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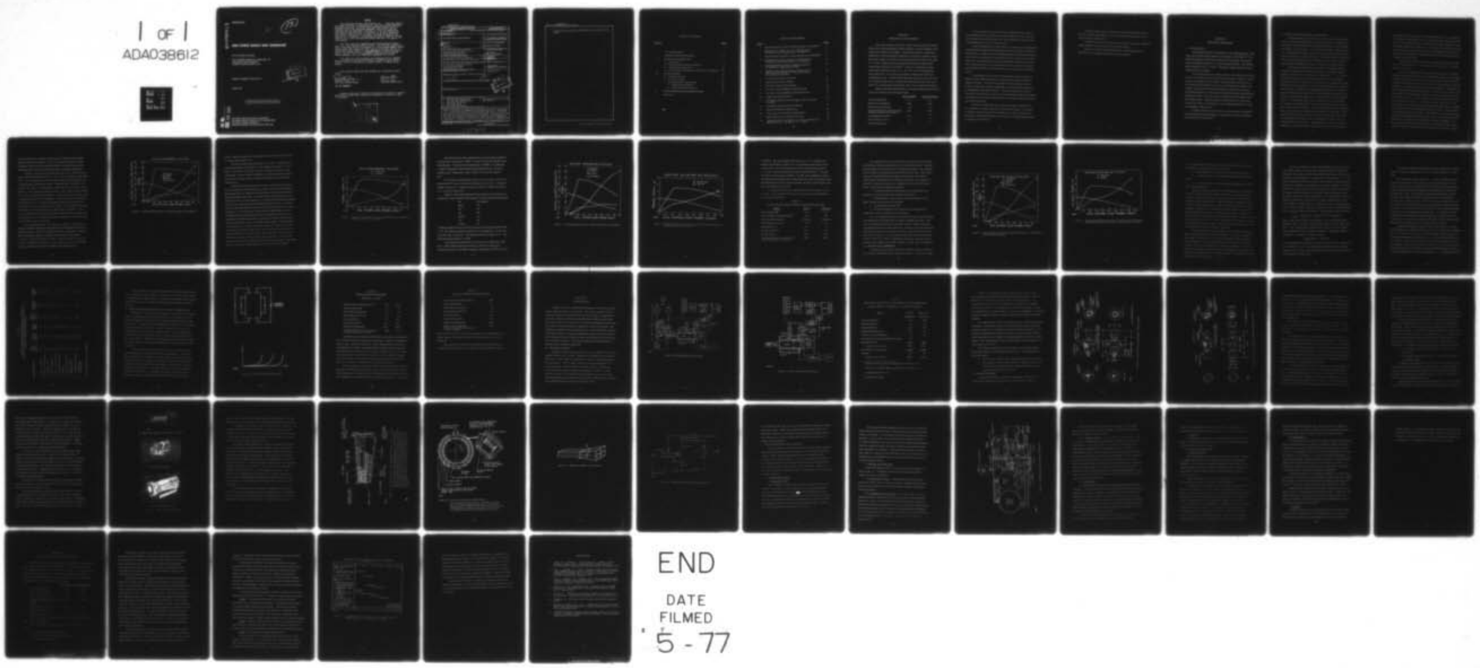

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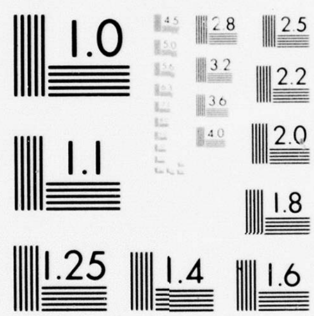

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HIGH POWER DENSITY MHD GENERATORS

FINAL TECHNICAL REPORT

AVCO EVERETT RESEARCH LABORATORY, INC.
2385 REVERE BEACH PARKWAY
EVERETT, MASSACHUSETTS 02149

TECHNICAL REPORT AFAPL-TR-76-71

MARCH 1976

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This report has been reviewed by the Information Office, (ASD/OIP) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication.

Robert F. Cooper
High Power Program Manager

Philip E. Stover
High Power Branch Chief

FOR THE COMMANDER

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7. MHD Generators

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Operating parameters were calculated for MHD generators operating at power densities in the channel of 500 MW/m^3 and with power outputs of 30 - 35 MW (nominal). Liquid-fueled generators, using hydrocarbon fuels such as JP-4 or RP-1 and oxygen, and solid fuel generators were investigated. Designs of both liquid and solid fuel generators are described, and estimates of their weights and sizes are given. Operation of generators at power densities of 1000 MW/m^3 was investigated. Assessments of feasibility and risks involved in achieving high power density operation are made. A development plan for construction of

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flightweight high power density MHD generator power supplies is presented.

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SECTION I

INTRODUCTION AND SUMMARY

This report presents results of a study of the feasibility of portable MHD electric power generator systems operating at power densities in the channel of 500 MW/m^3 and higher. Operating parameters, weights and dimensions of MHD generators operating on various fuel-oxidizer combinations were studied, for machines with electrical power output in the range 30 - 35 MW. Design layouts were made for two systems with nominal channel power density of 500 MW/m^3. These are a liquid fuel system operating on hydrocarbon fuels (e. g., RP-1 or JP-4) and liquid oxygen, with cesium seed, and a system operating on a double-base solid fuel, seeded with cesium. Operation of the MHD generator was considered both in a continuous mode and in a pulsed mode with a typical duty cycle of 20 pulses of 7 seconds duration per pulse, with 2 to 5 seconds between pulses.

Channel operating characteristics and system weights and dimensions for the two systems are summarized below:

	RP/O_2 System	Solid Fuel System
Power Output [MW]	31.5	33.2
System Dry Weight [kg]	2305	1695
Mass Flow Rate [kg/sec]	30	30
Total Weight (60 sec operation) [kg] (includes reactants and coolant)	4625	3820
Peak Magnetic Field [T]	4.6	3.6
Overall Diameter [m]	1.6	1.3
Overall Length [m]	3.7	3.7

The dry weight of the solid fuel system depends to some extent on the operating duration required, because the weight of the burner depends on the amount of reactant required, for a given propellant weight fraction. The propellant mass fraction assumed is 0. 9.

Major development, for both systems, is required for the lightweight superconducting magnet which represents the heaviest single component of the generator. Another area of development required, for pulsed operation, is for burners, particularly of solid fueled burners capable of the required duty cycle. The potential for electrical breakdown and damage in the channels is considerably in excess of experience to date, because of the high power density operation, and development may be required in channel technology.

In comparing the two systems, the solid fuel system is about 17% lighter in total weight and requires a magnet of lower peak field than the liquid fuel system. The liquid fuel system has the advantage of using a readily available fuel-oxidizer combination, and allows pulse durations to be independent of the initial fuel load. The choice between the solid and liquid fueled generators will also be influenced by their respective operating characteristics and by the reactant storage and handling systems and auxiliary systems required.

Operation of MHD generators at power densities of 1000 MW/m^3 was considered, using the same fuels considered previously. The weight reductions achieved by this mode of operation are small, and the risk of electrical breakdown and damage to the channel is considerably higher than in operation at 500 MW/m^3.

Section II of this report presents electrical operating characteristics of the two systems investigated, and also presents characteristics of channels operating at 1000 MW/m^3.

Section III presents the design layout of the MHD generator, estimated system weights and some system design considerations.

Section IV contains recommendations for a development plan for construction of a prototype high power density generator.

SECTION II

OPERATING PARAMETERS

A. INTRODUCTION

Operating parameters are presented for two MHD generators, both operating at nominal power density, in the channel, of 500 MW/m^3. One generator operates on liquid hydrocarbon fuels and oxygen, with cesium seed, and the other operates on a cesium-seeded solid fuel. The nominal power output level is 30 - 35 MW. Preliminary weight estimates are presented for the two systems.

The operating parameters shown provide some indication of the risk of failure or damage involved in the channels described. However, assessments of risk based solely on specific operating characteristics tend to underestimate the potential for serious or even destructive damage to the channel, resulting from electrical breakdown of channel wall elements. The damage potential is influenced by the channel operating characteristics, operating duration, and by the specific configuration of the channel walls and loading scheme. Detailed discussion of these factors is beyond the scope of this report, but estimates of risk and damage potential are made in paragraph C of this section.

In addition to the two systems above, which operate at 500 MW/m^3, operating parameters and weights are presented for systems operating at power densities of 1000 MW/m^3

B. GENERATOR PERFORMANCE PARAMETERS

Typical operating characteristics of interest for the two generator systems of primary interest were calculated by means of a computer program which calculates generator operating characteristics (power output, axial fields, current density, etc.) and generator length, volume and area, etc., with channel inlet Mach number for specified input burner pressure and gas mixture (fuel, oxidizer and seed). Constraints such as Hall parameter, electrical field limitations and diffuser recovery requirements are imposed when establishing the regions of optimum operating conditions.

Operating characteristics are calculated as outlined below; the mathematical details of the analytical techniques used in the computer program are described in previous AERL publications.[1-4] It is assumed that the flow in the channel is developing rather than fully developed. Therefore, the flow is divided into an inviscid core occupying most of the channel area and a boundary layer confined to the immediate vicinity of the channel walls. Boundary layer displacement thicknesses are calculated from momentum integral equations for both electrode and insulator walls, taking into consideration shape factor, compressibility and wall-cooling effects. Wall-roughness effects on the skin friction are also included. The boundary layer shape factor is used to predict boundary layer separation or channel stall conditions. The electrical dissipation in the boundary layer is generally small compared to the wall heat transfer rate. Consequently, the usual (no MHD) compressible flow relation between velocity and enthalpy for the boundary layer is sufficiently accurate. Flow nonuniformity effects are included. Nonuniformities in velocity, electrical conductivity, and Hall parameter in the vicinity of both the electrode and

)

insulator walls are considered. The combustion products are assumed to be in chemical equilibrium at the local conditions and all points in the flow field, and the electron density is assumed to be in Saha equilibrium at the translation temperature of the plasma. The electrical conductivity and the Hall parameter are calculated as a function of temperature and pressure using Frost's approximation with the effects of electron attachment to OH^- and other species included.

The principal results from these calculations are presented in the form of graphs which show major operating characteristics of the MHD systems of interest.

The curves shown should be regarded only as typical, in that they represent operating characteristics for particular generator inlet conditions (stagnation pressure, mass flow rate, reactant mixture) and for channels designed with minimum technical risk in terms of the operating parameters presented. Tradeoffs can be made in the inlet conditions, which would result in different operating characteristics. For instance, the channel could be operated at reduced stagnation pressure, in order to reduce the convective heat transfer rate, but then a higher mass flow rate would be required for the same power output; or, the channel could be operated at a lower mass flow rate, in order to reduce the total weight of the system, including fuel, but this would result in higher axial electric fields. These tradeoffs are discussed in more detail below. Such tradeoffs are essentially between minimum total weight and minimum technical risk. The design philosophy followed was to minimize the technical risk as much as possible. Also, the generators described are not optimized, in the sense that the channel geometry, magnetic field distribution and electrical loading have not been precisely tailored to each other to the degree necessary for the detailed design of a particular channel. The curves shown do, however, display the general features of the systems described, and neither these nor the weight estimates made will be affected greatly by further optimization.

Figures 1 and 2 present operating parameters for a generator operating on liquid hydrocarbon fuel (RP-1, JP-4, etc.) and oxygen, with cesium seed. These reactants are readily available and have been commonly used in MHD generator experiments to date. Stoichiometric combustion is assumed. The burner is regeneratively cooled by the fuel, in order to reduce heat loss. The channel is separately cooled. Power output of the generator is 31.5 MW. The generator operates at a mass flow rate of 30 kg/sec, with a stagnation pressure of 30 atmospheres. The channel inlet Mach number for this design is 2.2, at which value (approximately) the value of σu^2 is maximized, in order to maximize power density. The calculated electrical conductivity of the working fluid at the channel inlet is 49 mho/m. This value was obtained using an estimated value of 4% of the total enthalpy input for combustion losses, including combustion inefficiencies, heat losses and non-isentropic effects in the nozzle.

The operating characteristics shown are valid for a channel of two-terminal diagonal configuration operating at the design point (no axial current flow) and for a channel of segmented Faraday configuration. Figure 1 shows parameters which are indicative of the electrical and thermal "stresses" to which the channel is subject. These parameters are the electric power output $\mathbb{P}$, the transverse current density, j_y, the axial electric field E_x, and the convective heat transfer to the channel walls, $\dot{q}$.

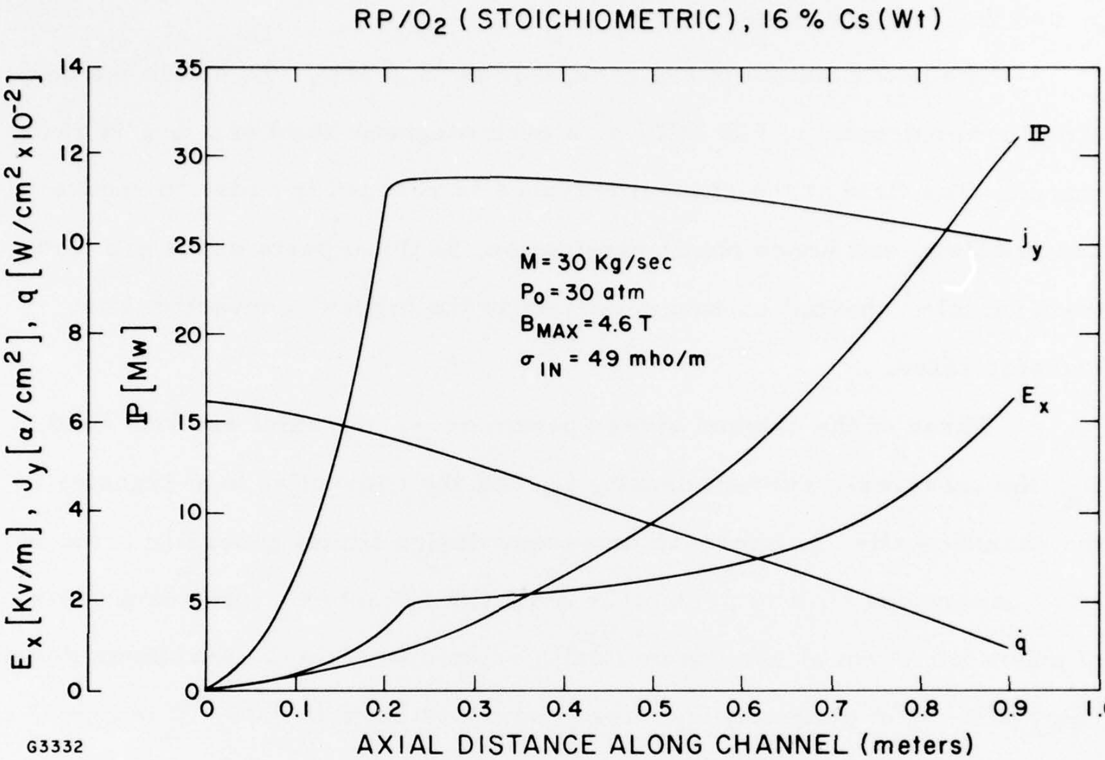

Figure 1 Operating Characteristics of RP/O_2 System at 500 MW/m^3

Figure 2 shows distributions of the magnetic field, B, the static pressure, p, and the Hall parameter $\omega\tau$.

The power output of the generator is 31.5 MW. To obtain the desired power density of 500 MW/m^3 a peak magnetic field of 4.6 T is required. The field at the channel entrance is reduced in order to reduce current flow, and hence ohmic dissipation, to those parts of the gas flow train (nozzle, channel entrance) subject to the highest convective heat transfer rates.

Three of the channel stress parameters: the axial electric field, E_x, the transverse current density j_y, and the convective heat transfer to the channel walls, $\dot{q}$, approach or exceed design limits generally found in MHD generators built to date. The axial field reaches a maximum value of about 6.6 kV/m at the channel exit, as compared to the maximum design value of 4 kV/m generally used for generators built to date. It is noted, however, that axial fields in excess of 4 kV/m have been observed in some machines (e.g., the AERL Mk VI generator) for short times, and it is possible that fields exceeding this value by considerable margins can be sustained by generators operating for short times without need for major advances in the state-of-the-art of MHD channel design. The transverse current density j_y reaches a peak value of about 11.5 amp/cm^2, and the convective heat transfer to the channel walls reaches a maximum value of about 650 W/cm^2 at the channel inlet. This value requires careful design of the cooling system, but presents no basic difficulties. For example, heat transfer rates up to 1 kW/cm^2 are found in conventionally cooled MHD burners, such as the compact MHD burner recently built by AERL.[5]

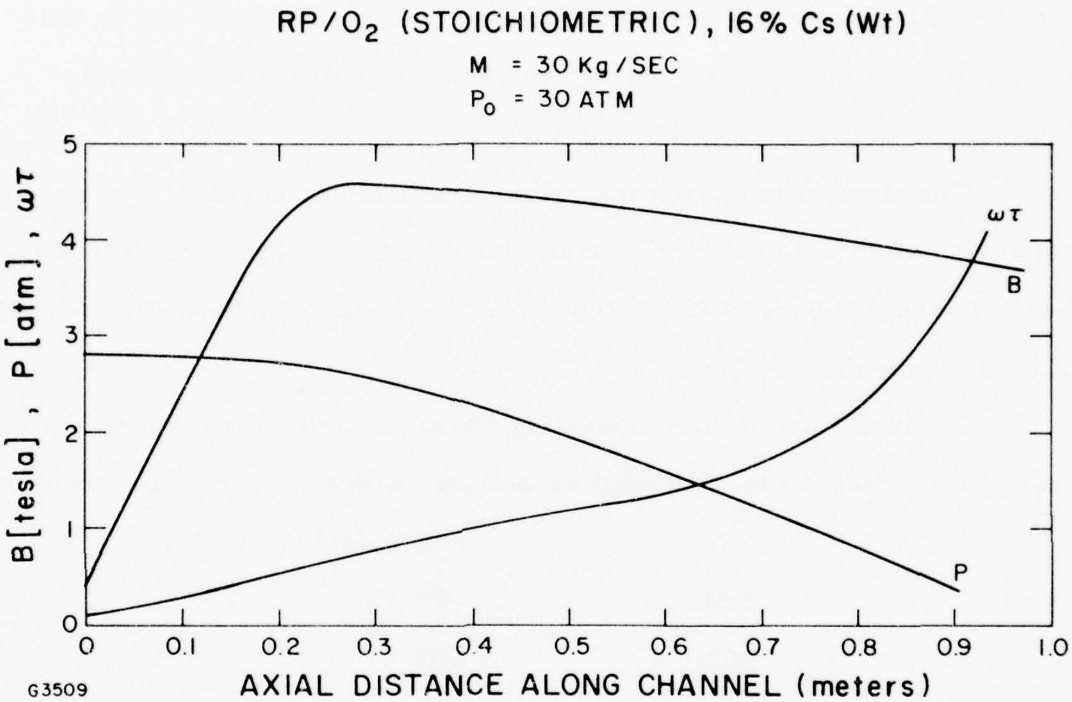

Figure 2 Magnetic Field, Static Pressure, Hall Parameter Distributions of RP/O_2 System at 500 MW/m^3

The total heat loss in the channel due to convective heat transfer to the walls was calculated at 3.4 MW, or about 1% of the total thermal input to the channel. The channel wall temperature is 2000°K. An additional 2.4 MW is dissipated in the electrode wall boundary layers, due to the boundary layer voltage drop, which is about 135 volts at the channel exit.

The channel is approximately square in cross section, with an inlet dimension of 20 cm (gas side) and an exit dimension of 53 cm. The active length is about 0.9 m. Channel construction details, further dimensions, etc., are given in Section III

Figures 3 and 4 show operating characteristics for a generator operating on a cesium-seeded solid propellant, with the following composition:

Aℓ:	23% (weight)
HMX:	8%
NC:	13%
NG:	38%
NDPA:	1%
TA:	2%
$CsNO_3$:	15%

A similar mixture has been used for generators operated previously in the U.S.[6] The effective stagnation pressure is 30 atmospheres, and the total mass flow rate is 30 kg/sec. The channel inlet Mach number is 2.4. The generator power output is 33.2 MW.

The channel inlet conductivity in this system is higher than in the RP-1 + LOX system discussed previously, (70 mho/m compared to 49 mho/m) because of the higher stagnation temperature (4000°K compared

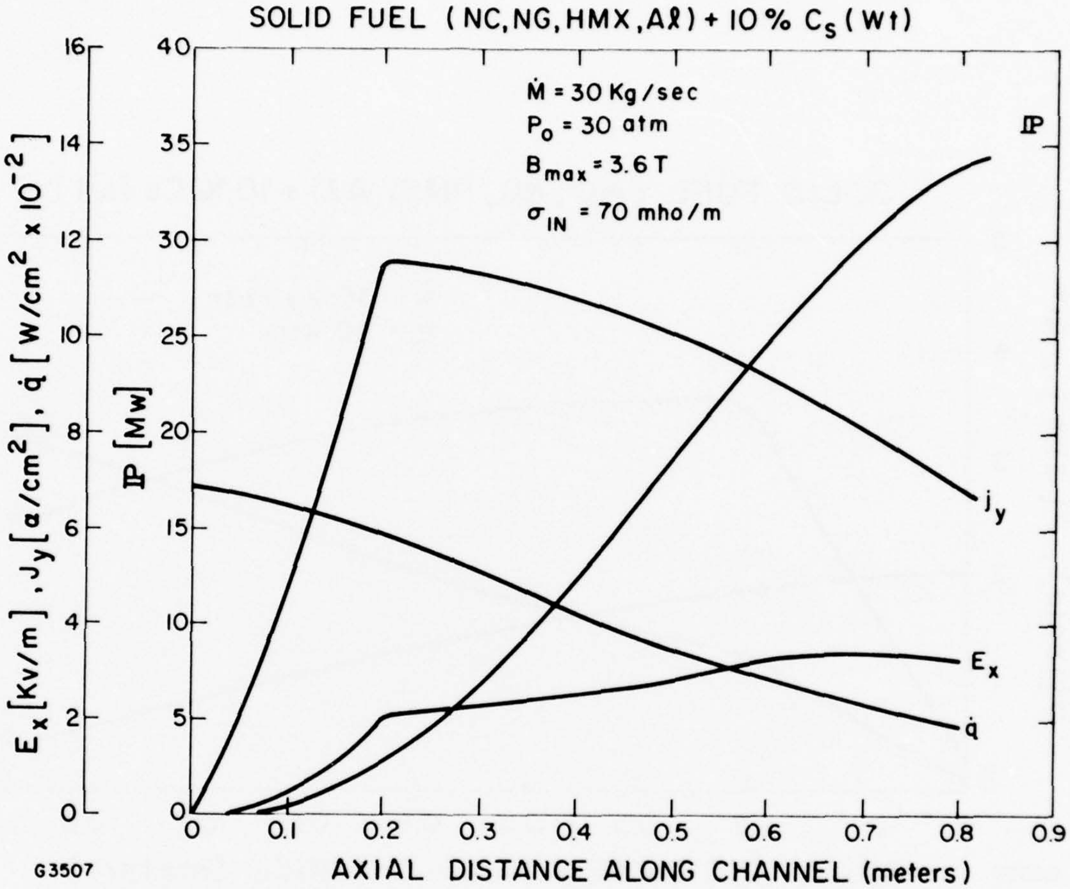

Figure 3 Operating Characteristics, Solid Fuel System at 500 MW/m^3

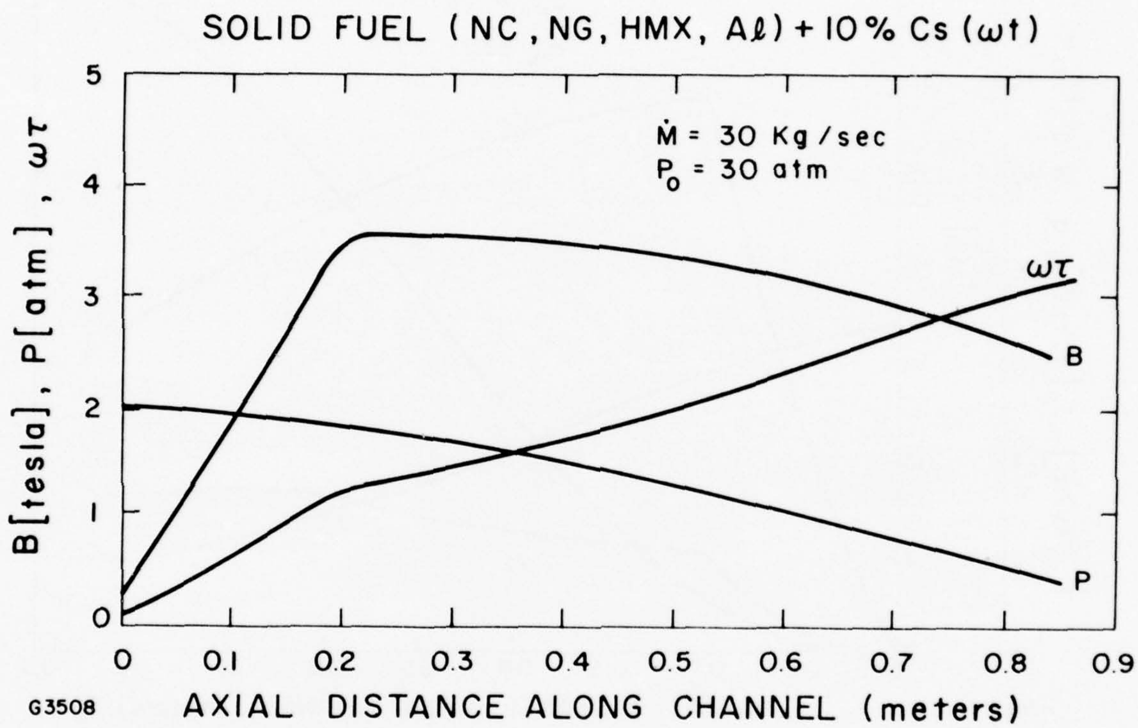

Figure 4 Magnetic Field, Static Pressure, Hall Parameter Distribution, Solid Fuel System at 500 MW/m^3

to 3500°K). The peak magnetic field required is 3.5 T, and the active length of the channel is about 0.8 m. The maximum axial electric field is about 3500 V/m, the maximum transverse current density is about 11.5 a/cm^2, and the maximum heat flux is about 700 W/cm^2. The total convective heat loss in the channel is 3.8 MW, and an additional 2 MW is dissipated due to boundary layer voltage drop (120 volts at the channel exit). The channel inlet is 24 cm square (gas side), the exit is 45 cm square, and the active length is about 0.8 m.

A comparison of the major characteristics of each system is given in Table I. The weight estimates given are for the systems described in more detail in Section III.

TABLE I

MAJOR PARAMETERS, 500 MW/m^3 MHD POWER SYSTEMS

System	RP/O_2	Solid Fuel
Power Output [MW]	31.5	33.2
Power Density, Nominal [MW/m^3]	500	500
Mass Flow Rate [kg/sec]	30 kg/sec	30 kg/sec
Peak Magnetic Field [T]	4.6	3.6
E_x(max) [kV/m]	6.6	3.5
j_y (max) [amp/cm^2]	11.5	11.5
Dry Weight [kg]	2305	1695
Total Weight (60 sec operation) [kg] (includes reactants and coolant)	4625	3820

The stagnation pressure and mass flow rate chosen for the systems described previously are typical and can be varied within limits. Detailed tradeoff studies would be necessary to establish feasibility, risks and benefits of variations in stagnation pressure and mass flow rates. Such tradeoffs were not performed as part of this work, but some of the factors which require consideration are outlined briefly below. For example, an increase in stagnation pressure, as compared to the systems described above, could involve the following tradeoffs:

1. Increased efficiency (reduced flow rate requirement) if expansion is carried out to the same channel exit pressure.

2. Reduced diffuser requirement at the same efficiency since higher channel exit pressures are possible.

3. Increased heat transfer rate.

4. Increased magnetic field requirement (increased magnet weight) due to lower conductivity of working gas.

At a given stagnation pressure, the mass flow rate could be reduced by expanding the flow further than is required at higher flow rates. However, the channel exit pressure would then be lower, and the axial field strength higher than its already high value. Figures 5 and 6 show operating parameters for the same solid fuel as in Figs. 3 and 4 except for a mass flow rate of 25 kg/sec. It is seen that the axial field increases about 50% from 3.5 kV/m to 5.2 kV/m. Operating at even lower mass flow rates is possible, but at higher axial fields, and hence, greater risk to the channel.

C. CHANNEL RISK ASSESSMENT

The major cause of forced shutdown of MHD generators is destructive electrical breakdown between axial wall elements. Assessment of the

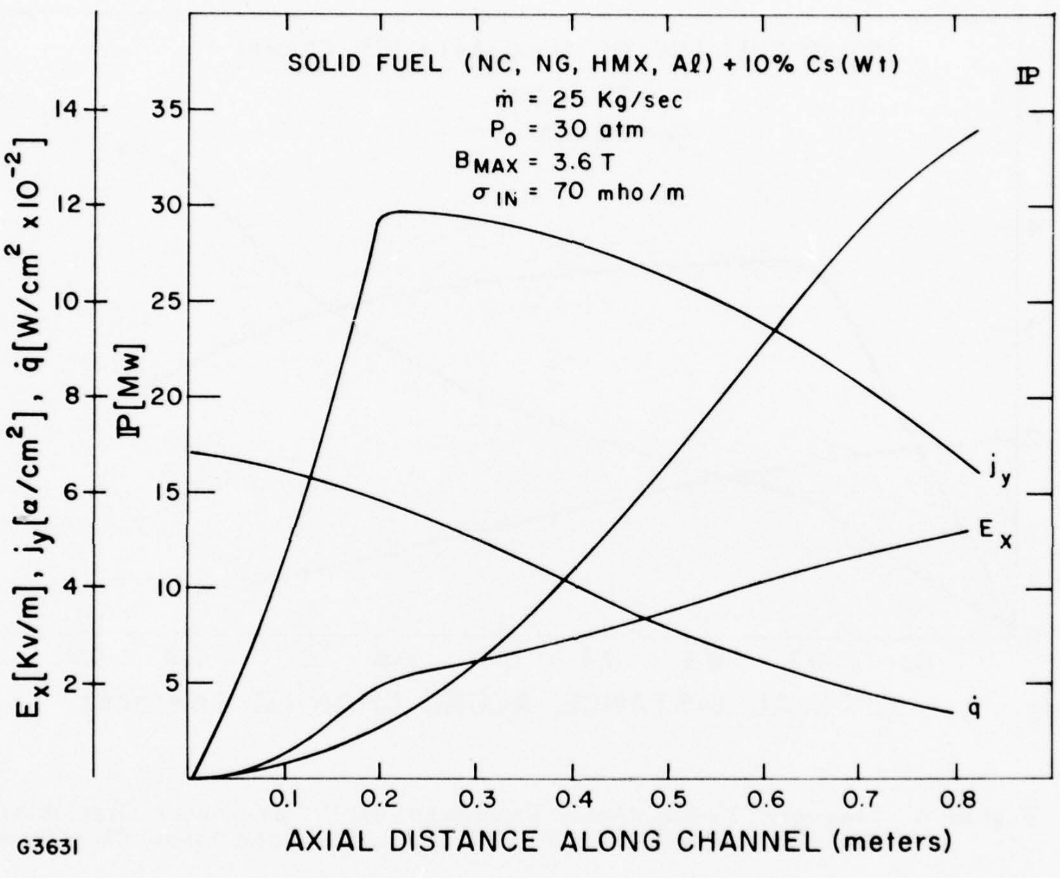

Figure 5 Operating Characteristics for Solid Fuel System at 500 MW/m^3, Reduced Mass Flow Rate

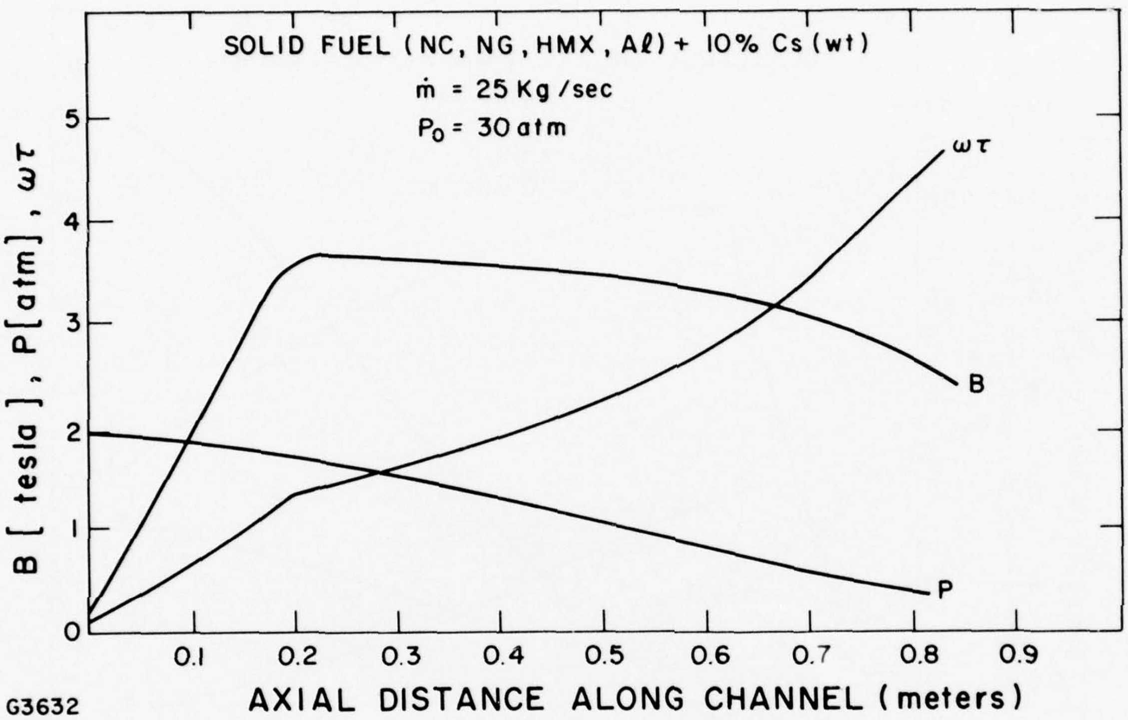

Figure 6 Magnetic Field, Static Pressure, Hall Parameter Distribution for 500 MW/m^3 Solid Fuel System, Reduced Mass Flow Rate

risk of such shutdowns, which can be associated with extensive damage to the channel, is influenced by three main factors:

a) The probability of occurrence of axial breakdown (arcing).

b) The potential power available either to couple into such breakdowns.

c) The time duration over which the potential fault power can act (total operating duration).

The main criterion used to assess the probability of occurrence of breakdown is the axial electric field in the channel, because breakdown occurs in a short time, of the order of a few seconds, at values of axial field above some threshold value. High axial fields for durations exceeding a few seconds are therefore a major risk factor in channel design and operation. Operation at low axial fields does not, however, ensure that axial breakdown will not occur. Such breakdown could, for example, be initiated by the partial shorting of an interframe insulator, which could occur for a variety of reasons, e.g., local overheating of the insulator or seed or water penetration into the insulator material over some time period or over some number of generator startups or shutdowns.

Because of the fault, current leakage occurs through the insulator, with an associated amount of power dissipation. If the power dissipation in the insulator is nonuniform, as is likely, that region in which the highest power dissipation occurs reaches higher temperature than surrounding regions, with a corresponding drop in electrical resistance. This in turn draws more leakage current to that region, thus further increasing the dissipation and worsening the fault, and the net result is a strong local current concentration in the insulator, i.e., an arc.

The power available to couple into breakdowns caused by excessive axial electric fields or by faults such as described above is influenced strongly by the specific details of the channel design and its control devices. Therefore, this fault power is not shown on the curves of Figs. 1 - 6. Accurate quantitative prediction of damage power leading to channel failure is in fact not yet possible, but estimates can be made, as follows. The power which can be coupled into an insulator breakdown or fault is of the order of the voltage difference between the adjoining current-carrying elements times the current carried by such elements. For a channel of two-terminal diagonal configuration, constructed of so-called "window frames" with active length ℓ, and with pitch p, the interframe voltage is $(E_x p)$ and the frame current is $(J_y \ell_p)$, where E_x is the axial electric field in the channel and J_y the transverse current density. The fault power is then given by:

$$p_{fault} = (E_x J_y)\, \ell p^2 \cong (E_y J_y)\, \ell p^2 \; (\sim 45^{\circ} \text{ connection})$$

$(E_y J_y)$ is the power density in the generator. It is clear that the pitch should be made as small as is practically possible in order to reduce fault power. For a window frame channel, this is about 1 cm, since window frames thinner than this are difficult to fabricate. The power density is 500 MW/m^3. Assuming 1 cm pitch, we have:

$$p_{fault}\,[\text{watts}] = 500\, \ell\,(\text{cm})$$

The RP/O_2 channel has an inlet cross section of 20 cm x 20 cm and an exit cross section 53 cm x 53 cm as described previously. Thus, a typical dimension ℓ for a frame about in the middle of the channel is 36.5 cm and the fault power is about 18 kW.

The solid fuel channel has dimensions of 24 cm (inlet) and 45 (outlet) with an average frame dimension of 34.5 cm, and the fault power is about 17 kW.

The channel risk factors listed in a) - c) above, together with other performance parameters of interest for various generators are shown in Table II, which lists as a summary of the present status of this technology, combustion-driven generators designed for high performance which have been operated to date. Both liquid and solid-fueled generators are listed. The Mk V (two terminal) and Pamir-1 generators have non-segmented electrode walls without insulators. These have a different breakdown mechanism from the other channels shown, and so comparison on the same basis is not valid. The 30 MW generator in the table is a two-terminal diagonally connected channel of window frame construction. It is seen that in terms of fault power and operating duration, the high power density generators considered herein operate in a regime considerably in excess of the existing state-of-the-art and thus must be considered high risk devices.

A potential technique by which the risk can be reduced is to reduce the breakdown power available to produce an arc or to couple into an insulator fault. For a fixed value of pitch it was shown that the breakdown power increases linearly with the generator size, i.e., scales up like the power per unit wall area. When the generator size becomes large enough, as in the design channel, so that excessive breakdown power exists, the breakdown power per wall element can be kept below the value which would result in wall destruction by limiting the size of the wall element, i.e., by splitting the frames.

TABLE II

TYPICAL OPERATING PARAMETERS OF VARIOUS COMBUSTION DRIVEN MHD GENERATORS COMPARED TO DESIGN 30 MW MHD GENERATOR

MHD GENERATOR	Mass Flow Rate (kg/sec)	Power Density (MW/m^3)	Power Output (MW)	Axial Electric Field (kV/m)	Operating Duration (sec)	Breakdown Power (kW)
1. MK II - Faraday	2.7	40	1.5	1.5	10	3.2
2. MK II - Circular Hall	4.3	20	1.0	2.3	10	0.5
3. LORHO - Pilot	52	10	18	2.8	60	1.5
4. MK V - Segmented	52	10	32	1.5	60	5
5. MK V - Two Terminal	50	16	25	0*	60	-
6. APL High Performance	0.82	150	0.4	2.7	10	0.75
7. VIKING I	2.7	75	1.4	2	3	1
8. Hercules (Solid Fuel)	3.3	120	2.4	4	5	2.2
9. Pamir I - USSR (Solid Fuel)	25	500	15	0*	3	-
10. 30 MW Design (RP/O_2)	30	500	30	6.6	60	18
11. 30 MW Design (Solid Fuel)	30	500	30	3.5	60	17

*Two terminal Faraday Configuration

This technique can be used in conjunction with current control devices (e.g., resistors, in the simplest case) in order to reduce the power capable of coupling into any single element. A possible segmentation/control scheme, typical of that used in the AERL Mk VI long-duration generator, is shown in Fig. 7.

D. OPERATING CHARACTERISTICS OF 1000 MW/m^3 GENERATORS

Operation of channels at power densities of 1000 MW/m^3 was investigated. In principle, these high power densities can be obtained by use of increased magnetic fields, and/or by use of gases with higher value of the produce σu^2. For the reactants investigated, the product σu^2 was approximately maximized, and for these reactants, high power densities can be achieved only by use of increased magnetic fields. This results in large increases in axial electric field and thus increases the risk of axial breakdown in the channel. Furthermore, the high magnetic fields required result in heavier magnets, which offsets the weight grains which otherwise might be expected.

Table III shows some parameters of the cesium-seeded solid fuel system operated at a nominal power density of 1000 MW/m^3. Characteristics for operation at 500 MW/m^3 are also shown for comparison. It can be seen that at power densities of 1000 MW/m^3 axial fields in the channel are high, and that the reduction in total weight is less than 10% compared to operation at 500 MW/m^3. The axial fields can be reduced by operation at higher mass flow rate, as explained previously, but the total weight, including reactants, is then greater for operating durations of interest.

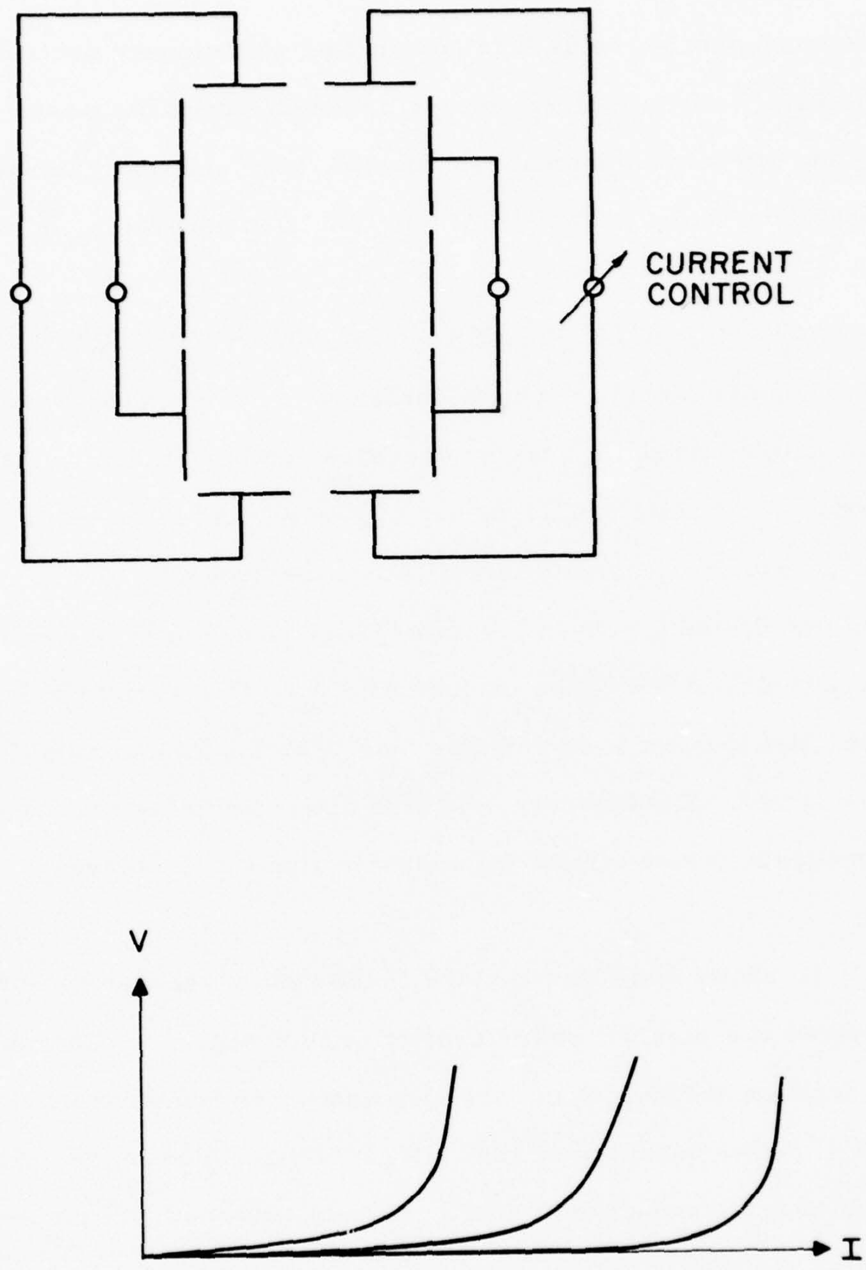

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Figure 7 Frame Segmentation and Control

TABLE III

SYSTEM WEIGHTS COMPARISON

(Solid Fuel, Cs Seed)

Nominal Power Density [MW/m^3]	500	1000
Power Output [MW]	33	32
Mass Flow Rate [kg/sec]	30	30
Peak Magnetic Field [T]	3.6	4.5
E_x (max) [kV/m]	3.5	8.8
j_y (max) [amp/cm^2]	11.5	13.6
System Dry Weight [kg]	1695	1480
Total Weight (60 sec operation) [kg] (includes reactants and coolant)	3820	3530

Operation at power density of 1000 MW/m^3 and with lower axial fields can be achieved by use of working gases with higher electrical conductivity, such as $C_2N_2 + O_2$ with cesium seed. This working gas has an electrical conductivity of 150 mho/m, about double that obtainable with the solid fuel. Operating parameters for this case are shown in Table IV and it is seen that axial fields reach a maximum value of about 6.5 kV/m, which is considerably less than those of the solid fuel systems operated at the same power density. Transverse current density is increased by about 15%.

The most attractive systems are the cesium seeded solid fuel systems, operated at 500 MW/m^3 and the RP/O_2 system, also at 500 MW/m^3. Operation at higher power density increases significantly the risks involved in channel development, with reduction in total weight of only about 10%. To choose

TABLE IV

$C_2N_2 + O_2$ SYSTEM CHARACTERISTICS

Nominal Power Density [MW/m^3]	1000
Power Output [MW]	33.6
Mass Flow Rate [kg/sec]	30
Peak Magnetic Field [T]	4.2
E_x (max) [kV/m]	6.5
j_y (max) [amp/cm^2]	19.2
System Dry Weight [kg]	1660
System Total Weight [kg] (includes reactants and coolant for 60 sec operation)	3730

between the two systems requires consideration of reactant handling and storage systems and auxiliary systems. Some discussion is given in Section III.

The cyanogen fuel systems can probably be eliminated from consideration because the fuel is toxic and poses severe handling problems.

SECTION III

SYSTEM DESIGN

Figures 8 and 9 are functional block diagrams of the RP/O_2 system and the solid fuel system, respectively. The major components and subsystems are shown, including the gas flow train, magnet, cooling system controls, and the reactant storage and feed system (RP/O_2 system only). The cooling system is necessary for the channel and diffuser for pulse durations which exceed the component capability for heat sink operation. The liquid fuel combustor is regeneratively cooled, and the solid fuel combustor is ablatively cooled. The principal difference between the solid and liquid-fueled systems is that no reactant storage and feed system is necessary for the solid-fueled generator. The major subsystems of the generators are discussed in the following subsections.

A. ESTIMATED WEIGHTS

Estimated weights are given in Table V for the MHD generator power supplies shown in Figs. 8 and 9. Weights given include those of the burner and nozzle, channel, diffuser (operation at sea level is assumed), magnet and consumables. Table V shows weights of systems designed for continuous operation, or pulsed operation at short intervals, and therefore include also the weight of a channel cooling system. In the case of the solid fuel systems, the weight of the burner depends on the total amount of reactant required, since burner and reactants are integral with each other. The propellant weight fraction was assumed to be 90%.

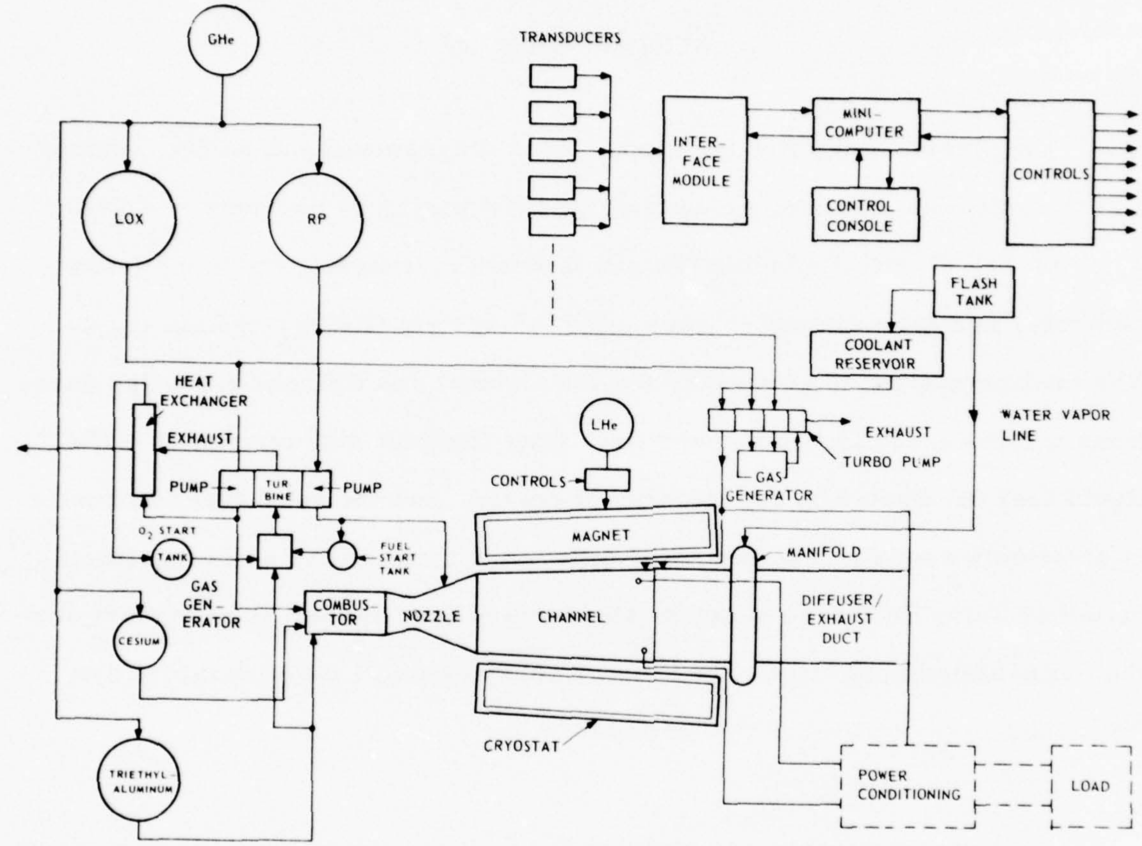


Figure 8 RP/O_2 System Block Diagram

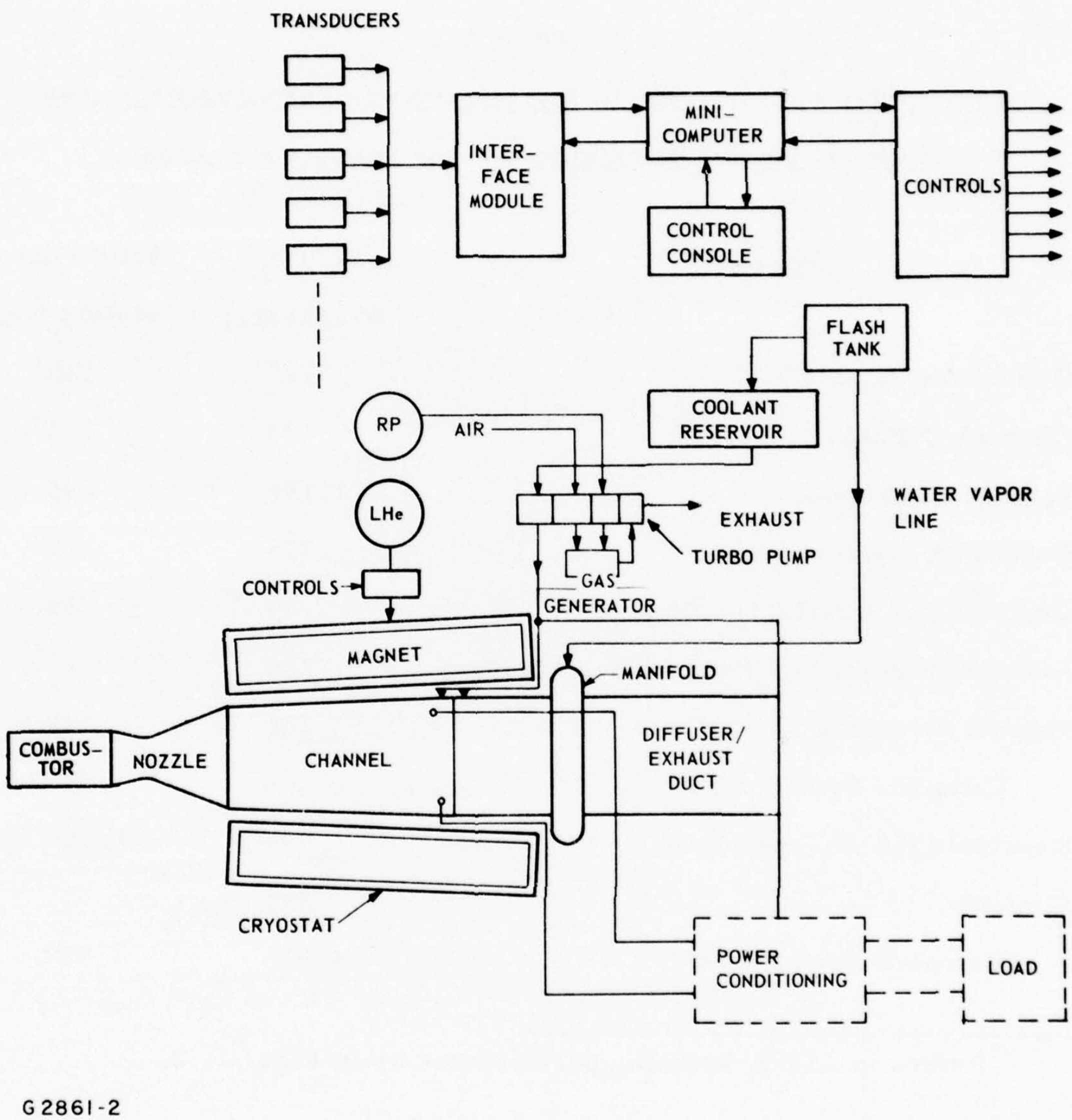


Figure 9 Solid Fuel System Block Diagram

TABLE V

ESTIMATED WEIGHTS OF 30 MW (NOMINAL) MHD GENERATORS

POWER DENSITY IN CHANNEL: 500 MW/m^3 (NOMINAL)

System	RP/O_2 * Weight (kg)	Solid Fuel** Weight (kg)
Combustor/Nozzle	125	180†
Channel/Diffuser	130	110
Magnet Subsystem	1,190	890
Cooling Subsystem (dry)	215	215
Controls and Instrumentation	80	80
Reactant Storage and Feed Subsystem (dry)	285	-
Support Structure	280	220
Complete System (dry)	2,305	1,695
Reactants (60 sec operation)	1,995††	1,800
Coolants	325	325
Complete System (wet)	4,625	3,820

*Refers to RP/O_2 system, performance as in Figs. 1, 2.

**Refers to solid fuel system, performance as in Figs. 3, 4.

† Propellant fraction = 0.9.

†† Includes 10% ullage.

Estimates of component weights in Table V are based on recent work including the detailed design of a ground-based prototype 10 MW MHD generator,[7] and represent current state-of-the-art technology. The weights shown do not include the weight of power conditioning equipment which may be required. If shielding is necessary for the magnet, the magnet weight and thus the system weight, is increased considerably. The specific amount by which the weight is increased depends on the degree of shielding required.

The cooling system in the table is primarily for cooling of the channel and diffuser, but not of the burner, since liquid fuel burners can be regeneratively cooled by the reactants and solid fuel burners are uncooled. For operation at durations up to about 30 seconds, heat-sink operation of flow train components may be possible, thus eliminating the need for the cooling system. The weight saving so made is considerable, for most systems, as can be seen from Table V.

The solid fuel system is about 17% lighter in total weight than the liquid fueled system, for 60 seconds operating time. This is possible for two main reasons:

1. The solid fuel system needs no reactant storage and feed system.
2. The magnet is of lower field, and hence, lighter weight, because of the increased conductivity of the solid fuel (70 mho/m) compared to the liquid fuel (49 mho/m).

B. GENERATOR DESIGN

Design layouts of the gas flow train and magnet for both the solid fueled and the liquid fueled generators are shown in Figs. 10 and 11.

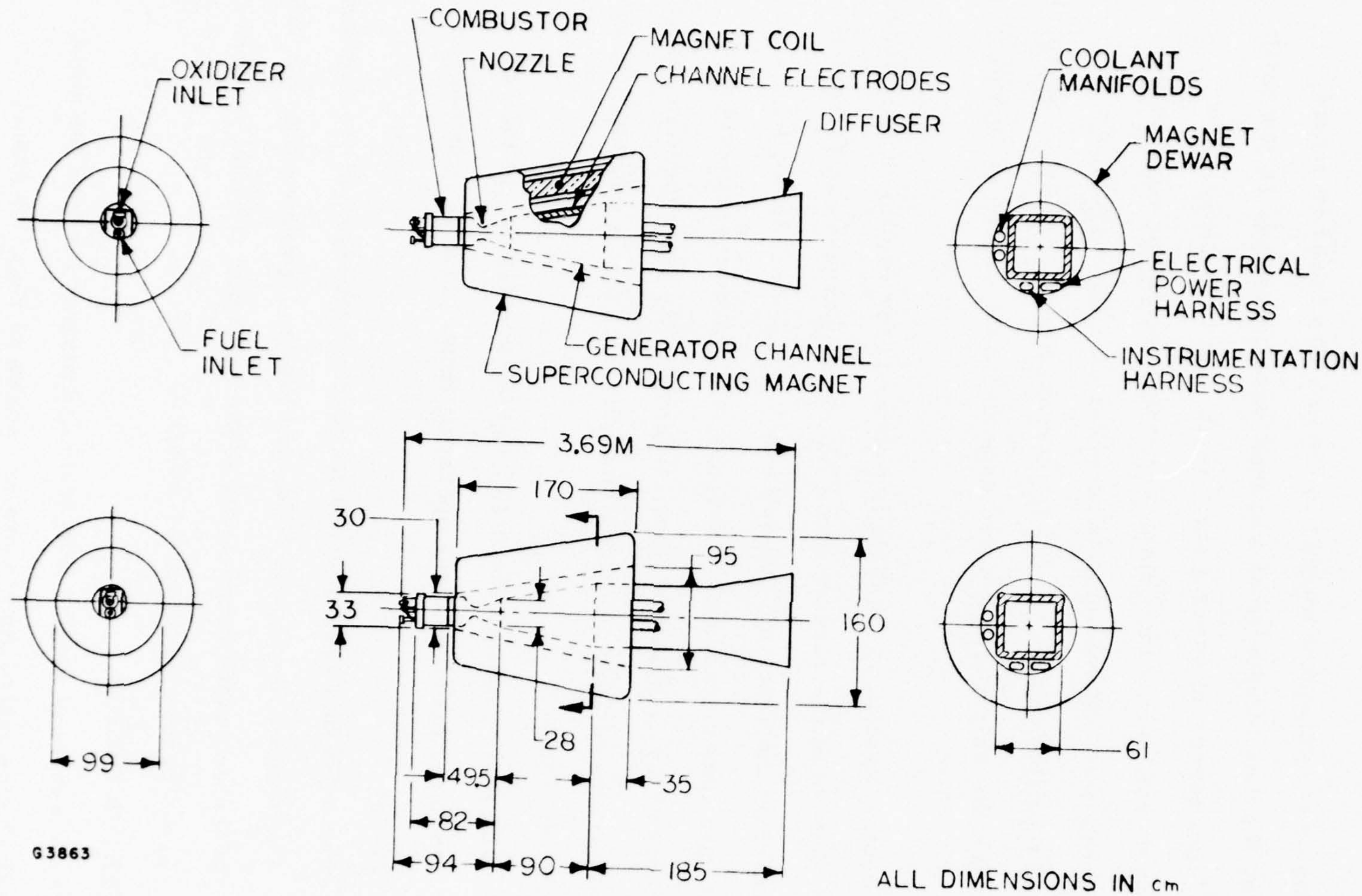


Figure 10 Gas Flow Train and Magnet, RP/O_2 System

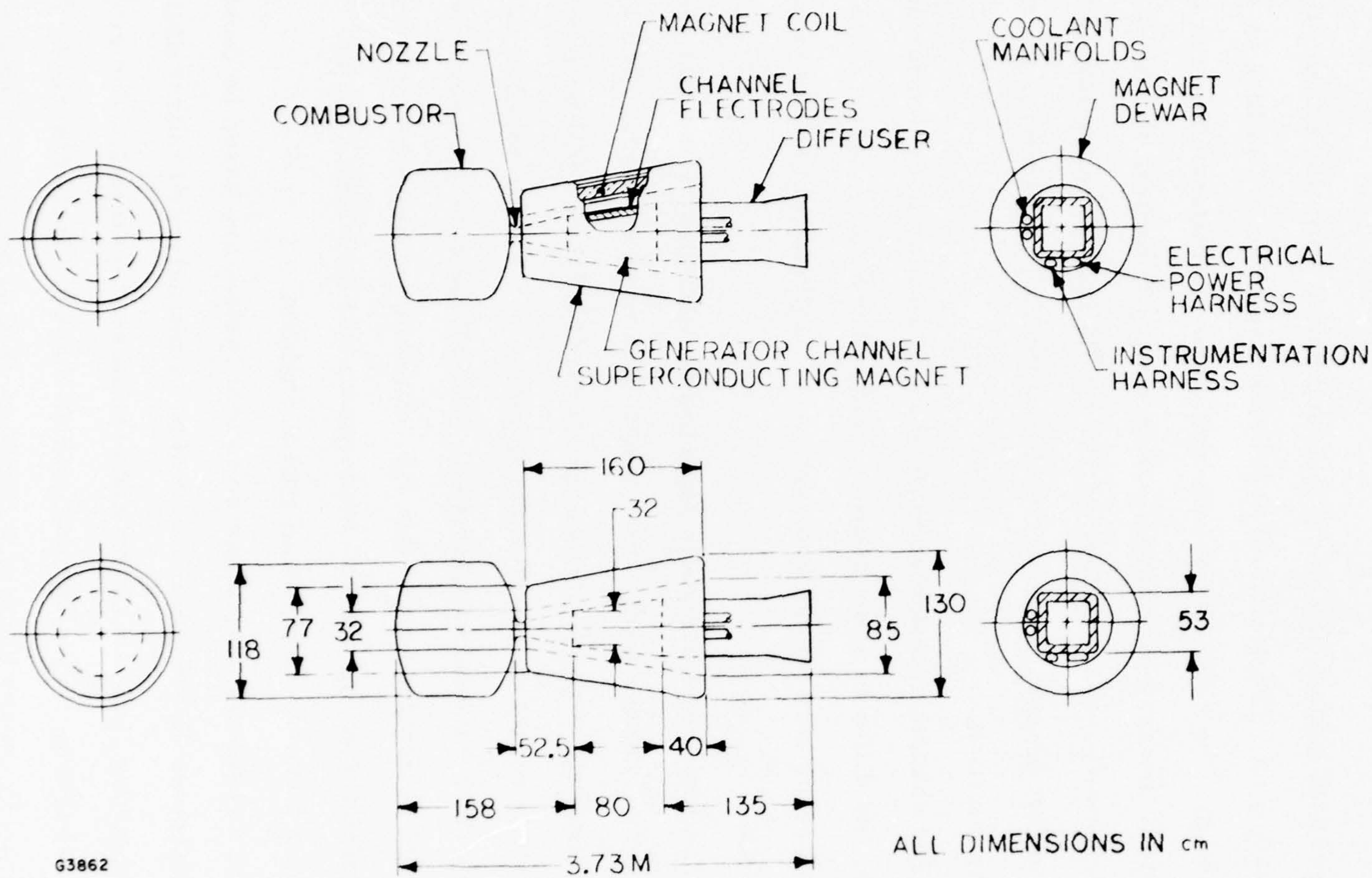


Figure 11 Gas Flow Train and Magnet, Solid Fuel System

The liquid fuel system has an overall length of 3.7 m, and an overall diameter of 1.6 m. The solid fuel system is also about 3.7 m long by 1.3 m in diameter. The solid fuel system has a shorter diffuser than the liquid fuel system, because the channel exit pressure is higher, and the diffuser can have lower pressure recovery. The solid fuel burner is larger than the liquid fuel burner, because it contains the fuel required for the total operating duration.

The channel, magnet and diffuser are similar in design for both systems, but differ to some degree in dimensions and weights. The principal difference between the two systems is in the burners and associated subsystems.

The liquid fuel burner is regeneratively cooled by the fuel, and follows conventional rocket engine practice in most respects. The need for adequate seeding of the generator means that the burner will be somewhat larger than a rocket engine with the same mass flow rate to allow adequate residence time for seed vaporization. For pulsed operation some development would be required since this type of operation imposes requirements on the ignition system, the fuel feed system and the cooling system which differ from those of conventional rocket engines.

The reactants used in the solid fuel system are based on those used for the Hercules X-259-A6 rocket motor: a nitroglycerin-nitrocellulose base, containing HMX aluminum and cesium seed material. The grain is internally burning, with a burning rate of about 0.3 inches/second. This combination is chosen because it has been used as an MHD generator fuel by Hercules Powder Company,[6] at effective stagnation pressures of about

30 atmospheres, as required in the generators investigated here. For continuous operation a scaled version of the X-259-A6 motor itself could be used. The motor contains about 1200 kg of propellant and has an action time of about 33 seconds. For continuous operation of an MHD generator at 20 kg/sec for 60 seconds (nominal conditions), the web of the grain would be about twice as thick as in the rocket motor, and the grain would be shorter.

For pulsed operation of solid fueled gas generators of the size required for the MHD generator more extensive development will probably be required. Solid rocket motors operated in multiple bursts to date have been relatively small. A multiple burn solid propellant rocket motor design was used in the SRAM program. The multiple burns were accomplished by means of insulator/igniter units in the form of wafers which separate individual grains. However, the gas generator for the MHD applications would differ in the following major respects from the SRAM rocket motor:

1. A multi-burn capability of 20 is required, versus 2 for the SRAM motor.
2. The MHD gas generator is about 2 - 2 1/2 times the diameter of the SRAM motor.

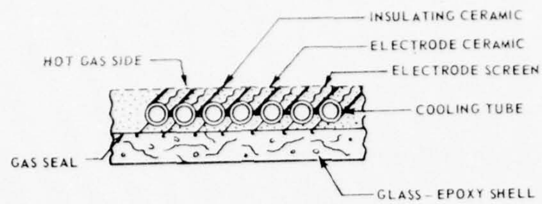
In addition to the SRAM motor, which was less than half the diameter of the proposed MHD gas generator, another motor, also with separator wafers, was operated for some 40 pulses of 5 second duration per pulse.[8] However, this motor has a mass flow of about 2.7 kg/sec, or about 10% that of the proposed MHD gas generator.

Pulsed operation using wafer insulator/igniters, in the sizes required for the MHD application, would require an end-burning grain configuration with a faster burning rate than the grain used in the X-259-A6 motor. For typical pulsed applications, i.e., pulses of 7 seconds each at a mass flow rate of 30 kg/sec, the grain length per pulse is about 5 cm, at the burning rate of 0.3 inch/sec. The grain weight required is 210 kg, and the grain diameter can then be found to be about 1.7 m. A grain of this configuration may be difficult to ignite with SRAM-type wafers, because of the very small thickness of the grain, relative to the diameter. Higher burning rates would allow longer grains of smaller diameter. A burning rate of 0.6 inch/sec was assumed for the design layouts.

The channel, magnet, diffuser and channel cooling system follow designs developed previously for a compact 10 MW MHD generator.[7] Figure 12 shows details of channel construction and also shows a non-power producing model channel which was built and tested in a previous program to verify the design ideas. The channel is constructed of essentially continuous window frames. If segmented frames are found to be necessary, as discussed in the previous section, design modifications can be made to accommodate this requirement.

The frames are formed of thin-wall copper tubing which is shaped to form the proper cross section and which are oriented at the appropriate diagonal angle to the flow (Fig. 12(b)).

The gas side (current-carrying) surfaces are of zirconia ceramic cast between fins which are brazed to the tubes (Fig. 12(a)). Insulating ceramic (magnesia or alumina) is cast between adjacent tubes. A filament-wound glass reinforced epoxy shell is laid up around the tubes and bonded to them. The shell is the main structural member of the channel. The gas



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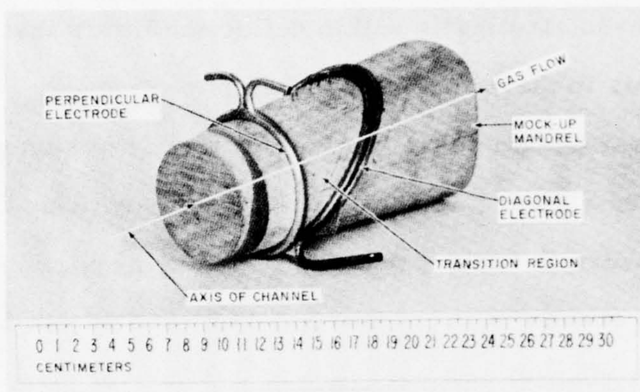
a) Lightweight Channel Construction Technique



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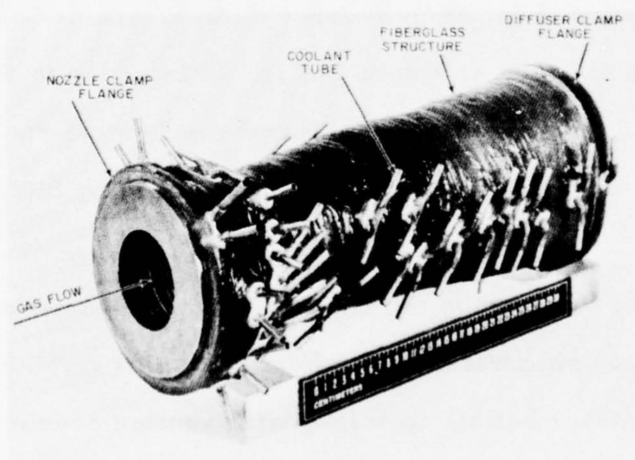
b) Frame Construction



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LIGHTWEIGHT OPERATIONAL MODEL CHANNEL WEIGHT ~30LBS

c) Lightweight Model Channel

Figure 12 Lightweight Channel Design

seal is a layer of silicon rubber between the shell and the tubes. The gas-tight seals are made around the tubes which project through the outer shell.

A conceptual design of the magnet is shown in Figs. 13 and 14. The magnet uses fully bonded coil windings to support transverse shear and compressive forces. A support structure external to the windings supports overall magnet loads elastically within deflection limits that do not induce excessive stresses in the winding structure.

The diffuser design consists of a constant area supersonic diffuser section followed by a diverging subsonic diffusion section. The length of the diffuser is governed by the pressure recovery required (ratio of ambient pressure to channel exit pressure). For recovery to 1 atmosphere (sea level) from a channel exit pressure of 0.45 atmospheres, as for the RP/O_2 system (Fig. 2), a diffuser of length equal to about 3 inlet diameters (channel exit diameter) is required. For the solid fuel case with higher channel exit pressure (Fig. 4), a shorter diffuser can be used. The diffuser can be partitioned as shown in Fig. 15 in order to reduce the effective length, but this introduces additional mechanical and cooling system complexity. Thrust loading could be minimized by bifurcation of the exhaust duct.

The cooling system for the channel is a pump-driven forced convection closed loop using water as the heat transport fluid, in combination with a secondary water boiloff open loop with venting overboard. The flow diagram for the system is shown in Fig. 16. Similar systems, but on

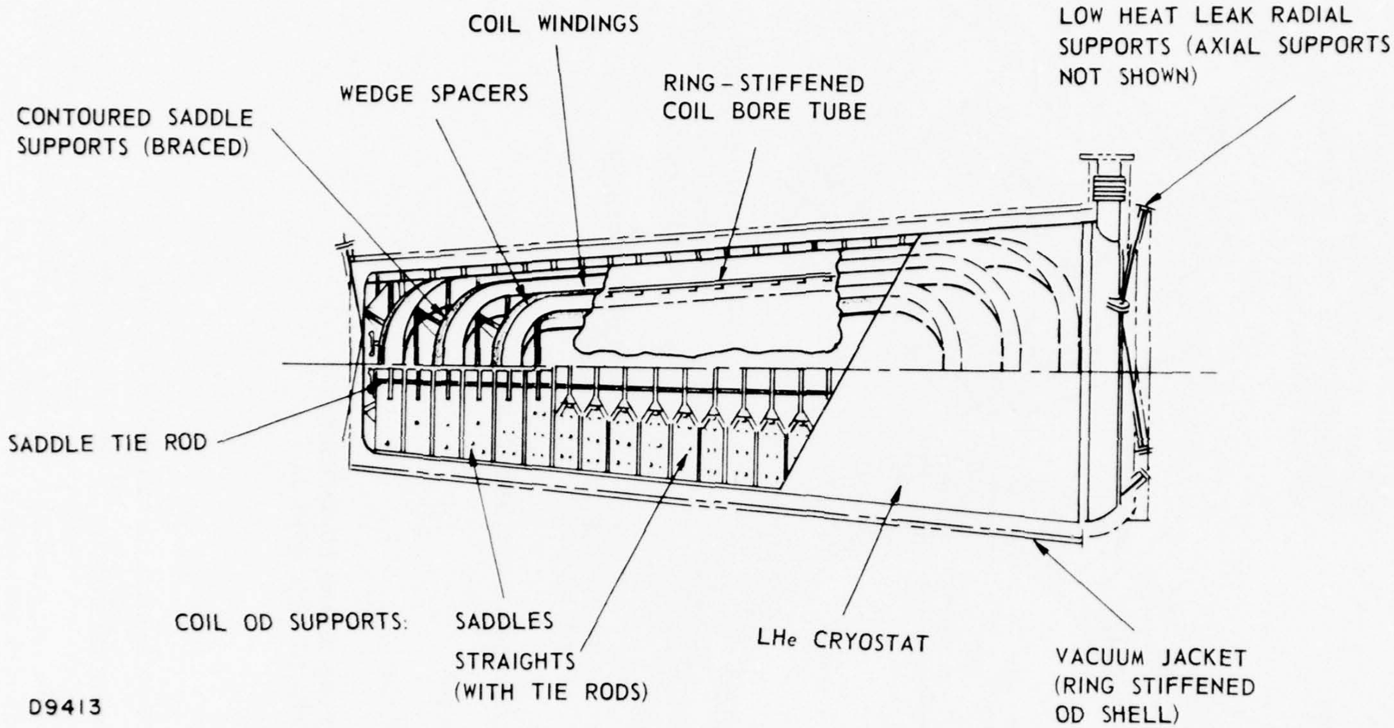

Figure 13 Conceptual Design of the Coil Support and the Cryostat Assembly

The main features of the coil geometry, the support approach and the cryostat construction are indicated. The coil has six individual winding regions (Case No. 19 geometry). The lateral support combines the bore tube and the OD support members along with the wedge spacers and the windings to form a stiff overall beam section. The saddle supports combine the bore tube, members anchored to the bore tube, clamp rings and axial tie rods to provide three-dimensional constraint of the windings.

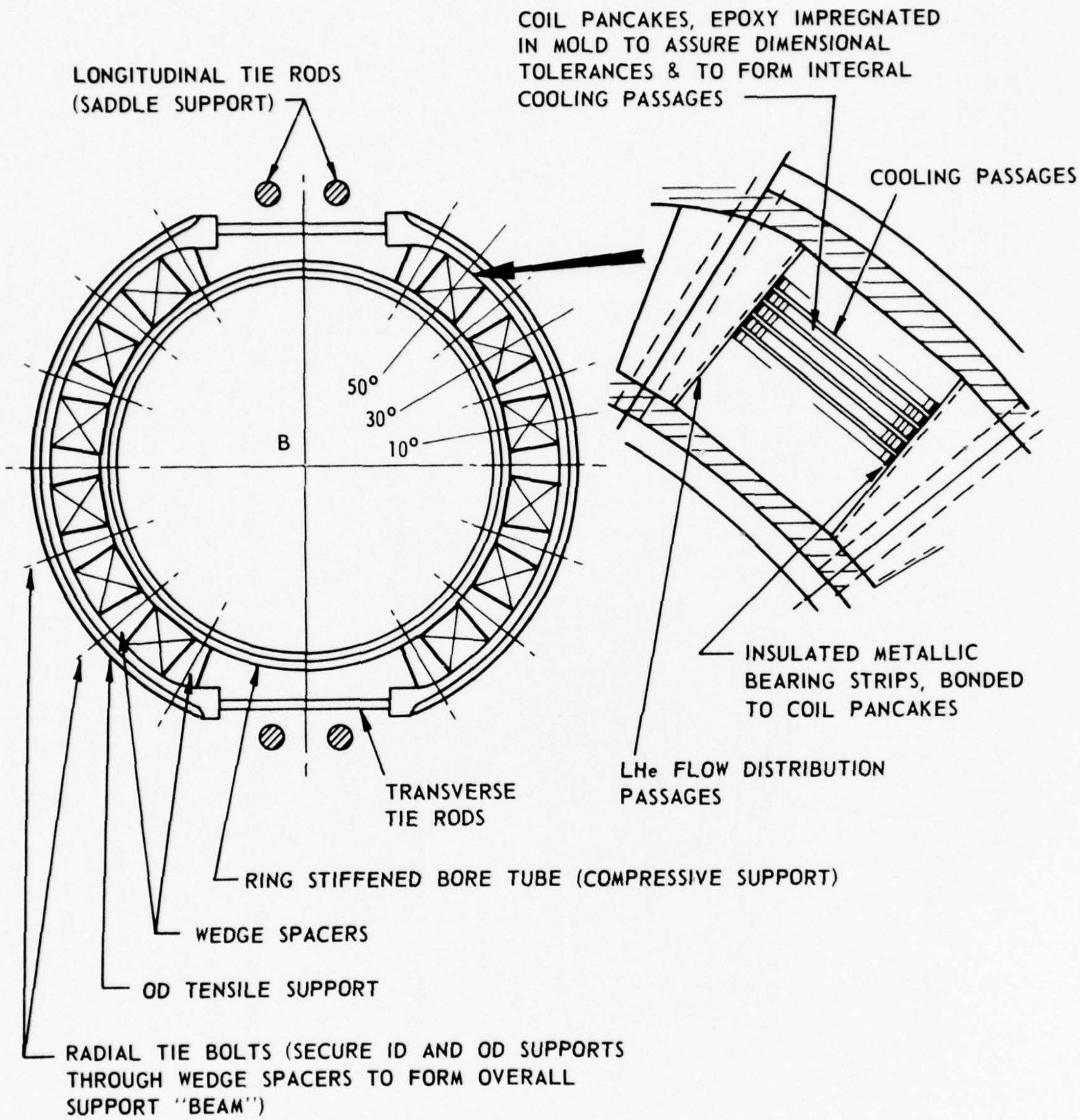

Figure 14 Transverse Section through the Magnet

The conceptual details of the lateral support structure and the winding arrangement are shown. The cooling passages in the windings and the flow distribution passages in the support structure are indicated, but the overall circulation pattern and flow manifolding is not shown.

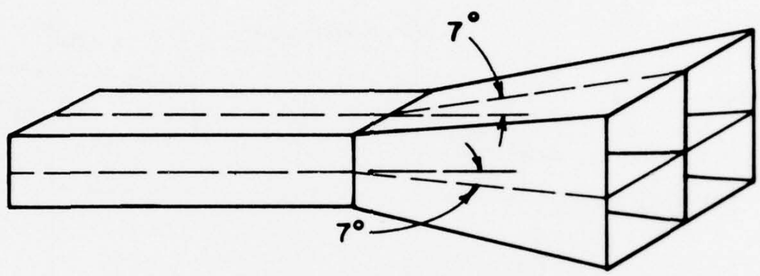

Figure 15 Multi-Cell Diffuser Configuration

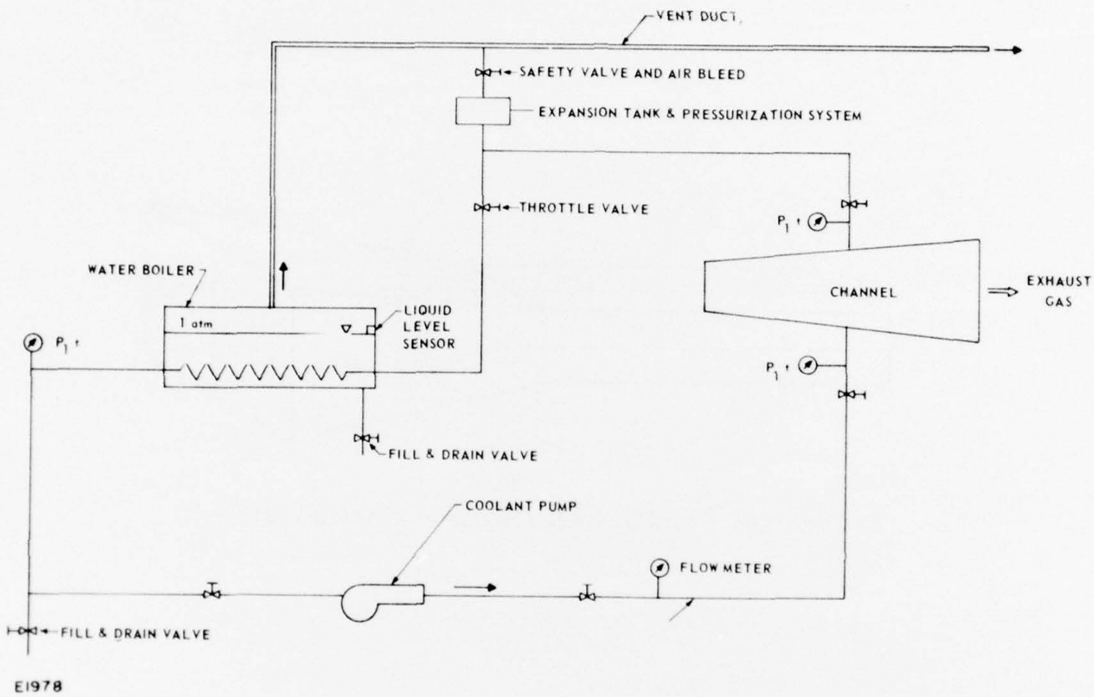

Figure 16   Flow Diagram for Channel Cooling System

a much smaller scale, have been used successfully for airborne electronics equipment cooling. Lightweight, high-performance pumps which meet anticipated temperature and pressure requirements are available and the water boiler can be custom designed on the basis of aerospace heat exchanger design experience.

C. REACTANT STORAGE AND HANDLING

A major difference between the liquid fuel system and the solid fuel system is that the liquid fuel burner requires a reactant storage and feed system, and the solid fuel burner does not, since the burner and its reactants are essentially integral. The reactant storage and feed system is an important subsystem of the liquid fuel generator and affects both the size and weight of the complete system and its operation. Differences between the two systems due to the storage, feed and handling of the reactants are discussed below.

1. <u>Liquid Fuel Combustor</u>

a) <u>Operational Mode</u>

The combustor is regeneratively cooled, using the RP fuel as the coolant. The oxidizer is liquid oxygen, fed to the combustion chamber injector by a trubo-pump which also pumps the RP through the system. The turbo-pump system was selected over a pressurized tank feed system in order to avoid pressurizing large reactant tanks. Seed is injected into the combustion chamber as a liquid from a pressurized tank. The tank is small because of the small amount of seed used.

The main operational advantage of this system over the solid propellant system is that the number of firing pulses and the minimum pulse length can be varied. The importance of this depends on the specific application. Because of the many components in the liquid fueled system, its inherent reliability is not as high as that of the solid propellant system. However, experience gained with space hardware has demonstrated that high reliability can be obtained. By using a programmable sequencing logic system in conjunction with all the start/stop and running steps, it is possible to have essentially the same one push button firing control as in the solid propellant system.

b) Storage and Feed Systems

A schematic diagram of the reactant storage and feed system is shown in Fig. 17. The system is sized for 60 seconds of operation. Briefly, the system consists of:

(i) Gas Storage Assembly - A titanium alloy helium tank with a capacity of 6 lbs at 3000 psi, fill and vent valve, isolating valves, regulators and check valves to prevent the inadvertent feedback of propellants into the gas system.

(ii) Propellant Storage Assembly - The oxygen tank is a vacuum insulated aluminum alloy tank of 3020 lb capacity with a design operating pressure of 35 psia. The fuel tank is aluminum alloy with a capacity of 1250 lbs and operating pressure of 15 psia. The cesium tank of A286 stainless steel has a capacity of 300 lbs and an operating pressure of 660 psia. The triethylaluminum used for igniting the propellants is stored at 400 psia. 21 lb of triethylaluminum is provided. The tank is made of 6061-T6 aluminum alloy.

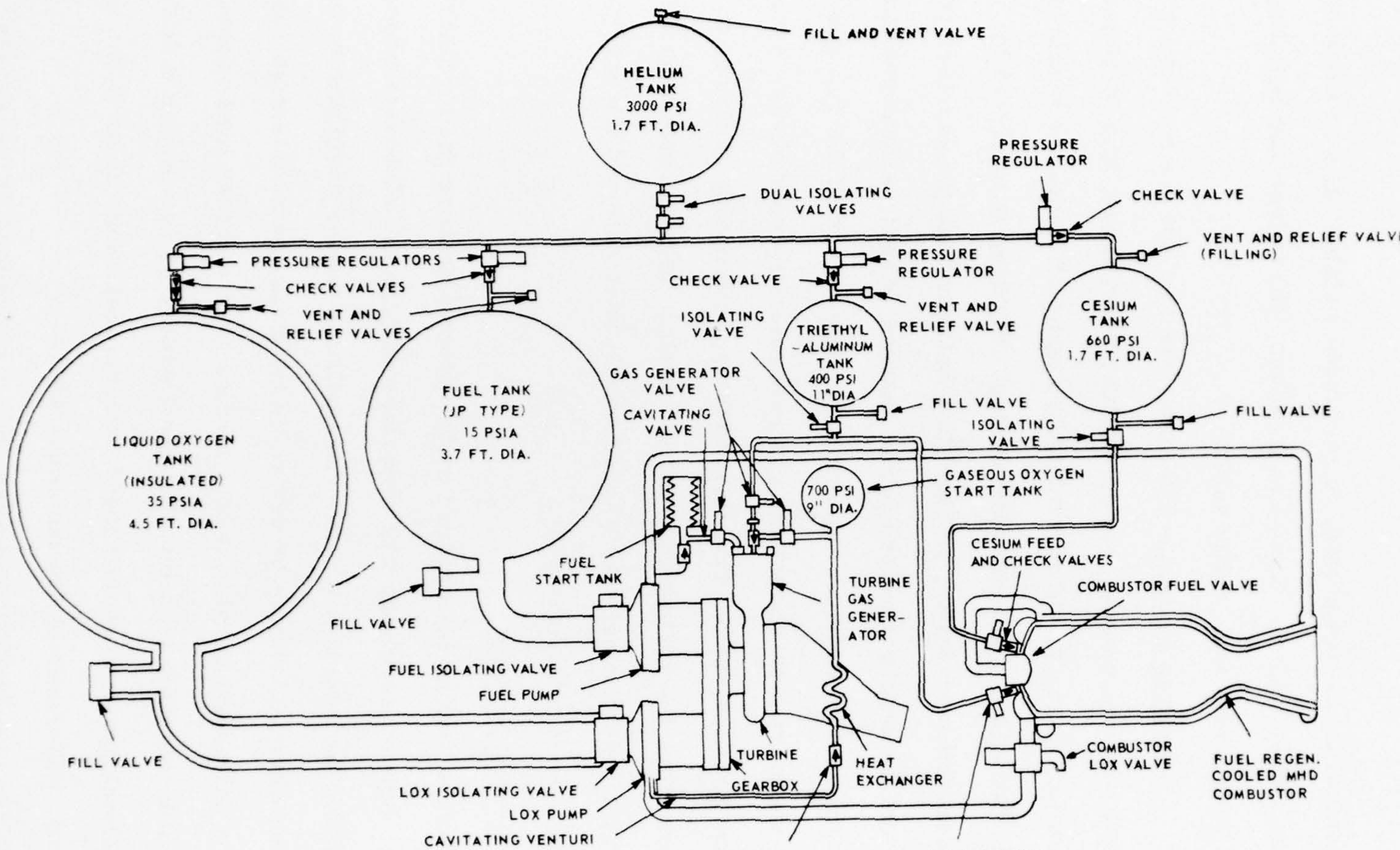

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Figure 17 MHD Combustor Feed System Schematic

Spherical tanks are shown, to minimize weight. The propellant storage assemblies include manual vent valves, fill valves and isolating valves and an oxidizer tank relief valve.

(iii) Turbopump System - This consists of a hot gas turbine, gear box, oxidizer and fuel pumps, gas generator, start tanks, and turbopump control system. Pump speed control is by means of cavitating venturis in the liquid propellant feed from the pumps. Starting is achieved by using pressurized start tanks, the fuel in a bellows tank pressurized with an inert gas, and the oxidizer stored in the gaseous phase. A heat exchanger mounted in the turbine exhaust vaporizes the oxygen fed to the gas generator and the start tank so that the gas generator injector always operates with gaseous phase oxygen. The start tanks automatically recharge to full pressure when the turbopump reaches design running conditions. Check valves prevent loss of start tank charge on the inlet side and the start/stop control valves on the delivery side.

c) *Ground Service*

Reactant loading is required on the ground because the oxidizer is cryogenic. Ground servicing will therefore employ the elaborate procedures established for the space program. To facilitate easier servicing by not involving the aircraft, it may be desirable to mount the reactant storage system on a pallet and service it in a remote area and then load aboard the aircraft. The interface with the electrical generator is simpler than for the solid propellant system because major mechanical connections (i.e., gas generator to MHD channel) are not required.

Besides the loading requirement, a procedure is necessary for servicing the empty propellant system after landing, which is critical when recycling the system. More and higher skilled ground personnel would be required for reloading this system versus the solid system.

d) Logistics

The shipping and storage of JP-4 and seed material present no difficulty. Shipping and storage of LOX requires more elaborate procedures, such as are used in the space program.

2. Solid Propellant Combustor

a) Operational Mode

The main operational advantage of the solid-fueled system compared to a liquid fueled system is in the simplicity of firing the gas generator. Initiation of a burn consists essentially of pushing the fire button for each required pulse, with a minimum of pre-operation checkout. Standard interlocks with the electrical power genèrator system would be connected to the firing circuit.

Another advantage is that the Cs seed material is cast into the grain, thus eliminating the need for a separate seed feed system.

A disadvantage of this system is the fact that the lengths of the burn and hence the lengths of the electrical pulses are fixed by the fuel grain design. The minimum pulse burn time is, normally, that required to burn an individual grain, unless emergency shut-down procedures are employed. Thus, the duration(s) of the electrical pulse or pulses are predetermined by the initial grain size and configuration. Flexibility with respect to pulse duration and interval is limited. The length of the electrical pulse from the MHD generator is essentially the same as the length of the burning pulse, because the generator produces power as long as the working gas flows through the channel. Electric power production can be interrupted only by shutting off the magnetic field, which is not possible during the short pulse length, or by open circuiting or short-circuiting the generator, which would cause excessive electrical stresses within the channel.

b) Ground Service

The most likely mode of operation expected is that the reactant grain and the combustor/nozzle are integral, and that the complete unit will be assembled to the rest of the MHD generator for each mission. This will require careful handling of large units: for 60 second operation, the assembly is about 1.2 m in diameter, 1.6 m long, and weighs about 2000 kg. It is proportionally larger if longer operation is required. Besides the actual lifting of the combustor/nozzle/reactant unit aboard the aircraft, it is necessary to control the movement of the unit so that the gas seal between it and the generator channel can be properly accomplished.

A possible design with some handling advantages is to mount the gas generator on a structural pallet which would take up the thrust load, support the combustor, and act as the lift structure for putting the unit aboard the aircraft. This in turn would be attached to the airframe when in place.

Another mode of operation is to load the reactant grain into a combustor shell which remains attached to the MHD channel. In this case, the nozzle would require cooling so that it need not be replaced after each mission as would be necessary for the ablatively cooled nozzle used in the first mode of operation described above.

c) Logistics

The logistics plan for the gas generator would be the same as that used for missile weapon systems. One added feature which can be considered is the recycling of the empty propellant case to the propellant loading contractor. The shipping containers presently used for missiles are returned to the factory, and the empty combustor cases can be sent with them. Rocket motor cases can be recycled and considering the end use application, such an approach is justifiable and cost effective.

SECTION IV

CONCLUSIONS AND RECOMMENDATIONS

A study was performed of MHD generators operating at power densities in the channel of 500 MW/m^3 and 1000 MW/m^3. Operation at 500 MW/m^3 can be achieved either by use of hydrocarbon fuel (RP-1 or JP-4) and oxygen, with cesium seed, or by use of a cesium-seeded double-base solid fuel. Major characteristics of these systems are summarized below, for generators producing 30 - 35 MW (nominal) power output.

	RP/O_2 System	Solid Fuel System
Power Output [MW]	31.5	33.2
System Dry Weight [kg]	2305	1695
Mass Flow Rate [kg/sec]	30	30
Total Weight (60 sec operation) [kg] (includes reactants and coolant)	4625	3280
Peak Magnetic Field [T]	4.6	3.6
Overall Diameter [m]	1.6	1.3
Overall Length [m]	3.7	3.7

The major technical risk arises from the high potential for damage which exists in the channel.

Major development is judged to be required for the following components:

1. Lightweight superconducting magnet.
2. Burners for pulsed operation, if required.
3. Lightweight MHD channel.

The magnet is regarded as a critical component because a) failure to produce the required fields would result in degradation of generator power output; b) the magnet is the heaviest single component of the system, and represents about 50% of the system dry weight (more if shielded); c) the gap between existing technology and required technology is large, with respect to size and weight of the required magnets compared to magnets which have actually been built.

The burner is another important component because of its dominant influence on the gas electrical conductivity, through the effects of burner losses on gas temperature. Relatively small reductions in gas temperature, due to increases in burner losses, result in large reductions in electrical conductivity, and hence, in generator power output. Development of burners for continuous operation represents a relatively straightforward application of existing rocket technology, either solid or liquid fueled. Some modifications are necessary to ensure seed vaporization and uniform seed distribution in the gas. This is probably more easily accomplished with solid fuel burners than with liquid fuel burners. For pulsed operation, with the reactants to be used for the MHD generator, some development of burners will probably be necessary, particularly of solid-fueled burners, as this type of operation represents a larger departure from existing rocket engine technology than does continuous operation.

The channel operates in a regime in which the potential for damage resulting from axial electrical breakdown is much higher than in other MHD channels operated to date. Therefore the channel must be considered a high-risk component. Development of lightweight power-producing channels is required. Lightweight model channels have been built and operated under hot gas flow conditions, but not yet to produce power.

Operation at 1000 MW/m^3 increases the risks for the magnet, because of the higher fields required, and for the channel, because of the more severe electrical stresses, particularly the axial electric field. System weights are reduced by about 10%, compared to operation at 500 MW/m^3. Risks can be reduced by use of reactants producing higher electrical conductivity, which allows lower magnetic and electric fields. However, the disadvantage, perhaps crucial, of such reactants is that they are highly toxic and difficult to handle.

A development plan and suggested schedule is shown in Fig. 18 for generator operation at 500 MW/m^3. The plan is in three phases, as follows:

Phase 1 - Fabrication and operation of a channel operating at 500 MW/m^3 in an existing MHD test facility. The objective of this phase is to verify channel operating characteristics. This phase would also include the development of a burner which produces a working gas with the required electrical conductivity. The flow train components in this phase need not be light in weight, and the magnet need not be superconducting.

Phase 2 - Design, construction and testing of a first generation prototype generator. This generator would use a superconducting magnet and would be light in weight, although not as light as the eventual airborne units.

Phase 3 - Fabrication of a flightweight generator.

The three phases of the development plan would overlap to some extent, as shown in Fig. 18, as experience was gained during each phase which would enable the next phase to be started. The first phase would be completed in twenty-four (24) months, the first-generation ground based

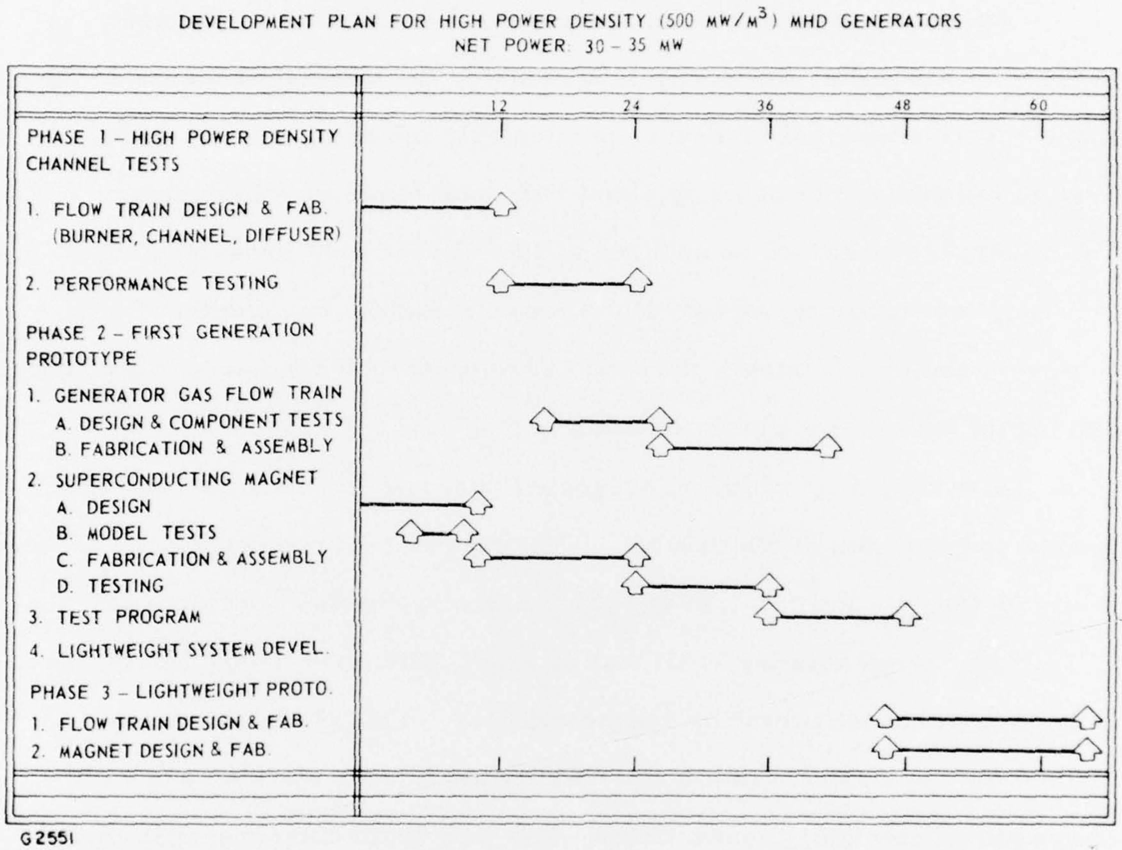

Figure 18 Development Plan for High Power Density (500 MW/m^3) MHD Generators. Net Power: 30 - 35 MW

prototype (Phase 2) would be completed by fifty-four (54) months and the flightweight generator (Phase 3) by sixty-eight (68) months. The program could be advanced by eighteen (18) months by eliminating Phase I, and by eliminating the test program for the superconducting magnet. With this program modification, the first generation prototype would be completed in thirty-six (36) months and the flightweight prototype in fifty (50) months. The technical risk of the shortened program would be considerably higher.

Operation at 1000 MW/m^3 would add an estimated eighteen (18) months to the program, to solve problems which would be expected to occur in the more highly stressed channels and higher field magnets which would be required.

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