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CALIFORNIA INSTITUTE OF TECHNOLOGY
PASADENA, CALIFORNIA

LIQUID METAL MAGNETOHYDRODYNAMICS
(LMMHD)
TECHNOLOGY TRANSFER
FEASIBILITY STUDY

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FOREWORD

The feasibility of applying liquid metal magnetohydrodynamics (LMMHD) to utility power generation was studied by the Jet Propulsion Laboratory (JPL) under sponsorship of the NASA Technology Utilization Office. LMMHD has been the subject of applied research by JPL since 1961. The previous work, also sponsored by NASA, has been for application of LMMHD as a power conversion alternative to nuclear electric propulsion. The average funding has been $600, 000 per year, and the total funding through 1973 was $6. 0 million. Part of this report reviews the status of LMMHD and progress of the JPL development program. Recent analysis of LMMHD indicated that it could be applied to utility power generation to increase efficiency, reduce pollution and, possibly, reduce costs. These preliminary estimates have been verified by the study results.

ABSTRACT

Our society is expressing an increasing awareness and concern over the implications of emerging limitations in energy availability, and the current and potential environmental impact of fossil fuel and nuclear energy conversion technologies. Additionally, our Nation's ever-increasing demand for electrical power in virtually every aspect of energy use has led to increased interest in new, more efficient methods of power generation. Liquid metal magnetohydrodynamics (LMMHD), which has been the subject of research and development by NASA at the Jet Propulsion Laboratory for more than ten years, is one possible method. LMMHD provides a means of generating electrical power without moving mechanical parts. It utilizes a heat source to produce a high velocity liquid metal stream which interacts with a magnetic field to produce electrical power.

LMMHD research in the United States has been directed primarily toward the application of space power conversion. This study examines the potential application of LMMHD to central station utility power generation through the period to 1990. Included are: (1) a description of LMMHD and a review of its development status, (2) LMMHD preliminary design for application to central station utility power generation, (3) evaluation of LMMHD in comparison with conventional and other advanced power generation systems and (4) a technology development plan.

Major conclusions of the study are:

1) The most economic and technically feasible application of LMMHD is a topping cycle to a steam plant, taking advantage of high temperatures available but not usable by the steam cycle.
2) Of the known LMMHD cycle and working fluid alternatives, the two-component lithium-cesium cycle was selected because of its superior efficiency and low overall cost.
3) A two-stage LMMHD plant is the most economical design.

4) The nominal LMMHD two-stage cycle efficiency is 13.5%; the nominal 1980 capital cost is $282/kW.

5) Conceivable plant design improvements could increase the cycle efficiency to 17.2% and reduce the 1980 capital cost to $185/kW.

6) Coal- and oil-fired LMMHD/steam plants offer potential 1980 generation cost improvements of 0.2 to 0.6 mills/kWh over conventional fossil-fueled plants.

7) The LMMHD/steam plant utilizes 12% less fuel than a conventional fossil-fuel plant with the same power output.

8) The LMMHD/steam plant reduces air and thermal pollution when compared with conventional plants.

9) The LMMHD/steam plant has nominal generation costs comparable to the plasma MHD/steam plant and the potassium Rankine/steam plant, but less than the gas turbine/steam plant.

10) If nuclear plants would provide higher source temperatures than currently available, or when fusion heat sources become a reality, LMMHD applied as a topping cycle would reduce nuclear power generation costs and thermal pollution.

11) Technology demonstration is progressing satisfactorily; no major technological problems are foreseen that would prevent economic development of the sytem.

ACKNOWLEDGEMENTS

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1) Analytical and design assistance:

   Dr. D. G. Elliott
   Y. Nakamura
   P. S. Zygielbaum
   K. Solomon, UCLA

2) Review Board Members

   To facilitate transfer of the LMMHD technology from NASA to the public sector and to provide objectivity to the study, a Review Board of individuals experienced in power generation technology was established. The Review Board reviewed the study progress, provided inputs to the study, and critiqued the study results. The Review Board members were:

   a) Dr. Steven Schrock, Manager, Mass Transfer Studies, Westinghouse Electric Corporation, Advanced Reactors Division.
   b) Otto Shulze, Manager, Nuclear Systems International.
   c) Dr. Paul Zmola, Assistant Product Manager, Research and Development, Combustion Division, Combustion Engineering, etc.
   d) Dr. Ira Thierer, Associate Director of Research and Development, Southern California Edison Company.
   e) David Willyoung, Manager, Technical Resource Planning, General Electric Company, Steam Turbine Power Division.

3) The NASA Technology Utilization Office which sponsored the study.

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*The views expressed in this report represent those of the authors and not necessarily those of the reviewers.

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SECTION I

INTRODUCTION

Energy consumption in the United States is predicted to continue its dramatic increase. Electrical power consumption is estimated to increase even more rapidly than the total energy consumption (see Appendix A). As a result an energy crisis has been forecast. These predictions indicate that alternative means for alleviating the impending crisis must be implemented. One approach includes the development of new power generation alternatives which will preserve material resources, protect the environment and generate electrical power at reasonable costs. Liquid metal magnetohydrodynamics (LMMHD), which is under research by NASA for space power conversion applications, is one of the new technologies which could be applied advantageously to terrestrial power generation. LMMHD utilizes a heat source to produce a high velocity liquid metal stream which interacts with a magnetic field to generate electrical power.

The objective of this study is to assess the potential of LMMHD to improve utility power generation. The period through 1990 was considered. The results of the study indicate that LMMHD has its most economical and technically feasible application as a topping cycle to a conventional steam plant. The resulting binary plant has the potential for reducing power generation costs by 0.3 to 0.8 mills/kWh and reducing environmental pollution by 12 to 20% when compared with conventional central station steam power plants.

In arriving at the topping cycle application, alternative LMMHD cycles and working fluids were analyzed and compared (Appendix C). Specifically, two separator cycles were selected for detailed analysis (Appendix D). The potassium separator cycle efficiency was determined to be about 6% which is significantly less than the 14% efficiency of the two component cessium-lithium separator cycle selected. It was determined that even though the cesium-lithium system required the use of more expensive materials than the potassium system, its superior efficiency and lower overall cost dictate its selection.

A preliminary design of the cesium-lithium separator cycle was conducted for central station applications (Appendix E). A two-stage topping system having an efficiency of 13.5% was selected. The topping plant efficiency produces a binary plant efficiency of 45% when combined with a 40%-efficient steam plant using an 86%-efficient furnace. Two stages were selected, rather than a large number, to reduce the capital cost while incurring only moderate efficiency reductions. Cycle conditions were established, components described and a layout of the LMMHD system prepared. LMMHD 1980 capital costs were estimated to be about $230/kW, including the cost of the liquid metal inventory. Further system optimization could reduce 1980 capital costs to about $140/kW.

The LMMHD/steam binary plant was evaluated in comparison with alternative power generation systems (Appendix F). Conventional nuclear and fossil fuel steam systems and selected advanced power generation systems were described and their characteristics defined (Appendix B). The evaluation of the LMMHD/steam binary plant was conducted on the basis of generation costs, environmental pollution, reliability and maintainability, safety and technological status. The evaluation of LMMHD was favorable enough to recommend detailed consideration by the utility industry and accelerated research leading to a system feasibility demonstration.

Specific recommendations are provided in Section II of this volume.

A preliminary technology development plan, which indicates the necessary future actions, possible participants and their functions, and funding required to bring LMMHD to commercial status, has been provided.

The following sections of this volume summarize the results of the study. Detailed supporting analyses and references are provided in the Appendixes, Volume 2.

SECTION II

RECOMMENDATIONS

Based on the results of this study it is recommended that:

1) The utility power industry evaluate the study results and provide appropriate critiques of the recommended technology demonstration plan.
2) LMMHD system optimization analyses be completed by JPL to ascertain the full potential of LMMHD to utility power generation.
3) More detailed system design studies be conducted by an independent system contractor (A and E Company) in conjunction with JPL and a local utility company, considering:

   a) More detailed design and economic analysis of a cesium-lithium LMMHD topping cycle to a fossil-fuel steam plant.
   b) Possible retro fit of existing fossil fuel plants with a LMMHD topping cycle.
   c) Potential topping cycle applications with advanced high-temperature nuclear plants.

4) Key research and technology areas, which need investigation to validate the cycle analysis and establish the feasibility of a long-life topping cycle, should be supported, including:

   a) Experimental performance of a LMMHD generator with a cesium-lithium mixture.
   b) Performance of advanced surface separator concepts at lower void fractions and dynamic load than for a single stage system.
   c) Long-term stability of Haynes-25, and compatibility with other super alloys, in a high-velocity two-phase mixture of cesium vapor with droplets, and in low-velocity lithium.

The study recommendations are supplemented by the technology development plan in Section VI.

SECTION III

LMMHD DESCRIPTION AND STATUS

A. LMMHD CYCLE SELECTION

1. Alternative Cycles Considered

The basic process which is common to all LMMHD cycles is the acceleration of a liquid metal to a high velocity to generate electrical power in a magnetic field. Many different thermodynamic cycles have been proposed to achieve this acceleration in a closed system operating between a heat source and heat sink. Comprehensive summaries of these cycles and the working principles are given in the references of Appendix C. In general, the cycles proposed have evolved from simple, single-stage systems of low efficiency to more sophisticated systems with power extraction at several stages of the acceleration process and/or regenerative heating to achieve higher levels of efficiency.

The most highly developed LMMHD systems are the two-component separator, single-component separator, injector, and emulsion flow MHD cycles. Each of these is described and illustrated in Appendix C. The emulsion flow cycle is the only LMMHD cycle applicable as a primary cycle. It utilizes a noncondensing gas, permitting high pressures at low temperatures and reasonable duct sizes. For the other LMMHD cycle alternatives, the duct sizes would be too large at low temperatures for economic consideration as primary cycles. All of the other cycles, however, are applicable as topping cycles. Topping cycles utilize heat at temperatures higher than applicable to primary cycles, and then reject heat to the steam cycle at peak steam cycle temperatures. Because the emulsion flow cycle would have lower efficiencies than steam plants operating between the same temperature limits it was not considered further. Of the remaining LMMHD cycles the analysis was limited to the two-component and single-component separator cycles since the injector cycles have not yet demonstrated adequate performance. The separator cycles have had the benefit of much greater applied research than other LMMHD cycles and have demonstrated adequate hydraulic performance. They offer the greatest potential of known LMMHD cycles for application to central station power generation. These two separator cycles are described as follows.

2. Two-Component Separator Cycle

In the two-component separator cycle, shown in Fig. 1, a liquid metal with low vapor pressure (such as lithium) is heated and mixed with a liquid metal of high vapor pressure (such as cesium) resulting in a two-phase mixture. The vapor performs work on the liquid, accelerating it to high velocity in a nozzle. Subsequently the liquid phase is separated from the vapor phase. The high-velocity liquid phase flows through the MHD generator, producing electric power. The kinetic energy remaining after extracting the power is used to circulate the liquid through the heat source and to the mixer. The vapor, which was separated, flows to a heat exchanger where it is condensed, with the heat being rejected to either ambient or to another power cycle. The cesium is subsequently pressurized and returned to the mixer by a pump.

The multistage cesium-lithium system is shown schematically in Fig. 2 for five stages of power extraction. Lithium and cesium are mixed in the first stage nozzle and expanded to an intermediate pressure and velocity and then separated. The resulting velocity stream of lithium passes through the first MHD generator and is then remixed with the cesium vapor from which it had been separated. The mixture is further expanded in the second-stage nozzle and the separation and power generation steps repeated. This process is continued to the last stage where sufficient dynamic pressure is retained in the lithium to return it through the heat source to the first-stage nozzle. The separated cesium vapor from the last stage flows through a regenerative heat exchanger to the condenser where it is condensed and then it is pressurized by a pump and returned through the heat exchanger to the first-stage nozzle. The multistage cycle achieves a major portion of the separation at higher pressures and presents lower-velocity flow to the MHD generator than the single

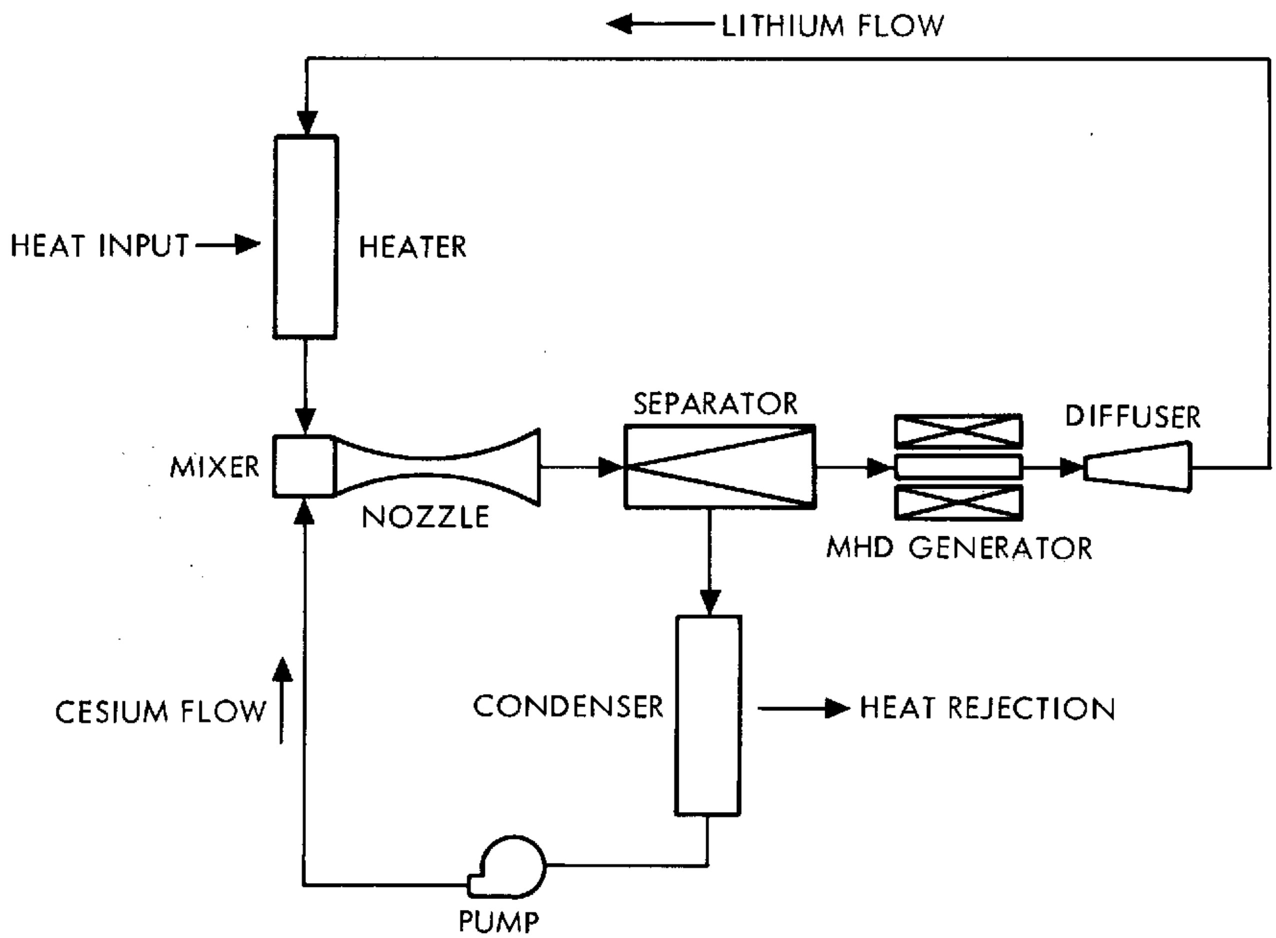

Fig. 1. Two component, single-stage separator cycle (cesium and lithium shown)

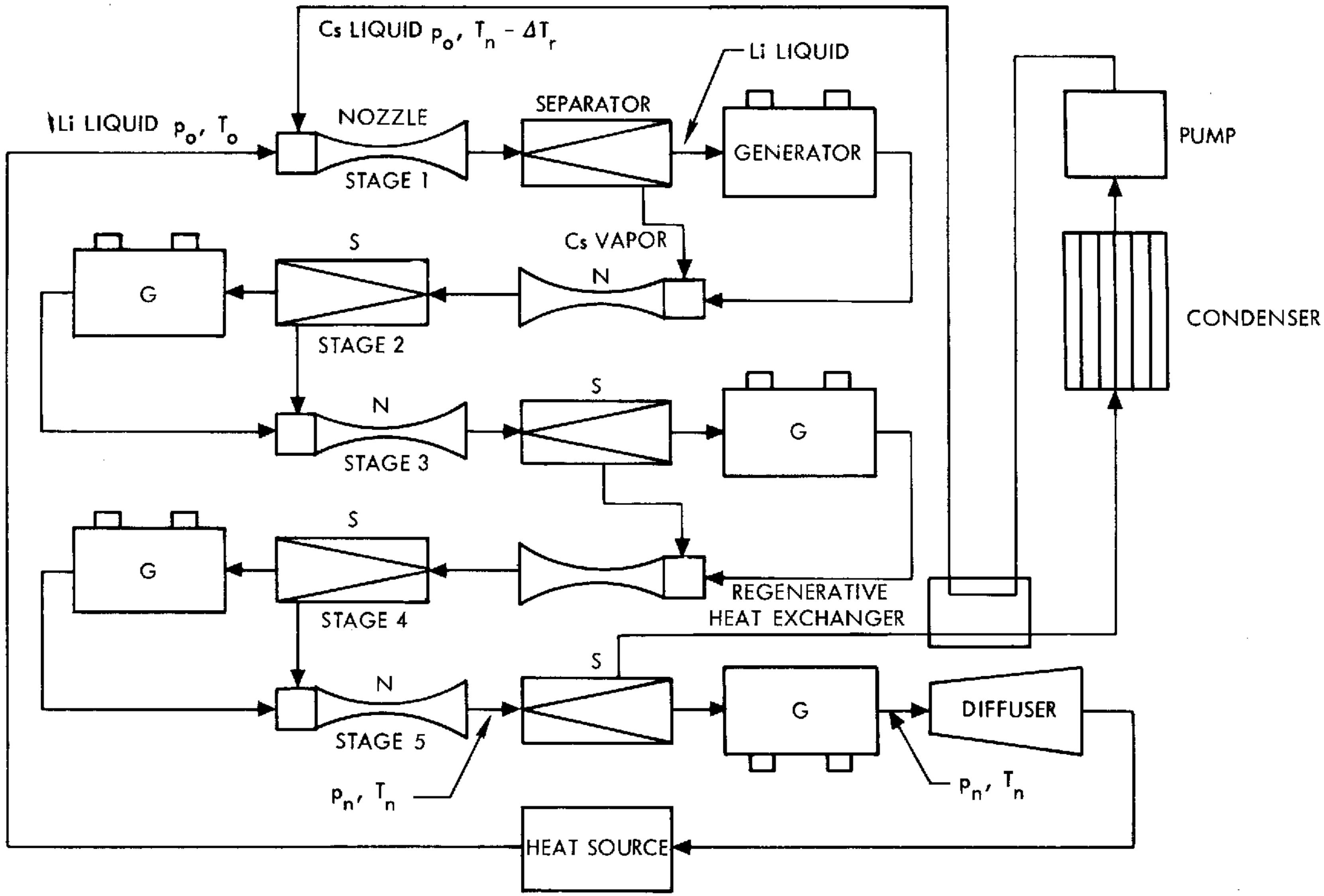

Fig. 2. Multistage cesium-lithium system

stage. Consequently the separator volume, area per unit flow rate, and frictional losses are reduced, which decreases the specific capital costs and increases overall system efficiency when compared with a single-stage system.

3. Single-Component Separator Cycle

The single-component separator cycle, as shown in Fig. 3, uses a single liquid metal (such as potassium). This fluid is vaporized in the heat source to a low quality (mass ratio of vapor to total fluid, typically 1-5% vapor) and is expanded to a higher quality and high velocity in a nozzle. The resulting high-velocity liquid is separated from the vapor and passed through the MHD generator and then returned to the heat source. The vapor is condensed and returned to the heat source by a pump.

An example of a multistage potassium separator system with regenerative heating is given in Fig. 4. Heat is added to the liquid metal flow in the upper stage of a multistage system. This heat input results in a two-phase flow of low vapor quality (1-10%) at the maximum cycle temperature. The flow is expanded in a nozzle to a pressure resulting in a higher velocity and higher quality. This two-phase stream impinges on a surface separator. The high velocity liquid flows through the MHD generator, producing power, and is returned to the first stage heater. The vapor flows to a regenerative heater in the second stage. The first stage condensate is pressurized by a pump and returned to the first-stage heater. This process continues through several stages. Finally, in the last stage, the heat from the condensate is rejected.

4. Efficiency Comparison of Selected Cycles

Efficiencies of the potassium and cesium-lithium separator cycles were calculated as described in Appendix D. There had been some evidence that reasonably good efficiencies could be achieved for the potassium separator cycle, i.e., 11% to 12%. If these efficiencies could be achieved, the potassium cycle would be the favored cycle because potassium is less corrosive and less expensive than the cesium and lithium working fluids. A detailed analysis of the potassium cycle, however, produced the efficiencies shown in Fig. 5. The

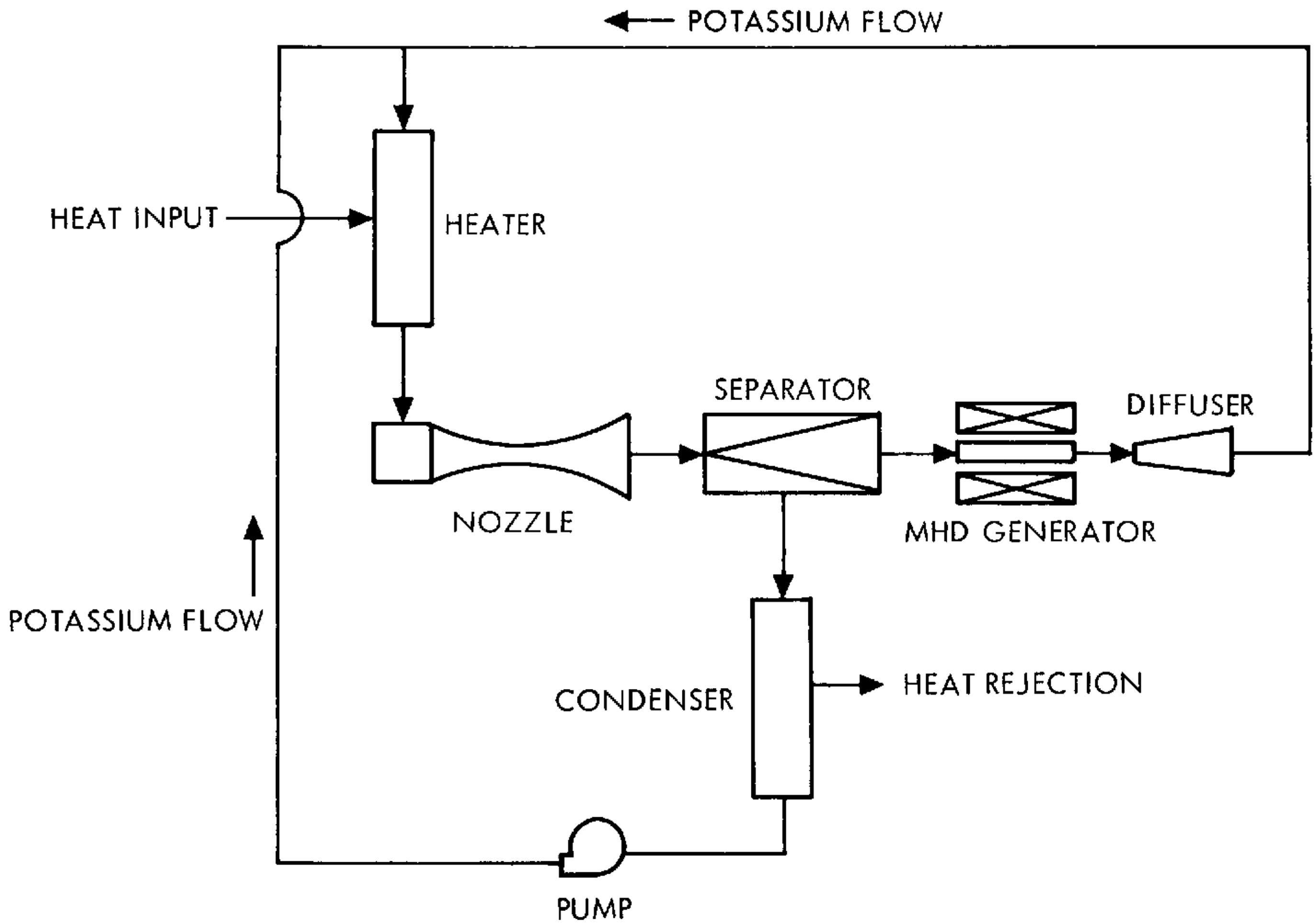

Fig. 3. Single-component, single-stage separator cycle
(potassium shown)

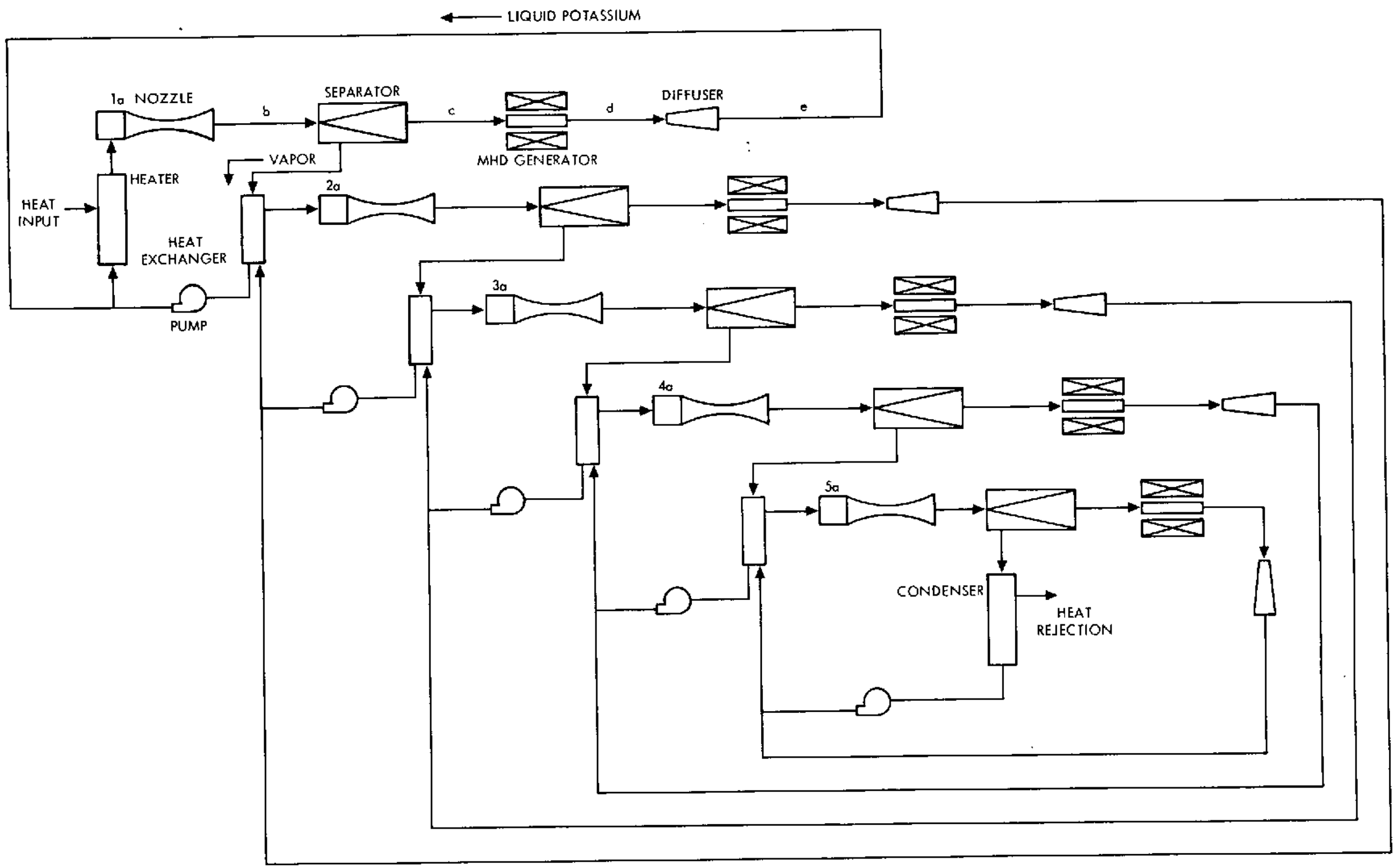

Fig. 4. Multistage single-component separator cycle (five-stage potassium shown)

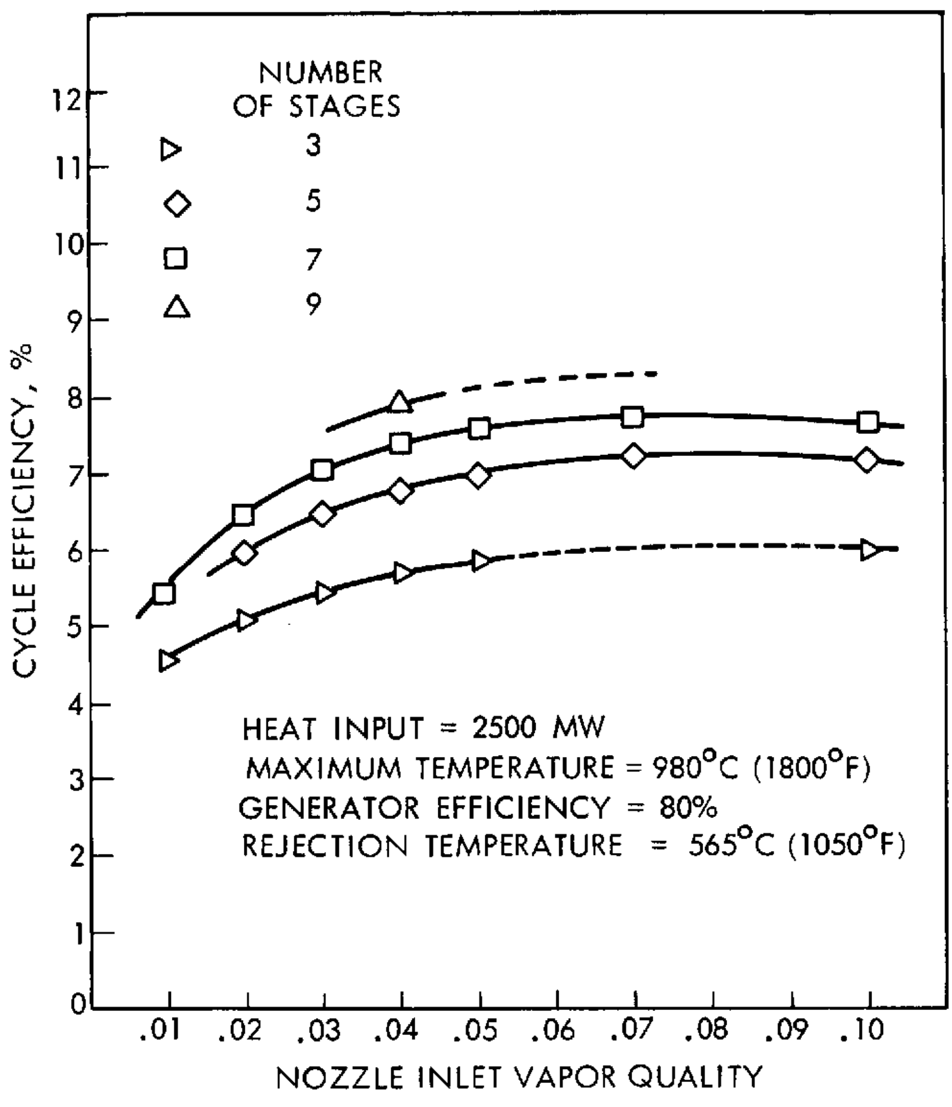

Fig. 5. Efficiency of multistage potassium separator cycle versus nozzle inlet vapor quality

figure shows that even with nine stages the peak efficiency would be only about eight percent. If three stages were selected, the maximum efficiency would be only 6%.

The efficiency calculated for the cesium-lithium separator is shown in Fig. 6. Efficiencies greater than 14% are possible with three or more stages. Also note that the reduction in efficiency from a three-stage to a two-stage system is only about 0.6 percentage points, with the two-stage system having an efficiency greater than 13.5%.

Because the cesium-lithium system has such a significantly higher efficiency than the potassium system, it was selected for preliminary design.

B. COMPONENT DEVELOPMENT STATUS

The major loss mechanisms in the LMMHD system are amenable to analysis. Theory has been developed for the performance of components such as the nozzle, separator and diffuser. The theory has been substantiated for the components of the cesium-lithium separator cycle with extensive tests using other test fluids. Therefore, the analysis can be extended to predict the performance with the cesium-lithium mixture (Appendix C). Table 1 summarizes the component performance and development status. Generally, the technology development is making good progress. Thus predicted performance used in the preliminary design is achievable.

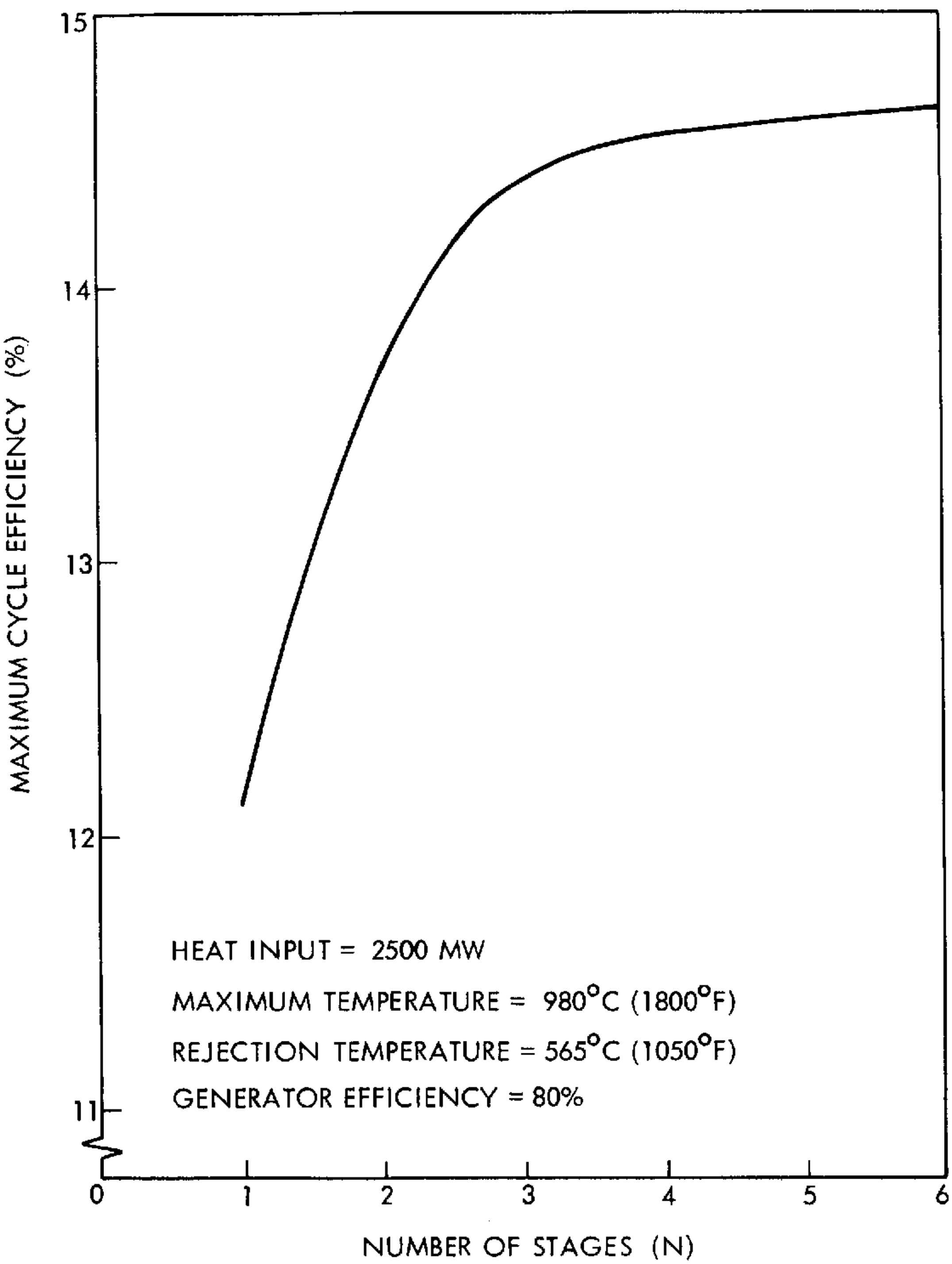

Fig. 6. Maximum efficiency of multistage cesium-lithium MHD topping cycle versus number of stages

Table 1. Component status, cesium-lithium LMMHD separator cycle

Component	Efficiency	Development status and test experience*
Nozzles	• 79% (N_2-H_2O) • 85% (Freon-H_2O)	• Tests with 50 in. long nozzles using N_2-H_2O and Freon-H_2O mixture have been accomplished. • High efficiencies (85%) have been obtained. • Tests validate theory which predicts exit velocities 90% of isentrophic values. • Design techniques for high efficiency (85%) are well established.
Separators	• 60% (N_2-H_2O) • 90%-95% (calculated for multi-stage systems)	• Separators tested with N_2-H_2O provided 99% liquid flow at outlet with 60% energy efficiency. • Tests validate predicted separator exit velocities. • Low-loss separators may achieve efficiencies to 95%.
Generators	• 75% (dc, single-phase flow) • 59% (dc, two-phase flow) • 40%-50% (ac) • 80%-85% (calculated for large ac systems)	• Single- and two-phase NaK and K tests have been conducted. • Two-phase flow efficiencies are lower than single-phase flow due to lower fluid conductivity and vapor-liquid slip. • Low ac efficiencies due to small scale of tests. • Tests validate the theory that predicts efficiencies of 85-85%.
Diffusers	• 85% (measured for single phase flow) • 75% (measured for two-phase flow)	• Single phase flow in the diffusers is most likely with 85% efficiency achievable. • The effects of two-phase flow results on efficiency have been established and agree well with analysis. • The efficiency with the maximum expected gas-liquid ratios is 75%.
Other Components		• Components such as heat exchangers, pumps, high temperature piping, and valving are conventional and have received operating experience at temperatures higher than the 1800°F considered herein. • Materials compatible with lithium and cesium at temperatures of interest (1800°F) and higher have been identified. • The effects of high velocity, corrosion, and protective coatings have been investigated.

*See Appendixes C and E for more detailed information and references.

SECTION IV

LMMHD TOPPING CYCLE PRELIMINARY DESIGN

A. INTRODUCTION

The LMMHD topping cycle chosen for preliminary design is a two-stage system which produces 21% of the binary plant power at a combined plant efficiency of 45%. The design is described in Appendix E and summarized below, including selection of the number of stages, definition of the topping plant efficiency, determination of the cycle conditions, plant layout, and component descriptions and costing.

B. NUMBER OF STAGES

Consideration of the tradeoff between capital cost and plant efficiency as they affect power generation costs led to the conclusion that two stages were the optimum for the cesium-lithium topping cycle application (supporting analyses are given in Appendix E, subsection C and Appendix F, subsection C). The cycle efficiency decreases only about one percentage point as the number of stages is reduced from three to two, whereas the capital cost is reduced about 50% (more than $100/kW). A single stage is not desirable since there would be a need for return lines to the furnace which can be replaced by a second power-producing stage at little cost increase.

C. PLANT EFFICIENCY

The efficiency for the two-stage topping cycle is 13.5%, based on the optimum lithium/cesium mass ratio (≈ 14) as shown in Fig. 7 (Appendix E, subsection C). This efficiency and mass ratio will probably not produce the minimum power generation costs, however. Reduced mass ratios will reduce the efficiency but will also reduce the physical size and liquid metal inventory. It has been estimated that a reduction of the mass ratio to 7 would produce a

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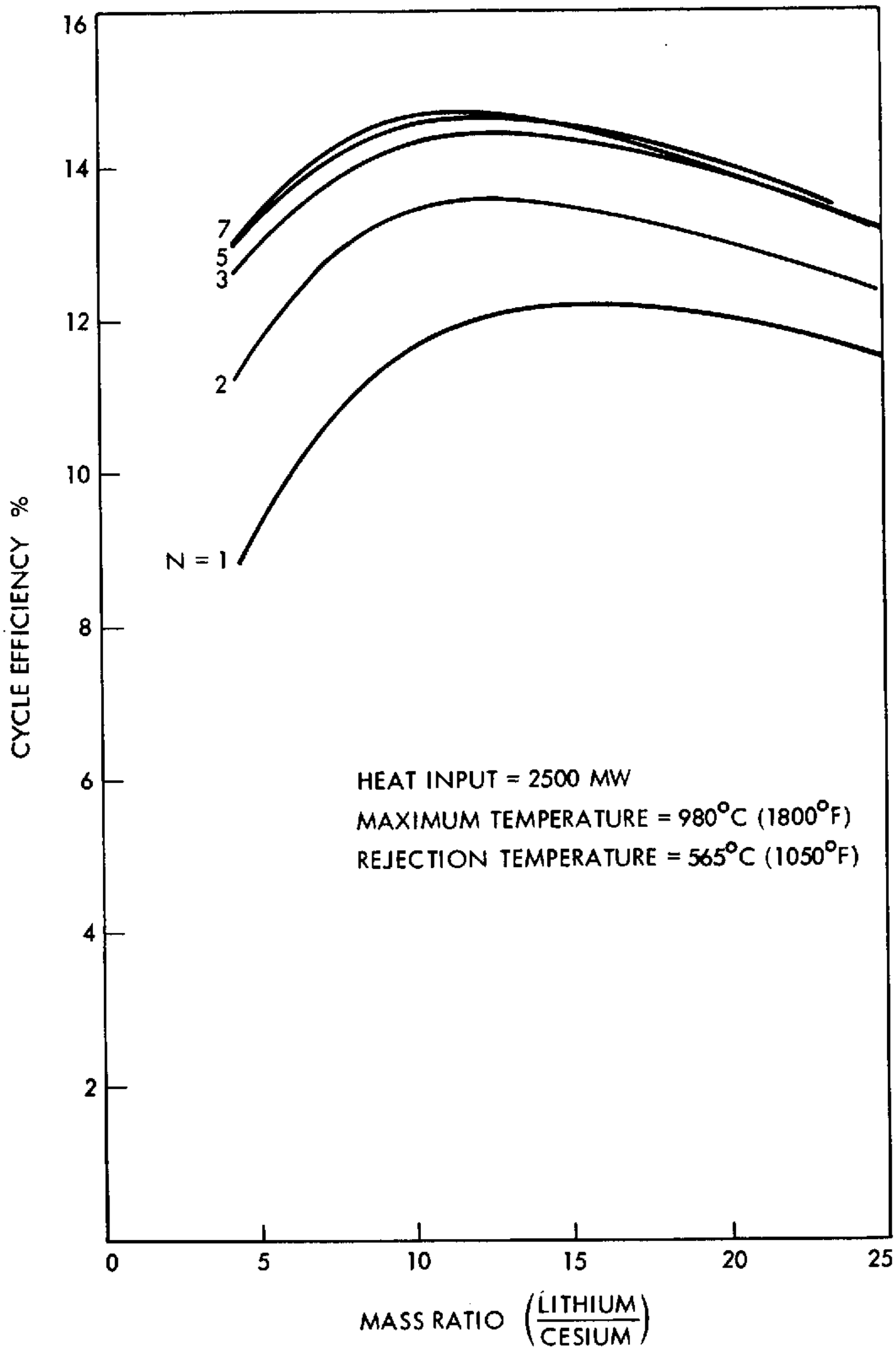


Fig. 7. Efficiency of multistage cesium-lithium topping cycle versus mass ratio

25% reduction in LMMHD plant capital costs, while reducing the topping cycle efficiency only by about 1 percentage point. Corresponding power generation costs reductions are discussed in Section V.

The LMMHD/steam binary plant efficiency is 45% as determined from the expression:

$$\eta_P = 0.8\,\eta_f\left[\eta_T + (1 - \eta_T)\eta_B\right] + 0.2\,\eta_f\eta_B$$

where η_T = the LMMHD topping cycle efficiency = 13.5%

η_f = furnace efficiency = 80%

$\eta_f\eta_B$ = bottoming plant efficiency = 40%

The expression assumes that 80% of the furnace heat is transferred to the LMMHD heater and 20% is transferred to the steam cycle.

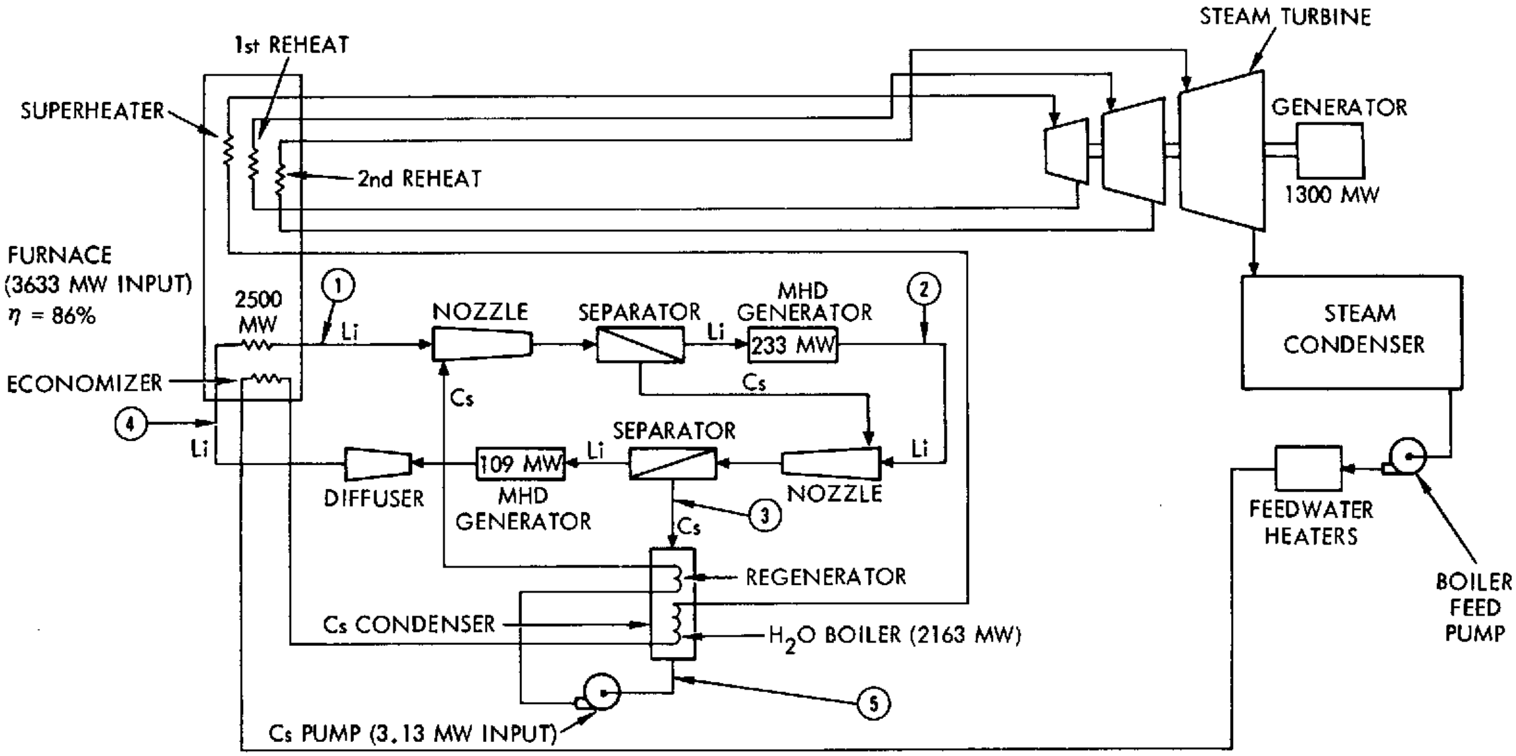
D. LMMHD/STEAM PLANT DESCRIPTION

Figure 8 is a schematic diagram of the two-stage LMMHD/steam binary plant showing the heat input, power output, and LMMHD state points used in the preliminary design.

1. Power

The heat input to the LMMHD cycle was selected as 2500 MW which is comparable to a conventional fossil fueled steam plant producing 1000 MW of power. With a furnace efficiency of 86% and assuming that 20% of the furnace heat is transferred directly to the steam cycle, the heat input to the furnace becomes 3633 MW.

The power generated by the LMMHD plant is 233 MW from the first stage and 109 MW from the second stage. The auxiliary power requirements are 5 MW. Thus the net power output from the LMMHD topping plant is 337 MW. The steam plant power output is 1300 MW. Total power output is then 1637 MW. For convenience in comparing the LMMHD/steam system with alternative costs, environmental factors were normalized for a 1000 MW plant.



LMMHD STATE POINTS

	°F	psia	lb/s	lb/s
	T	p	m_{Li}	m_{Cs}
1	1808	142	1×10^5	—
2	1792	25.7	1×10^5	—
3	1784	4.8	—	7.09×10^3
4	1785	152	1×10^5	—
5	1000	4.3	—	7.09×10^3

NOTE - STEAM CONDITIONS TYPICAL OF MODERN DOUBLE REHEAT CYCLE, 1050°F MAXIMUM TEMPERATURE.

Fig. 8. Schematic diagram of cesium-lithium LMMHD/steam turbine binary cycle

The MHD power output can be matched with the power output characteristics of the steam turbine-generator. For purposes of this study the MHD power output was selected to be 4160 V, 60 Hz ac. The voltage would remain constant as load decreases.

The LMMHD/steam binary plant produces 12% more power than a conventional fossil-fueled plant with the same heat input (same fuel consumption) at a generation cost reduction of 0.2 to 0.6 mills/kWhr.

2. State Points

The LMMHD plant state points are given in Fig. 8. The temperature at the inlet to the first-stage generator was selected to be 1800°F which produces the maximum efficiency for a cesium-lithium system. The corresponding furnace exit temperature is 1808°F. This temperature is compatible with conventional coal- or oil-fired furnace practice. Also, the alloy L-605 (Haynes-Stellite No. 25) has a demonstrated resistance to liquid metals and furnace gases at that temperature.

The rejection temperature for the cesium vapor (1050°F) was selected to be compatible with modern steam conditions (1005°-1010°F).

The total flow rate of lithium is about 1×10^5 lb/s and that of cesium is 7090 lb/s. The maximum lithium velocity is about 400 ft/s. The lithium temperature change is only 23°F and thus the heat input process is nearly isothermal, minimizing thermal stresses. The maximum lithium pressure is 150 psia. The condensing pressure for cesium is 4.8 psia.

E. PRELIMINARY DESIGN

1. Design Layout and Component Descriptions

The LMMHD preliminary design is shown schematically in the layout of Fig. 9. Structural ribbing is shown, but the supporting structure is omitted for the sake of clarity. The furnace is outlined to indicate LMMHD plant size and scale.

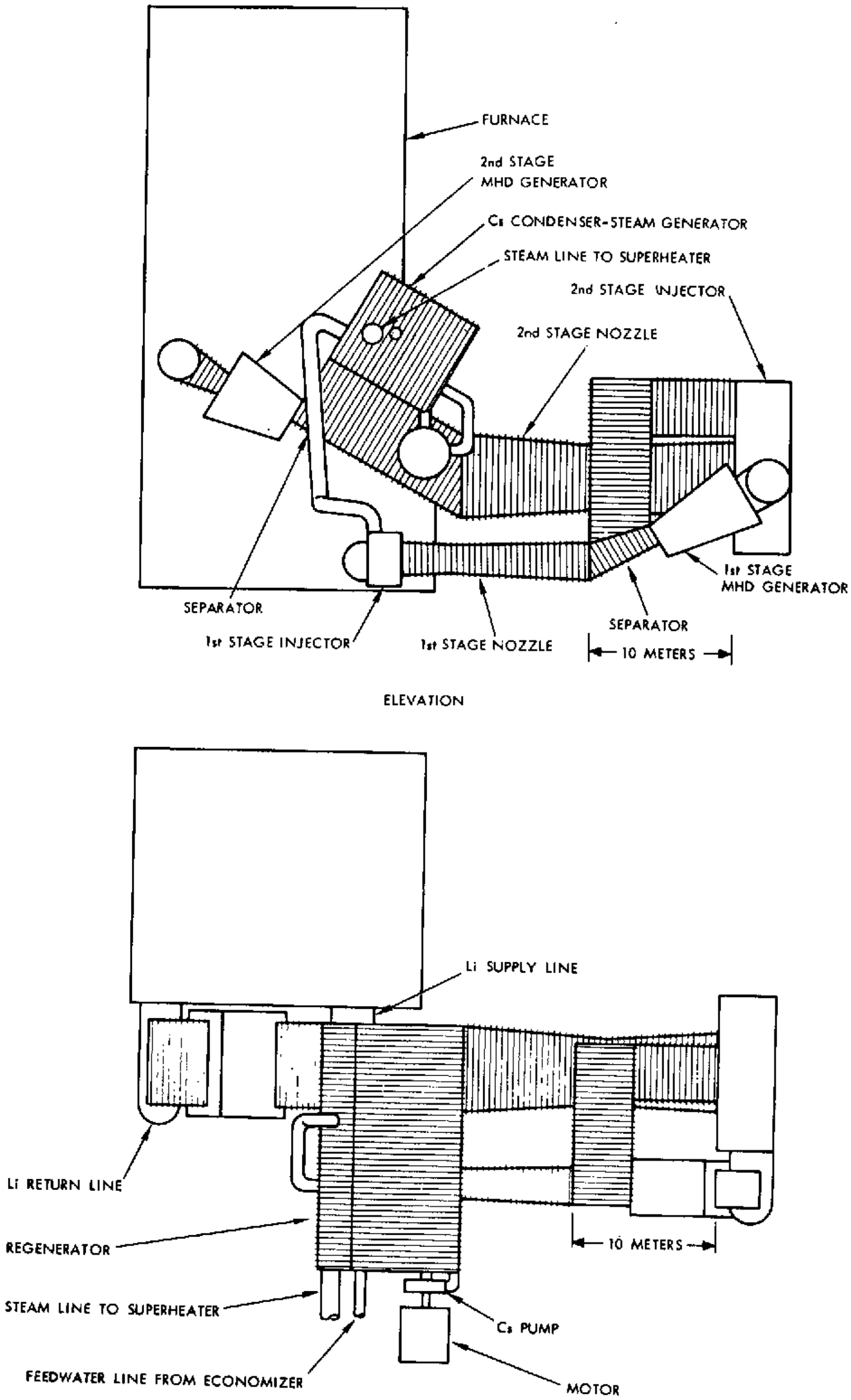


Fig. 9. Schematic design of cesium-lithium topping plant (337 MWe output, 13.5% efficiency)

Characteristics of the major LMMHD converter components are summarized in Table 2. Table 3 contains a brief description of the system components.

Table 2. Summary of characteristics of LMMHD converter components

1) First-stage nozzle
   a) Length - 50 ft.
   b) Exit area - 100 ft^2
   c) Exit velocity - 407 ft/s
   d) Exit temperature - 2252°R

2) First-stage separator
   a) Surface area - 200 ft^2
   b) Inclination angle - 30°
   c) Efficiency - 0.905
   d) Exit velocity - 387 ft/s

3) First-stage generator
   a) Inlet aspect ratio (width/height ratio) 10.8
   b) Length - 26 ft
   c) Height - 0.92 ft
   d) Width - 10 ft
   e) Power output - 233 MW

4) Second-stage nozzle
   a) Length - 75 ft
   b) Exit area - 517.7 ft^2
   c) Exit velocity - 399 ft/s
   d) Exit temperature - 2244°R

5) Second-stage separator
   a) Surface area - 1035 ft^2
   b) Inclination angle - 30°
   c) Efficiency - 0.742
   d) Exit velocity - 344

6) Second-stage generator
   a) Aspect ratio (width/height ratio) 50
   b) Length - 21 ft
   c) Height - 0.46 ft
   d) Width - 22.8 ft
   e) Power output - 109 MW

Table 3. LMMHD topping plant component description

Component	Description
Furnace	• Design similar to conventional coal- or oil-fired furnaces. • Includes lithium heater section, steam superheater, two steam reheat loops and a conventional economizer. • Main difference from conventional system is the replacement of a boiler section with the liquid metal heating section. • Small temperature change in the lithium decreases thermal stresses. • 1 in. Haynes-25 alloy tubing with 1/8 in. walls used in the heater section. Total length required is 543, 300 ft. • Fireside corrosion experimental data needed with Haynes-25. • Boiler efficiency of 86%, consistent with current practice, used in analyses.
Injectors	• Square array of 1/4-in. tubes, 1 ft in length leading from plenum to nozzle. Lithium passes through the tubes and mixes with cesium which is introduced into the nozzle through space between the lithium injector tubes. • Injectors contribute significant losses to the system. The losses become larger with increased numbers of stages.
Nozzles	• Design closely related to separator design to provide high velocity and low vapor quality for the MHD generators. • Designed with square crossection to be compatible in inclined-plane separators and for fabrication simplicity. • Characteristics are given in Table 2.
Separators	• Inclined flat plate separators selected. • Liquid forms a layer following the plate and gaseous flow is forced into the area above the plate. • Liquid flows to MHD generator and the gas is ducted off. • Velocity recovery and separation of fluid phase are important; this component contributes the largest component loss to the topping cycle. • Calculated separator efficiencies for design are: first stage 90%, second stage 74%, predicted maximum separator efficiency 95%. • Characteristics are given in Table 2.

Table 3 (Contd)

Component	Description
MHD generators	• Multiwave length ac induction generators used. • Has a set of copper windings in a removable stator, insulated from hot channel by ceramic plates. • Fabrication techniques used for large linear induction motors are applicable. • Ceramic plates are protected by Cb-1% Zr sheet which is attached to Haynes-25 alloy backing structures. • Water cooling of stator backside limits stator temperature to 200°F. • Magnetic field is about 1.0 Tesla. • 85% maximum efficiency predicted, 80% used in analysis. • Other characteristics are given in Table 2.
Regenerative heat exchanger and steam generator	• Haynes-25 alloy shell contains both regenerative heat exchanger and steam generator. • Regenerative heat exchanger is an array of 100, 6 in., Haynes-25 pipes occupying about a 4 ft length of the shell. • Steam tubing headers are either series 300 stainless steel or chrome-moly steel. • Careful design is required because of temperature extremes.

2. Materials and Structural Preliminary Design

The high temperatures involved in the LMMHD topping cycle result in serious problems of structural design. In addition, the materials contacting the liquid metals must resist erosion and corrosion for the lifetime of the system. Among the few materials which have been found to be resistant to liquid lithium at high temperatures and flow rates are Haynes-25 alloy and Cb-1%Zr alloy. Of these, the latter is better in terms of corrosion resistance, but its high cost (about $60 per pound of sheet or plate) makes it undesirable as a basic structural material of the system. Haynes-25, on the other hand, has an average cost of about $5.55 per pound for plate, which makes it acceptable as a structural material despite its somewhat lower corrosion resistance as compared with Cb-1%Zr. However, the acceptable stress levels for Haynes-25 at the higher temperatures in the topping cycle are so low that it would not be economically feasible to build the nozzles and other components from this metal only. In fact, the fabrication scheme chosen as the basis for the cost analysis of the system employs Haynes-25 only for its resistance to corrosion by the liquid metals, and not as a main stress-bearing material.

Many of the components of the system lend themselves to forms having square or rectangular, rather than circular, cross sections, therefore, it is advantageous to make use of fabrication techniques appropriate for the use of large flat-plates or sheets of structural material such as in wind tunnel practice. The following preliminary design concept, which has been used previously, was devised to take advantage of this consideration, as well as to provide structural integrity at a minimum cost. It should be noted that the technique could also be used in the fabrication of the large-diameter circular ducts in the system.

Using chrome-molybdenum steel plate, 1-in. thickness, for most of the topping cycle components, and somewhat thicker for the high-pressure regions, an outer shell is fabricated. Before or after this assembly, studs are welded to the inside of the plate at intervals of approximately 2 ft. Then a surface of an appropriate forming material (such as plywood) is placed over the studs so that an air space of about 3 in. is formed between the outer metal shell and the inner wooden one.

Next, castable ZrO_2 is poured into the air space, filling it completely. Upon curing, this ceramic forms a thermal insulator for the outer shell. The forming mold is then removed and a Haynes-25 plate is attached by welding it to the exposed ends of the studs.

Thus, the Haynes-25 is primarily used to resist corrosion by the liquid metal while the studs and ceramic backing serve to transfer the pressure stresses to the outer steel shell. The insulating layer would allow a maximum outer shell temperature of less than 800°F, making 1/2 in. and 1 in. chrome-moly steel plate satisfactory for most of the system. The heat loss associated with this wall temperature gradient is less than 1 MWt for the whole system.

The system must be supported to allow for thermal expansion. The support system has not been designed.

Haynes-25 appears sufficient to resist corrosion by the liquid metal in most parts of the topping cycle. The actual corrosion rates must be determined by extended duration tests. The inclined plates in the separators, however, are subjected to continual impact by high-temperature, high-velocity droplets of liquid lithium. Haynes-25 could not withstand this bombardment without severe erosion and mass transfer. However, mechanically attached sheets of Cb-1%Zr alloy have been used for mass transfer protection under similar conditions. Previous test data for 2000°F high-velocity lithium flow, discussed in Appendix C, indicates a maximum mass transfer deposit build up of 0.015 in. per year, quite insignificant for the dimensions of the separator surface and generator duct. Installation of the plate is discussed in Appendix E, D-2.

3. Interface With Steam System and Startup

The LMMHD topping cycle presented here interfaces with the steam turbine system in the primary evaporator section of the cycle. Economizer, superheater, and both reheat sections are located in the furnace. Startup of the steam turbine system will occur before startup of the LMMHD system. Furnace heat is transferred from the furnace to the cesium condenser-steam generator by evaporating cesium in the lithium heater. The cesium evaporates at a temperature close to the condensation temperature and flows to the steam generator where it condenses, transferring heat to the boiler. Cesium condensate is continually recycled to the furnace heating section by the cesium pump. When steady-state operation of the steam turbine system is attained, 1800°F lithium is injected into the first-stage nozzle. Injection is continued until steady-state operation is reached (~10-20 sec.). Injection startup used with a smaller NaK-nitrogen LMMHD conversion system results in steady-state operation in 1-2 sec.

Shutdown of the system must be sequenced so that steam flow is not lost before the heat input has been reduced to a low level. Part load operation will enable the heat load to be reduced while maintaining a constant temperature of the LMMHD system. The steam plant can be operated without the MHD generator so long as the MHD system is operable.

Although the primary application of the LMMHD system would be for base loading, it is possible for the system to operate under varying load conditions. By reducing the furnace heat, the maximum temperature of the liquid metal would be reduced, consequently reducing the liquid metal flow rate and the MHD power generation. The steam system would be throttled to match the liquid metal conditions. The voltage can be maintained constant as the liquid metal velocity is reduced. The control parameters on the furnace and steam turbine system, therefore, are identical to those for a conventional system. The control means for matching the LMMHD output to changing furnace heat rates is to vary the cesium inlet pressure and flow rate.

4. Auxiliary Systems and Controls

The auxiliary systems required for the LMMHD topping cycle are quite similar to those required for the steam turbine system and, in general, such systems can be shared. Control air, vacuum systems, cover gas systems, auxiliary electrical, instrumentation and readout, and electronics are all conventional in nature. Control during startup is accomplished with conventional air-operated valving and gas-pressure regulation equipment. During steady-state operation, control is achieved by conventional furnace controls and controls on the steam turbine system.

F. COST ESTIMATE

A cost estimate for the LMMHD topping cycle was performed for the following assumptions:

1) The design life is 30 years.
2) The cost of the MHD generators is comparable to that of large electrical motors (on a unit power basis).
3) Haynes-25 corrosion characteristics are adequate for cesium vapor and low-velocity lithium flow.
4) Cb-1%Zr plate is used to protect high-velocity regions (see Section III) from dissolution and/or extensive mass transfer.

5) The costs of components and materials are based on present-day manufacturers' quotations. Costs in 1980 were derived by assuming a five percent annual increase which was also applied to the alternative systems that were compared with the LMMHD/steam system.

With these constraints a summary of the cost estimate for the configuration of Fig. 9 is given in Table 4. It should be reiterated that the system has not yet been optimized with respect to cost. Operation at a lower mass ratio of lithium to cesium could result in a lower cost for the structure and liquid metal inventory while lowering the cycle efficiency by a small amount (i.e., about one percentage point).

The main cost uncertainty is the amount of Cb-1%Zr plate required to protect the internal surfaces from high-velocity lithium mass transfer. For the costs shown only the separator and MHD generator surfaces were protected. If the other portions of the MHD circuit (cesium vapor and low-velocity lithium) had to be protected, the material costs would increase by about $\$6 \times 10^6$. However, on the basis of published corrosion data and experience at JPL, this probably would not be necessary. A possible reduction in cost could be achieved if it were possible to substitute a low-cost refractory material (such as silica) for the castable ZrO_2 backing structure. The use of more efficient separators would decrease the cost per kW by enabling the production of more power. For example, if a separator efficiency of 95% could be obtained in the first stage and 90% in the second stage, the cycle efficiency could be increased to 16.2% from the calculated value of 13.5% while the capital costs remained essentially constant. The specific capital costs, \$/kW, would thus be reduced.

Table 4. Cost estimate summary for topping cycle for LMMHD/steam turbine binary power plant (1300 MWe steam, 337 MWe LMMHD)

Material Costs		($ x 10^6)	
Haynes-25 alloy plate	981,000 lb @ $ 5.55/lb	5.44	
Cb-1%Zr plate	7,600 lb @ 60.00/lb	.46	
ZrO_2 backing structure	2,704,000 lb @ 1.85/lb	5.00	
Cr-Moly steel plate	1,686,000 lb @ 1.00/lb	1.69	
Haynes-25 alloy tubing	543,300 ft @ 7.02/ft	3.81	
	74,300 lb @ 10.00/lb	.74	
	53,400 lb @ 10.00/lb	.53	
Structural steel (installed)	1,470,000 lb @ 1.00/lb	1.47	
Foundation (installed)	1,600 yd @ 50.00/yd	.10	
Insulation (installed)	41,300 ft^2 @ 1.30/ft^2	.05	
Component Costs			
MHD generators	342,000 kW @ 13.20/kW	4.53	
Cs pump		.50	
Capacitors	1,014,000 kvar @ 1.66/kvar	1.66	
Controls		.50	
Auxiliary Systems		1.00	
Dump and start tanks		4.87	
Total material and component costs		32.35	
Construction cost (25% of component costs, not including installed costs)		7.68	
Total direct costs		40.03	
Indirect costs (25% of direct costs)		10.01	
Total 1972 costs less liquid metals		50.04	
Liquid metal inventory 1972 costs			$ 14.38
Liquid metal inventory 1980 costs			21.24
Total 1972 cost with liquid metals			64.42
Total 1980 cost without liquid metals			73.90
Total 1980 cost with liquid metals			95.14
Specific cost, 1980, without liquid metals (337 MWe)			$219.0/kW
Specific cost, 1980, with liquid metal (337 MWe)			$282.0/kW
Specific cost, 1980, liquid metal inventory			$ 63.0/kW

SECTION V

EVALUATION OF LMMHD

A. SUMMARY

The characteristics of conventional and advanced power plants, described in Appendix B, were compared with the LMMHD/steam binary plant. The comparison was made on the bases of costs and environmental impact. Also, technology status, reliability, maintainability, and safety have been briefly considered.

B. COST EVALUATION

1. Nominal Cost Comparison

Nominal values for capital cost, plant efficiency, operations and maintenance costs, etc. were developed for competing systems in Appendix B and for LMMHD/steam binary plants in Appendix F. Nominal power generation costs were then computed for each system. Influence coefficients were provided for each system which permit determination of the effect on the generation cost of changes in the cost components. Figure 10 compares nominal 1980 power generation costs of conventional power plants with the LMMHD/steam plants and Fig. 11 is a similar comparison for advanced plants. The figures show the nominal 1980 generator costs for 1000 MW plants. Variations of these nominal costs with changes in fuel cost are indicated. For the LMMHD/steam plant nominal values are shown with a range of costs. The lower limit represents an optimized system; the upper limit represents capital costs 50% greater than the nominal values.

The following can be concluded from the figures.

1) The coal-fired LMMHD/steam binary plant has the potential for economic improvement over conventional coal-fired and nuclear plants of 0.2 to 0.6 mills/kWh. This cost reduction is due to the

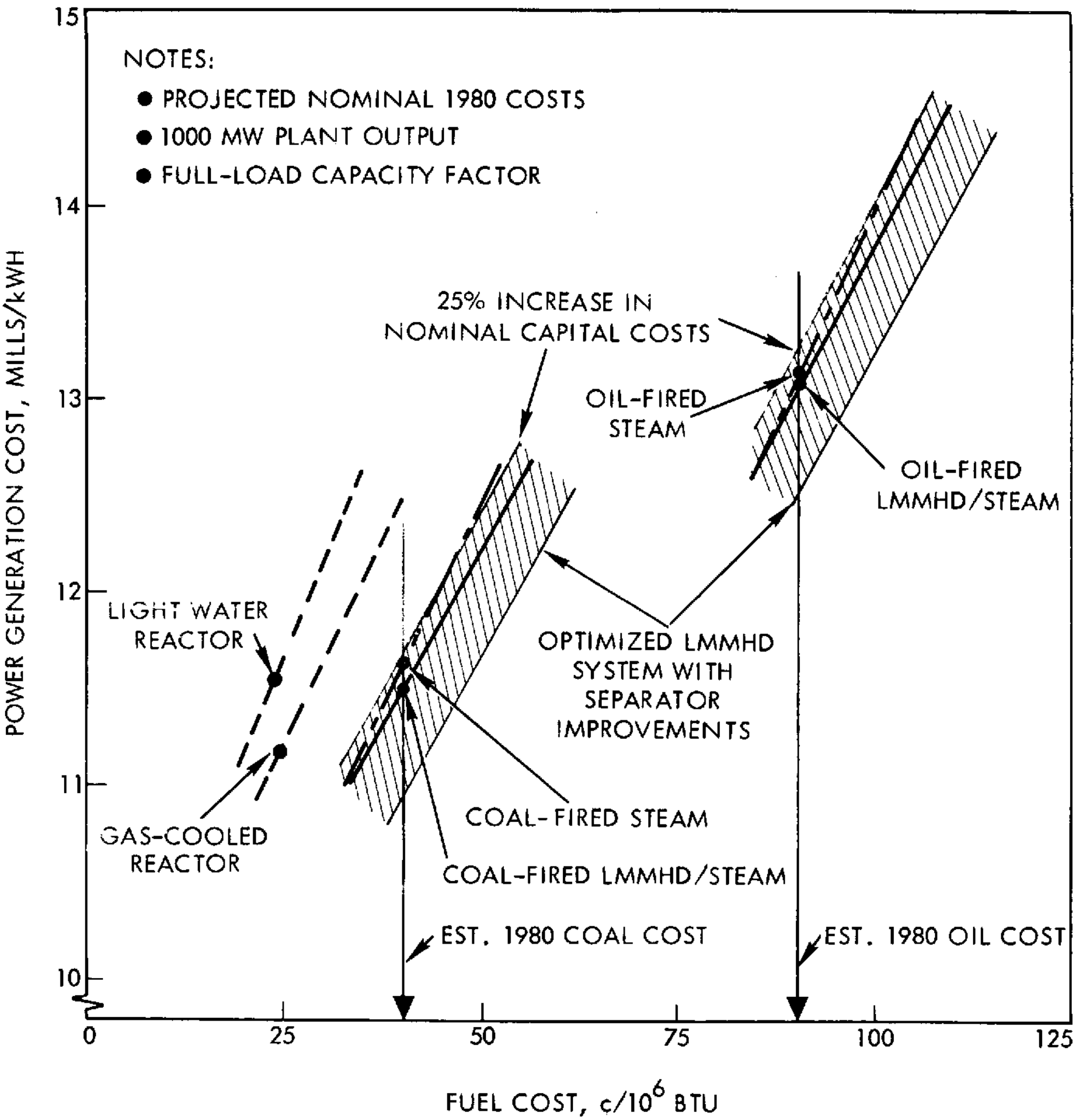


Fig. 10. Comparison of power generation costs of conventional power plants and LMMHD/steam plants

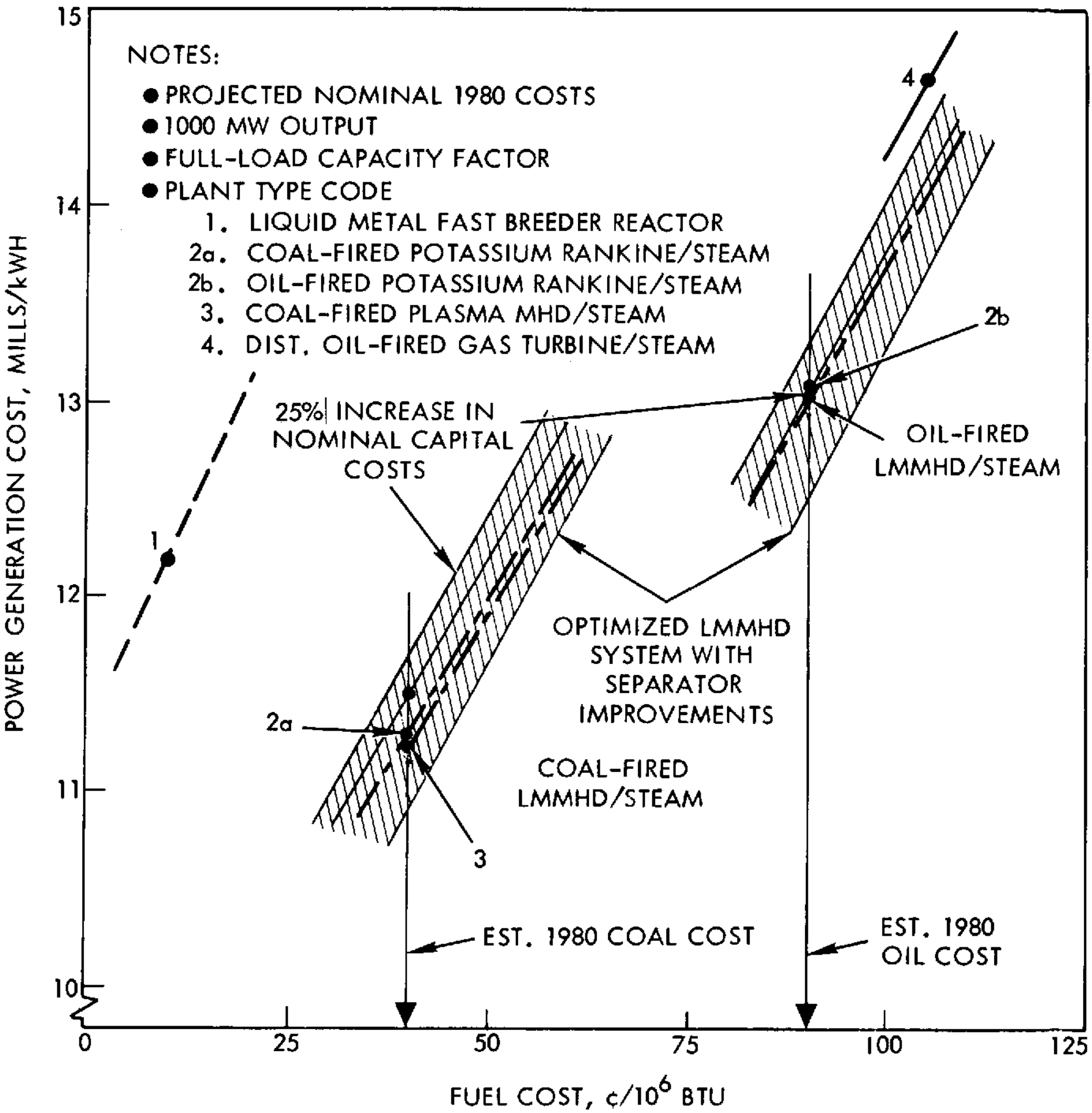


Fig. 11. Comparison of power generation costs of advanced power plants and LMMHD/steam plants

efficiency improvements at low capital cost. The annual cost savings for a 1000 MW coal-fired LMMHD/steam binary plant derived from the nominal cost differential from a conventional coal-fired plant shown in Fig. 10 is about $1 million. At a 15% annual fixed charge rate this is equivalent to about a $7 million capital cost reduction. If the optimized system proves to be achievable, the annual savings would be about $4.5 million for a 1000 MW system.

2) The oil-fired LMMHD/steam plant has potential nominal 1980 generation costs 0.1 to 0.6 mills/kWh lower than the conventional oil-fired plant. Corresponding LMMHD/steam plant annual cost savings compared with the conventional oil-fired steam plant would be 0.5 to 4.5 million dollars for a 1000 MW plant.

3) As fuel costs increase, the power generation cost of the LMMHD/steam plant will be reduced even more with respect to the conventional plants due to the higher efficiency of the LMMHD/steam plant.

4) The LMMHD/steam plant has nominal generation costs comparable to the plasma MHD/steam plant and the potassium Rankine/steam plant.

5) The LMMHD/steam plant has lower generation costs than the gas turbine/steam plant.

6) Considering the uncertainties in advanced systems' generation costs the LMMHD/steam plant has the potential of achieving lower generation costs than any of the other advanced systems considered.

Although not shown in Figs. 10 and 11, LMMHD combined as a topping cycle with an advanced nuclear plant (if the required temperatures could be achieved) could provide for significant cost reduction due primarily to reductions in specific capital cost, and secondarily to improved plant efficiency.

2. Alternative Fuel Scenarios

The LMMHD/steam binary plant is compared with alternative systems under various fuel expectations as follows:

1) Nuclear Power Restrictions - Nuclear power restrictions due to environmental constraints would probably increase the requirements

for fossil fuel-fired systems. An increase in the need for fossil fueled systems could result in increased fuel prices which would favor the application of LMMHD.

2) Coal Restrictions - If the use of coal were restricted (except for gasified coal) due to environmental constraints, the application of nuclear power would probably be increased. The LMMHD topping plant would be deprived of one of its primary applications. The use of oil and gasified coal would probably increase and fuel prices would probably rise. Oil-fired LMMHD/steam plants would provide increasingly lower generation costs, when compared to conventional oil-fired systems, as the fuel cost increased. Also, if a high temperature nuclear reactor were developed the LMMHD topping plant could be advantageously coupled with it to lower the generation cost.

3) Oil Restrictions - Oil restrictions due to import constraints would probably increase the application of coal-fired and nuclear plants and raise the price of oil. All of these factors would favor the application of LMMHD topping cycles.

4) Nuclear and Coal Restrictions - Nuclear and coal restrictions would probably result in increased use of oil and gasified coal. LMMHD topping cycles would become increasingly attractive as the oil prices rise.

5) Nuclear, Coal, and Oil Restrictions - Restrictions of nuclear, coal and oil plants would probably increase the use of gasified coal or synthetic oil. Fuel prices would rise and advanced power systems having high efficiency would be favored. The LMMHD/steam plant would have lower generation costs than conventional gas-fired plants.

C. ENVIRONMENTAL POLLUTION EVALUATION

Environmental pollution is a function of fuel type, plant design, and efficiency. The environmental effects of the LMMHD/steam binary plant were compared with alternative systems, considering both air pollution and thermal pollution. The results are as follows.

1. Air Pollution

The major air pollutants produced by fossil-fuel plants are: particulates, oxides of sulfur, and oxides of nitrogen. The production of these pollutants for conventional plants is given in Appendix B. The emissions produced per unit of electrical output are affected by plant design, combustion processes and plant efficiency. While it is not within the scope of this study to evaluate plant design and combustion processes, it is likely that LMMHD and other advanced binary plants will reduce plant emissions (other than oxides of nitrogen) by a decrease in fuel usage. Appendix E, subsection E, provides a procedure for comparing the air pollution produced by the LMMHD/steam plant with competing systems. As an example, Fig. 12 shows the annual production of oxides of sulfur from a 1000 MW power plant for the various competing systems. The LMMHD/steam plant provides 12% reductions from the conventional fossil fuel systems for any fuel. However, other advanced plants, because of their potentially higher efficiency, could reduce the air pollutants even further.

Comparisons for air pollutants, other than NO_x, would produce results similar to Fig. 12. Note that the maximum air pollution reduction, for any specific fuel, due to reduction in power plant fuel usage, is about 20%. For larger reductions in air pollution, modifications of the combustion process, fuel processing, stack gas cleaning, etc., would be required.

The level of NO_x emissions from steam plants is related to burner design, boiler design, and control of the combusion process. Attention to each of these factors will be necessary to control NO_x emissions to acceptable levels. Emissions of NO_x are generally lowered by either reducing the available oxygen in the flame, or by reducing peak combustion temperatures. In existing steam plants, low-NO_x operation is achieved by low excess air firing (for coal) or by fuel-rich burner operation followed by controlled addition of the remaining combustion air (for gas and oil). Product gas recirculation, a technique which lowers peak flame temperatures, can also be used to lower NO_x production.

The main difference between a steam system with a topping cycle and a conventional steam plant is the higher mean temperatures required in the liquid metal tubewall.

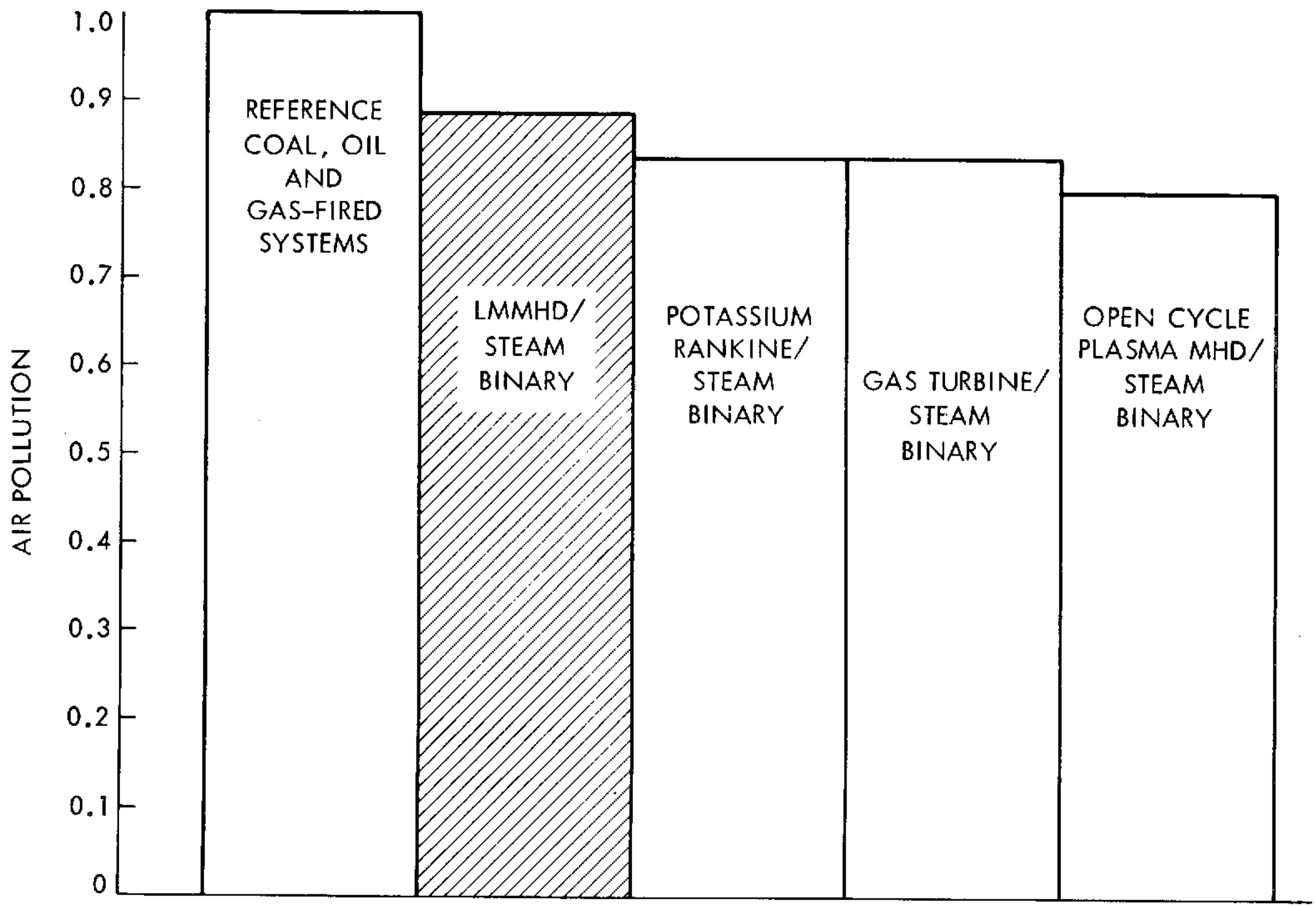


Fig. 12. Air pollution (except NO_x)

1200-59

The mean temperatures required are not sufficiently high to produce NO_x in themselves, even in the presence of large amounts of oxygen. Careful control of the combustion process will be needed, however, to prevent increased local flame temperatures that would produce large amounts of NO_x. In addition, modified boiler design may be needed to increase heat transfer in the hottest combustion zones. Future work should include detailed analysis of NO_x emissions.

2. Thermal Pollution

Thermal pollution, or the heat rejected in air and water by a power plant, is related to the plant's efficiency. The bar graph of Fig. 13 compares the thermal pollution of the alternative systems.

The LMMHD/steam binary plant is seen to produce less thermal pollution than conventional plants (20% less than conventional fossil-fuel plants and 70% less than the LWR plants). But somewhat more thermal pollution is produced by the LMMHD/steam plant than other advanced systems which have higher potential plant efficiencies.

D. TECHNOLOGY EVALUATION

The status of the technology of liquid metal MHD and the alternative systems is assessed in this subsection. Conventional systems, which are currently developed and require little or no technology advancements, are:

1) Coal-fired steam plant.
2) Oil/gas-fired steam plant.
3) Light water nuclear reactor plant.
4) High temperature gas-cooled thermal nuclear reactor plant.
5) Gas turbine/steam binary plants. (This system has more growth potential than the other conventional systems listed).

The advanced plants which require technology advances to achieve a commercial status are:

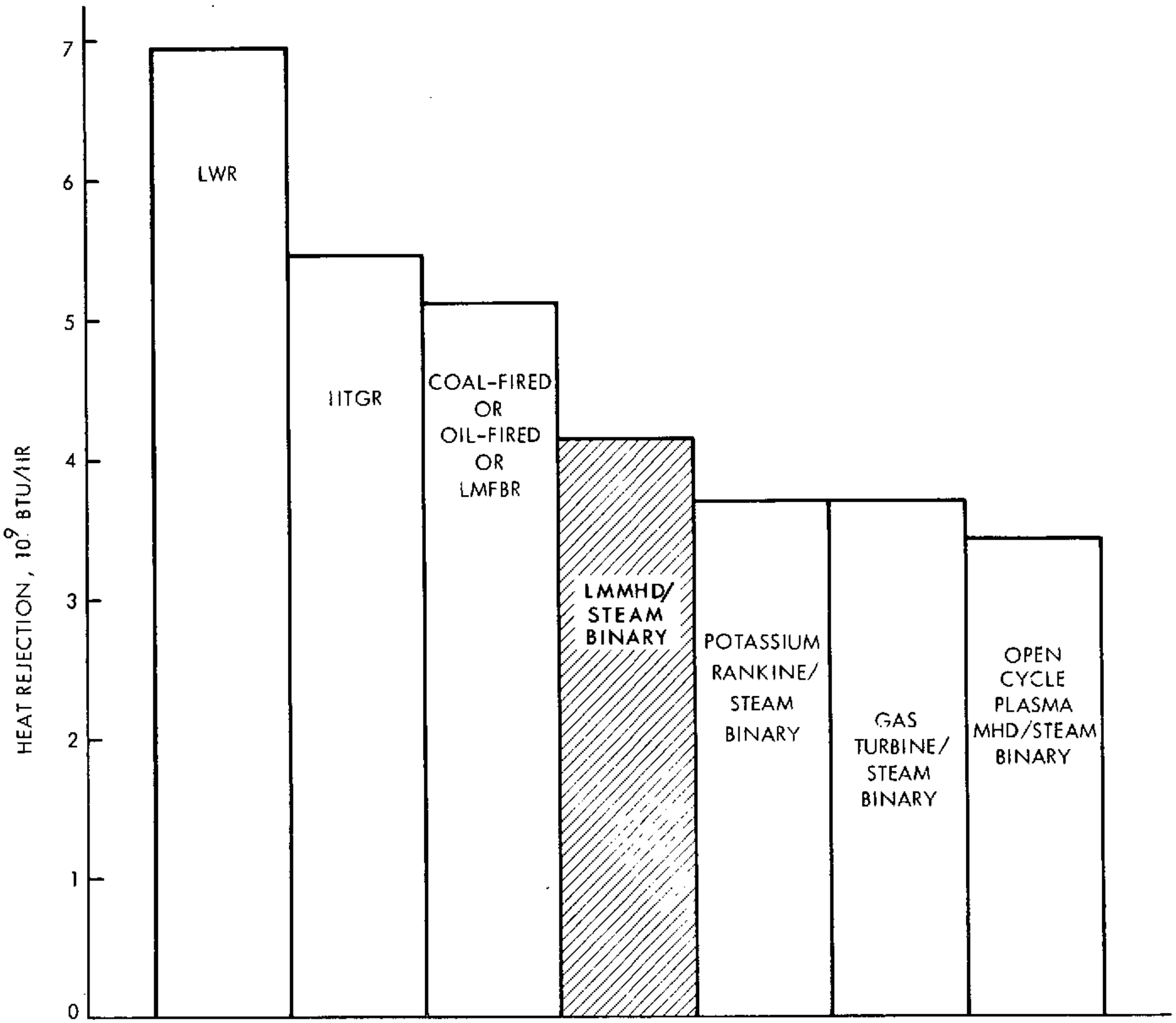


Fig. 13. Thermal pollution

1) Open-cycle plasma MHD/steam binary plant.
2) Potassium Rankine/steam binary plant.
3) Liquid metal fast breeder nuclear reactor plant.
4) Liquid metal MHD/steam binary plant.

The technology status and development requirements of the advanced plants, including the gas turbine/steam plant, are summarized in Appendix F, Section E.

Of the advanced plants considered, the development of the gas turbine/steam plant has progressed the furthest. Plants with mid-range power capability are now being installed for swing plant application. A major technical challenge in the future will be to increase plant efficiency, primarily by increasing turbine inlet temperature and compressor pressure ratio.

Open cycle plasma MHD has been subjected to considerable research and development. Considerable development is required, however, to demonstrate long-life and high performance. The fundamental problem areas which require continued development work include: materials, generator performance, gas conductivity and combustion, and seed recovery.

The potassium Rankine system has undergone considerable research, and small complete systems have been operated for periods up to one year. Primary development problems encountered have been with turbine blade erosion and with seals. Advanced materials research will be required to achieve the predicted high efficiencies.

The liquid metal fast breeder reactor is being subjected to considerable development with commercial availability scheduled for the mid-1980s. Major development problem areas include design for core stability and development of an adequate fuel element. There are also operational problems in transportation and reprocessing of the fuel and in waste handling.

Of all the systems considered, LMMHD is the least developed. Development is required to verify performance, validate materials application for long-term use, and establish furnace and cesium condenser design. LMMHD, however, has received funding one or two orders of magnitude less than other advanced systems. If funding were increased the LMMHD development status could be comparable to other advanced systems.

E. RELIABILITY, MAINTAINABILITY AND SAFETY

It was not possible in this study to conduct detailed studies of reliability, maintainability, and safety. The following several statements can be made, however, regarding LMMHD characteristics in these categories:

1) Reliability - The LMMHD system is very simple, requiring no moving parts. This suggests high inherent reliability. Its high temperature operation, however, requires system demonstration with economically viable materials; and long-term operation needs to be proven.

2) Maintainability - The primary factors affecting maintainability will be erosion and deposition within the ducting, and operations related to liquid metal handling. Erosion rates have been predicted to be quite low, requiring little maintenance. The maintenance requirements due to liquid metal handling, periodic servicing and inspection of the system, etc. must be established in the future as the LMMHD system becomes better defined.

3) Safety - The primary safety hazard inherent with LMMHD is its use of liquid metals at high temperatures. Liquid metal loops have been operated successfully, however, in numerous cases. For example, high temperature ($>2000°$ F) lithium systems have been built and operated for time periods to 10,000 hours. Personnel and equipment hazards are similar to those faced by the liquid metal fast breeder reactor development, except that there is no radioactivity hazard.

SECTION VI

TECHNOLOGY DEVELOPMENT PLAN

A. INTRODUCTION

A preliminary technology development plan has been prepared, outlining the future tasks required to develop LMMHD for commercial status. Figure 14 summarizes the plan. Included in the figure are the scheduled program elements, an estimate of the possible participants and their functions at each stage of the program, and the approximate funding required. The level of effort of this study did not permit detailed planning, but Fig. 14 does provide a view of the overall scope required to develop LMMHD for commercial utility power applications. The following subsections briefly describe the work necessary to develop LMMHD.

B. SYSTEM DESIGN STUDIES

The study reported herein has only surveyed the applications of LMMHD to utility power generation. There is much to be done to fully ascertain its potential. Specifically, work is required in the areas of applications, system optimization and system design as follows.

1. Application Studies

The applications emphasized in this study were primarily for LMMHD as a topping plant for coal-fired and oil-fired steam plants. There are other possible applications which should be considered, however. Specifically, these are:

1) Retrofitting LMMHD to existing fossil fuel plants.
2) Application of LMMHD topping plants to nuclear plants.

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PROGRAM ELEMENT	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	PARTICIPANT FUNCTION	POSSIBLE PARTICIPANT	TOTAL PHASE COST $\$10^6$
1. SYSTEM DESIGN STUDIES																			• FUNDING AND PROJECT REVIEW • PROJECT MGR AND OPTIMIZATION STUDIES • APPLICATION AND DESIGN STUDIES • CONSULTATION AND REVIEW	• GOVERNMENT NSF (NASA) • JPL • SYSTEMS CONTRACTOR A&E CO. • LOCAL UTILITY CO. • UTILITY ASSOCIATION • MANUFACTURERS	
• APPLICATION STUDIES																					
• OPTIMIZATION STUDIES																					
• SYSTEM DESIGN																					
FUNDING $\$10^6$	0.25	0.5																			0.75
2. RESEARCH AND TECHNOLOGY DEMONSTRATION																			• FUNDING AND PROJECT REVIEW • PROJECT MGR • CONSULTATION AND REVIEW	• GOVERNMENT/UTILITY ASSOCIATION • JPL • SYSTEMS CONTRACTOR A & E CO. • LOCAL UTILITY CO • MANUFACTURERS	
• ADVANCED SEPARATOR TESTING																					
• MATERIALS TESTING (Cs-Li LOOP)																					
• 300 kW (OUTPUT) Cs-Li CONVERSION SYSTEM																					
• DESIGN																					
• FABRICATION																					
• STARTUP																					
• TESTING AND ASSESSMENT																					
FUNDING $\$10^6$	1.5	1.5	1.5	1.5	1.5																7.5
3. 30 M LMMHD OUTPUT DEMONSTRATION SYSTEM (150 MW TOTAL)																			• FUNDING AND PROJECT REVIEW • PROJECT MGR • CONSULTATION AND REVIEW	• GOVERNMENT/UTILITY ASSOCIATION • SYSTEMS CONTRACTOR A & E CO. • JPL • LOCAL UTILITY CO. • MANUFACTURERS	
• DESIGN																					
• FABRICATION																					
• STARTUP																					
• TESTING																					
• APPROXIMATE MINIMUM FUNDING $\$10^6$ *						1.5	2.5	5.0	5.0	3.0	3.0										20
4. CENTRAL STATION DEMONSTRATION PLANT																			• FUNDING AND PROJECT REVIEW • PROJECT MGR • CONSULTATION AND REVIEW • PLANT OPERATION	• UTILITY ASSOCIATION/GOVERNMENT/LOCAL UTILITY • SYSTEMS CONTRACTOR A & E CO. • JPL • LOCAL UTILITY CO. • MANUFACTURERS • LOCAL UTILITY CO.	
• DESIGN																					
• FABRICATION																					
• STARTUP																					
• OPERATION																					
• APPROXIMATE MINIMUM FUNDING $\$10^6$ **																					63
5. TOTAL FUNDING $\$10^6$ *, **	1.75	2.0	1.5	1.5	1.5	1.5	2.5	5.0	5.0	3.0	3.0	3.0	5.0	20.0	20.0	15.0					99

* APPROXIMATE COST OF LMMHD TOPPING PLANT ONLY; COST OF 120 MW (ELECTRICAL OUTPUT) BOTTOMING PLANT WOULD BE APPROXIMATELY \$30 to \$40 MILLION (1980 COSTS)

** APPROXIMATE COST OF LMMHD TOPPING PLANT ONLY; COST OF 790 MW (ELECTRICAL OUTPUT) BOTTOMING PLANT WOULD BE APPROXIMATELY \$180 to \$250 MILLION (1980 COSTS)

Fig. 14. LMMHD central station topping cycle technology development plan

Retrofitting existing fossil-fuel plants with LMMHD systems would provide a means of upgrading existing plants. The power output could be increased by 12 to 15% for the same fuel input. The addition of the LMMHD topping plant would require considerable modification of the existing plant. The boiler would have to be replaced by a furnace, etc. Thus, careful consideration of the technical and economic feasibility of this option is required.

Although there are no known plans for a high temperature nuclear reactor, utilization of LMMHD with such a reactor should be investigated. Preliminary analyses made during this study indicate that combining LMMHD with a high temperature nuclear reactor could significantly reduce generation costs and thermal pollution. Nuclear reactor programs and technology should be reviewed to determine the technical feasibility for developing reactors with sufficiently high temperatures to permit LMMHD topping plants. The economic potential of such an option should be assessed, including the cost implications of a new reactor program. Emphasis in the analysis should be placed on the breeder reactor application. Application with fusion plants should also be considered (if only briefly at this time). The application of LMMHD to fusion plants may be facilitated because lithium has been proposed as the fusion plant coolant and as one of the LMMHD working fluids. Possible programmatic options should be considered, including development and demonstration of LMMHD with earlier reactors, i.e., advanced breeder reactors, in preparation for later applications with fusion reactors.

2. System Optimization Studies

The LMMHD system described herein was not optimized on a cost basis. The mass ratio of lithium to cesium, for example, was selected to provide maximum efficiency. It has been estimated that significant LMMHD capital cost reductions can be made by reducing the lithium-cesium mass rates to optimize the design on a cost basis. Optimization studies should be conducted to improve the LMMHD system design and provide a more substantial basis for evaluating the LMMHD system for the various applications. In addition, experimental work is being conducted, primarily on new separator designs, which could significantly increase the LMMHD topping plant efficiency. The results of the experimental work should be incorporated into the optimization studies.

3. System Design

The study scope permitted only a preliminary examination of the LMMHD/steam plant design with emphasis on fossil-fueled plants. More detailed design is required to firmly establish the binary system design and capital costs. System design, utilizing the services of experts in the field, should be accomplished to provide guidance to the research and technology program, support the optimization studies and more accurately assess the potential advantages of the LMMHD/steam system. The system design effort should emphasize: 1) system integration and design of components critical to the LMMHD/steam interface, such as the furnace and cesium condensor/steam boiler; 2) optimum LMMHD system design and costs; 3) plant construction, including alternate fabrication methods and methods to reduce field fabrication; and 4) operational characteristics, reliability, maintainability and safety. The fossil-fueled topping cycle application should be emphasized unless the applications studies, described above, indicate otherwise.

4. Schedule and Funding

If LMMHD continues to show promising applications to utility power, a key element of the system design will be to prepare a more detailed plan for the technology development. The recommended schedule for the above tasks is shown in Fig. 14. The three activities are shown to begin in FY'74. The applications and optimization studies are scheduled for one year; the system design is scheduled for two years incorporating the results of the two other studies.

The funding is shown to be \$250 K in the first year, increasing to \$500 K the second year.

5. Participants

It is recommended that the government and an association of utility companies, such as the new Electric Power Research Institute, share in the funding. JPL would manage the studies, but the major study and design efforts would be conducted by a systems contractor (Architectural and Engineering Company) experienced in power plant design and construction. JPL would support the design work by providing the LMMHD system optimizations. Consultation and review would be provided by a local utility company, an association of utility companies and appropriate manufacturers.

C. RESEARCH AND TECHNOLOGY DEMONSTRATION

Technology demonstration will be required to implement LMMHD. A program to develop and demonstrate the LMMHD technology for application to central station topping cycles has been outlined as shown in Fig. 14. The recommended research and technology demonstration program elements are outlined as follows.

1. Description of Research and Technology Demonstration

The key research and technology areas, which need investigation to validate the cycle analysis and establish the feasibility of a long-life topping cycle, are the following.

1) Advanced LMMHD Converters - Experimental performance of an LMMHD generator with a cesium-lithium mixture requires verification. (LMMHD generators have been tested with NaK and with potassium.) Tests of a 200-300 kWe generator would be conducted to validate the duct insulation design and to determine the dissolution kinetics for the cesium-lithium mixture. The conversion system would be designed to utilize an existing 5 MW power source and an existing 5 MW NaK heat rejection system. Haynes-25 alloy and Cb-1%Zr alloy would be the materials of construction for the flow system.
2) Multistage Components - Performance of surface separators at lower void fractions and dynamic head than for single-stage systems must be established. Analysis and testing of separators for multi-stage systems will be performed to determine the effects of reduced liquid inertial forces and increased vapor drag forces on separation

of the vapor and liquid phases. Tests will be performed using water and nitrogen as test fluids for geometries resulting from analyses of systems for central station applications.

Performance of advanced separator concepts should be established. Some concepts have been identified which have the promise of much higher efficiencies. Among the more promising of these are liquid-surface impingement at steeper impact angles, impingement of two-phase jets and use of rotary separators. Each of these concepts will be investigated with water and nitrogen test fluids to determine optimum geometries and the resultant separator efficiencies.

3) Inexpensive Structures and Materials - The long-term stability characteristics of Haynes-25 alloy and other super alloys in a high-velocity two-phase mixture of cesium vapor with lithium droplets, and in low-velocity lithium must be determined. Tests will be conducted in an existing cesium-lithium test system after suitable modification. Test components of Haynes-25 alloy and Cb-1%Zr alloy will be installed in the test system which is constructed of Cb-1%Zr alloy. Tests of at least 5000 hours duration will be performed to establish the mass transfer rates for these materials at the full temperature (1800° F) and flow velocities (20-450 ft/s) of the topping plant application.

The long-term compatibility of Haynes-25 alloy or other super alloys with refractory metal components and/or coatings in a dynamic liquid metal system requires investigation. Part of this task would be accomplished in conjunction with activities mentioned in 3) above. In addition, long duration tests of candidate materials with small natural convection loops would be conducted. These tests would be for at least 2 years duration at the temperature of interest (1800°F).

The basic liquid metal technology necessary for the furnace, piping, steam-generator and other components has been or will be developed in the many NASA liquid metal programs and in the breeder reactor program.

2. Schedule and Funding

Figure 14 shows the Research and Technology Demonstration task scheduled for four and one-half years at an annual cost of $1.5 million. It would be possible to compress the schedule to two or three years, provided funding were increased by approximately $1 million. For the schedule shown, the advanced separator and materials tests would be completed during the first two years. These technology investigations are critical to the verification of the system's performance and lifetime. The testing of the 300 kW output cesium-lithium demonstration unit completes the schedule shown.

Considering that the possible benefits to the utility industry are from $2 to 6 million/year saving for each 1000 MW unit utilizing the LMMHD topping cycle, this investment for research and technology demonstration is small indeed.

3. Participants

It is recommended that funding for the research and technology demonstration project be provided jointly by the government and a utility association, such as the new Electric Power Research Institute. JPL would manage the program and conduct the research and technology work. Consultation and review of the project would be provided by system contractor(s), a local utility company and manufacturers.

D. THIRTY-MW LMMHD DEMONSTRATION PROJECT

If the results of the initial work are favorable, a pilot plant at a scale of about 30-MW LMMHD electrical output (150 MW total plant output) should be constructed and operated to bring the LMMHD topping cycle to a state of development necessary for its commercial application. The primary purposes of the demonstration project would be to verify performance and lifetime of LMMHD components and system design, and plant operating characteristics; and assess maintenance problems, plant control, and costs, etc.

It is estimated that the design, fabrication and startup could be accomplished in three to five years. A five-year project scheduled to begin after completion of the research and technology phase is shown in Fig. 14. A minimum LMMHD development cost for this demonstration plant has been estimated to be approximately $20 million. This cost could double, depending upon developmental problems encountered. The cost does not include the furnace and bottoming plant which could add $30 to $40 million to the LMMHD cost. Those estimates are based on the specific capital costs for steam plants used in this report. Future studies should provide improved schedule and costs for the demonstration program.

Participation in this project would differ from the previous design and research projects. In those projects JPL was recommended as the project manager. With the development of the 30-MW LMMHD demonstration plant the project manager would become the system contractor (A and E Company). It is recommended that funding continue to be provided jointly by the government and a utility association. JPL would provide research necessary to support the project. Additional consultation would be provided by a local utility company and manufacturers.

E. CENTRAL STATION DEMONSTRATION PLANT

If the 30-MW LMMHD demonstration plant proves the LMMHD/steam system to be economically and technically feasible, the development of a demonstration plant of commercial size would be required. The central station demonstration plant project would provide system performance, lifetime, cost, and operation and maintenance information necessary to evaluate commercial applications of LMMHD topping plants.

The total cost of the central station demonstration plant is difficult to estimate accurately with the limited information currently available. Very approximate funding is shown in Fig. 14 to permit an overall assessment of total development program costs. These costs are subject to change as design and development progresses; future program planning exercises are required to establish more accurate costs.

The participants in the central station demonstration project are similar to those for the 30-MW LMMHD demonstration project. The primary difference is in increased participation by the local utility company, both in providing some of the funding and in operating the completed plant.

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