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DOE/NASA/10769-17
NASA TM-82609

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(NASA-TM-82609) ASSESSMENT OF DISK MHD GENERATORS FOR A BASE LOAD POWERPLANT (NASA) 17 p HC A02/MF A01 CSCL 10A
N81-23611
Unclas
G3/44 42353

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Washington, D.C. 20545
Under Interagency Agreement DE-AI01-77ET10769

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Abstract

A summary of the results from a recent Westinghouse-MIT systems study of the disk MHD generator are presented. Both open and closed-cycle disk systems were investigated in the Westinghouse-MIT study. Costing of the open-cycle disk components (nozzle, channel, diffuser, radiant boiler, magnet and power management) was done. However, no detailed costing was done for the closed-cycle systems. Preliminary plant design for the open-cycle systems was also completed. Based on the system study results, an economic assessment of the open-cycle systems is presented in this paper.

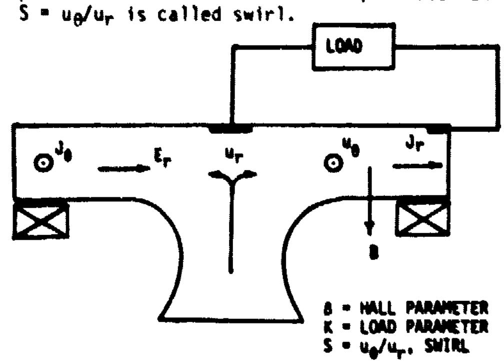
The following open-cycle plant efficiencies, η_t, were calculated. For a directly fired preheat system with 1920°K (2996°F) preheat temperature η_t = 45.5%, for a directly fired system with 1650°K (2500°F) preheat temperature η_t = 43.4%, for a separately fired preheat system at 1920°K (2996°F) η_t = 39% and for an oxygen enriched system with low temperature recuperative preheat η_t = 40.5%. Costs of the open-cycle disk components are less than comparable linear generator components. Also, costs of electricity for the open-cycle disk systems are competitive with comparable linear systems.

Advantages of the disk design simplicity are considered. Improvements in the channel availability or a reduction in the channel lifetime requirement are possible as a result of the disk design.

I. Introduction

A systems study[1] of both open and closed-cycle disk MHD generator power plants has recently been completed by a contract team managed by the NASA Lewis Research Center under contract to the Department of Energy. The Westinghouse Advanced Energy Systems Division was responsible for the overall study while MIT supplied design data for both the open and closed-cycle disk generators. Burns and Roe, Inc. supplied costing and plant layout data and Fluidyne Engineering furnished design and costing data, also. Some of the channel design information has already been reported in references 2-4. This paper will summarize the systems study results and present an economic assessment of the open-cycle systems.

Figure I-1 is a schematic diagram of an outward flow disk MHD generator. Flow is introduced on the axis of the disk with both radial, u_r, and azimuthal, u_θ, velocities. These velocities interact with the applied axial magnetic field, B, to induce both radial, J_r, and azimuthal, J_θ, current densities. The load current is made up of the radial current density, J_r, while the azimuthal current density, J_θ, is shorted within the plasma. Thus the disk generator with both radial and swirl flow can be considered the cylindrical analog of the linear diagonal MHD generator. The original descriptive paper[5] of the disk generator points out the importance of the swirl velocity in obtaining increased efficiency. In the power density expression the term $(\beta + S)$ acts like an effective Hall parameter. Where β is the Hall parameter and $S = u_\theta/u_r$ is called swirl.



$$\text{POWER DENSITY} = -J_r E_r = \frac{\sigma u_r^2 B^2}{1+\beta^2}(\beta+S)^2 K(1-K)$$

FIGURE I-1 MHD DISK GENERATOR

The initial disk experiments[6,7] were fundamental studies of plasma properties, nonequilibrium ionization and plasma interaction with a magnetic field. Later experiments introduced swirl into the flow and steady improvements in enthalpy extraction were obtained[8-13]. These experiments have established the potential of the disk as an MHD generator.

Early theoretical assessments of the disk as a possible commercial power plant were made in references 14 and 15. Recently, the feasibility of using a radial inflow disk generator has been investigated by a Stanford group[16,17]. The Stanford group has also recently begun an experimental program[18].

Since the disk generator walls are insulators, larger electric fields than exist over the electrode walls of a linear generator can be sustained. The possibility of large electric fields means large magnetic fields and resulting high enthalpy extraction rates. Thus the size of the disk will be relatively small (~ 10 m diameter for 1000 MW system). Magnet design for the disk can be either a single coil as shown in figure I-1 or a Helmholtz pair with the channel between the coils. Either magnet design is simpler than the magnets necessary for linear generators. Also, the inverter system for the disk is simpler than for a linear generator since a limited number of electrodes are necessary to collect the load current. The minimum number would be a two terminal connection like that in figure I-1.

One advantage of the disk generator is its simplicity. The channel, the magnet, and the inverter system for the disk will all be simpler and more economical than for a linear generator. Simplicity of the disk system should also mean greater availability and reduced maintenance. One of the objectives of this study was to assess the importance of the disk simplicity.

In the next two sections of this paper, the systems results for both the open and closed-cycle disk generators will be presented. It is emphasized that this study[1] represents a first major attempt to integrate the disk generator into an electric power plant. It should, therefore, be considered a preliminary systems study. Design detail of the MHD components for the open-cycle system was carried only to the extent necessary to obtain reasonable cost estimates. Only preliminary cost estimates of the closed-cycle components were made.

Following the performance, plant design, and cost results sections, the economic assessment section is presented. In this section, cost of electricity (COE) results for the open-cycle systems are presented. Also, improvements in availability and reduced channel lifetime requirements resulting from disk simplicity will be estimated. Finally, the COE resulting from improved availability and disk efficiency will be calculated.

II. Open-Cycle Studies

Systems

Studies have been performed for directly-fired, separately-fired, and oxygen-augmented MHD power plants incorporating a disk geometry for the MHD generator. As a result of these studies, base parameters for near-optimum-performance MHD/steam power systems of various types have been defined. The base parameters for the selected systems and a performance summary for each are presented in Tables II-1 and II-2, respectively. The selected systems consisted of two directly-fired cases, one at 1920K (2996°F) preheat and the other at 1650K (2500°F) preheat; a separately-fired case where the air is preheated to the same level as the higher temperature directly-fired case; and an oxygen-augmented case with the same generator inlet temperature of 2839K (4650°F) as the high-temperature directly-fired and the separately-fired cases. Supersonic Mach numbers at the generator inlet, gas inlet swirl, and constant Hall field operation were specified based on disk generator optimization conducted as part of the study. System pressures were based on optimization of MHD net power. Supercritical reheat steam plants were used in all cases.

TABLE II-1. BASE PARAMETERS FOR THE NEAR-OPTIMUM-PERFORMANCE OPEN CYCLE DISK GENERATOR SYSTEMS

	DIRECTLY-FIRED 1920K PREHEAT	DIRECTLY-FIRED 1650K PREHEAT	SEPARATELY-FIRED 1920K PREHEAT	O_2 ENRICHED
Plant Size, MWe	1000 Nominal	1000 Nominal	1000 Nominal	1000 Nominal
Oxidant	Air	Air	Air	O_2 Enriched
Oxidant Preheat Temperature, K	1920	1650	1920	[illegible]
Oxidant Preheater Type	Directly-Fired HTAH	Directly-Fired HTAH	Indirectly-Fired HTAH	Metallic Recuperators
Generator Inlet Mach Number	1.8	1.7	1.8	1.8
Generator Inlet Swirl	0.5	0.5	0.5	0.5
Generator Design Mode	Constant Hall Field	Constant Hall Field	Constant Hall Field	Constant Hall Field
Maximum Hall Field, kV/m	12	12	12	12
Diffuser Pressure Recovery Factor	0.6	0.6	0.6	0.6
Magnetic Induction, T	7	7	7	7
Steam Bottoming Plant	3500/1000/1000 Extraction Type	3500/1000/1000 Extraction Type	3500/1000/1000 Extraction Type	3500/1000/1000 Extraction Type
NO_x Scrubbing System	NO_x Scrubber	None Required	None Required	None Required

TABLE II-2. PERFORMANCE SUMMARY FOR THE NEAR-OPTIMUM-PERFORMANCE OPEN CYCLE DISK GENERATOR SYSTEMS

	DIRECTLY-FIRED 1920 K PREHEAT	DIRECTLY-FIRED 1650 K PREHEAT	SEPARATELY-FIRED 1920 K PREHEAT	O_2 ENRICHED
Coal Input to Plant, MW_t				
MHD Combustor	3077.1	2704.0	1453.9	2367.8
Gasifier	-	-	1030.6	-
Seed Regeneration	41.5	[illegible]	38.1	47.4
Total	3118.6	[illegible]	2522.4	2415.2
Gross Power Out, MW_e				
MHD	596.0	522.3	607.4	608.6
Steam	627.4	738.6	727.0	610.2
Gas Turbine	-	-	131.0	-
Total	1223.3	1260.9	1466.3	1209.0
Power Consumption, MW_e				
Cycle Air Compressor	154.6	160.3	160.1	126.1
Boiler Feed Pumps	21.6	25.1	24.8	27.7
Oxygen Plant	-	-	-	71.9
NO_x Scrubber	12.2	-	-	-
Other	72.1	77.3	169.6	58.1
Total	260.3	2[illegible]	362.5	272.8
Generator Inlet Pressure - Atm.	8.15	6.07	8.16	8.13
Generator Mass Flow - kg/s	736.0	800.6	575.2	542.6
Generator Inlet Temperature - K	2839	2731	2839	2839
Disk Inlet Radius (m)	1.26	1.31	1.08	0.92
Disk Outlet Radius (m)	5.21	5.19	4.41	3.36
Radial E - Field (kV/m)	12	12	12	12
Voltage (kV)	47.4	66.5	40.3	53.1
Total Enthalpy - disk inlet (MW)	3102.5	3170.6	2177.0	2006.0
Enthalpy Extraction (%)	19.2	16.4	18.8	18.3
Generator Isentropic eff. (%)	60.0	66.9	60.3	62.5
Plant Net Power Out, MW_e	963.0	1012.0	983.8	970.0
Plant Efficiency, %	45.5	43.4	39.0	40.5

The resulting power plant efficiencies shown on Table II-2 are found to be in the range of similar studies on linear systems. As expected, a large difference of 6.5 percentage points in efficiency exists for the directly and separately-fired cases at the same preheat level. The separately-fired case studied used a pressurized coal gasifier to fire the preheaters and a gas turbine energy recovery system driven by the preheater exhaust. The efficiency of the oxygen-augmented system is found to be slightly higher (1.5 percentage points) than the separately-fired case with the same generator inlet temperature. Thus, previous conclusions on the performance competitiveness of oxygen-enriched systems for linear generators also hold true for the disk systems.

In the case of the directly-fired system with a preheat level of 1920K (2996°F), it was found that the temperatures out of the radiant boiler to the preheater had to be at such a high level as to preclude attaining the desired low level of NO_x in the boiler exhaust gas. Thus, for that case an NO_x scrubber was specified.

The results of sensitivity studies on plant efficiency for the directly and separately-fired cases are presented in Table II-3.

TABLE II-3. OCD Power System Sensitivity Study Results

OCD DIRECTLY-FIRED SYSTEM

VARIATION	EFFICIENCY DELTA - %
Half Power 1000 MWe → 500 MWe	-0.6
Reduced Channel Wall Temp. 2000 K → 1800 K	-0.2
Fuel Substitution Illinois #6	+0.8
Reduced Preheat 1920 K → 1810 K	-0.6
1800 K Preheat + 32.5 wt. % O_2	-2.0
Subsonic, Constant Velocity Disk 1800 K Preheat	-5.2
Radial Flow Disk Swirl = 0	-0.4
Swirl Increase 0.5 → 1.0	±0.0
Improved Diffuser Recovery Coefficient 0.45 → 0.60	+0.5
Hall Field Decrease 12 kV/m → 6 kV/m	-0.5
Hall Field Increase 12 kV/m → 16 kV/m	±0.0
Reduced Magnetic Field 7 T → 6 T	-0.5
Increased Magnetic Field 7 T → 8 T	+0.4
Increased Magnetic Field 7 T → 12 T	+1.2
Increased Combustor Pressure Loss 8% → 10% of P_{in}	-0.2
Double Power 1000 MWe → 2000 MWe	+0.5

OCD SEPARATELY - FIRED SYSTEM

VARIATION	EFFICIENCY DELTA - %
Double Power 1000 MWe → 2000 MWe	+0.3
Half Power 1000 MWe → 500 MWe	-0.6
Subsonic Constant Velocity 1800 K Preheat	-2.2
Radial Flow Disk Swirl = 0	-0.2
Swirl Increase 0.5 → 1.0	±0.0

OCD OXYGEN-ENRICHED SYSTEM

VARIATION	EFFICIENCY DELTA - %
20% Increased Conductivity	+0.4
20% Decreased Conductivity	-0.7

A review of this table results in some interesting observations. First, it is to be noted that over the range of 500 MW_e to 2000 MW_e the overall plant efficiency is affected approximately 1%. This is less variation than is found for comparable studies on linear generator systems.

Good system performance data does not require inlet swirl above 0.5 and performance is not overly sensitive to swirl below this level. Thus, assuming combustors can introduce swirl in the range of 0.5, extraordinary measures to introduce swirl are not required to be built into the generator.

For this study, the design Hall field was initially selected to be 12 kV/m. This value was somewhat arbitrarily assigned, recognizing that the disk should be theoretically capable of a much higher value than a linear generator, but with a desire to remain on the conservative side. The study results indicate that no significant performance improvement is achieved with reasonable increases above this value. The size of the disk, however, can be decreased with higher values of Hall field and thus the tradeoff can be between cost and risk of electrical breakdown without performance penalty.

Performance sensitivity to a B-field increase from 7T to 8T and 12T was evaluated. Based on the recommended configuration for the disk and magnet (see Power Train Arrangement Section), increased tesla design conditions appear to be more easily attained for the disk than for the linear system. In the single coil disk magnet design, the major structural limitations encountered in the design of linear system magnets with high tesla fields are not expected to be present. An efficiency increase of 1.2 percentage points was calculated for the increase of magnetic induction from 7T to 12T.

The diffuser recovery coefficient is reasonably influential on overall performance, with 0.5 points of efficiency gained by increasing the assumed recovery factor from 0.45 to 0.60. For a well-integrated generator, diffuser, and radiant boiler design, the higher values of recovery factor can be more easily achieved in disk generator systems, since boundary layer blockage at the diffuser entry is expected to be minimal, and the hot wall design of the disk generator and diffuser minimize density and velocity differences in the flow cross-section at any radius.

In performing and reviewing this study, it was found that differences in calculated plasma conductivities exist when compared to companion linear generator studies. Specifically the Parametric Study of Potential Early Commercial MHD Power Plants (PSPEC) study performed by Avco[19] uses higher conductivities, and the PSPEC study performed by General Electric[20] uses lower conductivity values. High plasma conductivity is important for the open-cycle disk generator configuration, which optimizes from a performance standpoint at supersonic inlet velocities. The uncertainty in conductivity differs from the other parameters studied in this program, because it is not a design parameter, except insofar as it is affected by the selection of a seeding level. Its importance lies primarily in assuring consistency between the results of various studies from which conclusions are to be drawn. Although the evaluation of the effects of a gross percentage change in conductivity is felt to be an extreme simplification (since the actual conductivity changes are derived from which species are included, rate constants, ionization potential, calculational methods, etc.), two cases, one each for an "across-the-board" increase and decrease in conductivity, were calculated and are included in Table II-3. As expected, the performance of the disk generator and thus the overall power system is sensitive to conductivity variations, though not unduly so. Variations in plasma conductivity affect the division of power generation capability between the topping cycle and the bottoming plant, more so than they cause significant changes in overall plant power output. The most significant effect of conductivity is the change in extraction length required to maintain equivalent performance from the generator. Variations in generator size have a great effect upon disk and magnet sizes, and therefore, costs. A direct and truly valid comparison of the overall performance and costing results obtained in this study with other studies can only be made following review and careful consideration of the differences in methods and assumptions used in the studies.

The study called for an estimate of the costs of the major components in open-cycle disk MHD plants that can differ significantly in design from their linear counterparts. A summary of this data is presented in Table II-4. A review of the cost of these disk-related components against their counterparts in the most recent linear studies[19,20] indicates a potential cost reduction from 24-56% for the disk components, or in absolute dollars a value of $\$23 \times 10^6$ to $\$103 \times 10^6$ (mid-1978 basis) for the 1000 MW_e plants investigated. The large range results from major differences in the estimated cost of the generator and the magnet for the comparison linear systems. It was found that the combustor system will be of similar cost to that for linear systems. The MHD generator consisting of the nozzle, channel, and diffuser, the magnet, and the channel power management system will all have significantly lower costs than for a linear system of similar power rating. The radiant boiler, as conceived for this study, is slightly higher in cost than for a linear system. Based on observations of the physical design differences, and based on the National Magnet Laboratory assessment of magnet costs, the potential for cost savings is heavily biased toward the upper end of the 23-103 million dollar range indicated above. Verification of this conclusion is dependent on resolution of the large differences presently existing in studies of the linear system components.

TABLE II-4. MAJOR SUBSYSTEM COST ESTIMATES FOR DISK GENERATOR POWER PLANTS OF 1000 MWe CAPACITY

	COST - DOLLARS, MID-1978 BASIS			
SUBSYSTEM	DIRECTLY-FIRED [illegible] PREHEAT	DIRECTLY-FIRED [illegible] PREHEAT	SEPARATELY-FIRED [illegible] PREHEAT	[illegible]
COMBUSTOR	$ 917,000	$ [illegible]	$ [illegible]	$ [illegible]
NOZZLE AND CHANNEL	1,[illegible]	1,[illegible]	1,780,000	1,[illegible]
DIFFUSER	2,919,000	2,[illegible]	2,[illegible]	2,[illegible]
MAGNET	[illegible]	[illegible]	47,112,000	[illegible]
DISK POWER MANAGEMENT	[illegible]	21,[illegible]	17,414,000	[illegible]
RADIANT FURNACE	[illegible]	[illegible]	[illegible]	[illegible]

Power Train Arrangement

A selection study was performed to arrive at a candidate plant arrangement. Figure II-1 is a drawing of the MHD portion of the disk generator plant selected for layout. An attempt has been made to utilize the natural features of the disk to provide significant advantages in cost, operation, and maintenance. A simple single solenoidal coil magnet is used and is positioned below the radial outflow disk at ground level. This allows for an easily supported magnet installation with rapid access from above to the channel for maintenance and replacement. The combustor is in a vertical orientation for gravity slagging and fires upward through the central hole in the magnet into the center of the disk. Tunnel access is provided to the combustor for servicing and removal, and for routing of feed lines.

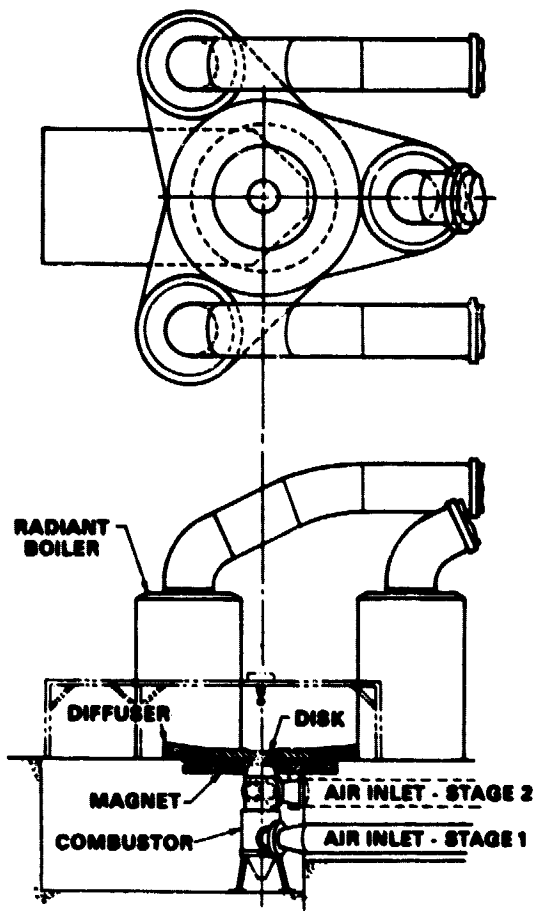


Figure II-1. MHD Portion of the Disk Generator Plant

The outflow of the disk undergoes sonic transition and is radially diffused at the disk periphery, where it is fed to three upright cylindrical radiant boiler sections. The flow from these three radiant boiler sections is collected by means of insulated ducting and manifolding and directed to a single train of heat and seed recovery equipment with configurations virtually identical to equipment used in linear systems.

The overall arrangement of the channel and combustor is especially encouraging from serviceability, support, and structures considerations. The diffuser design, and that of the radiant boilers and ducting, is straightforward and feasible; yet it appears that considerable work must be done in this area to combine the functions of these three elements and optimize their performance as integrated portions of the heat recovery and gas dynamic systems.

There are several features of the disk power train which, when combined, could result in major operating systems advantage. These can be in the form of power plant availability advantages or power plant integration advantages. It is believed that the selected simplified arrangement of the disk and magnet could result in major time advantages for removal and/or repair of the disk. Likewise the disk itself with many fewer parts and electrical interconnections may well prove to be considerably more rugged than linear units. The quantification of such features in terms of plant availability is very difficult without operating experience, yet if even 1-2% availability difference can be attributed to these features, it can overcome a sizable plant efficiency difference when viewed from the standpoint of cost of electricity. In terms of plant integration, the lower heat loss from the walls of the disk channel as compared to the linear makes the combining of the turbine plant feedwater train with the channel cooling load an easier task. The use of stainless steel cooling passages in the disk, as designed herein, assures compatibility of water chemistry requirements with the bottoming plant. The incompatibility of copper passages, as presently used in linear systems, has been avoided.

<u>Component Characteristics</u>

The combustor envisioned fires vertically upward with slag tapping at the bottom, and incorporates two stages of combustion. Its characteristics are like those for linear system combustors with the exception that swirl is desired at the inlet to the disk. This swirl is introduced by tangential inflow of the oxidant to both stages. Swirls up to 0.5, which improve the system performance, are conceived as being possible from the combustor alone, thus eliminating the need for swirl vanes in the disk generator inlet. The conclusion that such devices may not be necessary is an important one, and considerably enhances the engineering feasibility of the disk generator.

Preliminary calculations for a radial inflow design indicate large combustor heat losses. Therefore, a radial outflow design appears more desirable.

While most commercial-scale linear generators are designed for subsonic flows, the disk generators in these systems are designed for inlet Mach numbers ranging from 1.7 to 1.9. Disk generators designed for subsonic operations are found to have much inferior performance than supersonic disk generators. Particular emphasis was placed on determining electrical constraints, and a constant radial electric field throughout the channel was found to provide the best generator performance[2]. Although single-load (two-terminal) disk generators can be designed on the basis of this constraint, the off-design performance characteristics of such single-load devices are found to be highly undesirable. The single-load generator tends to operate as a constant current device at the typical magnetic field strength. Small variations in front-end load current would result in rather drastic changes in the generator behavior. Fortunately, segmenting the channel using a small number (3-5) of intermediate electrode rings permits satisfactory off-design operations without making the generator design unduly complicated. Control of the radial voltage gradient is achieved by the inverters between adjacent electrode rings.

The selection of a disk geometry brings about important simplification in the specification of channel wall requirements. Basically the walls of a disk generator have only to: (1) support the Hall field, and (2) provide power takeoff points which as explained above can be few in number. It is to be noted that the Faraday current closes on itself within the gas, and thus it is not necessary to provide external closure paths as in a linear diagonal machine, nor to accommodate multiple loading as in the linear segmented Faraday case. This also has important simplifying implications for the magnet and the power management subsystem as discussed below.

Figure II-2 indicates the conceptual design of the disk generator and its radial diffuser as developed in this study. The disk consists of two pierced fiberglas walls to which are joined water-cooled ceramic walls operating at high temperature. The electrodes are water-cooled copper rings separated from the refractory walls at their inner and outer radii by appropriate insulating materials. A typical diameter of 5.2 meters is shown for the active channel for a 1000 MW_e plant. Two points of design importance for the disk are: (1) the walls are much simplified from those of the linear systems with their complex and intricate multiple electrodes, and (2) the mechanical design should be easily scaleable from small size prototypes; a characteristic that is not obvious for linear systems.

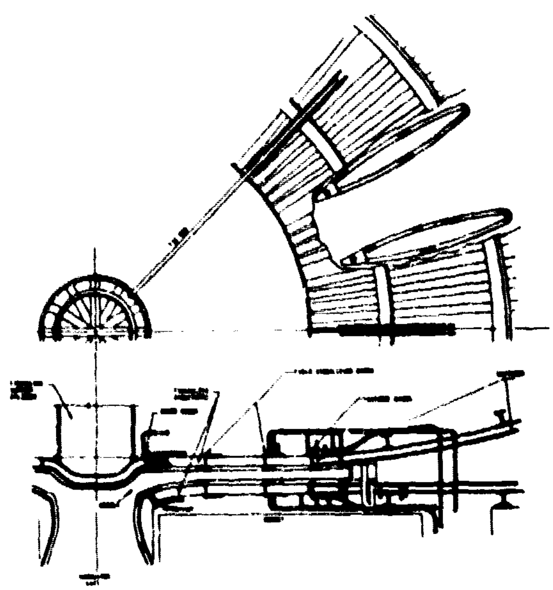


Figure II-2. Disk Generator Structural Concept

The choice in magnet configurations is between: (1) a pair of coils to provide a substantially uniform axial field with radius, but having difficult support requirements (penetration of the disk for upper coil support), thus making it difficult to maintain and replace the disk; and (2) a single coil below the disk generator with a substantial radial field that increases with radius as depicted in Figure II-3. The advantages of the single coil approach were considered so overwhelming that it together with a flat disk geometry was adopted for the study.

If the disk were dome shaped like the bottom half of figure II-3, then the flow would be perpendicular to the resultant magnetic field. This arrangement will give better magnetic field utilization. An increase in disk generator enthalpy extraction is to be expected if this approach is adopted, and it is recommended for future investigations.

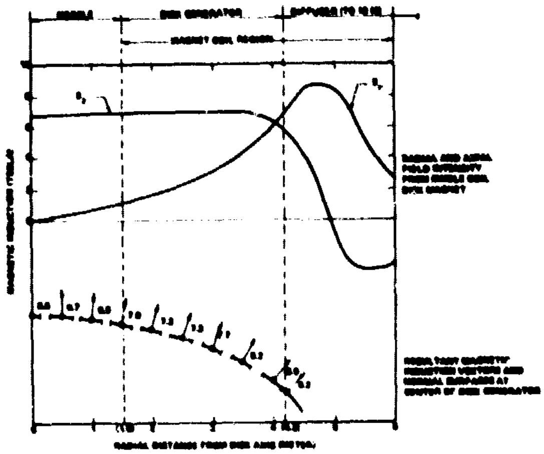


Figure II-3 Effect of Radial Field Component in Solenoidal Single Coil Magnet

The channel power management system consists of the equipment necessary for consolidation, conversion, and conditioning of the MHD generated power to make it acceptable for transmission.

As previously indicated, an initial review of the voltage-current relationship of the disk generator in a two-terminal configuration showed significant sensitivity at design point to current changes. For example, variations in front-end load current of less than 0.33 resulted in a 55% change in Mach number. This indicates that successful operation of the channel would require adjustment of the back-end electrical loading to maintain compatibility with gas dynamic conditions. This was accomplished by segmenting the channel into four parts by providing intermediate current take-off electrode rings which typically decrease in radial spacing from inlet to outlet. Although the feasibility of radial field control has been established by the study, future effort will be beneficial in defining more precisely the power takeoff electrode requirements, and their location, as well as defining potential regulator circuits applicable to the task.

The multiple electrode disk generator requires that inverter units of appropriate rating be connected in series across adjacent electrodes. The current levels required by the intermediate and outer electrodes are compatible with direct connection, to an inverter. Electrode current density considerations will probably require multiple (2-4) collecting electrodes, and an accompanying consolidation scheme. As this will be located in the fringe field of the magnet coil, the voltage will be low as in the end connection of a linear diagonal machine.

The closure of the Faraday current within the plasma should eliminate the need for local current control as in the frame current control of linear diagonal generators. The simplification of consolidation circuitry and dispensing with current control greatly simplifies the overall power management subsystem and provides the disk configuration with a key electrical advantage that translates into reduced cost and increased reliability. The costs of such a disk conversion system have been estimated to be approximately 43% of the cost of that for a linear generator MHD power plant, based on the simplification outlined above.

Figure II-1 indicated the general arrangement of the MHD power train and Figure II-2 indicated the conceptual design of the diffuser. As previously indicated, arrangement studies showed the highly desirable effects of locating the disk in a horizontal plane above the magnet. Likewise, the conceptual design of the disk generator indicated the desirability of a section of radial diffuser at the periphery of the disk generator through which struts could be built thus allowing it to serve as a structural member for supporting the disk walls. The additional desire to have an area of access over the disk for maintenance and removal resulted in the selection of a concept using three discrete silo-type radiant boilers located around the periphery of the radial diffuser. This appears to be a rather straightforward, low risk approach. Extensive insulated ducting and manifolding is required to collect the exhaust from the three radiant boilers and direct it to air preheaters or to a common train of downstream heat and seed recovery equipment.

Refractory water wall construction has been assumed for the diffuser and radiant boilers, and refractory-insulated exhaust ducting has been proposed. Costing estimates are consistent with that performed on similar studies for linear systems. Based on the costing information developed and on the best interpretations of linear MHD power plant data, the radiant boiler system was found to be approximately 40% higher in cost in the separately-fired case and 20% higher in the oxygen-augmented case.

The arrangement and design of the combined diffuser, radiant boiler, and ducting is not a feasibility problem, but it does appear that this area could benefit from additional conceptual effort directed at combining functions to minimize cost and complexity, and to optimize aerodynamic and heat recovery performance.

III. Closed-Cycle Studies

The study of closed-cycle disk systems required extensive effort in defining acceptable analytical representations for the disk generator and its integration into systems models. As a result, the primary effort in this study was concentrated on determining the general characteristics of the disk generator and on predicting the level of system performance with emphasis on overall plant efficiency. Conceptual design and costing were given only a cursory evaluation.

Systems Studies

The power plant configuration which was investigated consisted of regenerative refractory heaters fired directly with coal combustion products, heating an argon closed-cycle fluid seeded as necessary with cesium. On the basis of previous studies, and early exploration in this study, the energy derived from a supercritical steam bottoming plant was matched to the pump work required in the cycle, and electrical power output of the plant was totally derived from the disk generator. Figure III-1 is a schematic diagram of the cycle investigated.

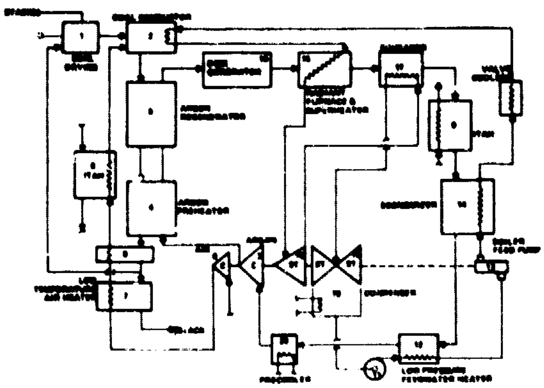


Figure III-1. Closed Cycle Disk Power Systems Flow Diagram

Thirty-three system performance cases are presented in the body of this report covering a range of disk generator variables. All calculations were performed with a 1920K (2996°F) inlet temperature to the channel and a magnetic field of 6T. Optimization of the closed-cycle disk is complicated by the fact that the electron population of the plasma is not in thermal equilibrium with the surrounding gas and electron temperature becomes an additional variable. Thus, plasma turbulence level and impurity level are parameters which must be considered in addition to swirl, Mach number, and seeding level.

The systems analysis covered a range of power levels, mass flow rates, inlet pressure levels, inlet swirls, inlet Mach numbers, and seed ratios; with selected investigation of turbulence level and impurities content. A summary of the performance survey results is presented in Table III-1. These cases have generally been optimized on system efficiency within the constraints of an effective Hall parameter limit, an exit Mach number of 1.0-1.1, and the required matching of steam power and pumping power. Several observations can be made from reviewing the information contained in this table.

TABLE III-1. CLOSED CYCLE DISK GENERATOR SYSTEM PERFORMANCE SURVEY (INLET CHANNEL HEIGHT = 0.1 METER)

CASE NO.	ARGON FLOW kg/s	INLET SWIRL	INLET MACH NO.	INLET PRESSURE ATM.	SEED FRACTION %	CHANNEL INLET RADIUS METERS	CHANNEL LENGTH METERS	POWER GENERATED MWe	SYSTEM EFFICIENCY %
100 ppm Impurities; Turbulence Level 0.2									
1	1000	2.0	2.02	4	.130	2.5	.79	370	44.2
2	1700	2.0	2.00	6	.005	3.0	.28	[illegible]	44.0
3	1171	2.0	2.37	6	.120	2.1	.46	416	45.7
4	2100	2.0	2.75	8	.005	3.0	[illegible]	763	45.1
5	1027	2.0	2.30	10	.100	2.5	.97	[illegible]	44.9
6	1100	1.5	2.00	6	.035	1.5	.36	[illegible]	45.1
7	1135	1.5	2.00	6	.015	1.5	.43	[illegible]	44.0
8	[illegible]	1.5	1.96	6	.005	2.5	.30	712	45.2
9	[illegible]	1.5	2.01	6	.015	2.5	.51	[illegible]	44.0
10	1344	1.5	2.36	6	.007	1.5	[illegible]	[illegible]	44.5
11	[illegible]	1.5	2.05	8	.036	3.0	.61	[illegible]	44.1
12	[illegible]	1.5	2.10	8	.015	3.0	.77	[illegible]	45.1
13	1700	1.5	2.20	10	[illegible]	1.5	.67	[illegible]	44.4
14	[illegible]	1.5	2.13	10	[illegible]	2.5	[illegible]	[illegible]	44.7
15	[illegible]	1.5	2.30	12	[illegible]	1.5	.84	677	44.0
16	[illegible]	1.5	[illegible]	12	[illegible]	2.2	[illegible]	[illegible]	44.3
17	[illegible]	1.5	2.21	12	[illegible]	2.5	1.11	[illegible]	44.4
18	[illegible]	1.0	1.96	6	.005	1.5	.84	715	43.5
19	[illegible]	1.0	1.83	8	.005	1.0	[illegible]	[illegible]	43.7
20	3106	1.0	1.91	8	.005	2.2	[illegible]	[illegible]	43.0
21	[illegible]	1.0	[illegible]	10	.005	1.5	[illegible]	[illegible]	[illegible]
22	[illegible]	1.0	2.00	10	.005	1.0	[illegible]	[illegible]	43.4
23	3307	1.0	2.05	10	.005	2.0	[illegible]	1140	43.4
24	3774	1.0	1.90	10	.005	2.2	1.00	[illegible]	[illegible]
25	4234	1.0	[illegible]	10	[illegible]	2.5	[illegible]	[illegible]	[illegible]
26	[illegible]	1.0	2.10	12	[illegible]	1.5	1.00	[illegible]	[illegible]
27	5016	1.0	[illegible]	12	.005	2.5	[illegible]	1700	43.3
100 ppm Impurities; Turbulence Level 0.5									
28	[illegible]	4.0	2.35	4	.300	2.5	[illegible]	162	44.2
29	[illegible]	4.0	2.30	4	.300	3.0	.42	197	44.3
30	318	4.0	2.75	6	.300	1.5	.43	[illegible]	43.7
31	[illegible]	4.0	[illegible]	8	.100	1.0	.01	[illegible]	43.2
32	[illegible]	4.0	3.02	10	.100	2.5	[illegible]	246	42.0
200 ppm Impurities; Turbulence Level 0.2									
33	[illegible]	2.0	2.50	8	.005	2.5	1.13	[illegible]	44.5

1. The level of optimum system efficiency for all the cases investigated lies within a relatively narrow band centered around 44% and is of a level comparable to that calculated for linear closed-cycle investigations.

2. The system efficiency does not decrease with power level, making the closed-cycle disk potentially attractive for small size plants.

3. For the optimized cases investigated, a change in the impurities from 100 to 200 PPM did not cause a significant degradation in performance. The impact of impurities on a given design needs further investigation.

4. High turbulence levels force a requirement for high swirl and high inlet Mach numbers, and as investigated herein, resulted in power plants that attained maximum efficiency at relatively low power levels (162-246 MW_e).

5. The seeding ratio declines with decreasing swirl, for example, to 0.005% at a swirl of 1.0 and thus implies limitations from the control viewpoint. However, the performance benefits afforded by the reduced plasma turbulence resulting from full ionization of the seed have not been investigated. Higher coefficients should be allowable which would increase the system efficiency. Better control of the generator operation is implied since the electron density is proportional to the gas pressure in the fully ionized limit.

The closed-cycle disk generator was found to be a compact high interaction unit. Swirl is much more beneficial to the performance of the closed-cycle disk than it is to the open-cycle disk, with the potential for a one-half to one percentage point gain in plant efficiency for a swirl increase of $S = 0.5$ at a given power level. The compact arrangement minimizes the friction losses in the generator and minimizes boundary layer thickness flowing to the diffuser. Within the constraints of the one-dimensional modeling of the closed-cycle disk used in this study, its turbine efficiency appears to be approximately four points higher than an equivalent closed-cycle linear Faraday generator[2] for the same enthalpy extraction.

The study has established that the MHD closed-cycle disk generator achieves levels of system efficiency which are comparable with or exceed those published in previous linear closed-cycle investigations[2]. This comparison is based on using compatible assumptions for the generator and diffuser in each case, together with less optimistic assumptions about losses throughout the remainder of the disk system than were used in the linear system studies. The study was not carried to the point where it was possible to determine cost or design concept relationships to the many variables. The use of a disk generator does not alter the demanding requirements on the regenerative argon heater defined in previous studies. Closed-cycle streams using direct combustion of coal for the reheat gas source to the heaters will also require scrubbers for SO_x and NO_x, since seed is not contained in the combustion gas stream to provide a means of sulfur removal, and no system comparable to the radiant boiler exists for reduction of the NO_x.

<u>Disk Generator Characteristics and Cost Trends</u>

Figure III-2 is a schematic arrangement of the closed-cycle disk generator where the aerodynamic configuration is drawn to scale. As a result of high interaction, the generator is relatively short ($L/D = 2.0$) and two-dimensional electrical and gasdynamic effects can be expected to be of some significance. For a representative 1000 MW_e power plant (Case 22 of Table III-1 has been selected as representative), the channel inlet radius is 1.8 meters, the exit radius is 2.78 meters, and the inlet channel height is 0.5 meters.

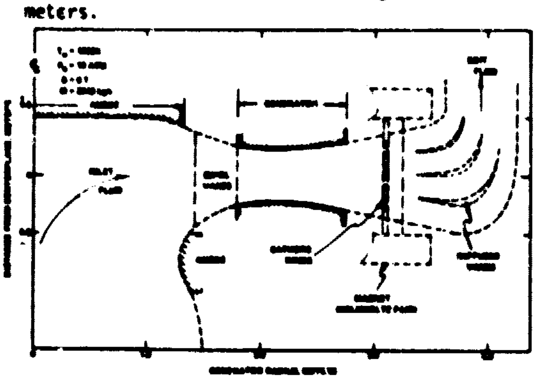


Figure III-2 [illegible]

Due to the compactness of the generator and its high current, low voltage characteristics, surface provisions within current density limits for the cathode and anode are best provided outside of the interaction length. The practical aspects of this requirement are evident in the selected case by the fact that nearly the entire wetted surface area available within the channel itself would have to be used as electrode surface area if current densities not exceeding 30-50 kA/m^2 are to be used. To ease this situation, the anode in the sketch of Figure III-2 is envisioned as consisting of the walls at the disk inlet and the cathode as a series of collector rings installed in the exit gas stream. Electrode consolidation circuits would therefore be required for cathode connection.

A simplified cost evaluation of closed-cycle disk components was performed by relating them to corresponding elements in the open-cycle part of this study. Case 22 in Table III-1 was again selected as typical for a 1000 MW_e closed-cycle disk configuration. The operating conditions of the closed-cycle disk which have a bearing on structural design of the disk itself are not markedly different. Therefore, the structural design could be assumed similar to that of the open-cycle disk and cost relations as a function of radius developed; such an approach indicates the closed-cycle disk structure can be expected to have a cost in the range of 30-50% of that for the open-cycle case. The complications of introducing electrodes with the large surface areas presumably required is expected to substantially affect design complexity and cost, which may offset this advantage to a large degree.

A similar approach was used on the magnet in applying cost scaling relationships derived during the open-cycle work. This indicated that the closed-cycle magnet could be expected to have a substantially lower cost than for comparable open-cycle generator cases.

Three major considerations enter into the cost of the power management system for the closed-cycle disk. First, since all power generated for transmission comes from MHD, the amount of power to be converted and conditioned is greater than twice that for the same size open-cycle plant. Secondly, without a steam turbine generator as part of the system, VAR compensation must be provided by added components, which may be either static or rotating. Thirdly, the high current, low voltage characteristic of the disk requires a large number of converter bridges to stay within accepted amperage limitations per bridge.

Taking these items into consideration, the cost of the power management system for the closed-cycle disk is more than twice the cost for an open-cycle plant of similar net electrical power output.

IV. Economic Assessment

Closed Cycle

Since no detailed costing of the closed-cycle disk components was done, it was not possible to calculate a COE for the closed-cycle systems. However, of all the disk closed-cycle components, only the inverter system will be significantly different in cost from the corresponding open-cycle disk component. Although closed-cycle COE's were not calculated, the cost advantages resulting from disk simplicity to be discussed for the open-cycle disk should apply to the closed-cycle disk.

Costs of Electricity for Open-Cycle Systems

Levelized cost of electricity (COE) was calculated for each of the open-cycle disk systems. Cost information for the disk components was obtained from reference 1. No costing of the steam plant and auxiliary components was done in the Westinghouse study. Therefore, the specific cost ($/watt) of these components was extracted from the PSPEC linear generator systems study completed by Avco[19] and General Electric[20].

Westinghouse's cost data for the separately-fired and O_2 enriched systems are compared with the PSPEC results in Table IV-1. The numbers appearing under the Avco and G.E. headings refer to case numbers used in references 19 and 20. The disk power management system is about one-half the cost of the linear system. Generator magnet costs compared to G.E. are also about one-half. Only the disk radiant boiler is more costly than the comparable radiant boiler for a linear system.

TABLE IV-1 COMPARISON OF COSTS FOR MAJOR COMPONENTS OF OPEN CYCLE DISK AND LINEAR MHD/STEAM POWER SYSTEMS (BASIS: MAJOR EQUIPMENT MATERIAL COSTS IN $1000's, MID 1978)

ITEM	SEPARATELY-FIRED SYSTEMS: OCD CASE 2	AVCO PSPEC CASE II PP-1	GE PSPEC CASE 2.11	OXYGEN-AUGMENTED SYSTEMS: OCD CASE 3	AVCO PSPEC CASE III PP-1	GE PSPEC CASE 3.2
COMBUSTOR	[illegible]	[illegible]		[illegible]	[illegible]	
MHD GENERATOR	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Channel & Nozzle	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Diffuser	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
MAGNET SYSTEM	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
POWER MANAGEMENT SYSTEM	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
RADIANT FURNACE	[illegible]	-	[illegible]	[illegible]	-	[illegible]

The expression used to calculate the capital costs of the disk systems is the following.

$$C_{cap} = \alpha_{ei} \left(C_{disk} + (c_{st} - c_{rb})\, P_{st} + (c_{aux} + c_{gas} + c_{O_2})\, P_{MHD}\right) \qquad (1)$$

Where C_{disk} is the capital cost of the disk components which include the combustor, nozzle, channel, diffuser, inverter, magnet, and radiant boiler. The specific cost factors taken from Avco and G.E. are c_{st} the steam plant specific cost, c_{rb} the radiant boiler specific cost (which must be subtracted from c_{st} since the radiant boiler cost is included in C_{disk}), c_{aux} the specific cost of the coal handling, preheater, and seed processing equipment, c_{gas} the specific cost of the gasifier system, and c_{O_2} the specific cost of the oxygen plant. Note that c_{gas} is used in equation (1) only when the separately-fired preheat system is being considered. Similarly, c_{O_2} is used only when the O_2 enriched system is being considered. Other terms appearing in equation (1) are P_{st} the gross power output of the steam plant, P_{MHD} the gross power output of the disk generator, and α_{ei} the escalation and interest factor given by the following.

$$\alpha_{ei} = CF/(1+E)^T \qquad (2)$$

Where CF is the cost factor which is a function of the escalation rate, E, the interest rate, I, and the construction time, T. Cost factors are tabulated in references 19 and 20. All costs in the PSPEC study are given in terms of mid-1978 dollars. Therefore, for purposes of comparison, mid-1978 dollars are used for costs in this study.

The specific cost factors are shown in Table IV-2. There is close agreement between the Avco and G.E. specific steam plant cost, c_{st}, for the separately-fired preheat system. For the O_2 enriched system the G.E. c_{st} is 12% higher than the Avco c_{st}. It was not possible to extract the Avco radiant boiler specific cost, c_{rb}, from the data of reference 19. Therefore, the G.E. radiant boiler cost, c_{rb}, was used in the COE calculations. Also, it was not possible to obtain a gasifier cost from the G.E. data. As a result, the Avco gasifier cost, c_{gas}, was used.

Table IV-2

Cost Factors Obtained From PSPEC Results

	Avco PSPEC Results: Separately-Fired Preheat	Avco PSPEC Results: O_2 Enriched	G.E. PSPEC Results: Separately-Fired Preheat	G.E. PSPEC Results: O_2 Enriched
Specific Steam Plant Cost, c_{st}, $/watt	[illegible]	[illegible]	[illegible]	[illegible]
Specific Radiant Boiler Cost, c_{rb}, $/watt	-	-	[illegible]	[illegible]
Specific Cost of Coal Handling, Preheater, and Seed Processing, c_{aux}, $/watt	[illegible]	[illegible]	[illegible]	[illegible]
Specific Cost of Gasifier, c_{gas}, $/watt	[illegible]	-	-	-
Specific Cost of O_2 Plant, c_{O_2}, $/watt	-	[illegible]	-	[illegible]

Using equation (1) to obtain the capital cost, C_{cap}, for the disk power plants, the COE's for each of the open-cycle systems was calculated using the following expression.

$$COE = \frac{C_{cap}\, FCR}{8760\, CF \times P_{el}} + LEV\, \frac{3.413\, FUEL}{\eta_t} + O\&M \qquad (3)$$

Where, FCR is the fixed charge rate (= .18 for PSPEC and this study), CP is the capacity factor (= .65 for PSPEC and this study), P_{el} is the electric power output of the plant in MW, η_t is the plant efficiency at the design point, FUEL is the fuel cost in \$/MBTU (= \$1.05 for PSPEC and this study), O&M is the operation and maintenance expense in mills/KWH, and LEV is the fuel and O&M levelizing factor (= 1.94 for Avco and = 1.882 for G.E.).

The COE's for the disk with directly-fired preheat systems are shown in Table IV-3. Results are presented for specific cost factors shown in Table IV-2 obtained from both Avco and G.E. The capital cost portion of the COE is nearly the same using either Avco or G.E. cost factor data. The major difference between the Avco based results and G.E. based results occurs in the O&M costs. As expected, the directly-fired system with 1920°K (2996°F) preheat has the lowest COE. However, it should be pointed out that a NOX clean-up system, which is required for the 1920°K preheat case, has not been included in the COE calculation.

TABLE IV-3 COST OF ELECTRICITY FOR DIRECTLY-FIRED PREHEAT DISK SYSTEMS

	[illegible] PREHEAT		1920°K(2996°F) PREHEAT	
	USING AVCO DATA	USING G.E. DATA	USING AVCO DATA	USING G.E. DATA
CAPITAL COSTS MILLS/KWH	22.67	24.30	23.26	24.50
FUEL COSTS MILLS/KWH	15.28	14.62	16.02	15.94
O&M COSTS MILLS/KWH	4.30	6.40	4.30	6.40
TOTAL COST OF ELECTRICITY, MILLS/KWH	42.35	45.32	43.86	46.92

Costs of electricity for the separately-fired preheat and O_2 enriched systems are presented in Table IV-4. For comparison the PSPEC results are also shown in Table IV-4. As Table IV-4 indicates, the capital cost portion of the COE for the disk is lower than the corresponding linear system except for the O_2 enriched Avco system. The main difference between the Avco based results and the G.E. based results for the disk COE is again caused by the O&M cost difference between Avco and G.E. data.

TABLE IV-4

COMPARISON OF OPEN CYCLE DISK AND PSPEC COSTS OF ELECTRICITY

1920°K(2996°F) SEPARATELY FIRED PREHEAT SYSTEMS

	DISK USING AVCO DATA	AVCO II, PP-1	DISK USING G.E. DATA	G.E. 2.11
CAPITAL COSTS MILLS/KWH	23.40	24.42	24.60	32.47
FUEL COSTS MILLS/KWH	17.83	15.92	17.29	15.30
O&M COSTS MILLS/KWH	4.30	4.30	6.89	6.80
TOTAL COST OF ELECTRICITY, MILLS/KWH	45.70	44.32	48.85	50.14

O_2 ENRICHED SYSTEMS

	DISK USING AVCO DATA	AVCO III, PP-1	DISK USING G.E. DATA	G.E. 3.2
CAPITAL COSTS MILLS/KWH	23.39	22.46	26.29	30.23
FUEL COSTS MILLS/KWH	17.17	16.00	16.66	15.72
O&M COSTS MILLS/KWH	3.41	3.41	7.12	7.12
TOTAL COST OF ELECTRICITY, MILLS/KWH	43.97	41.91	50.06	53.07

Based on the COE results in Table IV-4, the disk systems appear to be competitive with linear systems. The disk COE's are slightly higher than the corresponding Avco system. However, the disk COE for the separately-fired preheat system is significantly less than the corresponding G.E. system. The disk COE for the O_2 enriched system is slightly less than the corresponding G.E. system. Although the disk system already appears to be competitive with linear systems based on COE, it may be even more competitive if we consider the simplicity advantages of the disk.

Simplicity of Design Benefits

It is difficult to assess in a quantitative way the advantages of the disk generator design simplicity. However, the greatest impact of the disk simplicity should be on the plant capacity factor, CP. Referring to equation (3), it can be seen that the capital cost portion of the COE depends inversely on CP. Also, the fuel portion of the COE depends inversely on the total efficiency, η_t. For current fuel costs, the capital cost portion of the COE is always greater than the fuel cost portion of the COE. As a result, increasing CP will have a greater effect on reducing COE than increasing efficiency, η_t.

Consider the layout of the disk directly-fired system shown in figure II-1. As discussed in the Power Train Arrangement section, the time required to remove the nozzle, channel, and diffuser and replace them should be short. In a system where a spare channel, nozzle, and diffuser is available for replacement, the system availability is a function of this changeover time. A shorter changeover time means a higher availability.

If we assume that all outages of the disk power plant result from forced outages, then the availability, A = CP, where A is total plant availability. The total availability is the product of the component availabilities, $A = \prod A_i$. Therefore, shorter changeover time means higher capacity factor.

In reference 22, the following expression is derived for MHD channel availability.

$$A_c = \frac{1}{B}(1 + 2\alpha) \qquad (4)$$

Where,

$$B = (1+\alpha)^2 + 2S_T/MTBF \qquad (5a)$$

$$\alpha = MTTR/MTBF \qquad (5b)$$

Equation (4) is the availability for a two channel system. However, only one channel is in the generator system at any given time. The second channel is either being repaired or in a stand-by mode outside the generator system. Terms appearing in equation (5) are S_T, the time required to remove the channel from the system and replace it with another channel, MTBF, the mean time between channel failures and MTTR, the mean time to repair a channel.

Now consider the improvement in availability, A_c, that can be attained by reducing the changeover time, S_T, while keeping MTBF and MTTR constant. From equation (4) we obtain the following result.

$$\frac{\Delta A_c}{A_{c_0}} = \Delta S_T \Big/ \left[\frac{MTBF}{2} B_0 - \Delta S_T\right] \qquad (6)$$

Where,

$$\Delta A_c = A_c - A_{c_0} \qquad (7a)$$

$$\Delta S_T = S_{T_0} - S_T \qquad (7b)$$

$$B_0 = (1 - \alpha)^2 + 2\, S_{T_0}/MBTF \qquad (7c)$$

Figure IV-1 is a graph of equation (6) for MTBF = 2000 hrs., MTTR = 200 hrs., and S_{T_0} = 100 hrs. As figure IV-1 indicates, a 50% decrease in channel changeover time ($\Delta S_T/S_{T_0}$ = .5) yields about a 4% increase in channel availability ($\Delta A_c/A_{c_0}$ = .04). This would result in approximately a 4% reduction in the capital cost portion of the COE.

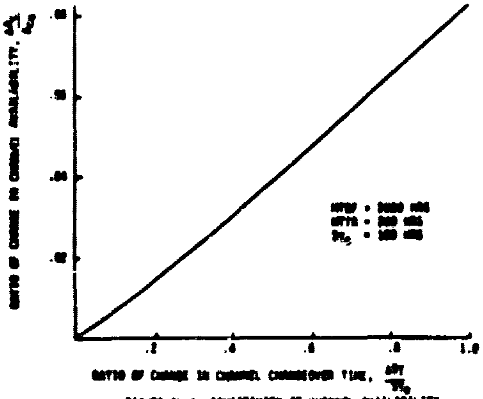


FIGURE IV-1 SENSITIVITY OF CHANNEL AVAILABILITY TO CHANNEL CHANGEOVER TIME

Rather than using the reduced changeover time to increase the availability, it may be more advantageous to keep the availability constant and reduce the MTBF requirement. Channel construction methods may not produce lifetimes of 2000 hours or more. Therefore, in order to have a workable system, it may be necessary to accept a smaller MTBF. Consider how MTBF depends on the changeover time, S_T. From equation (4), the following result is obtained.

$$MTBF = \frac{1}{1-A_c}\left\{A_c S_T - MTTR\,(1 - A_c) + \sqrt{(A_c S_T - MTTR(1-A_c))^2 + A_c (MTTR)^2 (1-A_c)}\right\} \qquad (8)$$

For cases of interest A_c > .9, therefore, it is a good approximation to assume $(1 - A_c) \to 0$. Making this approximation in equation (7) yields the following.

$$MTBF \simeq \{2A_c/(1-A_c)\}\, S_T \quad \text{for } (1-A_c) \to 0 \qquad (9)$$

Note that for this limit, the MTBF is independent of MTTR.

Equation (9) shows that MTBF is approximately a linear function of S_T. As a result, for a constant availability, any reduction in S_T will produce a corresponding reduction in MTBF. For the example presented in figure IV-1, the channel lifetime requirement can be reduced from 2000 hours to approximately 1000 hours if S_T is reduced from 100 hours to 50 hours with no change in channel availability. If channel lifetime requirements of 2000 hours or more cannot be satisfied, the same COE can be obtained with a system having S_T = 50 hours. The disk design simplicity offers the possibility for S_T in the range of 50-100 hours.

Possible Performance Improvements

Based only on a reduced changeover time, we have shown that about a 4 percent reduction in the capital cost portion of the COE can be attained. It is also possible that the fuel costs can be reduced. This will result if the efficiency can be increased. Most probable improvement in the total efficiency will result from increased enthalpy extraction of the disk generator. As discussed in the Component Characteristics section, larger enthalpy extractions are obtained by using a dome-shaped disk. With dome-shaped design, the magnetic field is always perpendicular to the flow direction.

From reference 19, the following expression for total efficiency is obtained.

$$\eta_t = \eta_{MHD} + \eta_{st}\,(1 - \eta_{MHD})f - L_{aux} \qquad (10)$$

Where, η_{MHD} and η_{st} are the disk and steam plant efficiencies, f is waste heat recovery factor, and L_{aux} are the auxiliary power requirements.

$$\eta_{MHD} = \frac{P_{MHD} - P_{comp}}{Q_{fuel}} \qquad (11a)$$

$$\eta_{st} = \frac{P_{st}}{Q_{st}} \qquad (11b)$$

$$f = \frac{Q_{st}}{Q_{fuel}\,(1 - \eta_{MHD})} \qquad (11c)$$

$$L_{aux} = \frac{P_{aux}}{Q_{fuel}} \qquad (11d)$$

The fuel power input is Q_{fuel}, the total disk power output is P_{MHD}, the compressor power required for the disk flow is P_{comp}, the steam plant power input is Q_{st}, and the auxiliary power is P_{aux}.

Consider the change in efficiency that results from a change in η_{MHD}. From equation (10), the following is obtained.

$$\Delta\eta_t = \eta_t - \eta_{t_0} = (1-\eta_{st}\, f)\,(\eta_{MHD} - \eta_{MHD_0})$$
$$= (1 - \eta_{st}\, f)\,\Delta\eta_{MHD} \qquad (12)$$

From the data of reference 1, the expected improvement in the enthalpy extraction from the dome-shaped disk channel is approximately .03. Therefore, assume $\Delta\eta_{MHD} \simeq .03$ and use the same steam plant efficiency as previously, $\eta_{st} = .42$. Also, using waste heat recovery factors calculated from the PSPEC results ($f \simeq .90$ for all open-cycle systems except the separately-fired system where $f \approx .78$) the following total efficiency improvements are obtained.

$\Delta\eta_t = .019$ - for directly fired preheat and O_2 enriched systems (13a)

$\Delta\eta_t = .020$ - for separately-fired preheat systems (13b)

For a .03 improvement in η_{MHD} we can expect approximately a .02 improvement in the total efficiency.

<u>Cost of Electricity for Improved Availability and Efficiency</u>

Consider how increased availability and efficiency will affect the disk generator system COE. Again assume that all plant outages are forced outages so that $CP = A = \prod A_i$, where A_i is the availability of component A_i. Therefore,

$$\frac{\Delta CP}{CP_0} = \frac{\Delta A_c}{A_{c_0}} \qquad (14)$$

As already discussed, the disk design simplicity should result in reduced channel changeover time, S_T. The results of figure IV-1 indicate that $\Delta A_c/A_{c_0} \approx .04$ if S_T is reduced from 100 hrs. to 50 hrs. Therefore, we used $\Delta CP/CP_0 \approx .04$ to obtain $CP = 1.04\ CP_0 = 1.04(.65) = .68$

As discussed in the last section, a dome-shaped disk design offers the possibility of improved enthalpy extraction. Assuming this improved enthalpy extraction would lead to $\Delta\eta_{MHD} = .03$, the efficiency improvements given by equation (13) result.

Using CP = .68 and the efficiency improvements given by equation (13), the COE's for all the disk systems were calculated. These results are shown in Table IV-5 along with the PSPEC results for the linear generator systems. With these improvements, all the disk systems become the cheapest except the O_2 enriched case. The O_2 case when compared to Avco is very nearly the same.

TABLE IV-5

COST OF ELECTRICITY FOR INCREASED AVAILABILITY AND EFFICIENCY

	DISK USING AVCO PSPEC DATA, MILLS/KWH	AVCO PSPEC, MILLS/KWH	DISK USING G.E. PSPEC DATA, MILLS/KWH	G.E. PSPEC MILLS/KWH
1920°K DIRECTLY FIRED PREHEAT	40.72	-	43.66	-
1650°K DIRECTLY FIRED PREHEAT	41.96	-	44.70	-
1920°K SEPARATELY FIRED PREHEAT	43.79	44.32	46.93	55.16
O_2 ENRICHED	42.17	41.91	48.15	53.07

III. Conclusions

First consider the disk closed-cycle system. No detailed costing was done for the closed cycle. However, the disk generator performance is better than comparable linear systems (for the same enthalpy extraction the isentropic efficiency of the disk is greater than that of a comparable linear system). Also, good efficiency is attainable at low power levels.

The open-cycle disk systems have lower overall efficiency than the corresponding PSPEC linear systems. However, the disk generator components (nozzle, channel, diffuser, magnet, and power management) are cheaper than comparable PSPEC components. Costs of electricity for the disk systems are within 5% of Avco PSPEC results and more than 5% lower than G.E. PSPEC results.

Disk design simplicity should lead to increased plant capacity factor, CP, or a reduction in the channel lifetime requirement. For a reduction in channel changeover time, S_T, from 100 hrs. to 50 hrs. a 4% increase in CP or a factor of 2 reduction in channel lifetime requirement was calculated. Also, open cycle disk enthalpy extraction can be increased with a dome-shaped channel design. An improvement of 2% ($\Delta\eta_t \simeq .02$ was calculated.

Using the improved capacity factor and efficiency, costs of electricity were again calculated. These results give disk COE's that are less than the comparable PSPEC linear systems except for the O_2 enriched system when compared with the Avco is very nearly the same.

Based on a COE argument, the disk open-cycle systems are competitive with linear systems. What the disk lacks in performance it makes up with lower cost. In addition, the disk design simplicity provides the possibility of reduced changeover time and greater availability.

References

1. Retallick, F. D.: Disk MHD Generator Study. NASA CR-159872 and Westinghouse Advanced Energy Systems Division TM E-3064, October 1980.

2. Teare, J. D.; Loubsky, W. J.; Lytle, J. K.; and Louis, J. F.: Optimization of Disk Generator Performance for Base-Load Power Plant Systems Applications. Seventh International Conference on MHD Electrical Power Generation, MIT, Cambridge, MA, June 16-20, 1980, CONF-800617-6, 1980.

3. Teare, J. D.; and Louis, J. F.: Disk Generators for Open-Cycle Base-Load Power Generators. AIAA-81-0251, AIAA 19th Aerospace Sciences Meeting, St. Louis, Missouri, January 12-15, 1981.

4. Loubsky, W. J.; Misra, B.; and Louis, J. F.: Disk Generators for Closed-Cycle Base-Load MHD Power Generation. AIAA-81-0317, AIAA 19th Aerospace Sciences Meeting, St. Louis, Missouri, January 12-15, 1981.

5. Louis, J. F.: Disk Generator. AIAA Journal, 6, 1674, 1968.

6. Klepeis, J.; and Rosa, R. J.: Experimental Studies of Strong Hall Effects and VxB Induced Ionization. 5th Symposium on Engineering Aspects of MHD, MIT, April 1964, pp. 41-55. Experimental Studies of Strong Hall Effects and UxB Ionization - II. 6th Symposium on Engineering Aspects of MHD, Univ. Pittsburgh, Pittsburgh, PA, April 1965, pp. 26-30.

7. Vitshas, A. F.; Golihev, V. S.; and Malikov, M. M.: Investigation of an Electrical Discharge in a Magnetic Field in the Presence of a Gas Flow. Proceedings of the Third International Conference on MHD Electric Power Generation, Salzburg, Austria, 1966, pp. 591-609. Investigation of Ionization Instability in a Disk-Shaped Hall Channel. Proceedings of the Fourth International Conference on MHD Electrical Power Generation, Warsaw, Poland, 1966, Vol. 1, pp. 529-545.

8. Louis, J. F.: Studies on an Inert Gas Disk Hall Generator Driven in a Shock Tunnel. Eight Symposium on Engineering Aspects of MHD, Stanford, California, March 1967, pp. 75-88.

9. Klepeis, J. E.; and Louis, J. F.: High Hall Coefficient Studies in a Disk Generator Driven by Molecular Gases. 10th Symposium on Engineering Aspects of MHD, MIT, March 1969, pp. 202-204. and Studies with a Disk Generator Driven by Molecular Gases. 11th Symposium on Engineering Aspects of MHD, Calif. Inst. Tech., Pasadena, California, March 1970, pp. 62-63.

10. Shioda, S.; and Yamasaki, H.: Generation Experiments with a Disk MHD Generator Under the Conditions of Fully Ionized Seed. Sixth International Conference on MHD Electrical Power Generation, Washington, DC, June 1975, Vol. III, pp. 105-114.

11. Loubsky, W. J.; Hruby, V. J.; and Louis, J. F.: Detailed Studies in a Disk Generator with Inlet Swirl Driven by Argon. 15th Symposium on Engineering Aspects of MHD, Philadelphis, PA, May 1976, pp. VI.4.1-VI.4.5.

12. Klepeis, J.; and Hruby, V.: MHD Power Generation Experiments with a Large Disk Channel: Verification of Disk Scaling Laws. 15th Symposium on Engineering Aspects of MHD, Philadelphia, PA, May 1976, pp. VI.3.1-VI.3.6.

13. Klepeis, J.; and Hruby, V.: The Disk Geometry Applied to Open Cycle MHD Power Generation: Experimental and Theoretical Considerations. 16th Symposium on Engineering Aspects of MHD, Pittsburgh, PA, 1977, pp. I.5.31-I.5.37.

14. Klepeis, J. E.; Cole, J.; Hruby, V. J.; and Louis, J. F.: The Disk Geometry Applied to Open Cycle MHD Power Generation. Sixth International Conference on MHD Electrical Power Generation, Washington, DC, June 1975, Vol. I, pp. 251-266.

15. Klepeis, J. E.: Open Cycle Disk Generator Studies. Fourth U.S./USSR Colloquium on MHD Electrical Power Generation, Washington, DC, October 1978, CONF-781009, pp. 411-414.

16. Nakamura, R.; and Jenkins, M. K.: Performance of Disk Generators for Open-Cycle MHD Power Generation. 18th Symposium on Engineering Aspects of MHD, Butte, Montana, June 1979, pp. B.3.1-B.3.11.

17. Nakamura, R.; Lear, W. E.; and Eustis, R. H.: Feasibility of the Inflow Disk Generator for Open-Cycle MHD Power Generation. AIAA 81-0250, AIAA 19th Aerospace Sciences Meeting, St. Louis, Missouri, January 12-15, 1981.

18. Jenkins, M. K.; Nakamura, R.; Vilas, T. R.; and Eustis, R. H.: Experimental Results of a High Magnetic Field Combustion Disk Generator. Seventh International Conference on MHD Electrical Power Generation, MIT, June 1980, CONF-800617, pp. 495-502.

19. Hals, F.: Parametric Study of Potential Early Commercial MHD Power Plants, NASA CR-159633, December 1979. Hals, F.; Kessler, R.; Swallom, D.; Westra, L.; and Zar, J.: Results from Study of Potential Early Commercial MHD Power Plants and from Recent ETF Work. Seventh International Conference on MHD Electrical Power Generation, MIT, June 16-20, 1980, CONF-800617, pp. 636-643.

20. Marston, C. H.: Parametric Study of Potential Early Commercial MHD Power Plants, NASA CR-159634, February 1980.
Marston, C. H.; Bender, D. J.; Hnat, J. G. and Dellinger, T. C.: Parametric Study of Prospective Early Commercial OCMHD Power Plants (PSPEC), Seventh International Conference on MHD Electrical Power Generation, MIT, June 16-20, 1980, CONF-800617, pp. 629-635.

21. Energy Conversion Alternatives Study (ECAS) - Phase I Final Report, NASA CR-134948, Vols. 1, 2, and 3, February 1976.

22. Cutting, J. C.; Del Bueno, R. P.; Eckels, R.; Maravada, S. N.; Chamow, M. F.; and Lynch, J. J.: The Influence of Component Redundancy on the Availability of Open-Cycle MHD Power Plants. Fourth U.S./USSR Colloquium on MHD Electrical Power Generation, Washington, DC, October 5-6, 1978, CONF-781009, pp. 129-160.