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STUDY OF COMPACT LIQUID-METAL MHD SYSTEMS
COUPLED TO HELIUM GAS COOLED REACTORS

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ENGINEERING DIVISION

JANUARY 1975

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SUMMARY

As part of a continuing series of system studies being carried out to evaluate the potential of liquid-metal MHD systems to reduce the weights and volumes of power plants suitable for naval application, an analysis was made of a dual-cycle liquid-metal MHD and gas turbine concept coupled to a helium gas cooled reactor, (HGCR). The reactor supplies 1700°F helium to four MHD generators connected electrically in series that develop 100 volt DC electrical power to drive the 140,000 hp ship propulsion motors. The power of the gas turbine, which is coupled directly to the compressor and liquid pump, is matched to supply only the compressor and liquid pump power requirements. The relatively high projected overall cycle efficiency of 0.40 allows reductions in reactor and component sizes, and thus aids in the development of a compact, light-weight power system.

The complete power plant is estimated to weigh 1,775,000 pounds, for a specific power density of 12.67 pounds per horsepower, and to occupy 25,500 cubic feet. Over half of the weight, 1,008,000 pounds, is for the reactor and its associated components, mainly the biological shield. The energy conversion system including the drive motors weighs 767,000 pounds, or 5.47 pounds per horsepower.

I. INTRODUCTION

Extensive cycle and system studies carried out at Argonne National Laboratory (ANL) over the past few years have indicated that two-phase liquid-metal magnetohydrodynamic (MHD) power systems possess excellent potential and offer significant advantages over conventional power systems for various naval applications, provided that their predicted performance can be realized. The advantages include relatively high cycle efficiencies, and reductions in power system weights and volumes.

Evaluation of liquid-metal MHD systems as an alternative to or in combination with steam turbine-alternator cycles or the more recent gas turbine-alternator cycles began at ANL in November 1969 under contract to the Division of Naval Applications, Office of Naval Research. In the initial phase detailed cycle and component analyses were made to establish realistic performance limits, identify the important system parameters, and determine the constraints imposed upon the parameters by the cycle.¹ The critical problem areas that required additional investigation were also identified.

The second phase of the program focused primarily on conceptual studies of liquid-metal MHD systems to develop plausible component layouts, and weight and volume estimates.² Four 30 megawatt electrical systems were considered in detail which trace the potential solution of the concept from a system based on essentially present-day technology to advanced systems that would utilize material and liquid-metal technologies that are expected to evolve in the future. Projected performance parameters for these initial systems were: overall efficiency, 0.24 to 0.42; overall energy conversion specific power, 34 to 56 lbs/SHP; and volume required for conversion systems, 32,000 to 64,000 cubic feet. (These figures include the primary heat exchanger but not the reactor or associated shielding.)

Since these studies were completed further cycle analyses and system studies have been made. These included evaluation of multiple expansion stages, the addition of a gas turbine to drive the compressor, and new cycle concepts. As an example of the latter, initial studies of a steam-tin Rankine cycle were carried out which appear to be especially interesting since the small heat exchangers and decreased pumping power inherent in the concept yield a compact light-weight system. A low-temperature 15,000 hp propulsion plant operating at 635°F and 2000 psi was estimated to have a specific power density of only 25.6 lbs/SHP.

In this report the results of a conceptual design study of a liquid-metal MHD system coupled directly to a gas cooled reactor are presented. The primary objective of the study was to develop a compact light-weight power system. In addition, it was desired to include new system features and the latest information on heat sources and materials that have evolved in the interim period since the previous studies.

The cycle and the overall system performance are described in Section II for several alternative sets of parameters. The selected design is not optimized. The description of the system concept developed is given in Section III along with the component and overall weights and volumes.

II. MHD - GAS TURBINE DUAL CYCLE

2.1 Cycle Description

A schematic of the cycle considered is shown in Fig. 1. The hot helium from the reactor is mixed with liquid lithium, and the resulting two-phase mixture enters the MHD generator. The MHD generator acts as a turbine and electric generator in one unit; where the gas expands, drives the liquid across a magnetic field, and thus generates electric power. Since the lithium has a high specific heat, the expansion occurs at almost constant temperature and there is considerable available energy in the gas after the MHD generator. Following separation from the lithium, the remaining available energy in the helium is extracted efficiently in a conventional gas turbine. The most compact system results when the turbine supplies just the power required for the compressor and the liquid pump through a common shaft. Then the external load power is supplied by the MHD generator, thereby eliminating the need for an electric generator or motor on the turbine shaft. (Alternatively, a two-stage turbine is chosen here, with the separate stages matched to the compressor and pump.)

After the separator the liquid is returned to the mixer by means of the liquid pump. (Here a combined separator-pump is used.) After the turbine the gas is returned to the reactor through the conventional gas turbine cycle components of regenerator, reject heat exchanger, and compressors.

2.2 Component Performances

The performances of all components except for the MHD generator are summarized in Table I. All of these are well understood except for the mixer and separator which are undergoing further study at ANL.

Figure 1. Schematic of Cycle.

Table I. Component Performances

1. Reactor:	38 psi pressure difference Gas exit conditions of 2160°R, 1500 psia
2. Mixer	5 psi pressure difference
3. Separator:	0 psi pressure difference Liquid kinetic energy losses due to 10° angle change and skin friction
4. Liquid Pump:	0.85 efficiency
5. Gas Turbine:	0.90 efficiency Adiabatic
6. Regenerator:	20 and 10 psi differences across hot and cold sides, respectively 0.90 effectiveness
7. Reject Heat Exchanger:	4 psi pressure difference 0.92 effectiveness 555°R coolant temperature
8. Compressor:	0.88 efficiency 2 stages with intercooling
9. Superconducting Magnet:	negligible power required
10. Nozzle:	0.90 efficiency
11. Diffuser:	0.90 efficiency

The electrical and flow characteristics of the MHD generator are calculated in detail by computer codes which account for all first order loss mechanisms, including viscous and ohmic losses. It is assumed that there is no slip between the gas and liquid phases in the generator. This assumption is based on the fact that slip is expected to be small at high temperature and velocity. Current experiments and analyses support this assumption, and an experiment to check this under actual operating conditions is presently under construction. Also, 90% of the end losses are eliminated, as justified by computer models and preliminary experiments.

For the range of cycle parameters considered the calculated generator efficiency is between 0.76 and 0.80. This efficiency is lower than that for a comparable turbine, but the cycle efficiency is higher because of the almost-constant-temperature expansion in the generator. Higher generator efficiencies are attainable at the cost of increased generator volume. Here the goal is a compact generator with 25 volts per module, which yields 100 volts terminal voltage with four modules connected electrically in series, adequate to drive homopolar motors or inverters.

The generator load factor^{*} is 0.92, higher than previously used, because this results in a more compact generator with negligible effect on generator or cycle efficiency. At 0.92 load factor the parameters for each 26 MW generator are:

Length	= 6.793 ft.
Electrode spacing	= 1.404 ft.
Height	= 2.045 to 2.761 ft.
Magnetic flux density	= 2.083 tesla
Efficiency	= 0.781

At 0.90 load factor the length is 8.87 ft., the magnetic flux density is 1.63 tesla, and the efficiency is 0.783.

^{*} Load factor is the ratio of the generator terminal voltage to the internally-generated or open-circuit voltage.

2.3 System Performance

The performance and state points of the power system as designed are shown in Table II. The overall efficiency for this non-optimized design is 0.396. More power is extracted in the turbine than in the MHD generator because of the required large compressor and pump powers. The inlet void fraction of 0.73 was chosen at what is believed to be about the upper limit for mixer design, though further study of this is required. It is stressed, however, that the cycle efficiency is essentially independent of the inlet void fraction in the parameter range of interest. Note that for all cases the gas temperature at the turbine entrance is at least 200°F cooler than the reactor exit temperature, resulting in a simpler and more reliable turbine.

2.4 Comparison with Alternative Systems

Most previous MHD cycle studies have used a nozzle-diffuser system to return the liquid to the mixer, where the nozzle converts sufficient gas energy to liquid kinetic energy to recover the pressure lost in the generator. This eliminates the separate liquid pump, but may not be suitable here because of the possible larger physical size of the nozzle and diffuser, the required high liquid velocities, and the adverse effect on diffuser performance if virtually all of the gas is not removed from the liquid in the separation process. The performance for this case is shown in Table III. The liquid temperature at all points is about 90°R less because the extra 3°R mixture temperature drop across the nozzle (in addition to the 8°R drop across the generator for both cases) means that more heat is removed from the gas to heat the liquid in the mixer. The reduced liquid temperature causes the lower cycle efficiency. The diffuser requires an inlet liquid velocity of 495 ft/sec and is about 6 feet long to recover the mixer inlet pressure. Since the diffuser length is slightly less than the generator length, this may also yield a compact unit. More study on the separator-nozzle-diffuser system is required to see if adequate diffuser performance is attainable.

Table II. State Points and Power Flows for Design System, 0.73 to 0.8
Void Fraction

<u>Location (Exit)</u>	<u>T, °R</u>	<u>P, psia</u>		
Reactor	2160	1500		
Mixer	1955	1495		
MHD Generator	1947	1005		
Separator (Liquid)	1947	1005		
Separator (Gas)	1947	1005		
Liquid Pump	1948	1500		
Turbine	1408	401		
Regenerator (Hot Side)	855	381		
Reject Heat Exchanger	579	377		
Compressor	794	1548		
Regenerator (Cold Side)	1347	1538		
Mass Flow Rates (Each Module):	Gas	61.9 lbm/sec		
	Liquid	2190 lbm/sec		
Power (Each Module):	MHD Generator	24800	Btu/sec	
	Turbine	41700	Btu/sec	
	Compressor	33300	Btu/sec	
	Liquid Pump	8350	Btu/sec	
Heat Flows (Each Module):	Primary Heat Exchanger	62900	Btu/sec	
	Reject Heat Exchanger	21400	Btu/sec	
	Intercooler	16600	Btu/sec	
Efficiencies:	MHD Generator	0.781		
	Overall	0.396		

Table III. State Points and Power Flows for Nozzle-Diffuser System,
0.73 to 0.8 Void Fraction

<u>Location (Exit)</u>	<u>T, °R</u>	<u>P, psia</u>	
Reactor	2160	1500	
Mixer	1862	1495	
MHD Generator	1854	1005	
Separator (Liquid)	1851	843	
Separator (Gas)	1851	843	
Diffuser	1851	1500	
Turbine	1407	389	
Regenerator (Hot Side)	861	369	
Reject Heat Exchanger	579	365	
Compressor	800	1548	
Regenerator (Cold Side)	1346	1538	
Mass Flow Rates (Each Module):	Gas	65.0	lbm/sec
	Liquid	2220	lbm/sec
Power (Each Module):	MHD Generator	24800	Btu/sec
	Turbine	36100	Btu/sec
	Compressor	36000	Btu/sec
Heat Flows (Each Module):	Primary Heat Exchanger	65800	Btu/sec
	Reject Heat Exchanger	22900	Btu/sec
	Intercooler	18600	Btu/sec
Efficiencies:	MHD Generator	0.785	
	Overall	0.380	

A two-stage compressor was chosen for this design so as to obtain a basis for comparison with a similar gas turbine study.³ With a five-stage compressor, as in most previous MHD analyses, the cycle efficiency is increased to 0.440, the turbine and compressor powers are reduced by about 20%, and most of the heat rejection occurs in the intercoolers. The state points and powers for this case are given in Table IV. Within the accuracy of the computer program, the MHD generator and liquid loops are identical for the two-stage and five-stage compressors because the initial conditions and power outputs are the same. Only the reactor and gas components change.

If the reactor is designed to heat both the gas and liquid phases by means of a higher reactor gas flow rate and a heat exchanger between the liquid and a fraction of the gas, than a higher mixer temperature is attainable for the same reactor temperature. The result for a mixer temperature of 2060°R, Table V, is an efficiency of 0.426 with reduced turbine and compressor powers. If a nozzle-diffuser system is used, Table VI, the efficiency is 0.432, the flow rates and generator are the same as with the liquid pump, and the turbine is substantially smaller. The nozzle-diffuser system efficiency is higher in this case because the mixer temperature is fixed, not the gas temperature. A mixer temperature higher than 2060°R may require a multistage expansion to reduce the effects of lithium vapor carryover into the gas loop.

The maximum attainable inlet void fraction is limited by the ability to build a suitable mixer and the stability of the homogeneous two-phase flow in the generator. Changing the inlet void fraction, Tables VII, VIII, and IX, has negligible effect on the cycle efficiency. However, increasing it results in lower turbine and compressor powers, and a lower liquid flow rate. The overall system performance, however, is independent of the inlet void fraction, and the change in system weight is expected to be small.

Table IV. State Points and Power Flows with Five-Stage Compressor,
0.73 to 0.8 Void Fraction

<u>Location (Exit)</u>	<u>T, °R</u>	<u>P, psia</u>		
Reactor	2160	1500		
Mixer	1955	1495		
MHD Generator	1947	1005		
Separator (Liquid)	1947	1005		
Separator (Gas)	1947	1005		
Liquid Pump	1948	1500		
Turbine	1510	490		
Regenerator (Hot Side)	721	470		
Reject Heat Exchanger	518	460		
Compressor	633	1548		
Regenerator (Cold Side)	1422	1538		
Mass Flow Rates (Each Module):	Gas	61.4	lbm/sec	
	Liquid	2170	lbm/sec	
Power (Each Module):	MHD Generator	24600	Btu/sec	
	Turbine	33600	Btu/sec	
	Compressor	25000	Btu/sec	
	Liquid Pump	8280	Btu/sec	
Heat Flows (Each Module):	Primary Heat Exchanger	56600	Btu/sec	
	Reject Heat Exchanger	11700	Btu/sec	
	Intercooler	20000	Btu/sec	
Efficiencies:	MHD Generator	0.781		
	Overall	0.440		

Table V. State Points and Power Flows for 2060°R Mixer Temperature,
0.73 to 0.8 Void Fraction

<u>Location (Exit)</u>	<u>T, °R</u>	<u>P, psia</u>	
Reactor	---	1500	
Mixer	2060	1495	
MHD Generator	2052	1005	
Separator (Liquid)	2052	1005	
Separator (Gas)	2052	1005	
Liquid Pump	2053	1500	
Turbine	1557	460	
Regenerator (Hot Side)	847	440	
Reject Heat Exchanger	578	436	
Compressor	768	1548	
Regenerator (Cold Side)	1478	1538	
Mass Flow Rates (Each Module):	Gas	58.6	lbm/sec
	Liquid	2150	lbm/sec
Power (Each Module):	MHD Generator	24700	Btu/sec
	Turbine	36300	Btu/sec
	Compressor	27700	Btu/sec
	Liquid Pump	8320	Btu/sec
Heat Flows (Each Module):	Primary Heat Exchanger	58400	Btu/sec
	Reject Heat Exchanger	19600	Btu/sec
	Intercooler	13900	Btu/sec
Efficiencies:	MHD Generator	0.778	
	Overall	0.426	

Table VI. State Points and Power Flows for Nozzle-Diffuser System at 2060°R
Mixer Temperature, 0.73 to 0.8 Void Fraction

<u>Location (Exit)</u>	<u>T, °R</u>	<u>P, psia</u>	
Reactor	---	1500	
Mixer	2060	1495	
MHD Generator	2052	1005	
Separator (Liquid)	2048	845	
Separator (Gas)	2048	845	
Diffuser	2049	1500	
Turbine	1696	498	
Regenerator (Hot Side)	848	478	
Reject Heat Exchanger	578	474	
Compressor	754	1548	
Regenerator (Cold Side)	1602	1538	
Mass Flow Rates (Each Module):	Gas	58.6	lbm/sec
	Liquid	2150	lbm/sec
Power (Each Module):	MHD Generator	24700	Btu/sec
	Turbine	25800	Btu/sec
	Compressor	25800	Btu/sec
Heat Flows (Each Module):	Primary Heat Exchanger	57400	Btu/sec
	Reject Heat Exchanger	19800	Btu/sec
	Intercooler	12900	Btu/sec
Efficiencies:	MHD Generator	0.779	
	Overall	0.432	

Table VII. State Points and Power Flows for 0.65 to 0.72 Void Fraction

<u>Location (Exit)</u>	<u>T, °R</u>	<u>P, psia</u>	
Reactor	2159	1500	
Mixer	1998	1495	
MHD Generator	1994	1075	
Separator (Liquid)	1994	1075	
Separator (Gas)	1994	1075	
Liquid Pump	1994	1500	
Turbine	1477	460	
Regenerator (Hot Side)	838	440	
Reject Heat Exchanger	578	436	
Compressor	767	1548	
Regenerator (Cold Side)	1406	1538	
Mass Flow Rates (Each Module):	Gas	65.5	lbm/sec
	Liquid	3430	lbm/sec
Power (Each Module):	MHD Generator	24900	Btu/sec
	Turbine	42300	Btu/sec
	Compressor	31000	Btu/sec
	Liquid Pump	11300	Btu/sec
Heat Flows (Each Module):	Primary Heat Exchanger	61700	Btu/sec
	Reject Heat Exchanger	21300	Btu/sec
	Intercooler	15500	Btu/sec
Efficiencies:	MHD Generator	0.764	
	Overall	0.403	

Table VIII. State Points and Power Flows for 0.7 to 0.77 Void Fraction

<u>Location (Exit)</u>	<u>T, °R</u>	<u>P, psia</u>
Reactor	2161	1500
Mixer	1975	1495
MHD Generator	1969	1035
Separator (Liquid)	1969	1035
Separator (Gas)	1969	1035
Liquid Pump	1969	1500
Turbine	1447	433
Regenerator (Hot Side)	846	413
Reject Heat Exchanger	578	409
Compressor	779	1548
Regenerator (Cold Side)	1380	1538
Mass Flow Rates (Each Module):	Gas	63.5 lbm/sec
	Liquid	2620 lbm/sec
Power (Each Module):	MHD Generator	24700 Btu/sec
	Turbine	41400 Btu/sec
	Compressor	31800 Btu/sec
	Liquid Pump	9420 Btu/sec
Heat Flows (Each Module):	Primary Heat Exchanger	62000 Btu/sec
	Reject Heat Exchanger	21200 Btu/sec
	Intercooler	15900 Btu/sec
Efficiencies:	MHD Generator	0.774
	Overall	0.401

Table IX. State Points and Power Flows for 0.8 to 0.85 Void Fraction

<u>Location (Exit)</u>	<u>T, °R</u>	<u>P, psia</u>	
Reactor	2161	1500	
Mixer	1970	1495	
MHD Generator	1960	1045	
Separator (Liquid)	1960	1045	
Separator (Gas)	1960	1045	
Liquid Pump	1960	1500	
Turbine	1601	592	
Regenerator (Hot Side)	809	572	
Reject Heat Exchanger	575	568	
Compressor	721	1548	
Regenerator (Cold Side)	1513	1538	
Mass Flow Rates (Each Module):	Gas	73.8	lbm/sec
	Liquid	1775	lbm/sec
Power (Each Module):	MHD Generator	24800	Btu/sec
	Turbine	33100	Btu/sec
	Compressor	26800	Btu/sec
	Liquid Pump	6230	Btu/sec
Heat Flows (Each Module):	Primary Heat Exchanger	59800	Btu/sec
	Reject Heat Exchanger	21500	Btu/sec
	Intercooler	13400	Btu/sec
Efficiencies:	MHD Generator	0.790	
	Overall	0.416	

Small changes in system performance will result from slight differences in the component performances, but will not affect the basic system or conclusions. The performances chosen, Table I, are generally on the conservative side. For example, including a pressure drop across the separator decreases the efficiency only slightly. The reject heat exchanger is quite conservative, and an exit temperature lower than 24°F above ambient is probably easily attainable.

III. CONCEPTUAL DESIGN OF POWER PLANT

3.1 Introduction

A primary objective in the design of power plants for marine propulsion is the minimization of component weights and volumes. For a given power output, a decrease in power plant weight may be reflected by an increase in vessel speed and maneuverability, while a reduction in power plant volume affords greater freedom in hull design. Since component sizes and weights are directly related to cycle efficiency, the more efficient the power plant, the more attractive it tends to become for marine service. The replacement of the rotating generator in a gas-turbine Brayton Cycle by a two-phase MHD generator is shown to increase the overall plant efficiency, and this contributes substantially to weight and volume reductions.

The advances in high-temperature materials technology, such as the use of ceramics as a structural supplement, have made the concept of a high-temperature, high-power-density, helium gas cooled reactor (HGCR) feasible. Several studies of this concept and its adaptability to a marine power plant have been made. For this study two primary references have been used: "Westinghouse SES Application"³ for the turbine package, and "Technical Presentation of Energy Sources and Convertors"⁴ for the reactor and biological shield.

This power plant design, as in Reference 3, is for a surface ship power plant coupled to an HGCR with a net power output of 140,000 hp. The systems differ in their treatment of the biological shield, the reactor pressure vessel, the arrangement of components, and the substitution of an MHD system for a superconducting rotating generator. Since the MHD system is comparable in weight and

volume to the rotating generator³, the significant difference lies in the efficiency increase from 0.35 for the conventional system to 0.40 for the MHD system. If both studies utilized the same criteria for design and selection of common components, then the MHD arrangement should be lighter.

The efficiency difference of 0.05 corresponds to a 262 Mwt reactor instead of a 300 Mwt reactor for the same useful power. This reactor power difference translates into a decrease of approximately 4% in reactor diameter with a proportional decrease in shield weight and volume. This in itself could amount to a weight saving of over 20,000 lbs. Further weight reduction may be realized because in a conventional gas turbine cycle the hot gas from the reactor is introduced directly into the turbo-generator, while in the MHD system the hot gas first flows through the MHD generator and then enters the turbine. Thus the turbine inlet temperature is about 200°F cooler than the reactor exit temperature, the turbine material demands are reduced, and the weight will vary accordingly.

The turbines will also be smaller here as they are required only to drive the lithium pump and gas compressors. The turbo-compressor design is not optimized, but rather patterned after Reference 3 with the exceptions of vertical installation, top and bottom housing outlets rather than side outlets, and the elimination of the reduction gear. Vertical installation allows straight-through removal for repair purposes, eases alignment requirements, and could reduce the support weights as compared to horizontal installation. Top and bottom helium ducts also simplify unit removal as the top duct is readily accessible and the

bottom duct could be designed with a self-guiding sliding seal. The reduction gear is not required because there is no rotating generator.

Helium as a reactor coolant offers the advantages of being compatible with structural materials at high temperatures, light in weight, and chemically inert. Helium, because of its low heat transfer coefficient, will not produce high thermal stresses in plant components when the power is quickly varied, thus allowing a wide range of efficient operation.⁵ Helium also reduces the possibility of radioactivity in the plant machinery, and so precludes the need for a secondary heat exchanger.

3.2 Layout

The power plant is arranged in a manner that allows ready accessibility to all components for their removal and repair. The reactor is contained in a prestressed concrete vessel which also serves as the biological shield. Four identical power modules are installed vertically in the biological shield, Figs. 2 and 3. The use of four modules provides redundancy for partial power in the event of a module failure, and the units are small enough to be easily manageable for repair or replacement. The entire power plant is contained within a cylindrical volume 30 feet in diameter by 32 1/2 feet high capped with a steel dome over the reactor area to protect the reactor control machinery. Auxiliary equipment such as the magnet refrigerators, cooling pumps, and gas storage tanks is located between the power modules but outside of the shield, as shown in Figs. 2 and 3. The helium accumulators, the tanks for emergency core cooling, and the lithium storage tanks are in a room under the reactor, Fig. 3.

Each power module consists of an MHD subsystem, turbo-compressors, and heat exchangers, Fig. 4. Although not indicated in Fig. 4, the

Fig. 2. Power Plant Plan

Fig. 3. Power Plant Elevation

Fig. 4. MHD-HGCR Power Module

MHD subsystem is completely enclosed by a secondary housing to contain possible lithium leaks. The turbines, compressors, and heat exchangers are located in a common vessel to yield an extremely compact design that eliminates the need for individual heat exchanger shells with their associated weights and volumes. This configuration is possible because the internal thermal insulation used to isolate the various heat exchangers is not affected by the inert helium.

Helium enters at the top of the reactor but is baffled to keep the pressure vessel liner at the lower temperature of the incoming helium. The HGCR is 11 feet high and 5-1/2 feet in diameter with the core size reduced by the use of a reflector and thermal shield combination instead of a conventional blanket and moderator. The helium exits from the bottom of the reactor and then is ducted to the MHD mixer. There the helium is mixed with the lithium and the resulting homogeneous two-phase mixture expands at constant velocity through a generator duct positioned in the field of a 2.08 tesla superconducting magnet. The mixture is then separated in a combination separator-pump which returns the lithium to the mixer and expels the helium directly to the turbine. The gas turbine provides the power for the two compression stages and the separator-pump. The helium exiting from the turbine is directed through a regenerator where this helium preheats the helium from the high-pressure compressor before the latter exits at the top side of the turbo-compressor package for return to the reactor. The water-cooled reject and intercooler heat exchangers are also located in the turbo-compressor package.

Each MHD unit produces 26.05 Mw at 25 volts and 1,042,000 amps. The four units are electrically connected in series with the buss bars located on the periphery of the biological shield. The 100 volt supply is then connected to the propulsion motors.

3.3 MHD System

The MHD system consists of four primary components; mixer, generator duct, superconducting magnet, and combination separator-lithium pump. The latter component both separates the lithium and helium fractions of the two-phase mixture and imparts sufficient energy to the liquid to return it to the mixer, yielding a very compact arrangement. The entire MHD assembly for generating 35,000 hp is about 12 ft. high and 6 ft. in diameter. There are no heat exchangers in the MHD system because the helium is conditioned in the turbo-compressor package and the lithium is returned directly to the mixer where it is heated by the helium.

3.3.1 Mixer

The mixer is similar to injectors designed for rocket engines. The helium enters the mixer plenum from which a perpendicular array of tubes permits the gas to impinge upon the lithium. A series of lithium downcomers from the separator-pump supply a circular manifold integral with the mixer. The manifold feeds numerous cross tubes which in turn carry lithium to a series of holes angled so that the lithium flow intercepts the helium gas. A homogenous two-phase flow is formed about one foot before the generator duct inlet.

The mixer is brazed directly to the generator duct housing. To minimize losses due to circulating currents, it is proposed to flame spray the refractory-metal mixer over its entire surface with an electrical insulator such as Al_2O_3 . A thin coating of tungsten or molybdenum would then be applied over the insulator for protection and to serve as a brazing surface at the cost of a high-resistance electrical path.

3.3.2 Generator Duct

The generator duct is rectangular in cross section with the distance between electrodes remaining constant while the flow area increases to maintain a given two-phase velocity. The duct is 6.8 feet long, the distance between electrodes is 1.4 feet, and the width increases from 2.04 feet at the generator inlet to 2.76 feet at the outlet.

Previous designs for the generator duct have been visualized as thin metal cans that are integral on two sides with the electrodes with the remaining sides electrically insulated from the containment pressure housing. Ideally the electrodes should be separated by an electrical insulator to prevent shorting and added ohmic losses. Since at present there are no known insulators compatible with high-temperature lithium, thin metal walls are required to minimize shorting. The structural housing required to contain the pressure in the duct while maintaining electrical isolation of the electrodes can evolve into a rather complex design. Thus a new approach has been proposed in this study - generator duct containment by the use of pyrolitic graphite.

Pyrolitic graphite is an excellent structural material for high temperature service, actually increasing in mechanical strength with temperature up to 4500°F. It exhibits a high resistance to thermal shock and can be manufactured with distinct anisotropic physical properties which make it attractive for MHD duct design. In one plane the electrical conductivity approaches that of aluminum while the thermal conductivity is near that of copper. In the other plane it behaves both electrically and thermally as a ceramic. Another interesting feature is that it is readily alloyed with refractory metals, ceramics, or other materials; yielding versatility in the control of its anisotropic properties and strength.

The geometry of the generator duct could be machined into a cylindrical block of pyrolytic graphite with the conducting plane parallel to the direction of the generated current, Fig. 5. Normal to this plane the graphite is an insulator. Graphite is not compatible with lithium so that a layer of tungsten or molybdenum must be flame sprayed on the duct surface and the ends of the housing. The mixer and separator-pump units can then be brazed to the generator housing for leak-proof seals. The graphite provides an integral housing and the desired electrical properties but is not strong enough to withstand the high pressures involved without structural backup. This backup is provided by the buss bars formed into flanged half rings extending the length of the generator and electrically insulated from the graphite except in the current-carrying areas, Fig. 5. The two buss bars with an insulating interface are bolted together to provide the necessary structure and also act as compensation for the induced currents generated in the lithium.

3.3.3 Separator-Lithium Pump

As the name suggests, the separator-pump has a two-fold purpose - separating the lithium from the helium and imparting velocity to the lithium for subsequent conversion to pressure head. The two-phase mixture after exiting the generator duct is tangentially directed onto the inner surface of a high-speed rotating cylinder (rotor), and there separation occurs due to the density difference of the two fluids. The lithium is forced against the rotor walls while the helium is concentrated at the center of the rotor. The lithium, being spun at high velocity, is then collected off the rotor walls by stationary diffuser vanes which communicate with the collector manifold. Downcomers from the manifold return the lithium to the mixer.

Figure 5. MHD Generator Layout

The rotor is directly connected to the turbine shaft. The shaft is hollow in the bearing support area and is designed with tangentially-drilled holes which act as pump impellers and allow the gas to exit from the separator-pump to the turbine. The helium pumping by the hollow shaft also acts as a secondary separator, where the centrifugal action imparted to the gas drives any lithium still mixed with the gas to the walls of the intermediate housing located between the separator-pump and the turbine casing. The lithium accumulating in the intermediate housing is returned to a low-pressure area.

The use of a mechanical separator-pump is lieu of a flat plate separator and nozzle-diffuser combination offers several advantages. Separation should be more complete since disassociation of the two fluids is "forced" by the centrifugal action rather than relying on a single directional change. Also, the deleterious effect of gas carryover on diffuser efficiency is not a problem. The proposed pump is superior to an electromagnetic pump in that erratic pumping power because of gas inclusion is not possible, and the magnet and its associated subsystems are not required.

3.4 Prestressed Concrete Pressure Vessel and Biological Shield

The gamma radiation will be attenuated by 3-1/2 inches of lead and boron carbide. Suggested neutron shielding materials include H_2O , B_4C , LH, Zirconia, B + C, and borated concrete. The required volumes of the various neutron shield materials are comparable but their densities vary. Concrete is about 40% heavier than the average of the other materials. Thus, at first glance concrete would seem to be a poor choice. However, when containment or structural reinforcement of the other shielding compounds are considered for total weight, concrete actually appears to be lighter. More important, some designers question the wisdom of

using steel pressure vessels for the temperatures and pressures associated with the high-power-density HCCR's.⁶ Prestressed concrete pressure vessels have been suggested as an alternative.

The use of concrete as a biological shield and pressure vessel for shipboard service will depend on the postulated design parameters. Since the use of concrete pressure vessels is relatively new, especially in this country, there are no "recipe" formulas for their design capabilities and each vessel requires an extensive, complex structural analysis unique to its own geometry. Pressurized concrete vessels are now being designed to withstand 300 atmospheres, and their use is being contemplated in Europe as backup blast suppressors for steel nuclear vessels.

The required biological shield thickness is about 6 feet, but the pressure vessel thickness could be less. This suggests that the shield might be a series of concentric prestressed concrete vessels separated by an energy-absorbing media that could withstand large dynamic forces such as those that might be encountered in vessel collisions.

3.5 Estimated Weights and Volumes

Previous ANL studies for the Office of Naval Research on two-phase liquid metal MHD power plants have provided a base for systems cycle analyses and plant design considerations. Conceptual designs were prepared for possible plant arrangements complete with weights and volumes of the propulsion plants.² The proposed schemes were primarily for 30,000 hp submersibles with a sodium-cooled reactor as the heat source. Reactor and shielding weights were not considered, but the estimated weights of cryogenic propulsion motors were included. The resultant power densities, as expressed in pounds per ship horsepower, varied from 56.6 lbs/SHP for a sodium-argon system at 1100°F and 1125 psi to 25.6 lbs/SHP for a tin-steam system at 635°F and 2000 psi, as summarized in Section I.

For the 140,000 hp surface vessel rather dramatic reductions in estimated weight are achieved, as shown in Table X. The intimate location of the power modules with the reactor and its shielding results in a lighter system but does not allow compartmentalized separation of the energy conversion components from the reactor system as in the other studies. For weight comparison purposes, if the weight of the HGCR and its controls plus the weight of the shielding are excluded, the resultant engine-room power density for the gas-turbine-MHD cycle is 5.47 lbs/SHP, an order of magnitude less than for the sodium-argon concept. The overall weight of the HGCR, shielding, and energy conversion machinery is 1,775,000 lbs or 12.67 lbs/SHP. For the sodium-argon concept the engine room alone, which was rated at only 30,000 hp, weighed the same as the entire power plant for the 140,000 hp HGCR proposal. The volume of the system is estimated at 25,500 cubic feet.

The weight reduction can be attributed to several factors: 1) the smaller MHD generator and the elimination of a separate electric drive motor since the compressors are driven by the turbine, 2) the low specific weight of the turbo-compressors, 3) the compact heat exchanger arrangement with all heat exchangers located in a common shell, 4) the small inventory of liquid metal and the low density of the helium, 5) exceptionally short piping runs, and 6) increased overall cycle efficiency.

IV. CONCLUSIONS

A two-phase MHD-gas turbine system combined with a HGCR heat source appears to be an attractive power system for surface ship applications. The system efficiency is projected to be higher than for the conventional gas turbine Brayton cycle. The effect of the increased efficiency on component sizes plus the reduced turbine operating temperature indicate that reduced weight and volume may be attained with the MHD system. The resulting weight and volume are very attractive, even though optimization studies have yet to be made. Further system improvements may be attainable with a liquid-cooled reactor or a separate gas-to-liquid heat exchanger, and the use of a nozzle-diffuser system in place of a liquid pump. However, further separator and diffuser studies are needed for the latter system.

Table X. MHD-HGCR 140,000 hp Power Plant Weights and Power Densities

REACTOR	Weight lbs x 10 ³	Power Density lbs/SHP
Reactor (HGCR)	47	0.34
Biological Shield	864	6.17
Containment & Structures	30	0.21
Emergency Cooldown	5	0.04
Control Gas Storage	62	0.44
Sub-Total	1008	7.20
ENERGY CONVERSION		
Turbine-Hx-Compressor Power Module	260	1.85
MHD-Gen.-Separator-Mixer	35	0.25
Superconducting MHD Magnets	56	0.40
Magnet Refrigeration & Cryogenics	20	0.14
Lithium Inventory	10	0.07
Helium Inventory	1	---
Cooling Water System	50	0.36
Pipe & Supports	18	0.13
Lithium Storage System	24	0.17
Power Transmission	173	1.23
Miscellaneous	30	0.21
Sub-Total	677	4.83
200 RPM Superconducting Motors & Refrigeration	90	0.64
TOTAL	1775	12.67

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