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THE PROSPECTS FOR NUCLEAR REACTOR - MHD

COMMERCIAL POWER PRODUCTION*

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IN NUCLEAR SCIENCE ABSTRACTS

ABSTRACT

Cycle analysis and preliminary plant component designs are made for prospective nuclear reactor - MHD commercial power plants, and the problems of development of the plant components are discussed. The concept of commercial MHD power production is compared with other nuclear reactor power plants, and recommendations as to the feasibility of the MHD concept are made. The results of the study, conducted by an ad hoc committee of staff members at the Los Alamos Scientific Laboratory, indicate that nuclear reactor - MHD power production is infeasible for the foreseeable future. The development of the major components for prospective plants is too extensive with the present undefined criteria, and, more importantly, at this time the apparent failure to gain a reduction in total power costs will not allow the nuclear MHD plant to compete with more conventional nuclear powered plants.

INTRODUCTION

The recent developments in the technologies of high temperature gas-cooled nuclear reactors and thermal equilibrium ionization magnetohydrodynamic (MHD) generators has prompted interest in the possibilities of their combina-

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tion for commercial power production. The extraction of energy from a gas stream in a Brayton cycle by an MHD device at temperatures greater than 3600°R offers the advantage of higher thermodynamic efficiency than present day fossil or fissile fueled power plants, and nuclear reactors appear to be the only thermal energy source capable of producing gas at this temperature in the foreseeable future.

Since the reactor application in this study requires long core lifetimes (>10,000 hours), the coolant must be an inert gas to avoid corrosive deterioration. There are no theoretical problems in using an inert gas as the working fluid for the MHD generator, but programmatic development of MHD generators to date has been accomplished only with combustion product gases as the working fluid. Since the commercially available inert gases, helium and argon, provide approximately the same generator performance, the choice of working fluid can be dependent on considerations of the reactor design. Helium is therefore used because its thermal conductivity is higher than that of argon. Since helium does not ionize sufficiently at the temperatures of interest, a material with a low ionization potential such as cesium must be added to the gas stream to provide sufficient electrical conductivity. The type generator selected for this study is a segmented electrode, Faraday generator with constant velocity, subsonic flow.

For proposed plant designs, two basic cycles are considered: the MHD topping-steam cycle, and the regenerative cycle. A variation of the regenerative cycle using "boot-strap" turbine-compressors for gas circulation is also considered. Preliminary design of the reactor and other loop components such as heat exchangers and compressors is presented

to establish credence to the loop temperatures and pressure drops, which affect the overall plant efficiency. The economics, ie., detailed capital costs, fuel costs, and other operating costs are beyond the scope of this study, but estimates are made of the relations of these costs to those of plants which either exist or are in the planning stage.

RELATION OF NUCLEAR REACTOR AND MHD GENERATOR

Since the cycle efficiencies are increased as the exit gas temperature of the energy source is increased, the reactor fuel and core materials should be selected for their capability to withstand the highest possible temperature for periods of about 10,000 hours. For the foreseeable future, there are only two types of reactors that could be used for this application; a graphite moderated, clad uranium carbide fuel reactor and a refractory metal clad refractory fuel matrix reactor.

The maximum fuel temperature of the graphite reactor is limited to about 4300°R by the vaporization (sublimation) of graphite.¹ Fuel particles of uranium carbide must be clad at this temperature since uranium will diffuse rapidly through a graphite matrix at temperatures greater than 3600°R. Recent developments in coating uranium carbide particles with pyrolytic graphite have shown promise for containment of uranium at temperatures up to 4300°R for lengthy periods. Other than uranium migration, problems involved in graphite systems are: (1) the probable escape of fission products into the gas stream, (2) the necessity of extremely low levels of oxidizing impurities (~1 ppm) to prevent excessive graphite corrosion, and (3) the possibility of formation of cesium-graphite compounds which would deteriorate the graphite structure.

The maximum temperature of the refractory metal system is more difficult to predict, but will certainly be higher than that of the graphite system. Current programs have demonstrated compatibility of tungsten, molybdenum, and their alloys with uranium oxide at temperatures in excess of 4500°R. Although lifetimes greater than 1000 hours and irradiation performance have not been accomplished at these temperatures, the results from work to date in the General Electric 710 program indicate no difficulties will be encountered in obtaining this performance and even longer lifetimes. The likely prospects for cladding material for the fuel matrix are molybdenum, molybdenum alloys, tantalum-tungsten alloys, tungsten, tungsten-rhenium alloys, and tungsten-rhenium-molybdenum alloys. The molybdenum, molybdenum alloys, and tantalum alloys have been demonstrated as a cladding for the fuel material, and the tungsten alloys, which are currently under development, appear to be even more desirable because of their higher strengths at temperatures up to 5000°R. The problems to be solved for the refractory metal system are: (1) the possibility of the formation of free uranium in the fuel matrix which will penetrate the cladding intergranularly, (2) the extent of the reaction of the refractory metals with oxidizing impurities which would require an extremely low level of these impurities (~1 ppm) in the gas stream, (3) the selection of the material for and the mechanical design of a support for a core made of these high density fuel elements at these very high temperatures, and (4) the development of a fuel element fabrication process which, when included in fuel cycle costs, may become competitive with contemporary power reactor fuel cycle costs.²

The principle consideration for the reactor designs is the economy of the fuel cycle. The present practice in selecting a fuel cycle is to include a fertile material which will undergo neutron capture and decay to a fissile material. Such fertile materials are thorium-232 and uranium-238 which are converted to fissile uranium-233 or plutonium-239 respectively. The thorium cycle occurs more readily in the thermal neutron spectrum, and the power density must be relatively low ($\leq 15 \text{ Kw/l}$) to prevent neutron capture by the intermediate decay product, protoactinium-233. Both of these requirements are satisfied easily in a graphite moderated reactor. The $\text{U}^{238} \rightarrow \text{Pu}^{239}$ reaction occurs more readily in a fast spectrum, which is necessary in a refractory metal reactor because of the high absorption cross section of all the refractory metals. Therefore, a refractory metal reactor must have a higher power density ($>100 \text{ Kw/l}$). Although less information is available at these temperatures about plutonium breeding than thorium conversion, the plutonium cycle is theoretically more desirable since breeding ratios (amount of fuel produced to amount of fuel burned) can approach 2.0, whereas it has been difficult to achieve a breeding ratio greater than 1.0 for the thorium cycle.³

Upon reflection on the above information, the inlet gas (stagnation) temperature to the MHD channel is chosen to be 4050°R for the graphite system and 4500°R for the refractory metal system. The other important variable effecting proposed plant designs and the overall efficiency determinations is the system pressure, which is dictated by the MHD generator performance. The determination of this pressure presents an anomaly which has a significant effect on the feasibility of the MHD closed Brayton

cycle concept. With the duct operating at a constant velocity, the generator length is given by:

$$L_g = \frac{KP_o \Delta T_g}{\sigma u B^2} \quad (1)$$

and σ is proportional to $P_o^{-1/2}$.⁴ Therefore, the length of the generator is increased with increasing pressure, and since the flow area decreases with increasing pressure, the length to diameter ratio (L_g/D_g) is further increased. Since the wall heat and friction (flow) losses are proportional to L_g/D_g , the "MHD turbine efficiency" must decrease with increasing pressure. On the other hand, the other plant components, i.e. heat exchangers, nuclear reactor, compressors, etc., can be smaller and will have less heat and friction losses at higher pressures.

In considering other parameters of equation (1) to minimize the generator length, the Magnetic field (B) and the product of conductivity (σ) and gas velocity (u) should be at a maximum. For subsonic flow of helium with 0.5 mole percent cesium, σu is a maximum at a mach number of about 0.5.⁴ For high field strength magnets with a minimum of ohmic heating losses, superconducting magnets are being developed rapidly. Superconducting magnets with field strengths of 45,000 gauss and bore sizes approximately one meter in diameter are being constructed, and present technology can be extrapolated to larger magnets at 70,000 gauss.

The remaining parameter for consideration is the stagnation temperature drop represented by the enthalpy change through the duct. This temperature difference is limited by the decrease in conductivity to insignificant levels below 3600°R, although some non-equilibrium affects may be derived in the range of 3600 to 3300°R by ion recombination (provided the gas

stream is "ionized" prior to decreasing in temperature to this range).⁴

Although no attempt has been made to "optimize" the MHD duct and system pressures with respect to overall efficiencies, calculations have been made by R. J. Rosa to determine MHD turbine efficiencies for the operating conditions of the two reactor types.⁵ The MHD duct operating parameters which were chosen from the results of Rosa's calculations for the cycle studies and preliminary plant component design are presented in Table I.

TABLE I
MHD GENERATOR CONDITIONS FOR CYCLE STUDIES

	<u>Graphite System</u>	<u>Refractory Metal System</u>
Inlet Temperature (°R)	4050	4500
Outlet Temperature (°R)	3290	3290
Inlet Pressure (psia)	117.6	294.0
Outlet Pressure (psia)	59.8	117.9
Inlet Diameter (ft)	5.00	3.20
Outlet Diameter (ft)	6.65	4.80
Length (ft)	51.3	182.0
Magnetic Field (webers/meter ²)	4.5	7.0
Turbine Efficiency (%)	75.0	85.0

For the graphite system, a flow rate of 1057 lb/sec of helium is required to withdraw 1000 MW of energy from the gas in the conversion to DC electricity. To compare the plant component designs, the same flow rate is used for the refractory metal system giving a net DC output of 1628 MW. In both systems, a 40°R temperature drop through the duct is assumed to allow for a wall loss of 50 MW.

THERMODYNAMICS

Calculations of overall efficiency (ratio of net electrical output to reactor thermal power) have been made for three types of cycles for each of the two reactor types: (1) an MHD-topping, steam cycle; (2) a pure

regenerative cycle with motor-driven compressors to circulate the gas; and (3) a regenerative cycle with "boot-strap" turbine-compressors for gas circulation. Schematics of each of these cycles is shown respectively in Figures 1, 2, and 3. The relations for the overall efficiencies for each of the cycles are:

$$\eta_{os} = \frac{\eta_i \eta_d T_o [1 - R_D^{\gamma-1/\gamma}] + \eta_s \Delta T_s - \frac{N_c T_c}{\eta_{cm} \eta_c} \left[R_c^{\gamma-1/N_c \gamma} - 1 \right]}{\eta_R (\Delta T_T + \Delta T_R + \Delta T_S) + (1 - \eta_R) \left\{ T_o - T_c \left[1 + \frac{1}{\eta_c} (R_c^{\gamma-1/N_c \gamma} - 1) \right] \right\}} \quad (2)$$

$$\eta_{or} = \frac{\eta_i \eta_d T_o [1 - R_D^{\gamma-1/\gamma}] - \frac{N_c T_c}{\eta_{cm} \eta_c} \left[R_c^{\gamma-1/N_c \gamma} - 1 \right]}{\eta_R (\Delta T_T + \Delta T_R) + (1 - \eta_R) \left\{ T_o - T_c \left[1 + \frac{1}{\eta_c} (R_c^{\gamma-1/N_c \gamma} - 1) \right] \right\}} \quad (3)$$

$$\eta_{ot} = \frac{\eta_i \eta_d T_o [1 - R_D^{\gamma-1/\gamma}]}{\eta_R (\Delta T_T + \Delta T_R + T_t (1 - R_t^{\gamma-1/\gamma})) + (1 - \eta_R) \left\{ T_o - T_c \left[1 + \frac{1}{\eta_c} (R_{ct}^{\gamma-1/N_c \gamma} - 1) \right] \right\}} \quad (4)$$

$$\text{where } R_c = \frac{1 + (\Delta P/P_o)_h + (N_c - 1) \Delta P_{ic}/P_o}{R_D - (\Delta P/P_o)_l} \quad \text{and } R_{ct} = \frac{1 + (\Delta P/P_o)_h + (N_c - 1) \Delta P_{ic}/P_o}{R_D - (\Delta P/P_o)_l - (\Delta P/P_o)_t}$$

The loop parameters that have the most significant effect on the overall efficiency (η_o) are compressor inlet temperature (T_c), MHD duct inlet temperature (T_o), recuperator temperature difference (ΔT_R), and total friction pressure loss (ΔP). The curves showing the effects of T_c and T_o

on η_o (Figure 4) indicate that a 100° change in T_c changes η_o by $2\frac{1}{2}\%$ whereas a 100° change in T_o changes η_o by $1\frac{1}{2}\%$. These results were calculated for the pure regenerative refractory metal system with the MHD duct, compressor, and recuperator efficiencies equal to one, an MHD duct temperature drop of 720°F , a recuperator temperature difference of 200°F , one compressor to circulate the helium, and no loop friction loss. The curves showing the effects of ΔT_R and ΔP on η_o (Figure 5) indicate that a 10% change in the ratio of ΔT_R to the temperature drop in the recuperator hot side changes η_o by 9% whereas a 10% change in the ratio of friction loss to inlet duct pressure ($\Delta P/P$) changes η_o by 2%. These results were calculated for the same system and conditions as Figure 4 with $T_c = 100^\circ\text{F}$ and $T_o = 4040^\circ\text{F}$. The parameter that has the greatest effect on η_o then is the recuperator temperature difference.

The comparative results of the calculations for the graphite system are shown also in Figures 1, 2, and 3 respectively for the topping, pure regenerative, and turbine-compressor cycles. The results indicated little difference between the overall efficiencies of the three cycles and that of the topping cycle is about one percentage point less than the others. The parameters for the steam plant are taken from those presented in the Target⁶ study, a proposal for a 1000 MW(e) gas-cooled reactor plant. Although the addition of the steam cycle lowers the overall efficiency, the decrease does not become significant until the ratio of steam power to total power becomes greater than .5. This effect is shown in Figure 6.

The results of the calculations for the regenerative refractory metal reactor cycle are presented in Figure 7. The comparative overall efficiency of the topping cycle with the refractory metal reactor was 52.5%, significantly lower than that of the regenerative cycle. The calculation for the corresponding turbine-compressor cycle could not be made since there is insufficient available energy at the turbine inlet (at 1600°F) to "boot-strap" the compressors.

For the studies of graphite systems, the recuperator temperature difference is assumed to be 100°R, since the geometry of the recuperators becomes unreasonable at ΔT_R less than this value. For the refractory metal system a ΔT_R of 200°R is used.

PLANT COMPONENT DESIGN

Reactor

The requirements for the forementioned fuel cycles are compatible with the thermal and flow characteristics of the respective reactor designs. The graphite reactor must be larger than the refractory metal reactor because in the graphite system a lower pressure is required for the corresponding MHD duct. The reactor thermal and flow calculations were made using a computer code for nuclear rocket reactor calculations.⁷ This code calculates the maximum fuel channel surface temperature and flow rate for a single channel model for given values of channel length and diameter, inlet and outlet stagnation pressures, and inlet and outlet stagnation temperatures. For the calculation, the channel is divided into axial increments with a one dimensional solution of Poisson's equation for conduction in the solid and a solution of the energy, momentum, and continuity equations in the fluid stream for each increment. The assumptions

for the calculations are: (1) no axial conduction, (2) heat transfer coefficients calculated by the Dittus-Boelter equation,⁸ (3) friction factors from empirical correlation of nuclear rocket reactor fuel element experiments,⁹ (4) a sudden contraction and expansion respectively at the inlet and outlet of the channel, and (5) a cosine power distribution axially. Assuming a uniform flow distribution among the fuel channels, the total number of flow channels and flow area is determined from the given total flow rate. The results of calculations and significant design parameters are presented in Table II.

TABLE II
DESIGN OF REACTORS FOR MHD CYCLES

Fixed Parameters:	Graphite	Refractory Metal
Power density (kw/l)	15	150
Total mass flow (lb/sec)	1057	1057
Temperature increase in gas (°R)	2050	1335
Arbitrary Parameters:		
Total pressure drop (psi)	5	25
Channel length (ft)	15	4
Channel diameter (in)	0.7	0.25
Resulting Parameters:		
No. of channels	1.47(10) ⁴	2.15(10) ⁵
Core diameter (ft)	27	13
Max. fuel channel surface temperature (°R)	4250	4650

Heat Exchangers

The principle goal in the design of the heat exchangers is a minimum recuperator temperature difference and friction pressure loss. For a flow rate of 1057 lb/sec, the relations describing these variables are:

Tube side:

$$\Delta T = .00985 \frac{L}{D_i} \Delta T_R \quad (5)$$

Shell side:

$$\Delta T = 1.397(10)^{-4} N_x D_o^{-5} N_t T_g^{-.375} \Delta T_R \quad (7)$$

Tube side(cont):

$$\Delta P = .803 \frac{L T^{1.2}}{D_i^{4.75} N_t^{1.75} P_g} \quad (6)$$

Shell side(cont):

$$\Delta P = 1.09 \frac{N_x^{3.5} T^{1.2}}{D_o^{1.25} L^{2.5} P_g} \quad (8)$$

Equation (5) is a simplification of the heat transfer relationship using the Dittus-Boelter correlation⁸ for heat transfer coefficient at a Reynolds Number of 8000. Equation (6) is the expression for the tube side friction loss using the Blasius correlation¹⁰ for friction factor. In Equations (7) and (8), the heat transfer coefficient and friction factor are derived from empirical data from Baldwin-Lima-Hamilton.¹¹ The heat exchanger geometry must then be chosen to satisfy these equations for the desired temperatures and pressures. Since the velocity at the MHD duct outlet must be reduced in a diffuser to minimize friction losses at the recuperator inlet, the practical diameter of this heat exchanger would be the diffuser outlet diameter. Also, since pressure losses are higher in the tube side, it is more practical to exhaust the low pressure gas at the diffuser outlet into the shell side of the recuperator. Results of the calculations for the heat exchangers of the topping plant and regenerative cycle are presented in Table III.

Compressors

Preliminary calculations to obtain estimates of compressor sizes have been made using scaling laws described by Stepanoff.¹² For these applications, it has been assumed that a staged, axial flow machine driven by a synchronous AC motor will be the most practical design. No attempt has been made to describe the aerodynamic design of these machines. The results of these calculations are presented in Table IV.¹³

TABLE III

HEAT EXCHANGERS FOR MHD PLANTS

REFRACTORY METAL SYSTEM, REGENERATIVE CYCLE:

	<u>Recuperator</u>	<u>Precooler</u>	<u>Intercooler</u>
No. of Units	1	1	6
Tube Side:			
Fluid	He	Water	Water
Flow Rate (lb/sec)	1057		
No. Passes	3 passes of 3 parallel bundles	1	1
No. Tubes	2209/bundle	361	712
Tube O.D. (in)	1.0	1.0	1.0
Tube Pitch (in)	2.0	1.5	1.5
Tube Length (ft)	24.0	24.0	3.25
Bundle Dia. (ft)	7.85	0.5 ft deep	3.9
Pressure Drop (psi)	1.9/pass 5.7 total		
Shell Side:			
Fluid	He	He	He
Flow Rate (lb/sec)	1057	1057	176.2
No. Crosses	Crossflow	Crossflow	Crossflow
Shell Dia. (ft)	24.0	24 x 24 x 0.5 deep	4.0
Pressure Drop (psi)	0.8	0.2	0.5

GRAPHITE SYSTEM, TOPPING CYCLE

	<u>Boiler-Superheater</u>	<u>Hi temp Recuperator</u>	<u>Lo temp Recuperator</u>	<u>Condensate Heater</u>	<u>Compressor Precooler</u>	<u>Compressor Intercooler</u>
No. of Units	1	1	8	8	8	8
Tube Side:						
Fluid	Water-steam	He	He	Water	Water	Water
Flow rate (lb/sec)	899	1057	132.1	859	1810	1930
No. Passes	6	16 parallel	1	1	1	1
No. Tubes	2292	8816	3093	480	547	547
Tube O.D. (in)	1.0	2.75	1.0	1.0	1.0	1.0
Tube Pitch (in)	2.0	4.125	1.5	1.5	1.5	1.5
Bundle Dia. (ft)	1.5	1.72	2.85	3.25	3.25	3.25
Pressure Drop (psi)	-	0.6	1.0	-	-	-
Shell Side:						
Fluid	He	He	He	He	He	He
Flow Rate (lb/sec)	1057	1057	132.1	132.1	132.1	132.1
No. flow crosses	1	1	Split	Split	Split	Split
Shell Dia. (ft)	27.0	27.5	7.5	3.0	3.5	3.5
Pressure Drop (psi)	0.6	1.3	0.3	0.5	0.8	0.4

TABLE IV
COMPRESSORS FOR MHD PLANTS

	GRAPHITE SYSTEM	REFRACTORY METAL SYSTEM
Number of units	16	12
Helium Flow Rate (lb/sec)	132.1	176.2
Inlet temperature (°F)	100	100.0
Compressor efficiency (%)	85	85
Compression ratio	1.507	1.669
Speed (rpm)	7200	7200
Wheel Diameter (in)	44	44
No. of stages	10	12
Length of stages (in)	66	78
Nom. motor rating (HP)	30,000	50,000

For the graphite system, the 16 compressors are arrayed as two sets of eight parallel machines, each set in series. For the refractory metal system, the 12 compressors are arrayed as two sets of six parallel machines, each set in series.

The compressors for any of these cycles will require development to meet the low density high flow, high pressure rise, high power level requirements. The most difficult problem will be to provide the necessary reliability and durability of bearing lubrication without contaminating the system. This requirement in present gas-cooled reactor coolant loops has led to the development of compressors with hydrodynamically lubricated gas bearings.

These machines can be totally "canned" and do not require the periodic maintenance of grease-lubricated bearing machines. Gas-bearing machines of this size are beyond the present "state-of-the-art".

Plant Layout

A possible plant layout using the previously established component characteristics for the refractory metal plant is illustrated in Figure 8.

Primary containment for the reactor is a pre-stressed concrete vessel. The reactor is located to provide neutron and gamma shielding for the super-cooled MHD duct magnet. The duct is oriented horizontally because of its length. The pressure energy is recovered at the outlet of the MHD duct through a center-body, subsonic diffuser. Primary containments for all components other than the reactor are cylindrical steel vessels and secondary containments are steel-lined concrete pressure vessels. The entire plant is constructed below ground level to provide biological shielding since the escape of fission products from the reactor fuel is very likely. The loop activity would be about 2×10^{10} curies for 100% fission product release.

A possible plant layout for the graphite system is illustrated in Figure 9. Again, one of the principle problems with component layout is the necessity of providing primary containment of the helium loop because of the possibility of fission product contamination. This requires a very large pressure vessel (about 250 ft long and 50 ft diameter) to enclose the reactor, MHD duct, recuperators, and steam generator. Although the compressors are located outside this primary containment, they must be within a secondary containment in case of leakage from these components. To contrast the regenerative plant, the components for this layout are oriented vertically with the reactor at the bottom for maximum biological shielding.

The overall plant characteristics for each of these plants are presented in Table V.

TABLE V

OVERALL MHD PLANT CHARACTERISTICS

REFRACTORY METAL REACTOR, REGENERATIVE PLANT:

MHD Net AC output (3% inverter loss)	1579.685 MW
Compressor Motor Input	426.096 MW
Auxiliary Power Rqmts.	5.000 MW
Net Station AC Output	1148.589 MW
Reactor Thermal Power	1994.615 MW
Net Plant Efficiency	57.6 %

GRAPHITE REACTOR, TOPPING PLANT:

Net MHD AC Output (3% inverter loss)	972.114 MW
Net Steam Turbine Alternator Output	661.480 MW
Compressor Motor Input	337.104 MW
Boiler Feed Pump Motor Input	12.340 MW
Condensate Pump Motor Input	.410 MW
Auxiliary Power Requirements (coolant pumps, magnet, control, etc.)	5.000 MW
Net Station AC Output	1278.899 MW
Net Plant Efficiency	50.7 %

DISCUSSION

Although the calculated plant efficiencies of the MHD plants are significantly higher than those of present commercial fossil or fissile fueled power plants (50-60% compared to 30-40%), there are factors which provide serious doubts at the present time as to the feasibility of the concept of the combination of a nuclear reactor and MHD for commercial power production.

The most significant of these factors is the subject of capital costs. Even though a detailed economic study has not been made, one important point can illustrate the problem. If the overall efficiency of an existing plant can be increased by X% at the expense of increasing capital cost by Y%, the capital cost is increased by the ratio $(100+Y)/(100+X)$ and the fuel cost is reduced by $100/(100 + X)$.¹⁴ This principle may be applied to a comparison between the refractory metal, regenerative MHD plant ($\eta_o = 57.6\%$) and the proposed Target plant ($\eta_o = 45.6\%$), if the fuel cycle and operating costs (on a \$/lb fuel basis) are assumed to be the same for both plants. If the power costs in mils/kwhr are the same for the two plants, the increase in capital cost is given by:

$$Y = X \frac{(C+F)}{C} \quad (9)$$

where C = capital cost (mils/kwhr) and F = fuel and operating costs (mils/kwhr) for the existing plant (in our case the Target plant). For this example C is 2.87 mils/kwhr, F is 1.5 mils/kwhr, and X is 26.3%. The MHD plant can be built then for a 40% increase in capital cost if the fuel cycle and operating costs are the same. For the MHD Topping plant ($\eta_o = 50.7\%$),

the percentage increase in capital cost is only 17%. However, it does not appear possible, in the foreseeable future, to build these MHD plants for these costs, because the MHD plant components are much larger, more difficult to design, and more expensive to fabricate than those of the Target plant.

The second factor suppressing enthusiasm for engineering a commercial plant is the profusion of development work necessary on the major components, particularly the reactor, MHD generator, and turbomachinery. Even the heat exchangers are unconventional because of the low system pressure and pressure drop features, which require large flow cross-sections, short lengths on the tube sides and cross-flow or split flow on the shell sides. Major development programs are also necessary to study high temperature materials and reactor fuels, the effects of impurities and impurity control, and methods of extracting and injecting the cesium seed from and into the gas stream to prevent fouling of heat exchangers and compressors in the low temperature portions of the loop. The performance requirements of these components well exceed the present "state-of-the-art", such that even plans for a pilot plant scale experimental loop cannot yet be considered.

Another undesirable feature of the MHD plant is the necessity of containing the entire primary loop to prevent escape of fission products to the atmosphere. Although cladding of the fuel prevents gross fission product release into the gas stream, a cladding which would absolutely contain all fission products is inconceivable, and the possibility of accidental fission product release by mechanical failure of a fuel element cladding cannot be precluded. Since the primary loop of the MHD plant is extremely large, the design of a containment vessel will be a formidable task. Even the amount of material necessary for the pressure vessel will

greatly increase the capital cost. Containment also places the loop components in an inconvenient location for maintenance or replacement, which requires redundancy or extreme reliability.

The outlook for a commercial inert gas Brayton cycle MHD power plant is poor for the near future (>10 years), and it is difficult to predict advancement in technology which could improve this outlook. Should the time arrive when this technology is at a point that the concept becomes attractive, the pure regenerative cycle or the turbine-compressor, regenerative cycle with a refractory metal reactor will be the ones to consider. Since the efficiencies of these cycles are about the same, the turbine-compressor cycle would be more practical if the development of "boot-strap" turbocompressors is realized. The advantage of the turbine-compressor over the electric motor driven compressor (other than higher overall efficiencies) is that the shaft is much lighter in weight. This fact becomes extremely important when gas-lubricated bearings are employed. The topping cycle with the graphite reactor was considered in this study because of the possibility of using presently available commercial high temperature materials, e.g. inconel, in the heat recuperator and boiler. However, even if this possibility were realized, this plant would probably not be competitive with the proposed Target plant on the basis of increased capital costs. In addition, the lower efficiencies of the topping cycle, particularly in the refractory metal reactor system, makes this cycle less attractive.

Although this study is based on thermal equilibrium ionization MHD processes, a cursory consideration of non-equilibrium processes was made.

First, the theory of non-equilibrium MHD processes have not been supported in experiments. Second, and more significantly, it is doubtful that a cycle based on this process could compete with a gas turbine closed Brayton cycle, even in case of "major breakthrough" in non-equilibrium MHD research. The temperature range in which non-equilibrium MHD processes are expected to operate ($<3400^{\circ}\text{R}$) is within the range of current gas turbine development. The efficiencies of gas turbines have been approaching 90%, whereas even the efficiencies of thermal equilibrium MHD generators have not exceeded 75% in practice. Also, gas turbine cycles could be operated at higher pressures, resulting in smaller reactors and heat exchangers and thus lower plant capital costs.

Recommendations

A more practical goal for the foreseeable future is the development of components for a commercial gas turbine power plant. This goal is more easily defined than that of the MHD plant, and the developments for the turbine plant would eventually be applicable to those necessary for the MHD plant.

Programs which may be accelerated or launched for the development of Brayton cycle technology are: (1) the design and testing of gas-cooled nuclear reactor fuel elements, (2) development of high temperature, large size turbomachinery, and (3) basic research in the physical chemistry and development of fabrication processes of high temperature materials.

For nuclear reactor fuel element development, programs such as UHTREX at LASL and 710 at General Electric are underway, but the UHTREX work is at the lower end of the temperature range of interest and the 710 work is

not directed toward the commercial power application. In the United States most of the gas-cooled reactor fuel element development is being supported by the government for nuclear rocket application. General Atomic is the only private concern which is engaged actively in fuel development for commercial gas-cooled reactors, and this activity is restricted to graphite fuels.

The present activity in turbomachinery development, particularly in regard to gas-lubricated bearings, is directed toward the high temperature commercial application, but the activity has been limited to small machines (<200HP). Since most of this work in the United States is being funded by private industry, the lengthy and expensive process of extrapolation and iteration to large machines will be retarded until the government or the power industry complex contributes massive support.

The programs in high temperature materials research, which apply to all components in these Brayton cycles, are supported principally by the government for space applications. Emphasis on this activity, more than any other, should accelerate the development and engineering of gas-cooled reactors and Brayton cycle turbomachinery. It is also the only activity that will apply to MHD generator development.

The development of MHD generators for the inert gas closed Brayton cycle plant will probably be retarded until the criteria for such a plant is better defined. Private industry interested in MHD is reluctant to undertake this expensive development until active support is obtained from the complex of the power industry. Naturally, the power industry is reluctant to provide support until the MHD concept is proven practical. This dilemma will probably continue until power production from Brayton cycle plants begins to replace the steam plants. At this time the MHD concept may become more attractive and re-evaluation of the feasibility of commercial MHD power production will be in order.

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Author's Note

The information presented in this paper is the result of a preliminary survey of an ad-hoc committee at Los Alamos for the purpose of investigating a possible interest in future research at LASL. It was originally felt that the work in the LASL Rover Nuclear rocket reactor and UHTREX gas-cooled reactor programs could be applicable to the nuclear reactor-MHD combination. A more detailed report of the findings of this committee will be published by LASL late in 1965.

Nomenclature

B	Magnetic field (webers/meter ²)
D	Diameter (ft)
D _g	Diameter of MHD duct (meters)
D _i	Inside tube diameter (ft)
D _o	Outside tube diameter (ft)
L	Length
L _g	Length of MHD duct (meters)
K	Constant in equation (1)
N _c	Number of series sets of compressors
N _t	Number of tubes
N _x	Number of crosses on HX shell side
P	Absolute pressure (psia)
P _o	MHD Duct inlet stagnation pressure (psia) (atm in equation (1))
P _g	Arithmetic average pressure in component
R _c	Pressure Ratio of compressor (Pout/Pin)
R _d	Pressure Ratio of MHD Duct (Pout/Pin)
R _t	Pressure Ratio of turbine (Pout/Pin)
T	Absolute Temperature (°R)
T _c	Compressor inlet temperature (°R)
T _g	Arithmetic average temperature in component (°R)
T _o	MHD duct inlet stagnation temperature (°R)
T _t	Turbine inlet temperature (°R)
u	Velocity (meters/sec)
γ	Ratio of specific heats (C _p /C _v)
σ	Gas conductivity (mhos/meter)
η _c	Compressor efficiency
η _{CM}	AC motor efficiency

η_i	Inverter (DC to AC) efficiency
η_o	Overall Plant efficiency
η_{o_r}	Regenerative Plant efficiency
η_{o_s}	MHD Topping Steam Plant efficiency
η_{o_t}	Regenerative Turbine-Compressor Plant efficiency
η_R	Recuperator efficiency $(1 - \Delta T_{loss}/\Delta T)$
η_s	Steam Plant efficiency (AC energy out/thermal energy in)
η_t	Turbine efficiency
ΔP	Friction Pressure loss (psi)
ΔP_{ic}	Friction loss through compressor intercooler (psi)
$(\Delta P/P_o)_h$	Ratio of high pressure side loop friction loss to P_o
$(\Delta P/P_o)_l$	Ratio of low pressure side loop friction loss to P_o
$(\Delta P/P_o)_t$	Ratio of turbine pressure drop to P_o
ΔT	Temperature drop through component ($^{\circ}R$)
ΔT_g	Temperature drop through MHD duct ($^{\circ}K$)
ΔT_R	Hot side to cold side recuperator temperature difference ($^{\circ}R$)
ΔT_s	Temperature drop from enthalpy exchange to Steam Plant ($^{\circ}R$)
ΔT_T	Total temperature drop through MHD duct including wall losses ($^{\circ}R$)

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Fig. 1

Fig. 1.

Fig. 2

Fig. 2

Fig. 3

Fig 4.

Fig. 5

Fig 6

Fig. 7

SCALE 0 10' 20' 30' 40'

Fig. 8

Fig 8

Fig. 9