Applied Technology Division
TRW Space & Technology Group
Redondo Beach, CA 90278

Space Power MHD System

Third Quarterly Technical Progress Report

15 March 1988

Period Covered: 1 November 1987-31 January 1988

Report No.: K535.88.RH-071

Contract No.: DE-AC22-87PC 79662

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Prepared for:

United States Department of Energy
Pittsburgh Energy Technology Center
Pittsburgh, Pennsylvania

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1. EXECUTIVE SUMMARY

This third quarterly progress report of the Space Power MHD System Project presents the accomplishments during the period 1 November 1987 through 31 January 1988. The scope of work covered by this quarterly report encompasses the definition of an MHD power system conceptual design and development plan (Task 1). Progress during this reporting period included the following:

- o Subcontracts were issued to the M.I.T. Plasma Fusion Center and the Westinghouse R & D Center.
- o The performance of the 100 MW 500 sec. power system was optimized and the design concept finalized, including mass and energy balances. Mass and cost estimates were prepared.
- o A design review was held at DOE/PETC. This also included the review of the technical issues definition (Subtask 1.2) and of the R & D Plan (prepared under Subtask 1.3).
- o Following the DOE review, a final iteration on the conceptual design was initiated. Formulation of the R & D Plan was continued.
- o Preparation of the Task 1 R & D Report was initiated.

Task 1 Schedule

2. INTRODUCTION

The general objective of this project is to perform a feasibility assessment of space-based multi-megawatt, magnetohydrodynamic (MHD) power systems for Strategic Defense Initiative Organization (SDIO) mission applications and to resolve technical uncertainties that may impact their future implementation.

The ultimate goal of the SDIO is to provide security for the United States and its allies. The near-term objective of the SDIO is to conduct research on those technologies for defensive systems that might be capable of intercepting ballistic missiles after launch and preventing them from hitting their targets.

Systems concepts currently being considered for space-based weapons applications will, if implemented, require specially tailored power systems. These power systems may possess characteristics and specifications lying considerably outside the design ranges of conventional devices. Their development may require major advances in existing technology and the accelerated development of entirely new approaches.

Numerous weapon devices for SDI applications have been proposed: Electromagnetic Launchers (EML); Free Electron Lasers (FEL); Neutral Particle Beams (NPB); High Energy Lasers (HEL); among others. Generally, these devices will require efficient, lightweight, compact, and reliable power systems, which, for certain operating modes, must be capable of generating high levels of burstpower (100's of MW) for extended periods (1,000's of seconds). The location and intended use of the weapons implies that the subject power system must function reliably under hostile circumstances. MHD power generation is a particularly promising technology for this type of application. Accordingly, an MHD technology feasibility assessment program has been initiated.

The first phase of the feasibility assessment program is to identify candidate MHD power system concepts and associated technical uncertainties, generate an R & D plan to address these uncertainties, and conduct tests to resolve the issues identified. This assessment is subdivided into two tasks.

Within Task 1, a specific space-based MHD power system and its component elements are to be identified and described; a conceptual design is to be prepared; technical uncertainties associated with this system will be specified and plans (including tasks, schedule, and costs) to resolve these uncertainties will be developed. Task 2 will involve implementation of the plans developed in the first task. At the present time, only Task 1 is to be implemented. Task 2 is an optional task.

Task 1 itself has been subdivided into four (4) subtasks:

Subtask 1.1 - Preparation of an MHD Power System Conceptual Design.

Subtask 1.2 - Identification and definition of Key Technical Issues.

Subtask 1.3 - Preparation of a Research and Development Plan.

Subtask 1.4 - Project Management.

This project is being conducted by the Combustion Technology System Department of the TRW Space and Technology Group. The majority of the work is performed at TRW's facilities in Redondo Beach, California.

3. PROJECT DESCRIPTION

Task 1, as previously mentioned, is subdivided into four subtasks. The work to be performed under each subtask is described hereafter:

Subtask 1.1 Preparation of an MHD Power System Conceptual Design - TRW will prepare a conceptual design for the MHD, Space-based Power System described in its proposal. The power system shall include, as applicable: (a) the heat source, (b) fuel storage and handling subsystem, (c) seed material storage and handling subsystem, (d) the MHD channel, (e) the diffuser, (f) the magnet and associated subsystems, (g) the power conditioning and control circuitry, (h) the cooling and heat-rejection subsystems, and (i) ancillary subsystems. The conceptual design shall be prepared to a level of detail that will permit gross system mass to be estimated to within $\pm 20\%$. The MHD system shall be designed for minimum size and mass. As part of the conceptual design, TRW shall prepare schematic drawings of the integrated power system showing both component layout and method for integrating the power system with the platform.

TRW shall provide a clear description of the overall operation of the system and of major components.

Conceptual design shall include, as a minimum, the following:

Total MHD System

- o An overall power system energy balance, including state point data such as fluid properties, flow rates, temperatures, pressures, and enthalpies.
- o Power System thermal input.
- o Channel enthalpy extraction.
- o Net electric power generated.
- o Total system weight.
- o Total system dimensions.
- o Estimated power system cost.

Major Components

- o Component performance.
- o Component dimensions and weight.
- o Materials of construction.
- o Estimated cost.

Justification shall be given for values assumed. TRW shall also provide sufficient information concerning the procedures or methods used to obtain calculated values to permit an evaluation of the resulting values.

TRW must identify and quantitatively characterize any dynamic loads, thrust vectors, and effluents produced by the power system. The system shall be designed for use with a hypothetical weapon system requiring 100 MW(e) of burst power for at least 500 seconds. Start-up and shutdown characteristics, including start-up time of the system must be considered, as well as steady-state operation. Standby, alert, and firing mode system operating requirements shall be identified.

Subtask 1.2 Identification and Definition of Key Technical Issues - Based on the system concept proposed and the conceptual design presented in Subtask 1.1, TRW shall identify the key technical issues or uncertainties that must be analytically and/or experimentally addressed, in order to successfully implement the proposed MHD power system.

TRW shall more fully develop and refine the technical issues outlined in its proposal. Each issue shall be clearly discussed, including reasons for its selection and a priority with respect to its potential impact on the MHD power system or total platform system.

Subtask 1.3 Preparation of a Research and Development Plan - Based on results of the conceptual design study (Subtask 1.1) and the definition of key technical issues (Subtask 1.2), TRW shall refine and more thoroughly define component or subsystem

experimental and analytical R & D plan outlined in its proposal.

TRW shall address technical, management, and cost aspects of the analytical and experimental investigations in the R & D plan. The plan shall include, but not be limited to, a description of schedules, components (existing and/or new), test facilities, test costs, analytical studies, personnel, key milestones, and decision points.

It is expected that this plan will be completed and presented to DOE approximately six (6) months after contract initiation. Following review of the R & D plan, DOE reserves the right to selectively choose analyses and experiments from those proposed, for implementation in Task 2.

The R & D Plan is a topical report.

Subtask 1.4 Project Management - Activities under this task are to provide for planning, technical and resource management, and reporting activities required for implementation of the work.

4. PROJECT STATUS

Progress under the principal subtasks is as illustrated in the schedule of Figure 4.1. During the reporting period, the effort was directed at completing subtasks 1.1 - Conceptual Design and 1.2 - Key Technical Issues. Subtask 1.3 was initiated and was still under progress at the end of the present reporting period. Subcontracts were placed with the M.I.T. Plasma Fusion Center in support of the superconducting magnet design and with Westinghouse R & D Center in support of the design of the power conditioning system. A comprehensive project and design review was held at DOE/PETC during the month of January. In the following, we summarize the final design concept selected and the approach proposed for addressing key feasibility issues. A more comprehensive description will be found in the R & D Plan/Task 1 Final Report, which documents in detail the results of the present effort.

4.1 Conceptual Design

The general approach taken was to select a concept which:

- o Emphasizes simplicity
- o Does not rely on technology breakthroughs
- o Exhibits attractive characteristics using state-of-the-art technology
- o Offers performance gains as the technology matures

Figure 4.2 is an isometric view of the system selected. A chemically fueled open cycle disk MHD generator system is proposed. Two 50 megawatt channels are operated in parallel in the magnetic field created by a single circular superconducting magnet. The magnet is energized at all times for faster response and minimization of interference with the rest of the system. A pressure fed gel reactant storage and feed system is selected which eliminates the need for feed pumps and cryogenic storage. This, together with the use of a TRW face shut-off injector, allows for very rapid repetitive start-up and shut-down. The fuel and oxidizer are stored in four (each) individual fiber wrapped tanks for redundancy. Helium gas is used as the pressurant. A closed loop water cooling system is used to reject heat to the reactants and

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Task 1 Schedule

Figure 4.1 Task 1 Schedule

Figure 4.2 Power System Isometric View

to a hydrogen flow. The hydrogen is also used to drive a set of four counter-rotating turbo-pumps for water circulation, prior to being used for cooling of the generators exit sections. The pure hydrogen boundary layers in the exhaust effectively shroud the platform from the products of combustion, thus virtually eliminating potential adverse effects on the beam, as well as on the platform sensors. The power conditioning system is of modular construction and is contained in a single bay located on the weapon side of the system. The dc-to-dc converter features voltage source single phase GTO inverter bridges in parallel. The rectifier units on the secondary side are in series. The overall size of the system, as depicted, is approximately 4 meters in diameter and 8.5 meters in length. Using state-of-the-art components, the total system weight is estimated at 50,000 kg. Approximately half of the weight is in consumables required for 500 second operation. The system can be fueled (or refueled) in space, and accordingly can either be launched "dry" or "wet". As the technology matures and the system performance is improved, a 40 percent weight reduction can be anticipated.

Gelled reactants have been selected for our design. The composition is as shown in Figure 4.3. The fuel is a monomethylhydrazine (MMH) aluminum gel. The oxidizer is an IRFNA gel containing both solid lithium nitrate and potassium nitrate, which acts as the seed. For the mixture ratio selected ($O/F = .975$), electrical conductivities in the range 50 to 100 mho/m are predicted under working fluid conditions typical of the proposed supersonic MHD channels. Figure 4.4 illustrates the variations in plasma conductivity with temperature and pressure for the products of combustion. The gels are storable at ambient conditions and can be pumped as liquids. Hypergolic ignition ensures rapid repetitive start-up capability.

Figure 4.5 shows the MHD generator assembly. Disk generators have been selected because they are well suited to high interaction-efficient single load operation (boundary layer stability). The topology of the disk is ideally suited to the design of high pressure ratio channels. The simplicity of the magnet design, yields a low heat leak, light weight, magnet which can be designed and built with a high level of confidence. The axisymmetric exhaust provides for first order thrust cancellation. Radial wedges in the exit section cancel torques. Figure 4.6 shows typical voltage current

	NAME	FORMULA	MOLECULAR WEIGHT	ENTHALPY AT 298 K (MJ/Kg)	STATE	RELATIVE DENSITY	WEIGHT (%)
OXIDIZER	LITHIUM NITRATE	Li NO ₃	69	-6.98	S	2.380	16.45
	POTASSIUM NITRATE	KNO ₃	101	-4.76	S	2.109	17.30
	IRFNA	HN _{1.09} O _{3.119}	66	-2.74	L	1.571	62.00
	OTHER	—	—	—	—	—	4.25
	IRFNA GEL	—	75	-3.74	GEL	1.754	100
FUEL	ALUMINUM	Al	27	0	S	2.703	60
	MMH	CH ₆ N ₂	46	+1.155	L	0.875	38.5
	OTHER	—	—	—	—	—	1.5
	MMH GEL	—	32.5	+0.370	GEL	1.485	100

NOMINAL O/F = 0.975 — REACTANTS ENTHALPY = 11.00 MJ/kg

Figure 4.3 Selected Baseline Reactants

Figure 4.4 Electrical Conductivity Dependence on Temperature and Pressure

Figure 4.5 Disk Generators Assembly

Figure 4.6 Voltage Current Characteristics
at Nominal Power and at Turn-down

characteristics for the individual channels. At the nominal flow rate of 23.75 kg/s, the output power is slightly in excess of 51 megawatts and the output voltage near 2900 volts. The nominal operating point corresponds to an all-supersonic flow which choked exit. For 25 percent turn-down, one generator is operated alone at 15.5 kg/s. The output voltage is maintained constant so as to minimize the impact on the power conditioning weight.

Figure 4.7 shows the overall generator arrangement and integration with the storage and feed system, as well as with the cooling system. Helium is used as pressurant (and purge) gas for the feed system. This choice is consistent with the expected duty cycle which is likely to include several shut-down and start-up cycles. For each generator assembly, two fuel tanks, two oxidizer tanks and two helium tanks are used. Single tanks are shown in the figure for clarity. The high heat flux components (combustion chambers, nozzles, channels) are water cooled. Heat removed by the closed-loop water cooling system is rejected, both to the reactants as they are fed to the combustion chamber (partial regeneration) and to a flow of hydrogen. Figure 4.8 shows a schematic of the cooling system, together with the fluid flow rates and corresponding state points. The hydrogen flow issuing the heat exchanger is used to drive a set of counter-rotating turbo-pumps for water circulation before it is used for cooling (convective + film) of the exit section.

The power conditioning system consists of 24 (12 per channel) dc-to-dc converters, as shown in Figure 4.9. The single phase voltage source inverter bridges are operated at a frequency of 300 Hertz and use gate turn-off thyristors (GTO). The inverter bridges are in parallel and the rectifier bridges in series, thus ensuring a 12 to 1 voltage ratio. For transformer ratios of 2.85 to 1, this ensures a 100 kilovolt dc output for the system.

4.2 Key Feasibility Issues

For the proposed system, key feasibility issues relate to:

- o Plasma generator design and combustion performance using gelled propellants to yield a high electrical conductivity plasma.

Figure 4.7 Integrated Generator Assembly

POINT NO.	PRESSURE		TEMPERATURE		FLOW RATE	
	MPa	(psia)	K	(°F)	kg/sec	(lb/sec)
WATER	1	2.76 (400)	400	(260)	61.5	(136)
	2	1.50 (217)	444	(340)	18.4	(40.6)
	3	1.93 (280)	443	(337)	21.9	(48.2)
	4	1.55 (225)	447	(344)	21.3	(46.9)
	5	1.57 (225)	452	(353)	21.9	(48.2)
	6	1.50 (217)	448	(346)	61.5	(136)
	7	1.38 (200)	424	(304)	30.8	(68)
	8	1.38 (200)	434	(322)	30.8	(68)
	9	1.38 (200)	429	(313)	61.5	(136)
	10	1.34 (195)	399	(258)	61.5	(136)
H ₂	11	0.69 (100)	23	(-419)	1.79	(3.95)
	12	0.69 (100)	304	(87)	1.79	(3.95)
	13	0.65 (94)	298	(77)	1.79	(3.95)
REACTANT	14	2.96 (430)	294	(70)	11.7	(25.8)
	15	2.16 (313)	394	(250)	11.7	(25.8)
	16	2.96 (430)	294	(70)	12.0	(26.5)
	17	2.16 (313)	444	(340)	12.0	(26.5)

LEGEND	
—	WATER
—	HYDROGEN
---	REACTANTS
ENERGY EXCHANGE - q = MW (Btu/s)	

Figure 4.8 Cooling System Flow Rates and State Points

Figure 4.9 Individual Converter Details

- o Combustion chamber, nozzle and MHD channel cooling and lifetime using a particle laden working fluid.
- o MHD channel performance at high levels of interaction, including stability, the effect of non-uniformities and the ability to sustain thermal and electrical stresses.
- o Combustion products plume geometry and exhaust effects on the platform during burst power operation.

Preliminary calculations were performed to assess the effect of the exhaust on the overall system. Some results are shown in Figure 4.10. Here we show the results of a rarefied plume study performed using a Monte-Carlo method of analysis. At the end of the platform (beam end), the column density was found to be equal to $3 \times 10^{15} \text{ cm}^2$. This is computed to result in a very small ($\leq 3\%$) attenuation of the beam. Furthermore, as hydrogen is used for film cooling of the exit section, the boundary layer flow is essentially pure hydrogen so that the concentration of the molecular species (H_2O , CO_2 , etc.) in the line of sight of the weapon, is essentially zero. This minimizes adverse effects on sensors.

4.3 R & D Plan

The effort proposed for Task 2 covers a period of 27 months. Figure 4.11 shows the overall schedule proposed (Task 1 + Task 2). For Task 2, the analytical and experimental effort was defined so as to address the key feasibility issues identified in Task 1. The proposed effort will generate the analytical and engineering data required for a realistic assessment of the performance potential of the proposed concept. A subscale (10 Kg/sec) experimental MHD power generator is proposed, aimed at unambiguously addressing feasibility issues. The approach is to:

- o Use gelled fuel and oxidizer formulations identical to these proposed for our baseline system, rather than "surrogate" or "similar" reactants.

Figure 4.10 Exhaust Plume Characteristics

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Overall Project Schedule

Figure 4.11 Program Schedule

- o Evaluate injection and combustion chamber characteristics representative of future systems (pressure, temperature, chamber L^*).
- o Operate under test durations long enough to establish steady state heat transfer and at stress levels representative of full scale generators.
- o Use magnetic field intensities and geometries representative of future systems.
- o Provide an initial evaluation of life and endurance issues (700 seconds total operation).
- o Make maximum use of existing test facilities at TRW.

Figure 4.12 shows the logic chart for the implementation of Task 2. In it we have identified, together with the program inputs, the various subtasks and the critical issues addressed as the program progresses. The resolution of each of the issues addressed and the acquisition of the related analytical and experimental data constitute the major program milestones.

Figure 4.12 Task 2 Logic

5. SUMMARY

The conceptual design of a 100 MW 500 second burst MHD Space Power System was completed. Major key technical issues were identified. Efforts were initiated to define the R & D effort required to address those key issues.