be achieved (particularly with the casing). Such a design effort, however, was beyond the scope of work intended for this study program.

It was ultimately concluded that a reasonable pump cost estimate could be made because of the similarity of the hydraulic designs. Thus, it was decided to extrapolate the Clinch River pump costs to the present LM-MHD case based on the number of stages and flow capacity. It is anticipated that the costs for higher LM-MHD pressure design conditions are somewhat offset by the costs for the Clinch River pump's nuclear code construction requirements.

The large liquid-metal flows and high-pressure heads require enormous pump power requirements 1020 MW shaft (1.37×10^5 hp). For the four-loop system, the specific drive requirements are 25.5 MW shaft (34,250 hp) per pump. With such large power requirements, direct coupling with a steam turbine drive from the steam plant should be considered. Two of the pumps could be driven in this manner. The remaining two pumps require motor drives.

For Point 11, the liquid-metal mechanical pumps are replaced with EM pumps. A preliminary design of an EM pump was prepared in order to determine size and cost of the system. Table A 11.5.3 summarizes the pump design data. Costing of this pump was based on weight at 517.6/kg ($8/lb).

Table A 11.5.2 - Summary of Basis for Design of LM-MHD Sodium Pump

DESIGN BASIS

Flow	-	250,000 gpm
Temperature	-	1200°F
Required Head	-	2320 ft Na
Sys. Operating Temp.	-	1200°F
Thermal Transients	-	None

PUMP DESIGN FEATURES

No. of Stages	-	5
Head/Stage	-	465 ft
Speed	-	500 rpm
Hydraulic Eff.	-	85%
BHP	-	146,000 hp
Impeller Dia.	-	80 in
Diffuser Dia.	-	120 in
Cross-over id	-	158 in
Casing id	-	195 in
Impeller Eve	-	53 in (suction end)
Shaft Dia.	-	26 in
Tank Wall	-	12 in

Table A 11.5.3

SC Electric Machinery Systems High Field dc Conduction Pump

Approximate Data - 4 units as follows:	
Flow	- 250,000 gpm, 1200°F, 2300 ft head
Weight	- 380,000 lb/unit
Size	- MHD channel to pump:
Transition section	- 10 ft long
Pump inlet	- 6 ft long by 30 ft od
Pump	- 9 ft long by 30 ft od
Pump exit	- 6 ft long by 30 ft od
Pump efficiency	- 90%
Power input	- 95.303 per unit, 1.3236 MA at 72 volt

A 11.5.3 Piping and Valves

Piping for the liquid-metal flows would be mostly designed and costed in a manner similar to that of the MHD ducts, in other words, utilizing steel plates and rib supports. Circular piping might be required at the manifolding to the primary heat exchanger and perhaps at the pump connections. The design for the piping system sizing is based on 6.094 m/s (20 to 40 ft/s) velocity, compatible with present breeder reactor technology. Design of the piping system would need to include provision for thermal expansion, either by use of expansion loops or by designing equipment interfaces with slip-joint connections. The piping system would be constructed from 316 SS and designed for 946.08 Ms (30 yr) life. At the large piping size requirements, valving of the main liquid-metal flow is not anticipated.

The algorithm derived for costing and sizing the liquid-metal ducting was previously given in Table 11.4.

The gas stream piping was divided into hot and cold legs. The respective length of each leg was estimated from the preliminary plans and elevation equipment arrangement sketches of the plants. Values for the length of hot and cold leg piping were approximated at 30.48 and 38.1 m (100 and 125 ft), respectively. The algorithms for sizing and costing the gas piping were given in Table 11.4. The calculations were made assuming a 30.48 m/s (100 ft/s) gas velocity. The equation is derived from:

- Mass continuity for the gas
- Equation for weight of circular pipe
- Stress equation for circular pipes.

These equations were combined to eliminate pipe diameter and thickness from the final expression. The cost coefficient in the weight equation was based on current design estimates for CRBRP large seamless stainless steel pipe.

A 11.5.4 Liquid-Metal Purification Subsystem

The liquid-metal purification system is required to maintain the concentration of certain contaminants at or below specified values. One of the most important of these contaminants is oxygen. High oxygen levels coupled with high temperatures can lead to severe corrosion of metal containment pipes and ducting. The corrosion of heat exchange tubes leads to reduced performance and ultimately the possibility of tube failure. Section 3.8 discusses specific materials requirements for sodium and lithium MHD systems.

With the liquid-metal (sodium) MHD system under study, the required sodium purity level (and hence, purification system requirements) may not be as stringent as those encountered in the breeder reactor designs. This observation is based on two factors: (1) liquid-metal temperature gradients in the MHD system are not severe (minimize mass transfer effects), and (2) high-pressure construction (thick walls) could relax corrosion allowances. Fouling of heat exchanger surfaces, however,

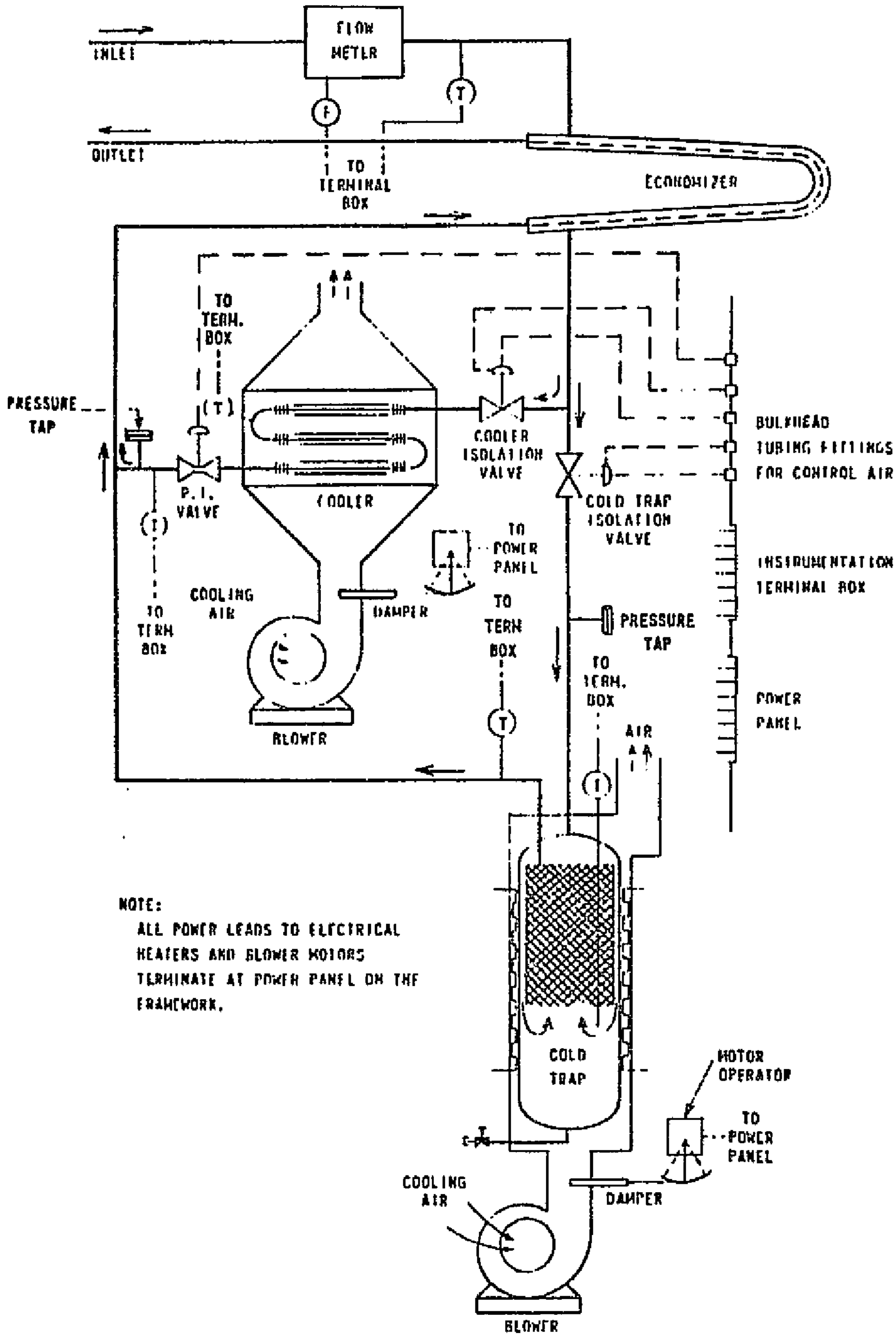

Fig. A 11.5.2—Flow diagram - Oxide control and indicating system compatibility of the liquid metal with the MHD duct materials, and plugging of flow passages with crud must still be considered in specifying purity requirements.

The liquid-metal MHD system cold trapping will require reducing sodium temperatures from above 922 to 394°K (1200 to 250°F). A schematic of the cold trap system and components is shown in Figure A 11.5.2. The system consists of a pump, flowmeter, regenerator, heat sink, cold trap tank, and associated instrumentation. The instrumentation would function to monitor the performance and effectiveness of the cold trap system to remove sodium impurities, and should include oxygen and hydrogen meters both before and after the cold trap and a Δp gage across the cold trap to monitor the pressure drop associated with impurity build-up in the cold trap mesh.

The design (and subsequent costing) of the LM-MHD purification system has been based on the following assumptions:

- The diffusion of oxygen and hydrogen through piping and duct walls is negligible.
- The oxygen, hydrogen, carbon dioxide, and water vapor concentrations in the sodium will occur via gettering from the argon gas.
- Argon purity as received (prepurified grade) will be:*

4 to 5 ppm (by volume)	O_2
1 ppm	CO_2
5 ppm	H_2
7 ppm	N_2
< 1 ppm	total hydrocarbons
5 ppm	H_2O

- Argon makeup requirements will be based on a leak rate per day of 0.1% of total volume.

*Private communication with representative from Matheson Gas Products.

An equation that relates the required purification flow rate to the purification requirements is given as:

$$y = Z \left[1 - \frac{N}{N + \left(\frac{\rho_\ell}{\rho}\right) \frac{(s)(c)}{(MR)}} \right] \qquad \text{(A 11.5.1)}$$

where y = required liquid-metal purification flow, gpm

N = allowed oxygen concentration on the liquid metal, ppm

ρ = density, g = gas, ℓ = liquid

s = argon leak rate

c = concentration of oxygen in the argon gas makeup, ppm

MR = mass flow rate ratio in MHD loop, i.e., liquid-metal gas

Z = total MHD liquid-metal flow, gpm.

For the specific conditions of sodium/argon with 0.1% leak rate under base case conditions, the equation reduces to:

$$y = Z \left(1 - \frac{N}{N + 1}\right) \qquad \text{(A 11.5.2)}$$

The cost model for the purification system was taken as:

$$C, \$ = 8572(y)^{0.6}$$

where C is the cost of the purification system in dollars and y the required capacity from Equation A 11.5.1. The constant 8572 and exponent 0.6 were determined on the basis of two cost estimates obtained from MSA

Research Corporation, supplier of liquid-metal oxide control systems. One of the cost quotations was based on a state-of-the-art 60 gpm flow rate, and the second was an estimate for an advanced state-of-the-art, 500 gpm purification system.

A 11.5.5 Liquid-Metal Inventory and Emergency Dump

The LM-MHD dump system was sized and costed on the basis of a very similar system now being designed for the CRBRP. This system consists of tanks, dump heat exchangers, valves, piping, pumps, and appropriate heat tracing. The tanks are lined carbon steel with capacities ranging up to 189.3 m^3 (50,000 gal). Drain lines range up to 45.72 cm (18 in) diameter. Costs for this system for CRBRP are expected to be about $4 million for 302.8 m^3 (80,000 gal) capacity. This does not include sodium inventory costs. A temperature capability of up to 700°K (800°F) is maintained for each tank to prevent metal solidification.

The costing for the liquid-metal dump system for the LM-MHD plant was based on the above described system using a 0.7 power scaling law. The required liquid-metal capacity was determined from piping and component volume calculations.

Sodium inventory costs were determined on the basis of the required capacity and costed at $3.01/kg ($1.37/lb). Present production capacity is limited; this price, therefore, includes the cost of storing and handling the large quantities of sodium required for the LM-MHD system and is thus higher than that usually charged for small quantities [< 454 kg (< 1000 lb)]. If production capacity increases, the cost of sodium can be expected to decrease, but in any case the impact of a lower price on total plant costs would be insignificant.

Figure A 11.9 illustrates the relative positioning of the dump tanks with respect to the MHD duct assembly.

Appendix A 11.6

COUPLING HEAT EXCHANGERS

A 11.6.1 General Methodology for Coupling Heat Exchangers

When the LM-MHD coupling heat exchangers were designed, the general theoretical methodology followed that previously described in Appendices A 9.2 and A 9.3 of the open-cycle MHD study. The general correlations and equations for calculating the various heat transfer coefficients are summarized there. In adapting this analysis to the present study, some simplification and alternative approaches were made. These are summarized here, along with the final results. Simplified size and cost algorithms were developed for the following heat exchanger systems:

- Primary (fired) coupling heat exchanger
- MHD-steam plant coupling heat exchanger
- Air-gas preheaters (or precoolers)
- Gas recuperators.

A 11.6.2 Primary Heat Exchanger Design Basis

In order to determine a realistic costing for the primary heat exchanger for the closed-cycle LM-MHD cycles, a series of heat exchanger calculations was performed for sodium-, argon-, and steam-cooled heat transfer surfaces. In general, the design practice of state-of-the-art cyclone-furnace-fired, water-cooled boilers was used for guidance on tube geometry, overall dimensions, and materials of construction.

No attempt was made in any of the calculations to optimize the designs or to produce parametric design data. Rather, the calculations were used to provide rough engineering estimates of the cost of these types of heat exchangers.

For the radiation section, sodium- and/or steam-cooled tubes were selected. For the 22.9 to 30.5 m (75 to 100 ft) high chambers, 5.08 cm (2 in) id tubes were selected for the calculations. Haynes alloy No 188 was chosen for these tubes because of its high-temperature creep strength. Also, these tubes were assumed to be clad (flue-gas side) either with one of the stainless steels or with some other oxidation-resistant coating. The usual wall thickness required for both strength and corrosion was 0.635 cm (0.25 in). For radiation exchange calculations, the 6.35 cm (2.5 in) od tubes were spaced on 12.7 cm (5 in) centers and located in a plane 13.97 cm (5.5 in) inside the refractory walls.

Once the hot products of combustion were cooled from the maximum flame temperature of around 2444°K (3940°F) in this radiation section, a second argon-cooled tube bundle was employed to further reduce the temperature of the combustion gases (while warming the argon to its final temperature). Once again, in this section of the heat exchanger the superalloy Haynes alloy No 188 was selected because of its high-temperature creep strength.

This second radiation-convection section of the exchanger was generally the most expensive section (on a $/Btu/hr of heat transferred basis) because the argon-cooling heat exchange coefficients were always 5 to 30 times lower than those for steam or sodium, respectively. Also, the tube external heat transfer coefficient in this section is about 4 times lower than in the radiation section. Finally, the tube wall temperatures are high enough here to require a substantial tube wall constructed from a high-cost superalloy.

The final section of the exchanger was designed to cool the flue gases to the desired 644°K (700°F) exit temperature. In this convection section, finned tubes were specified in the tube bundles to enhance the external heat transfer and to reduce the number and length of the tubes.

Tables A 11.6.1 and A 11.6.2 summarize the most significant physical characteristics and heat transfer parameters of the design for the base case and for parametric Point 8.

In order to scale the cost and size of the primary heat exchanger for the various parametric cases, a simplified analytical model was developed for estimating heat transfer surface areas and related parameters. The analytical model and calculation procedures were based on the concept of the Number of Heat Transfer Units (NTU), a term introduced by London and Kays (Reference 11.10). The physical model of the primary heat exchanger was simplified from the real case to consider only a radiation section followed by a straight convection section as depicted in Figure A 11.6.1.

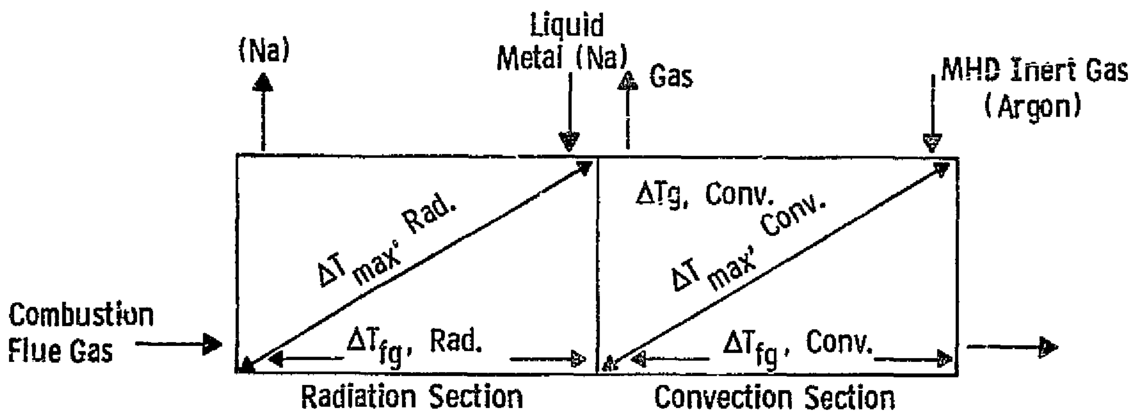

Fig. A 11.6.1 — Primary heat exchanger models

The heat capacitance ($\dot{m}\, C_p$) of the liquid metal was large when compared to that of the combustion gases, and its thermal resistance negligible. The required primary heat exchanger heat transfer surface areas were determined from:

$$A_{T_{conv}} = (NTU)_{conv}\, C\, \left(\frac{1}{U}\right) \qquad \text{(A 11.6.1)}$$

where $C = (\dot{m}\ C_p)_{argon}\ (\Delta T_g/\Delta T_{fg})_{conv}$, U is the overall convective heat transfer coefficient (see Section 9, Appendix A 9.2), and:

$$A_{T_{RAD}} = (NTU)_{RAD}\ C_{fg} (\frac{1}{h_{RAD}}) \qquad \text{(A 11.6.2)}$$

where C_{fg} is the specific heat of the combustion gas and h_{RAD} (see Section 9, Appendix A 9.2) is the radiation heat transfer coefficient.

For the various parametric cases, then, the required total heat exchanger tubing length, L_t, was scaled from the appropriate case previously summarized in either Table A 11.6.1 or A 11.6.2 (low- or high-system temperature, respectively) according to their heat transfer surface area ratio (this assumes the same tube geometry).

The characteristic dimensions of the heat exchanger (diameter and length) were determined on the basis of the required gas and combustion products flow areas, required heat transfer surface area, and specified pressure drop. The equations for the characteristic diameter and length were previously listed in Table 11.5 of the text. The expression for diameter was developed on the basis of total flow cross-sectional area ($A_{flue\ gas} + A_{inert\ gas} = \frac{\pi}{4} d^2$) and the known mass ratios between the two flows ($\dot{m}_{flue\ gas}/\dot{m}_{inert\ gas} = 0.190$). For this calculation, the mass ratio was assumed to be constant for all cases. The numerical constant 28 appearing in Table 11.5 represents four times the mass ratio times the ratio of the product of velocity and density ot the inert gas and combustion gas, respectively. This relation is derived from continuity considerations. It was further assumed that the flue gas velocity was approximately twice the inert gas velocity. Typical flue gas velocities ranged, therefore, from 15.24 to 30.48 m/s (50 to 100 ft/s).

The gas flow cross-sectional area, A_c, was calculated from the pressure drop and mass continuity considerations. The equation is:

Table A 11.6.1 Summary of Primary Heat Exchanger Design, Base Case

Item		Specifications
1	Combustor flue gas	8.69×10^6 lb/hr
2	Total heat load	8.5×10^9 Btu/hr
3	Liquid sodium flow	4.38×10^8 lb/hr
4	Sodium temperature rise	1181.4 - 1200°F (ΔT = 18.6°F)
5	Argon flow	4.27×10^7 lb/hr
6	Argon pressure	1250 psi
7	Argon temperature rise	560 - 1200°F (ΔT = 640°F)
8	Primary steam flow	5.124×10^6 lb/hr at 3500 psi
9	Primary steam temperature rise	800 - 1000°F (ΔT = 200 °F)
10	Reheat steam flow	5.124×10^6 lb/hr at 600 psi
11	Reheat steam temperature rise	550 - 1000°F (ΔT = 450°F)

Design Data - Radiation Section (steam cooled)

Physical

1. Tube id	0.9 in
2. Tube wall thickness	0.285 in
3. Tube material	Haynes Alloy No. 188 - clad with oxidation resistant material
4. Tubing required	34,355 ft

Thermal

1. Radiation heat transfer coefficient	50 Btu/hr-ft^2-°F
2. Steam side heat transfer coefficient	550 Btu/hr-ft^2-°F
3. LMTD	1929°F
4. Heat load	1.123×10^6 Btu/hr

Table A 11.6.1 Continued

Item	Specifications
Design Data - Radiation Section (sodium cooled)	
<u>Physical</u>	
1. Tube id	2.0 in
2. Tube wall thickness	0.25 in
3 Tube material	Haynes Alloy No. 188 - clad with oxidation resistant coating or metal
4. Tubing required	34,812 ft
<u>Thermal</u>	
1. Radiation heat transfer coefficient	55 Btu/hr-ft^2-°F
2. LMTD	1970°F
3. Heat load	2.54 x 10^9 Btu/hr
Design Data - Radiation/Convection Section (argon cooled)	
<u>Physical</u>	
1. Tube id	2.0 in
2. Tube wall thickness	0.25 in
3. Tube material	304 SS
4. Tubing required	99,695 ft
<u>Thermal</u>	
1. Heat transfer coefficient - external	15 Btu/hr-ft^2-°F
2. Heat transfer coefficient - internal	100 Btu/hr-ft^2-°F
3. LMTD	1345°F
4. Heat load	1.085 x 10^9 Btu/hr

Table A 11.6.1 Continued

Item	Specifications
Design Data - Convection Section (argon cooled)	
Physical	
1. Tube id	1.8 in
2. Tube wall thickness	0.1 in
3. Tube fin height	1.0 in
4. Fin thickness	0.030 in
5. Fin width	0.156 in
6. Tube material	SS
7. Tubing required	273,000 ft
Thermal	
1. Heat transfer coefficient - external	6 Btu/hr-ft^2-°F
2. Fin efficiency	65%
3. Heat transfer coefficient - internal	100 Btu/hr-ft^2-°F
4. LMTD	524°F
5. Heat load	2.41×10^9 Btu/hr
Design Data - Convection Section (water cooled)	
Physical	
1. Same as argon convection system	
2. Tubing required	152,000 ft
Thermal	
1. Same as argon section (flue gas side)	
2. Heat load	1.34×10^9 Btu/hr

Table A 11.6.2 Summary of Primary Heat Exchanger Design for Parametric Point 8

Item		Specifications
1	Combustion Products flow	8.69×10^6 lb/hr
2	Total heat load	8.5×10^9 Btu/hr
3	Liquid sodium flow	6.307×10^8 lb /hr
4	Sodium temperature rise	1481.3 - 1500°F (ΔT = 18.7°F)
5	Argon flow	4.86×10^7 lb/hr
6	Argon pressure	1200 psi
7	Argon temperature rise	660 - 1500°F (ΔT = 840°F)

Design Data - Radiation Section

Physical

1.	Tube id	2.0 in
2.	Tube wall thickness	0.25 in
3.	Tube material	Superalloy Haynes No. 188 - with oxidation resistant cladding
4.	Tubing required	76,500 ft

Thermal

1.	Heat transfer coefficient	51 Btu/hr-ft^2-°F
2.	LMTD	1397°F
3.	Heat load	5.0×10^7 Btu/hr

Design Data - Radiation-Convection Section

Physical

1.	Tube id	1.5 in
2.	Tube wall thickness	0.25 in
3.	Tube material	Haynes Alloy No. 188
4.	Tubing Required	652,000 ft

Table A 11.6.2 Continued

Item		Specifications
Design Data - Radiation-Convection Section - Continued		
Thermal		
	1. Heat transfer coefficient - external	12 Btu/hr-ft^2-°F
	2. Heat transfer coefficient - internal	112 Btu/hr-ft^2-°F
	3. LMTD	809°F
	4. Heat load	2.9 x 10^9 Btu/hr
Design Data - Convection Section		
Physical		
	1. Finned tubes (same as base case)	
	2. Tubing required	641,000 ft
Thermal		
	1. Heat transfer coefficient - external	6.0 Btu/hr-ft-°F
	2. Fin efficiency	65%
	3. LMTD	190°F
	4. Heat load	2.05 x 10^9 Btu/hr

$$A_c = \left[\frac{f \dot{m}^2 RT}{2g_c \frac{\Delta p}{p} p^2} A_s \right]^{1/3} \quad \text{(A 11.6.3)}$$

where f = fanning fraction factor

$\dot{m}$ = mass flow rate of the gas

R - gas constant

T - temperature

Δp = pressure difference

p = pressure

A_s = heat transfer surface area

The characteristic length of the primary heat exchanger was determined from the known geometry of the tube (specified) and the previously calculated heat transfer surface and cross-sectional flow areas.

The cost the primary heat exchanger was calculated on the basis of the quantity of tube material, assuming the average tube weight was taken at 43.40 kg/m (6 lb/ft). This value is approximately 30% higher than the calculated weight of a finned tube of the geometry described in Tables A 11.6.1 and A 11.6.2, and approximately equal to the weight of the thick-walled tubing used in the radiation and radiation-convection sections of the primary heat exchanger design. The finned-tube portion of the heat exchanger represents about 70% of the total tube required. The weight factor used, therefore, was actually about 20% higher and was assumed to account for various strucs and supports. The cost coefficient, C_{13} was taken as \$20.06/kg (\$9.10/lb) for the low-temperature case [922°K (1200°F)] and was derived on a weight averaged basis, from the following criteria:

- Radiation section - 1/10 of total weight at \$30.86/kg (\$14/lb) (Haynes cladded SS)
- Radiation convection - 1/5 of total weight at \$30.86/kg (\$14/lb) (Haynes cladded SS)
- Convection section - 7/10 of total weight at \$12.85/kg (\$5.83/lb) (316 SS)
- Tube fabrication cost - \$10/tube (10% of material cost)

The cost coefficients are used in Table 11.5.

For the high-temperature case, 1089°K (1500°F), the coefficient, C_{13}, was \$26.68/kg (\$12.10/lb), based on higher temperature materials in the final portion of the convection section. Approximately half of this section was assumed to require Haynes 25 tubing.

A 11.6.3 MHD-Steam Plant Coupling Heat Exchanger

Within the MHD system configuration, a heat exchanger is interposed between the MHD cycle and the steam bottoming plant wherein the waste heat of the MHD inert gas (argon) prior to compression is utilized to drive the steam turbine bottoming plant. The following sets of equations were derived to model the heat transfer and physical characteristics of this coupling heat exchanger for each parametric point.

It is assumed that the argon gas passes through the staggered tube array in crossflow. The heat transfer correlation appropriate to this situation is:

$$h = 0.33 \frac{k}{d_o} \left[\frac{(V_{max})(\rho)(d_o)}{\mu}\right]^{0.6} Pr^{0.33} \qquad \text{(A 11.6.4)}$$

This can most conveniently be expressed in the following form:

$$h,\ \text{Btu/hr-ft}^2\text{-°F} = (\phi_1)(V_{max}^{0.6})(d_o^{-0.4}) \qquad \text{(A 11.6.5)}$$

So that V_{max} might be expressed in ft/s units and d_o in inches, ϕ_1 must have the following form:

$$\phi_1 = \frac{(0.33)(12^{0.4})(k)(\rho^{0.6})(Pr^{0.33})(3600^{0.6})}{\mu^{0.6}} \left[\frac{in^{0.4}\ s^{0.6}\ Btu}{hr\text{-}ft^{2.4}\ {}^\circ F}\right]$$

(A 11.6.6)

Values of thermal conductivity (k, Btu/hr-ft-°F), density (ρ, lb/ft^3) and viscosity (μ, lb/ft-hr) are evaluated at the arithmetic mean gas temperature.

The pressure drop per row for flow over a staggered array of tubes is represented by the following equation:

$$\frac{\Delta p}{N_{row}} = \frac{4f\ \rho\ V_{max}^2}{2g\ \ 144} \quad \text{(A 11.6.7)}$$

where

$$f = \frac{0.507}{\left(\frac{V_{max}\ \rho\ d_o}{\mu}\right)^{0.15}} \quad \text{(A 11.6.8)}$$

Equation A 11.6.7 can, therefore, be conveniently expressed as follows:

$$\frac{\Delta p}{N_{row}} = \phi_2\ (V_{max}^{1.85}\ d_o^{-0.15}) \quad \text{in psi/row} \quad \text{(A 11.6.9)}$$

and so that V_{max} might be expressed in ft/s and d_o in inches

$$\phi_2 = \frac{(2)(0.507)(12^{0.15})}{(144)(3600^{0.15})(32.2)}\ \rho^{0.85}\ \mu^{0.15} \left[\frac{lb\ s^{1.85}}{in^{1.85}\ Pr^{1.85}}\right] \quad \text{(A 11.6.10)}$$

For the liquid-metal MHD cases, ϕ_2 takes on the value 0.507, and the units are as shown in Equation A 11.6.10.

The required surface area for heat transfer per steam generator is given by Equation A 11.6.11:

$$A_s,\ ft^2 = \frac{Q}{(N_{SG})(MTD)(h)} \quad \text{(A 11.6.11)}$$

Substituting Equation A 11.6.5 for h in Equation A 11.6.11, we obtain Equation A 11.6.12:

$$A_s,\ ft^2 = \frac{(Q)(V_{max}^{-0.6})(d_o^{0.4})}{(N_{SG})(MTD)\ \ \phi_1} \quad \text{(A 11.6.12)}$$

Equations A 11.6.13 and A 11.6.16, which follow, are fundamentally different ways of expressing the minimum area of flow per steam generator:

$$A_{f_{min}} = \eta \frac{\pi D^2}{4} \left[\frac{P_t - d_o}{P_t}\right] \quad \text{(A 11.6.13)}$$

In Equation A 11.6.13, η is a factor which expresses the fraction of the available area within the shell diameter (D) which is utilized for the tube banks. The tube pitch (P) is in inches, as is d_o.

For a situation where the tube banks are housed in a refractory metal duct of square cross section, which itself is housed within a cylindrical pressure containment shell, η has a maximum value of $2/\pi$.

Consequently, Equation A 11.6.13 can be restated as follows:

$$A_{f_{min}},\ ft^2 = \phi_3\ D^2 \left[\frac{P_t - d_o}{P_t}\right] \quad \text{(A 11.6.14)}$$

where

$$\phi_3 = (\frac{\pi}{4})\ (\frac{2}{\pi}) = 0.5 \quad \text{(A 11.6.15)}$$

The alternative way to express the minimum flow area is in terms of the mass flow rate of the gas, $\dot{m}_g$, and maximum velocity.

$$A_{f_{min}},\ ft^2 \equiv \frac{\dot{m}_g}{(N_{SG})(V_{max})(\rho)\ (3600)} \quad \text{(A 11.6.16)}$$

In Equation A 11.6.16, $\dot{m}_g$ is the total MHD duct gas mass flow rate in lb/hr; hence, the need for N_{SG} in the denominator to put the flow on a per moduler basis. The 3600 in the denominator is required because V_{max} is in units of ft/s.

Together, Equations A 11.6.14 and A 11.6.16 provide a means of expressing the inside shell diameter in terms of fundamental flow parameters.

$$\phi_3\ D^2\ \frac{P_t - d_o}{P_t} = \frac{\dot{m}_g}{(N_{SG})(V_{max})(\rho)\ (3600)} \quad \text{(A 11.6.17)}$$

Letting

$$\phi_4 = (\phi_3)\ (3600\ \rho)\ (\frac{s}{ft^3}\frac{lb}{hr}) \quad \text{(A 11.6.18)}$$

Equation A 11.6.17 can be conveniently rearranged as follows:

$$D = \left[\frac{\dot{m}_g}{\phi_4}\left[\frac{P_t}{P_t - d_o}\right]\right]^{0.5}\left[N_{SG}\ V_{max}\right]^{-0.5} \quad \text{(A 11.6.19)}$$

There exists yet another expression for the flow area, which is fundamentally different from those presented heretofore and which when equated with Equation A 11.6.16 will yield an equation for the length of tube per tube row (L). This equation is:

$$A_f,\ ft^2 = \frac{L\ (P_t - d_o)}{12} \quad \text{(A 11.6.20)}$$

Equation A 11.6.20 is equivalent to saying that for every foot of tube length, L, there is a gap between tubes through which gas may flow, which is of width $(P_t - d_o)/12$ ft.

Equating A 11.6.20 with A 11.6.16 we obtain:

$$L = \left[\frac{\dot{m}_g}{(P - d_o)\ \phi_5\ N_{SG}\ V_{max}^{0.5}} \right] \qquad \text{(A 11.6.21)}$$

where

$$\phi_5 = \frac{(\rho)(3600)}{12} \left[\frac{\text{lb}\ \ \text{s}}{\text{hr-ft}^2\text{-in}} \right] \qquad \text{(A 11.6.22)}$$

In order to formulate an equation for the number of tube rows required we evolve a second equation for the heat transfer surface area.

$$A_s = (\pi)(\frac{d_o}{12})(L)(N_{row}) \qquad \text{(A 11.6.23)}$$

This is equated with a previous equation for A_s, namely; Equation A 11.6.12. Hence:

$$\frac{(Q)(V_{max}^{-0.6})(d_o^{0.4})}{(N_{SG})(MTD)(\phi_1)} = (\pi)\ (\frac{d_o}{12})(L)(N_{row}) \qquad \text{(A 11.6.24)}$$

Now substituting Equation A 11.6.21 for L in Equation A 11.6.24 and expressing for N_{row} we obtain:

$$N_{row} = \frac{12\ (\phi_5)}{\pi\ \phi_1}\ \frac{Q\ (P_t - d_o)}{(MTD)(\dot{m}_g)}\ (V_{max}^{0.4})(d_o^{-0.6}) \qquad \text{(A 11.5.25)}$$

$$N_{row} = \phi_6\ \frac{(Q)(P/d_o - 1)}{(MTD)(\dot{m}_g)}\ (V_{max}^{0.4})(d_o^{0.4}) \qquad \text{(A 11.6.26)}$$

In Equation A 11.6.26:

$$\phi_6 = \frac{12}{\pi}\ \frac{\phi_5}{\phi_1} \left[\frac{\text{lb}\ \ \text{s}^{0.4}\ \ {}^\circ\text{F}}{\text{in}^{0.4}\ \ \text{ft}^{0.4}\ \ \text{Btu}} \right] \qquad \text{(A 11.6.27)}$$

From Equations A 11.6.27 and A 11.6.9 we can obtain an equation for the overall pressure drop.

$$\Delta p = \phi_7 \left[\frac{Q \ (P_t/d_o - 1)}{(MTD)(\dot{m}_g)} \right] (V_{max}^{2.25}) \ (d_o^{0.25}) \qquad \text{(A 11.6.28)}$$

In Equation A 11.6.28:

$$\phi_7 = \phi_2 = \phi_6 \left[\frac{lb^2 \ s^{2.25} \ {}^\circ F}{Btu \ in^{2.25} \ ft^{2.25}} \right] \qquad \text{(A 11.6.29)}$$

When the tubes are in an equilateral staggered array, the height of the tube bank is given by:

$$H = N_{rows} \ \frac{P_t}{12} \ \cos 30^\circ = N_{row} \left(\frac{0.867}{12}\right) P_t \qquad \text{(A 11.6.30)}$$

Substituting for N_{row} by Equation A 11.6.26 we obtain:

$$H = \frac{0.867}{12} \ \phi_6 \ P_t \ \frac{(P_t/d_o - 1) \ Q}{(MTD)(\dot{m}_g)} \ V_{max}^{0.4} \ d_o^{0.4} \qquad \text{(A 11.6.31)}$$

$$H = \phi_8 \left[\frac{P_t}{d_o}\right] \frac{(P/d_o - 1)(Q)}{(MTD)(\dot{m}_g)} \quad (V_{max}^{0.4})(d_o^{0.4}) \qquad \text{(A 11.6.32)}$$

This value of H does not include any allowance for spacing between the various tube bank sections nor does it account for the height of the vessel heads. For sizing purposes, vessel heads were assumed to be hemispherical.

The analysis assumes the steam and water side heat transfer coefficients are large compared to those of the argon gas side, thereby neglecting steam-side thermal resistance. Furthermore, in the calculation scheme, the log mean temperature difference, MTD, was approximated by the

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arithmetic mean. Solution of the equations was obtained by specifying tube geometry [2.54 cm (1.0 in) od; 0.508 cm (2.0 in) pitch for all cases] and designing to a fixed pressure loss, $\Delta p/p = 0.05$.

The equations for calculating the heat exchanger weight are given in Table 11.5. The weight of the pressurized vessel, W_1, was calculated after using the hoop stress relationship for thin-walled vessels to determine the required shell wall thickness. W_2 represents the total tube weight and can be calculated once the tube geometry and required heat transfer surface area are known. The costing of the steam generator was based on the calculated weight of both tube and shell, as indicated by the equations in Table 11.5. C_{14} and C_{15} are the appropriate cost coefficients for shell and tube, respectively. C_{14} was taken at \$1.46/kg (\$0.67/lb) and includes a factor for insulation. C_{15} depends on tube material and specific case and includes fabrication, which was taken at \$10/tube. The tube material costs, material type, and application to particular study points are summarized in Table 11.7.

A 11.6.4 Air Gas Preheaters and Recuperators

In cases where recuperator heat exchanger systems were utilized, the model for sizing was based on heat exchanger effectiveness, a concept widely applied in recuperative heat exchanger design. The equation expressing the required heat transfer surface area is:

$$A_s, \ \ ft^2 = 815 \left[\left(\frac{\varepsilon}{1-\varepsilon}\right)^{3/2} \frac{\dot{m}\,Pr}{f_p}\right] \frac{RT}{g_c \left(\frac{\Delta p}{p}\right)} \qquad \text{(A 11.6.33)}$$

where ε = effectiveness

$\dot{m}$ = mass flow rate, lb/s

Pr = gas Prandtl number

f = function factor

p = absolute pressure, psf

r = the gas constant, $\frac{ft\text{-}lbf}{lbm\text{-}^\circ R}$

T = average temperature, °R.

This equation was derived from the heat and mass balance around the heat exchanger, the usual pressure drop expression; and used Reynolds analogy, $h = f/2 \, \rho C_p V$, to estimate the heat transfer coefficient. The equation is solved by specifying the effectiveness and friction factor.

For the air preheaters (argon precoolers), a similar approach to calculating the required heat transfer surface area was employed. For purposes of sizing and costing, the air preheater was taken to include both the air-to-argon exchanger and the air-to-flue gas stack-gas cooler. Equation A 11.6.14 was modified, therefore, to include a second term that accounted for the stack-gas cooler. This second term is given as

$$A_{s_1} = 141 \, (MR) \, \dot{m} \qquad \text{(A 11.6.34)}$$

where MR is the air-to-gas ratio determined from an overall system heat balance. Equation A 11.6.34 is actually a simplified form of Equation A 11.6.14 where ε, p, f, t and Δp are fixed for all cases.

The expressions for calculating the characteristic size, weight, and cost for both the recuperators and air-gas preheaters were derived in a manner similar to that previously described in Section A 11.6.2. As before, tube geometry is fixed. For simplicity, 2.54 cm (1 in) od tubing was assumed. The derived size and cost algorithms are summarized in Table 11. . The cost algorithm shows two terms. The first term, C_9 accounts for tube material costs, and the second term, C_{10}, accounts for fabrication costs taken at $10/tube.

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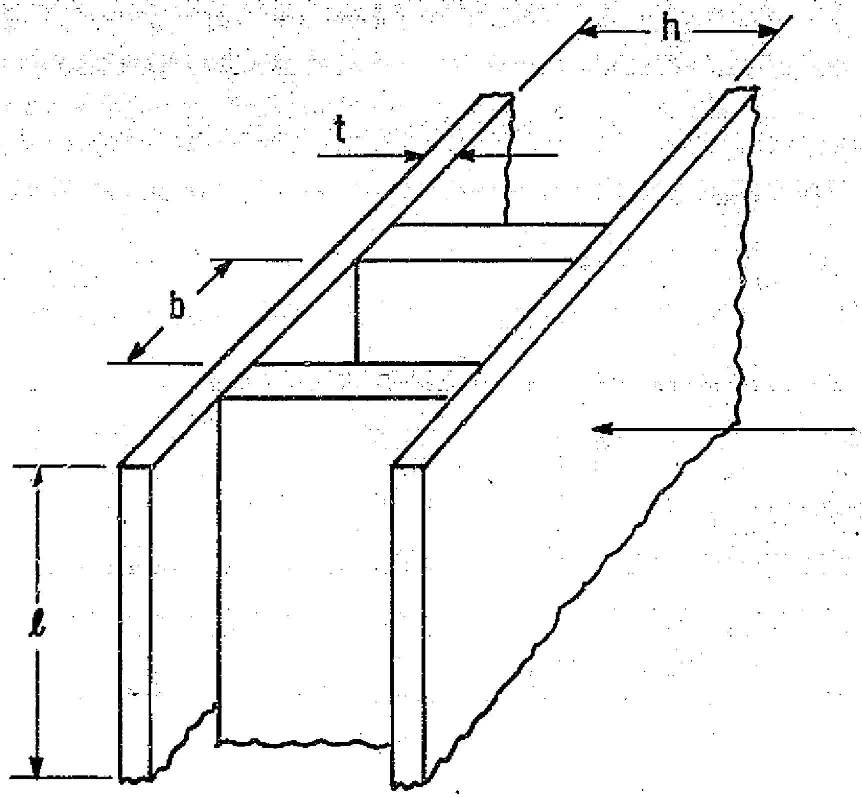

Fig. A 11. 7. 1—Ribbed support structure for LM-MHD high pressure component design

Appendix A 11.7

STRUCTURAL REQUIREMENTS - MHD COMPONENTS

High system pressure, high temperatures, long operating life, and the large MHD component sizes result in structural requirements that must be properly addressed to assure a viable, economical, and consistent design. To meet these stringent design requirements, a basic ribbed support structure has been assumed, Figure A 11.7.1. The design approach for the pressure structure was to calculate a section modulus to accommodate the specific operating pressure and design stress conditions. The section modulus for the rib geometry used is approximated by (neglecting some second-order terms):

$$I/c \cong 4\,bht/3 \qquad \text{A 11.7.1}$$

where b is the spacing between ribs, t is the thickness of the plates and h is the spacing between plates (length of the rib).

For a beam with uniform load, p, on simple supports:

$$I/c = pb\ell^2/8\,\sigma_d \qquad \text{A 11.7.2}$$

σ_d is design stress and ℓ the unsupported length of the section. Assuming the web thickness is 0.6 t and h is 2 b (based on standard I-beam designs), the weight of the section per unit pressure surface area is given by Equation A 11.7.3:

$$W/A = 0.30\,\rho p\ell^2/\sigma_d \qquad \text{A 11.7.3}$$

where ρ is the material density.

This expression can be written as:

$$W/A = K \left(\frac{p\bar{\ell}^{2}}{\sigma_d}\right)$$

where $\bar{\ell}$ is in feet and W/A is in lb/ft^2, where K is a function of material and section geometry, and the remaining variables are specified based on the component size and operating conditions (p,σ_d). With material density specified, K will depend on the rib dimension, h, which in turn is limited by practical size considerations (bending is a factor but is not significant over the range of sizes considered realistic for the MHD design purposes). For example, for the design of large MHD ducts [say 9.14 m (30 ft) long, 1.829 m (6 ft) wide], reasonable dimensions for h would be between 0.609 to 0.914 m (2 to 3 ft). For smaller duct (or other components) sizes, h would decrease. On this basis and over the range of component size for LM-MHD, the following expression for K was developed (assuming steel construction):

$$K = 155 - 17.5\,\bar{\ell}$$

where $\bar{\ell}$ is the characteristic unsupported dimension of the component in feet and K is in lb/ft^4.

This ribbed-plate support configuration served as the structural design member for two of the MHD duct walls and all remaining liquid-metal ducting and components, including the dewar for the magnet. The two MHD duct walls adjacent to the iron were designed assuming that the iron pieces (see Figure A 11.7.1) interposed between the MHD ducts served as load-bearing members. These duct walls were designed from flat plates assuming support I-beams at designated spacing along the plate. One of the flanged ends of the I-beams rests against the iron pieces. The thickness of the plate forming the side wall is sufficient to support the load between I-beams and is given by fixing rib spacing at 0.3048 m (12 in):

$$t, in = 8.48\ (p/\sigma_d)^{1/2}$$

The spacing between the I-beams is determined from physical constraints imposed by the design of the dewar.

The weights calculated for each MHD component were based on the geometry of the support structure described above. Weight equations and required sizing models for each specific component have been summarized in Table 11.5.

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