EVALUATION OF CRYOGENIC POWER CONDITIONING SUBSYSTEMS FOR ELECTRIC PROPULSION SPACECRAFT

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ABSTRACT

The power requirement of vehicles designed to transport cargo supporting a piloted expedition to Mars is in the range of megawatts. Therefore, it is imperative that the megawatt-class power processing unit designed for high-power nuclear electric propulsion vehicles using turboalternators and advanced magnetoplasmadynamic (MPD) thrusters should be such that the overall system efficiency is as high as possible with minimum system specific mass. This paper examines the use of cryogenic power conditioning subsystems to achieve that goal since they have very high efficiency.

However, in the past, cryogenic power conditioning subsystems have shown complexity of design and implementation and were costly and somewhat uncertain. With recent advances in materials, devices used in power conversion and cooling methods, further improvements in efficiency and specific mass are realizable. Cryogenically cooled MOSFETs and MCTs are considered for power conversion and two configurations have been examined.

It is found that a system efficiency of 92.67% and specific mass of 9.99 kg/kW$_e$ can be realized using MOSFET-based cryogenic power conditioning systems for electric propulsion spacecraft using MPD thrusters. With cryogenically cooled MCTs, the specific mass decreases to 9.77 kg/kW$_e$, but the efficiency also decreases to 90.94%.

INTRODUCTION

Figure 1 shows the schematic arrangement of various components of a MW-class NEP vehicle. An electric space propulsion system consists of a power source (e.g., nuclear reactor and thermal-to-electric power conversion system), a

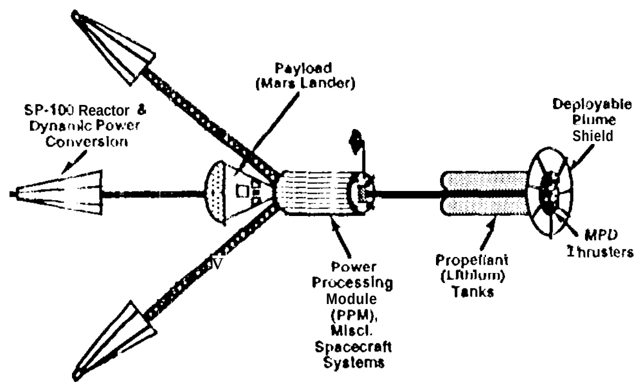

FIGURE 1. MEGAWATT-CLASS NUCLEAR ELECTRIC PROPULSION (NEP) VEHICLE WITH Li-PROPELLANT MPD THRUSTERS

power processing unit (PPU) which converts the power source's power output (voltage) to the form required by the thrusters, and the electric thrusters. In this study, PPUs for a 1.5-MW$_e$ nuclear electric propulsion (NEP) using a dynamic power conversion system (e.g. Rankine) and high-power magnetoplasmadynamic (MPD) thrusters are evaluated. The baseline configuration for the NEP vehicle considered here consists of 3, SP-100 category, dynamic power conversion units, a power processing module (PPM) containing the PPU electronics, and 2 clusters of Li-propellant 16 MPD thrusters.

Specific mass (α) expressed in units of kilograms per kilowatt of electric power (kg/kW$_e$), and efficiency (η) expressed as the ratio of power output to power input are two primary figures of merit for electric propulsion systems. This study has addressed these two figures of merit.

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The 1.5-MW$_e$ nuclear power system has a low-voltage (100 v), 400117, three-pljasc AC output from its dynamic power conversion system (which provides constant power output during an Earth-to-Mars transit). Thus, the output from the nuclear power system can be directly fed to a PPU rectifier for conversion to the DC voltage required by the thruster.

Li-propellant applied-field MPD thrusters are selected because of their projected good efficiency at low specific impulse (Isp). By contrast, a self-field MPD has a lower projected efficiency and lower operating voltage than a corresponding applied-field MPD thruster. The PPU for an NEP vehicle using MPD thrusters must supply different systems in the vehicle (Frisbee et al, 1993), (Das et al, 1991), (Frisbee and Hoffman, 1993). Circuit arrangements are shown in the reference (Krauthamer et al, 1995).

Figure 2 shows a baseline NEP-MPD PPU circuit diagram with power distribution. Figure 3 shows the circuit arrangement of a proposed NEP-MPD PPU with MOSFETs or MCTS, and filter configuration, Figure 4 shows input/output control for both the baseline and the other two configurations.

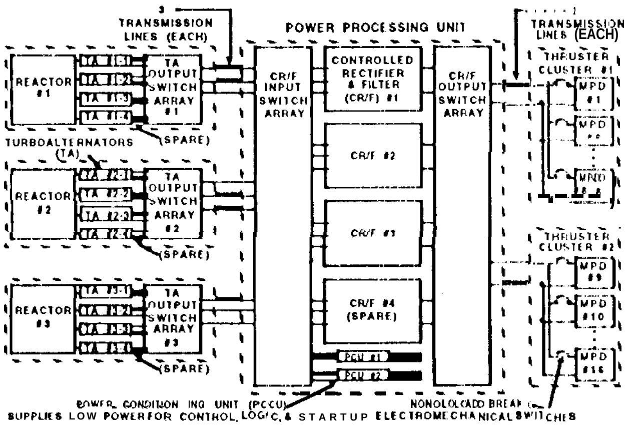

FIGURE 2. BASELINE NEP-MPD PPU CIRCUIT DIAGRAM SHOWING POWER DISTRIBUTION AND POWER CONVERSION WITH SCRs

The primary driver in PPU design in this case is a requirement of low voltage and high power. This requirement results in use of high-current capacity devices (e.g., 1300 to 7500 Amps). Also, the PPU must be designed to accommodate startup and shutdown transients, and be capable of isolating thruster and PPU component failures without compromising the remainder of the power or propulsion system. Thus, the PPU designs discussed below consist of both a primary high-power system and a smaller low-power power conditioning unit (PCU). For convenience, the PPU electronics components (rectifiers, filters, etc.) and switches are treated separately from the component "bus bar" wiring (both within the PPM as well as in the long booms between the PPM and thrusters or between the PPM and the nuclear power systems).

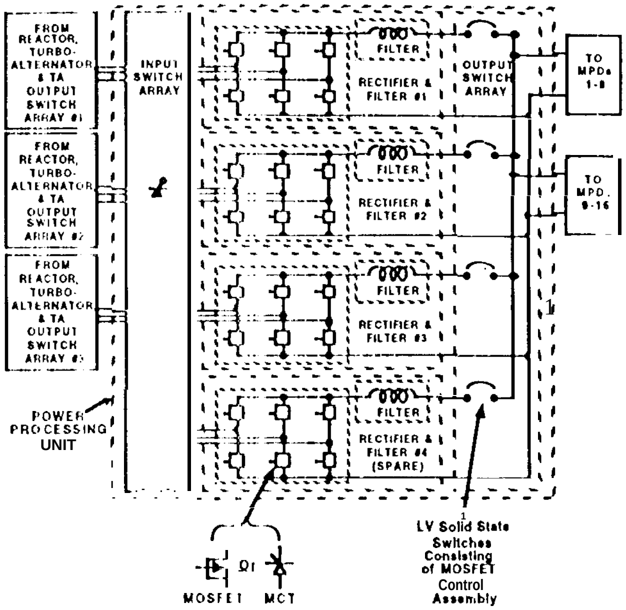

FIGURE 3. PROPOSED NEP-MPD PPU CIRCUIT DIAGRAM SHOWING MOSFET OR MCT-BASED RECTIFIERS AND FILTERS

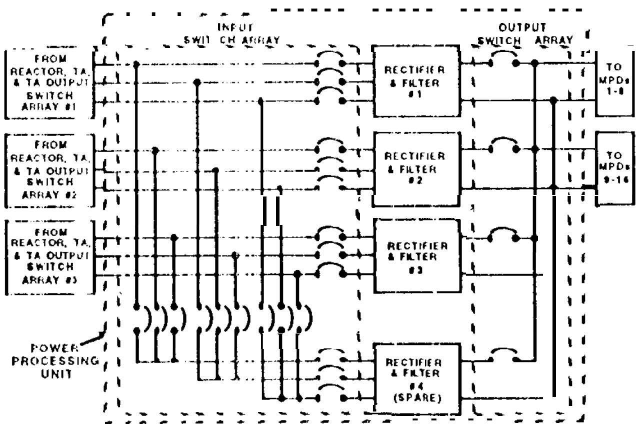

FIGURE 4. NEP-MPD PPU CIRCUIT DIAGRAM SHOWING RECTIFIER/FILTER INPUT AND OUTPUT SWITCH CONFIGURATION

In each configuration, the switches used are non-load break type electromechanical devices that are designed to disconnect (or connect) thrusters and other components. For example, electrical power is disconnected from a thruster by first turning off the power conversion system, and then by opening the non-load break thruster switch. Similarly, any of the various turboalternators or power conversion switches can be isolated by first driving the turboalternator voltage to zero. The switches can then be opened without arcing. However, the need to isolated the various components in the system does result in a complex switching topology.

POWER MOSFETs

A n]ctal-oxide-scmic.onductor field cf feel transistor (MOSFET) acts as a switch. It is a voltage-controlled majority-carrier dcvicc. It requires a continuous application of gate-to source voltage of appropriate magnitude to remain in "on" state. Transition of state takes place when the gate capacitance is being charged or discharged. The dcvicc is in the. "on" condition when the gate-to-source voltage is below a threshold value. The switching time is very short, in the range of nanoseconds, The on-resistance of MOSFETs is very small and can be controlled either by device geometry or by blocking voltage rating. Because of high switching speed, tbc switching loss can be very small. MOSFETs arc available in voltages up to 1000V and currents up to 700A ratings. The on-resistance has a positive temperature coefficient and therefore MOSFETs can be paralleled. MOSFETs when in parallel can handle large power.

RATIONALE BEHIND HIGH EFFICIENCY CRYOGENIC POWER CONVERSION

The requirement of ultra-high efficiency of high power conversion for Mars-bound spacecraft using electric propulsion prompted the usc of Power MOSFETs because the on-resistance of MOSFETs can be lowered by cryogenic cooling, thereby increasing power conversion efficiency. Commercially available low-cost, high-voltage MOSFETs are good candidates for cryogenic power conversion (M uller and Herd, 1993). Cryogenic Power MOSFETs operated at the temperature of liquid nitrogen have the following features: (i) their on-resistance can be reduced by a factor of 1 ()-1 S at low drain currents and by a factor of 25-30 at the rated drain current compared to room temperature operation, (ii) by paralleling, the effective on-resistance can be reduced as much as desired, (iii) reduction of on-resistance by paralleling is not possible with other majority carrier devices such as IGBTs, GTOs MCTs

A cryogenic power MOSFET is any MOSFET which is working at the temperature of liquid nitrogen (77 K). Several commercially available devices have much smaller on-resistance when immersed in liquid nitrogen at 77K compared to when heatsink is at 300K. It is also found that the improvement factor is higher al higher drain current. In addition, a transistor rated at lower current can be operated at 77K with higher rated current. It is found that the cryogenic power conversion with MOSFETs may be advantageous even at higher temperatures in the range of 200K. The thermal conductivity of silicon and most substrates increases by a factor of 5-10 if cooled down to 77K. in addition, the specific heat, heal capacity and thermal time constant decreases in cryogenic cooling (Mueller and Herd, 1993).

There arc two kinds of losses in high- frequency power conversions: (i) conduction losses in the on-state of the switches and (ii) switching lo sscs. The conduction losses can be reduced by cooling and thereby reducing on-resistance. The switching losses arc exceedingly small compared to high-frequency applications of MOSFETs.

By cryogenic cooling. we reduce the power dissipation in power electronics. This means that the refrigeration power requirements arc reduced to sufficiently low levels 10 afford an ultra-high overall efficiency. For example, in a 3-ϕ bridge circuit, three switches arc in series. Assuming a voltage drop (V_d) of 0.3V in each, the total voltage drop is 0.9V. Therefore, for a 100V DC input, the device voltage drop is 0.9/100= 0.9%. If the on-resistance crrn drop by a factor of 4.S (Mueller and Herd, 1993), then the device voltage drop will be further reduced to 0.2% and the corresponding efficiency is 99.8%. Assuming a 100 kW system, the loss is 200 W. If a refrigeration factor (ratio of refrigeration power compared to dc.sired power dissipation in dc.vices) of 6 is assumed, the total loss is 1400 W and thr system efficiency of 98.6% is realized.

PPU OPTIONS

Two options with cryogenic cooling have been considered in this paper. The block schematic diagram in Figure 2 represents the baseline system while Figures 5a and 5 b represent these two options. The following factors influence the selection of a PPU option: (1) PPU and cabling mass; (2) PPU efficiency; (3) PPU redundancy so that each thruster dots not have a dedicated PPU; (4) PPU thermal control.

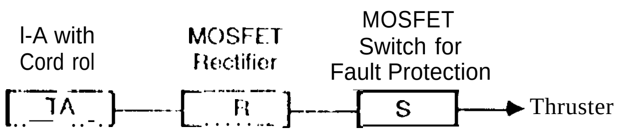

FIGURE 5a, POWER CONVERSION AND CONTROL PROPOSED IN OPTION i.

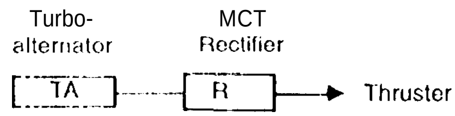

FIGURE 5b. POWER CONVERSION AND CONTROL PROPOSED IN OPTION II

A MOSFET is a variable resistance device. Because of low frequency (400 1 Iz) of switching, the switching loss is very small; the.rcforc, the only significant loss is duc to on-resistance. This loss is also small because of cryogenic cooling The MOSFETs are operated in a synchronous rectifier mode. The control in Option I is with the 'f 'A. In other words, TA senses the voltage and current of the thruster and immediately adjusts parameters by its own control, Short-circuit protection is provided by a solid state contact and is MOSlli'1'-based. If MCTs arc used, as shown in Figure 5b corresponding to Option II, rectification, and protection and control both can be achieved similar to the baseline which used SCRs. Using MCTs provide potential for higher efficiency because of lower forward drop for MCTs.

PERFORMANCE CALCULATION

Tables 1, 2 and 3 show the breakdown of mass, power losses and efficiencies of various items in the baseline configuration. The overall specific mass is found to be 9.99 kg/kW_e and the overall PPU efficiency is about 90.2%.

TABLE 1. POWER CONDITIONING MASSES AND EFFICIENCY

Item	Quantity	Total Mass (kg)	Total Losses (kW)	Comments
Turboalternator (TA) Switches (1 OOVAC, 1333A)	36	246	1.5	Sum of all Switches
TA Dallas! Switches (100 VAC, 3300 A)	36	736		
CR Input Switches (100 VAC, 3300A)	21	430		
Controlled Rectifiers (CR) (100 VAC, 5030A)	4	136	40.0	
Output Chokes (Filters, F) (100 VDC, 5000 A)	4	80	3.0	
CR/F Output Switches (1 oqvoc, 5w3oA)	4	114		
Thruster Switches (loo VOC, 75O3A)	16	656		
Housekeeping PCU	2	344	3.0	63 kWe in, 60 kWe out PCU has its own radiator
Structure		100		
Radiator		931	(44.5)	Total PPU radiator load
Total		3773	107.5	PCU input counted as loss

TABLE 2. CABLE AND BOOM MASSES AND EFFICIENCIES

Item	No. of Cables	Length Each (m)	Current Each (A)	Total Mass (kg)	Total Losses (kW)
Reactor Booms					
1 A-to-I A Switch	36	2.2	1100	605	0.9
T A Parallel Connections	9	1.5	1100	103	0.2
1 A-to-Ballast Resistor Switch	36	1.5	1100	412	0s3
Ballast Resistor Parallel Connections	9	2.2	3300	269	1:2
Reactor Boom	9	24.0	3300	?931	12.9
Docking Connectors	18	0.25	3300	90	2.0
Structure (?5 %)				1103	
Subtotal (Specific Mass" .3.675 kg/kWe, Efficiency = 98.8 %)				5,513	17.8
PPM Cabling					
Input-to-Switch-to-CR	12	2.2	3300	358	1.6
Input-to-Spare CR Switches	9	0.9	3300	110	0.5
Controlled Rectifier (CR) Intemal	12	0.9	3300	147	0.6
CR.to-Fdt@rto-Switch-t&O@ul	6	0.5	5000	122	0 2
Output Parallel Connections	2	2.0	7500	122	06
Structure (25 %)				215	
Subtotal (Specific Mass". 0.716 kg/kWe, Efficiency = 99.8 %)				1 ,0/4	35
Thruster Cluster (TC) Booms					
PPM-to-TC Boom	4	30.0	7500	3075	19.5
TC Boom	4	2.0	7500	244	1.1
TC Connections	4	2.5	7500	378	1.1
Structure (25 %)				925	
Subtotal (Specific Mass* = 3.084 kg/kWe, Efficiency = 98.6 %)				4 626	?1.7

* Nominal power input = 1500 kWe

POWER LOSS, EFFICIENCY, AND MASS CALCULATIONS

The power loss and efficiency of any component are related by the equations:

$$\eta = \text{Output Power/input Power, arid}$$

$$P_{loss} = (1-\eta) \cdot \text{Input Power}$$

Table 4 shows the calculated value.s of power losses and efficiency in each option along with the mass in calculating the radiator area (A) and mass (m), the following equations have. been used.

TABLE 3. MASS, SPECIFIC MASS AND EFFICIENCY ESTIMATES

Item	TA -to- PPU Cables (3 Sets)	PPM Electronics, Switches, Cables (1 Set)	PPM -to- Thruster Cables (2 Sets)	System Total
Electric Power Input (kWe)	PO- 1500	148?	1373	Po=1500
Losses (kWthermal)				
Cables	18	3	20	41
Electronics & Switches		44		44
Pcu (Electric)		59		59
PCU (Thermal)		3		3
Total	18	109	20	147
Electric Power Output (kWe)	148?	1373	1353	1353
Efficiency (%)	9881	92.60	98.55	90.20
Nominal Specific Mass (kg/kWe)	3.675	3.231	3.064	----
"Effective" Mass (kg) (Nominal Spec Mass • Elect Power Input)	5,513	4,789	4,233	14,535
"Effective" Specific Mass (kg/kWe) ("Effective" Mass / P.)	3.675	3.193	2822	9.690

$$A : (\text{Power Loss}) / (\sigma \cdot T^4 \cdot \varepsilon)\ (m^2)$$

and

$$m : A \cdot W \cdot CF\ (kg)$$

where,

σ	=	Stefan Boltzman constant
	=	5.67X10^{-8}
ε	=	Emissivity
	=	0.8
T	=	Temperature (Kelvin)
	=	298.15K in baseline design
W	=	Density
	=	5 kg/m^2, and
CF	=	Contingency Factor
	=	1.5

in the baseline configuration, the current is high throughout because of low voltage. As a result, these cables arc thicker and they also provide strength and integrity to the boom structure. The power losses in the cables arc 38 kW. The power loss in PPU switches is 109 kW. The total PPU mass is about 14,985 kg out of which the mass of cable with boom is I 1,212 kg. The PPM switches and radiator weighs about 3773 kg. The overall efficiency and specific mass are calculate.d to be 90.2% and 9.99 kg/kW$_e$, respectively.

PERFORMANCE ASSOCIATED WITH OPTIONS I AND II

Controlled rectifiers shown in Table 1 have 40 kW of power loss. If MOSFETs replace them in Option I and arc cryogenically cooled, power loss associated with them will go down to 3 kW. Similarly, the loss associated with the choke will be reduced because of low rms ripple current, Refrigeration loss will be approximately 18 kW (six times). House-keeping power loss will be unchanged. Radiator mass will go down but the refrigeration mass will be added. It is assumed that the sum of these two masses will not change significantly.

Cable masses arc assumed unchanged. Option II is essentially the same as Option IV in Krauthamer et al, 1995, except when MCT's arc used instead of SCRs. When cryogenic cooling is provide.d, the total power loss is 18 kW. It is possible to cool the various components to 77° K (for liquid nitrogen) by designing a system with minimum heat leaks from the warm spacecraft and maintaining a view of deep space rather than of a planet or the sun. Its potential advantage is reduction in size, weight and cost because there is no heat sink, pump or isolation requirement.

TABLE 4. COMPARISON OF TOTAL POWER LOSS, EFFICIENCY AND SPECIFIC MASS FOR VARIOUS OPTIONS

Options	Total Mass (kg)	Total Power Loss (kW)	Efficiency (%)	Specific Mass (kg/kWe)
Baseline	14985	147	90,20	9.99
Option I	14985	110	92.67	9.99
Option II	14661	136	90.94	9.77

ADVANCES IN POWER CONVERSION USING CRYOGENIC MOSFETS AND HIGH-TEMPERATURE SUPERCONDUCTORS

High-tempera ture superconductors for achieving improved performance and greater efficiency arc nearing real it y. American Superconductor Corporation, a pioneer in the field of superconductors, report that their superconducting power converters will be on the market by 1997. Efficiency will be higher and the reliability will be increased because components will not bc. subjected to the heat generated by electrical resistance in conventional power conductors (Ray, Gerber, Patterson, and Myers, 1995; and Solomon, 1986).

If power conversion devices are cryogenically cooled and wires arc superconductors, there will be additional power savings and overall efficiency will improve further. Inductors using superconducting wires and low-loss capacitors will provide additional improvements in efficiency. However, power required for cooling will have 10 hc factored into overall efficiency calculations.

This paper has consider cd only cryogenic cooling of power conversion devices; the impact of superconducting wires and cables has not been addressed. Hopefully, data wi II gradually become available to enable estimation of irl~[)rcl~'crilc.tits in efficiency anti specific mass for systems incorporating both cryogenically-cooled conversion dc.vices and superconducting wires and cables.

CONCLUSIONS

Based On the preliminary analyses presented in this paper, the following conclusions can bc made regarding the power conditioni ng subsystem efficiency and specific mass of nuclear-electric propulsion vehicles using MPD thrusters for Mars Cargo missions:

1. Both Options I and II have superior performance compare.d to the baseline design.

2. Option I, which uses cryogenically-cooled MOSFETs, has a higher efficiency than Option Ii, which uses cryogenically-co oled MCTs. However, Option II has a somewhat lower specific mass as compared to Option I.

3. Both options have a higher complexity of design and implementation as compared to tbc baseline system. The impact of this added complexity on cost has not been examined.

4. High-temperature superconducting wires and cables have not been included in the designs of Option I and II. The success of high-temperature superconducting power conversion has been recently demonstrated (Jaeger and Gaensslen, 1986; and Laramee, Aubin, and Cheeke, 1985), but further information is required to determine quantitatively the potential benefits of this technology for this application.

5. It is important that the impact of cryogenic cooling and high-temperature superconducting power conversion be examined together to evaluate further improvements in efficiency and specific mass for application to spacecraft electric propulsion systems. it is clearly seen that their combined use in power conversion may provide for significant synergistic systems-level benefits,

ACKNOWLEDGMENTS

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