REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE (DD-MM-YYYY)	2. REPORT TYPE	3. DATES COVERED (From - To)
06-10-2005	Conference Paper	

4. TITLE AND SUBTITLE

Propulsion and Power Generation Capabilities of a Dense Plasma Focus (DPF) Fusion System for Future Military Aerospace Vehicles (POSTPRINT)

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

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5d. PROJECT NUMBER
48470159

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Air Force Research Laboratory (AFMC)
AFRL/PRSP
10 E. Saturn Blvd.
Edwards AFB CA 93524-7680

8. PERFORMING ORGANIZATION REPORT NUMBER

AFRL-PR-ED-TP-2005-359

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Air Force Research Laboratory (AFMC)
AFRL/PRS
5 Pollux Drive
Edwards AFB CA 93524-70448

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S NUMBER(S)
AFRL-PR-ED-TP-2005-359

12. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for public release; distribution unlimited (AFRL-ERS-PAS-2005-240).

13. SUPPLEMENTARY NOTES

Presented at the Space Technology and Applications International Forum (STAIF) 2006, Albuquerque, NM, 12-16 Feb 2006. Published in AIP Conference Proceedings Vol. 813; ISBN: 0-7354-0305-8 (Bound volume) or ISBN: 0-7354-0306-6 (CD-ROM).

14. ABSTRACT   The objective of this study was to perform a parametric evaluation of the performance and interface characteristics of a dense plasma focus (DPF) fusion system in support of a USAF advanced military aerospace vehicle concept study. This vehicle is an aerospace plane that combines clean "aneutronic" dense plasma focus (DPF) fusion power and propulsion technology, with advanced "waverider"-like airframe configurations utilizing air-breathing MHD propulsion and power technology within a reusable single-stage-to-orbit vehicle. The applied approach was to evaluate the fusion system details (geometry, power, T/W, system mass, etc.) of a baseline p-^{11}B DPF propulsion device with Q = 3.0 and thruster efficiency, η_{prop} = 90% for a range of thrust, I_{sp} and capacitor specific energy values. The baseline details were then kept constant and the values of Q and η_{prop} were varied to evaluate excess power generation for communication systems, pulsed-train plasmoid weapons, ultrahigh-power lasers, shielding/cloaking devices and gravity or time-distorting devices. Thrust values were varied between 100 kN and 1,000 kN with I_{sp} of 1,500 s and 2,000 s, while capacitor specific energy was varied from 1 - 15 kJ/kg. Q was varied from 3.0 to 6.0, resulting in gigawatts of excess power. Thruster efficiency was varied from 0.9 to 1.0, resulting in hundreds of megawatts of excess power. Resulting system masses were on the order of 10's to 100's of metric tons with thrust-to-weight ratios ranging from 2.1 to 44.1, depending on capacitor specific energy. Such a high thrust/high I_{sp} system with a high power generation capability would allow military versatility in sub-orbital space, as early as 2025, and beyond as early as 2050. This paper presents only the views and recommendations of the authors themselves and are not necessarily those of the Air Force.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
					Dr. Franklin B. Mead, Jr.
a. REPORT	b. ABSTRACT	c. THIS PAGE	A	8	19b. TELEPHONE NUMBER (include area code)
Unclassified	Unclassified	Unclassified			(661) 275-5929

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. 239.18

POSTPRINT

Propulsion and Power Generation Capabilities of a Dense Plasma Focus (DPF) Fusion System for Future Military Aerospace Vehicles

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Abstract. The objective of this study was to perform a parametric evaluation of the performance and interface characteristics of a dense plasma focus (DPF) fusion system in support of a USAF advanced military aerospace vehicle concept study. This vehicle is an aerospace plane that combines clean "aneutronic" dense plasma focus (DPF) fusion power and propulsion technology, with advanced "waverider"-like airframe configurations utilizing air-breathing MHD propulsion and power technology within a reusable single-stage-to-orbit vehicle. The applied approach was to evaluate the fusion system details (geometry, power, T/W, system mass, etc.) of a baseline p-^{11}B DPF propulsion device with Q = 3.0 and thruster efficiency, η_{prop} = 90% for a range of thrust, I_{sp} and capacitor specific energy values. The baseline details were then kept constant and the values of Q and η_{prop} were varied to evaluate excess power generation for communication systems, pulsed-train plasmoid weapons, ultrahigh-power lasers, shielding/cloaking devices and gravity or time-distorting devices. Thrust values were varied between 100 kN and 1,000 kN with I_{sp} of 1,500 s and 2,000 s, while capacitor specific energy was varied from 1 - 15 kJ/kg. Q was varied from 3.0 to 6.0, resulting in gigawatts of excess power. Thruster efficiency was varied from 0.9 to 1.0, resulting in hundreds of megawatts of excess power. Resulting system masses were on the order of 10's to 100's of metric tons with thrust-to-weight ratios ranging from 2.1 to 44.1, depending on capacitor specific energy. Such a high thrust/high I_{sp} system with a high power generation capability would allow military versatility in sub-orbital space, as early as 2025, and beyond as early as 2050. This paper presents only the views and recommendations of the authors themselves and are not necessarily those of the Air Force.

INTRODUCTION

The objective of this study was to perform a parametric evaluation of the performance and interface characteristics of a dense plasma focus (DPF) fusion system in support of a USAF advanced military aerospace vehicle concept study (Froning, Czysz, 2006). This vehicle is an aerospace plane that combines clean "aneutronic" dense plasma focus (DPF) fusion power and propulsion technology, with advanced "waverider"-like airframe configurations utilizing MHD airbreathing propulsion and power technology within a reusable single-stage-to-orbit vehicle. Early versions of such an aerospace vehicle, available by 2025, would rapidly reach Earth orbit to deploy, sustain, and reconstitute space forces with flight operations and take-off weights that are comparable to those of current heavy Air Force jets. It would rapidly accomplish global reconnaissance or weapon delivery to ground, air, or space threats by sub-orbital flight around the Earth; and, there would be no requirements for jet tanker fleet logistics support. Such an aerospace vehicle would have: advanced sensors; communications; and structures; beam weapons; stealth features; and other unique features, characteristics, and capabilities that might be available by the 2025 time period to revolutionize propulsion and power capabilities in the more near-term.

Such a high thrust/high I_{sp} system with a high power generation capability would allow military versatility in sub-orbital space, as early as 2025, and beyond as early as 2050, with a vehicle that embodies advanced communications-guidance-navigation-control and airframe materials, and augments aerospace vehicle propulsion and power with field propulsion and power for flight acceleration and ΔV increases of as much as 400 percent for enhanced capabilities within near-earth and cis-lunar space (Froning, Czysz, 2006). This would be in addition to

enabling even more advanced forms of weapons and defensive capabilities, such as pulsed-train plasmoid weapons, ultrahigh-power lasers, and gravity devices (Davis, 2004).

Approach

The applied approach to this parametric study was to evaluate the fusion system details, such as geometry, exhaust power, thrust-to-weight ratio, system mass, etc., for a baseline p-^{11}B DPF fusion space thruster system for a range of thrust and specific impulse (I_{sp}) values with Q = 3.0, η_{prop} = 0.9 and capacitor specific energy varying between 1.0 kJ/kg to 15.0 kJ/kg. The range of thrust values that were considered was 100 kN to 1,000 kN at I_{sp} values of 1,500 seconds and 2,000 seconds.

These baseline system details were then held constant and the value of Q was varied between 3.0 and 6.0 and the resulting amount of additional power for electricity generation was determined. The same was done with the value of thruster efficiency, varying it between values of 0.9 and 1.0. The eventual use of the additional power generated was not considered in this study.

Bremsstrahlung Power Balance

By holding the specific impulse (2,000 s or 1,500 s), fusion gain (Q = 3.0), and repetition rate (10 Hz) constant, the resulting Bremsstrahlung energy and DPF electrode dimensions could be calculated. A parameter which heavily influences the performance of the DPF propulsion unit is the thruster efficiency, which is defined as:

$$\eta_t = \frac{\text{power of the jet}}{\text{electrical power input}} = \frac{\frac{1}{2} gIspF}{\Sigma IV} \tag{1}$$

Where F is the thrust, g is the local gravitational constant, Isp is the specific impulse, and ΣIV is the electric power input to the thruster. The thruster efficiency accounts for all the energy losses that do not result in kinetic energy, including (1) the wasted electrical power; (2) unaffected or improperly activated propellant particles (propellant utilization); (3) loss of thrust resulting from dispersion of the exhaust (direction and magnitude); and (4) heat losses (Sutton 2001). The importance of this parameter can be illustrated through Figure 1, which shows how the thrust-to-weight ratio varies with thruster efficiency (Thomas, 2005).
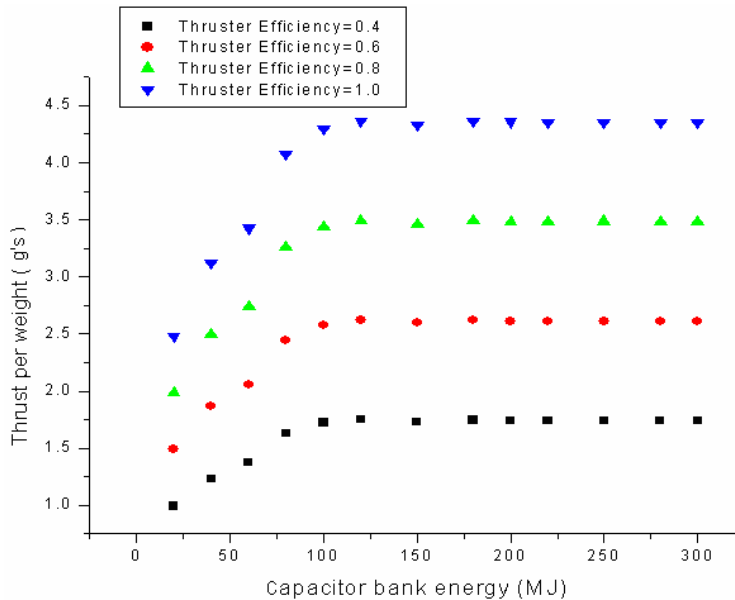

Figure 1. Thrust-to-Weight Ratio vs. Bank Energy.

For this analysis, an optimistic value of 0.9 was assumed. With these values, the Bremsstrahlung power lost could be calculated by simply subtracting the fusion power from the input power to the thruster. By assuming a certain percentage of Bremsstrahlung energy can be reflected back into the reacting plasma (50%) the total Bremsstrahlung power could be calculated. The total Bremsstrahlung energy can be found from the power density (Equation. 2) by multiplying by the pinch volume ($\sim 10^{-6}$ m^3) and the repetition rate (10 Hz).
:

$$P_{br} = 5.35 \times 10^{-37} Z_{eff} n_e^2 (kT_e)^2 \tag{2}$$

Where kT_e (keV) is the electron temperature, n_e (m^{-3}) is the electron number density and Z_{eff}, is the effective atomic number, which has a value of 13 for the p-^{11}B reaction. Since the power density is fixed, it is possible to vary the particle density to obtain a particle temperature that will not completely ablate the walls of the radiation reflector. For example, for a 500 kN DPF device, a particle number density (electron and ions) of 2 x 10^{22} cm^{-3} gives an electron temperature of 1.3 MeV. The fusion cross section can then be estimated from the plasma fusion power which is given by:

$$P_f = W_f V_{pin} \frac{n^2}{4} \langle \sigma v \rangle \tag{3}$$

Where W_f is equal to 8.7 MeV for the p-^{11}B reaction, and $<\sigma v>$ is the product of the fusion cross section, σ and relative velocity, v. The electrode length of the DPF device was estimated through an iterative method that varied the lengths keeping the compression ratio (anode radius/pinch radius) constant. The values of the anode and cathode radii for each combination of thrust and I$_{sp}$ are shown in Table 1.

TABLE 1. Anode and Cathode Radii for Specified Thrust and I$_{sp}$ levels.

Thrust (kN)	I$_{sp}$ (s)	Anode Radius (cm)	Cathode Radius (cm)
1000.0	2000	14	38
750.0	2000	12	34
500.0	2000	11	30
300.0	2000	10	30
100.0	2000	8	28
1000.0	1500	16	36
500.0	1500	14	30

Evaluation of System Details

With the previous information determined and a value of capacitor bank energy assumed, the rest of the system parameters can be determined. With the estimate of the capacitor energy in hand, to determine the mass of the capacitor banks, it was necessary to multiply the bank energy by the specific energy of the capacitors in kJ/kg, which ranged from 1.0 kJ/kg to 15.0 kJ/kg. The total system mass could then be determined by assuming the the capacitor bank mass was 50% of the system mass. Determining the thrust-to-weight ratio is then a straightforward manner. The volume of the capacitor banks and the DPF system as a whole can be determined by assuming a capacitor mass density. The current state of the art has been shown to be 3.0 MJ/m^3 (Winsor, et al., 1999). Assuming for additional advances in the ensuing 20 years, a feasible figure for capacitor mass density has been assumed to be 5.0 MJ/m^3.

The next step is the evaluation of potential power for electricity generation if the values of Q and thruster efficiency are varied from their baseline values of 3.0 and 0.9, respectively. With all other parameters held constant, increasing the Q value increases the fusion power produced while reducing the amount of Bremsstrahlung losses. Increasing thruster efficiency increases the power of the exhaust jet and increases both the fusion power and Bremsstrahlung losses.

RESULTS AND DISCUSSION
Baseline Design

Table 2 shows the projected baseline parameters of a DPF fusion space thruster for thrust levels of 500 kN and 1,000 kN at specific impulse levels of 1,500 s and 2,000 s. The Q value ($P_{fusion}/P_{capacitor}$) for the baseline design was 3.0 and the thruster efficiency was 90%. The specific energy of the capacitor banks was varied from 1.0 to 15.0 kJ/kg. This resulted in system masses ranging from 11.33 metric tons for τ = 500 kN, I_{sp} = 1,500 s and capacitor specific energy of 15.0 kJ/kg to 480 metric tons for τ = 1,000 kN, I_{sp} = 2,000 s and capacitor specific energy of 1.0 kJ/kg. This results in system thrust-to-weight ratios ranging from 2.08 kN/MT to 44.12 kN/MT and system volumes ranging from 25.5 m^3 to 72.0 m^3.

As the thrust levels are decreased to their minimum values for the study of 100 kN at 2,000 s, the total system mass decreases at each value of capacitor specific energy, but the thrust-to-weight ratio remains constant and the total system volume decreases. The minimum system mass at a thrust level equal to 100 kN and a specific impulse of 2,000 s, with a capacitor specific energy of 15.0 kJ/kg was 3.2 metric tons with a total system volume of 7.2 m^3.

TABLE 2. Baseline Parameters of DPF Fusion Space Thruster

Thrust (kN)	I_{sp} (s)	Q	Eff	Sp. Energy (kJ/kg)	Mass (MT)	T/W (kN/MT)	Volume (m^3)
500.00	2000.00	3.00	0.90	1.00	240.00	2.08	36.00
1000.00	2000.00	3.00	0.90	1.00	480.00	2.08	72.00
500.00	1500.00	3.00	0.90	1.00	170.00	2.94	25.50
1000.00	1500.00	3.00	0.90	1.00	340.00	2.94	51.00
500.00	2000.00	3.00	0.90	5.00	48.00	10.42	36.00
1000.00	2000.00	3.00	0.90	5.00	96.00	10.42	72.00
500.00	1500.00	3.00	0.90	5.00	34.00	14.71	25.50
1000.00	1500.00	3.00	0.90	5.00	68.00	14.71	51.00
500.00	2000.00	3.00	0.90	10.00	24.00	20.83	36.00
1000.00	2000.00	3.00	0.90	10.00	48.00	20.83	72.00
500.00	1500.00	3.00	0.90	10.00	17.00	29.41	25.50
1000.00	1500.00	3.00	0.90	10.00	34.00	29.41	51.00
500.00	2000.00	3.00	0.90	15.00	16.00	31.25	36.00
1000.00	2000.00	3.00	0.90	15.00	32.00	31.25	72.00
500.00	1500.00	3.00	0.90	15.00	11.33	44.12	25.50
1000.00	1500.00	3.00	0.90	15.00	22.67	44.12	51.00

Q Variance

The first parametric study that was considered concentrated on varying the value of Q from the baseline design, in order to evaluate the potential electrical power generation capabilities of the vehicle. Table 2 is the performance parameters of the thruster with Q = 3.5 and Table 3 is the same collection of parameters with Q = 6.0. Only the parameters for a thrust levels of 1,000 kN and 500 kN and I_{sp}'s of 1,500 seconds and 2,000 seconds are included for capacitor specific energies of 1.0, 5.0, 10.0 and 15.0 kJ/kg.

As expected the system mass decreases substantially as capacitor specific energy increases, from an upper limit of 480 metric tons with specific energy = 1.0, thrust = 1,000 kN, I_{sp} = 2,000 s to a lower limit of 11.33 metric tons for specific energy = 15.0, thrust = 500 kN and I_{sp} = 1,500 s. The thrust-to-weight ratio increases from a minimum value of 2.08 kN/MT to a maximum of 44.12 kN/MT for both thrust levels considered. The volume of the system changes with total jet power (difference in specific impulse and thrust) from 72.0 m^3 to 25.5 m^3. As the value of Q was increased from 3.5 to 6.0, the total available power for electricity generation increased from values of 1.2 GW and 850 MW for I_{sp} = 2,000 s and 1,500 s, respectively, to 7.2 GW and 5.1 GW for a thrust level of 1,000 kN. For a thrust level of 500 kN, the total available electricity generation increased from values of 600 MW and 425 MW for I_{sp} = 2,000 s and 1,500 s, respectively, to 3.6 GW and 2.55 GW, a factor of six increase.

TABLE 2. Performance Parameters of DPF Fusion Space Thruster with Q = 3.5.

Thrust (kN)	I_{sp} (s)	Q	Sp. Energy (kJ/kg)	Mass (MT)	T/W (kN/MT)	Power (MW)	Volume (m^3)
500.00	2000.00	3.50	1.00	240.00	2.08	600.00	36.00
500.00	1500.00	3.50	1.00	170.00	2.94	425.00	25.50
1000.00	2000.00	3.50	1.00	480.00	2.08	1200.00	72.00
1000.00	1500.00	3.50	1.00	340.00	2.94	850.00	51.00
500.00	2000.00	3.50	5.00	48.00	10.42	600.00	36.00
500.00	1500.00	3.50	5.00	34.00	14.71	425.00	25.50
1000.00	2000.00	3.50	5.00	96.00	10.42	1200.00	72.00
1000.00	1500.00	3.50	5.00	68.00	14.71	850.00	51.00
500.00	2000.00	3.50	10.00	24.00	20.83	600.00	36.00
500.00	1500.00	3.50	10.00	17.00	29.41	425.00	25.50
1000.00	2000.00	3.50	10.00	48.00	20.83	1200.00	72.00
1000.00	1500.00	3.50	10.00	34.00	29.41	850.00	51.00
500.00	2000.00	3.50	15.00	16.00	31.25	600.00	36.00
500.00	1500.00	3.50	15.00	11.33	44.12	425.00	25.50
1000.00	2000.00	3.50	15.00	32.00	31.25	1200.00	72.00
1000.00	1500.00	3.50	15.00	22.67	44.12	850.00	51.00

TABLE 3. Performance Parameters of DPF Fusion Space Thruster with Q = 6.0.

Thrust (kN)	I_{sp} (s)	Q	Sp. Energy (kJ/kg)	Mass (MT)	T/W (kN/MT)	Power(MW)	Volume (m^3)
500.00	2000.00	6.00	1.00	240.00	2.08	3600.00	36.00
500.00	1500.00	6.00	1.00	170.00	2.94	2550.00	25.50
1000.00	2000.00	6.00	1.00	480.00	2.08	7200.00	72.00
1000.00	1500.00	6.00	1.00	340.00	2.94	5100.00	51.00
500.00	2000.00	6.00	5.00	48.00	10.42	3600.00	36.00
500.00	1500.00	6.00	5.00	34.00	14.71	2550.00	25.50
1000.00	2000.00	6.00	5.00	96.00	10.42	7200.00	72.00
1000.00	1500.00	6.00	5.00	68.00	14.71	5100.00	51.00
500.00	2000.00	6.00	10.00	24.00	20.83	3600.00	36.00
500.00	1500.00	6.00	10.00	17.00	29.41	2550.00	25.50
1000.00	2000.00	6.00	10.00	48.00	20.83	7200.00	72.00
1000.00	1500.00	6.00	10.00	34.00	29.41	5100.00	51.00
500.00	2000.00	6.00	15.00	16.00	31.25	3600.00	36.00
500.00	1500.00	6.00	15.00	11.33	44.12	2550.00	25.50
1000.00	2000.00	6.00	15.00	32.00	31.25	7200.00	72.00
1000.00	1500.00	6.00	15.00	22.67	44.12	5100.00	51.00

Thruster Efficiency Variance

The second parametric study considered concentrated on varying the thruster efficiency from its baseline value of 90% up to 100%. It is recognized that these are both extremely optimistic values for thruster efficiency. However, the values are being continued from a previous study (Thomas, et al., 2005). Available power levels for the alteration of thruster efficiency were considerably less than that of the Q variance, nearly an order of magnitude. The values of system mass, thrust-to-weight ratio and system volume remain the same from the Q variance parametric study. The only major change occurs in the available power for electricity generation.

With a thruster efficiency of 92%, the minimum available power was 88.82 MW for a thrust level of 500 kN and an I_{sp} of 1,500 s, while the maximum available power was 236.86 MW for thrust = 1,000 kN and I_{sp} = 2,000 s. When the thruster efficiency is increased to 100%, though, the available power for a thrust level of 500 kN and an I_{sp} of 1,500 s is 408.58 MW, a factor of 4.6 increase. The available power for thrust = 1,000 kN and I_{sp} = 2,000 s was 1.089 GW, also a factor of 4.6 increase.

TABLE 4. Performance Parameters of DPF Fusion Space Thruster with $\eta_t = 92\%$.

Thrust (kN)	I_{sp} (s)	Eff	Sp. Energy (kJ/kg)	Mass (MT)	T/W (kN/MT)	Power (MW)	Volume (m^3)
500.00	2000.00	0.92	1.00	240.00	2.08	118.43	36.00
500.00	1500.00	0.92	1.00	170.00	2.94	88.82	25.50
1000.00	2000.00	0.92	1.00	480.00	2.08	236.86	72.00
1000.00	1500.00	0.92	1.00	340.00	2.94	177.64	51.00
500.00	2000.00	0.92	5.00	48.00	10.42	118.43	36.00
500.00	1500.00	0.92	5.00	34.00	14.71	88.82	25.50
1000.00	2000.00	0.92	5.00	96.00	10.42	236.86	72.00
1000.00	1500.00	0.92	5.00	68.00	14.71	177.64	51.00
500.00	2000.00	0.92	10.00	24.00	20.83	118.43	36.00
500.00	1500.00	0.92	10.00	17.00	29.41	88.82	25.50
1000.00	2000.00	0.92	10.00	48.00	20.83	236.86	72.00
1000.00	1500.00	0.92	10.00	34.00	29.41	177.64	51.00
500.00	2000.00	0.92	15.00	16.00	31.25	118.43	36.00
500.00	1500.00	0.92	15.00	11.33	44.12	88.82	25.50
1000.00	2000.00	0.92	15.00	32.00	31.25	236.86	72.00
1000.00	1500.00	0.92	15.00	22.67	44.12	177.64	51.00

TABLE 5. Performance Parameters of DPF Fusion Space Thruster with $\eta_t = 100\%$.

Thrust (kN)	Isp (s)	Eff	Sp. Energy (kJ/kg)	Mass (MT)	T/W (kN/MT)	Power (MW)	Volume (m3)
500.00	2000.00	1.00	1.00	240.00	2.08	544.78	36.00
500.00	1500.00	1.00	1.00	170.00	2.94	408.58	25.50
1000.00	2000.00	1.00	1.00	480.00	2.08	1089.56	72.00
1000.00	1500.00	1.00	1.00	340.00	2.94	817.17	51.00
500.00	2000.00	1.00	5.00	48.00	10.42	544.78	36.00
500.00	1500.00	1.00	5.00	34.00	14.71	408.58	25.50
1000.00	2000.00	1.00	5.00	96.00	10.42	1089.56	72.00
1000.00	1500.00	1.00	5.00	68.00	14.71	817.17	51.00
500.00	2000.00	1.00	10.00	24.00	20.83	544.78	36.00
500.00	1500.00	1.00	10.00	17.00	29.41	408.58	25.50
1000.00	2000.00	1.00	10.00	48.00	20.83	1089.56	72.00
1000.00	1500.00	1.00	10.00	34.00	29.41	817.17	51.00
500.00	2000.00	1.00	15.00	16.00	31.25	544.78	36.00
500.00	1500.00	1.00	15.00	11.33	44.12	408.58	25.50
1000.00	2000.00	1.00	15.00	32.00	31.25	1089.56	72.00
1000.00	1500.00	1.00	15.00	22.67	44.12	817.17	51.00

CONCLUSIONS

The conclusions that can be drawn from this study are that, if a DPF fusion space thruster were designed that had a Q value of 3.0 and a propulsive efficiency of 0.9 for thrust levels ranging from 100 kN to 1,000 kN with specific impulse values of 1,500 s and 2,000 s, the DPF system would have a total mass ranging from 11.33 metric tons to 480 metric tons and total system volume of 25.5 m^3 to 72 m^3 depending on the specific energy of the capacitors, which ranged from 1.0 kJ/kg to 15.0 kJ/kg. This was also assuming a mass density for the capacitors of 5.0 MJ/kg and that the DPF itself was one-half the size and mass of the capacitor banks. Thrust-to-weight ratios for the baseline design varied from 2.08 kN/MT to 44.12 kN/MT, depending on propulsion properties.

If all of the system parameters from the baseline design are held constant and the Q value of the reactor is increased, in this study ranging from 3.0 to 6.0, the power made available for electricity generation ranges from a minimum value of 425 MW for thrust = 500 kN, specific impulse = 1,500 s, Q = 3.5 to a maximum value of 7.2 GW for thrust = 1,000 kN, specific impulse = 2,000 s, Q = 6.0.

If the thruster efficiency of the DPF system is increased from 90%, in this study ranging from 90% to 100%, while maintaining a Q value of 3.0, the minimum value of power for electricity generation 88.82 MW for thrust = 500 kN, specific impulse = 1,500 s, η_{prop} = 92% to a maximum value of 1.09 GW for thrust = 1,000 kN, specific impulse = 2,000 s, η_{prop} = 100%.

This study has shown that a DPF fusion space propulsion system could be developed with thrust values between 100 kN and 1,000 kN with specific impulses of 1,500 seconds to 2,000 seconds with total system masses of 10's to 100's of metric tons with thrust-to-weight ratios ranging from 2.0 to nearly 50.0 depending on capacitor specific energies, which show promise to attain values of 15.0 kJ/kg in the next 20 years.

If the Q value of 3.0 is increased to 6.0 or the propulsive efficiency is increased from 90% to 100%, then it would be conceivable to expect additional power output that could be put towards electricity generation of up to 7.2 GW for Q values of 6.0 with thruster efficiency of 90%, or values of 1.09 GW for propulsive efficiencies of 100% with Q value of 3.0.

With a vehicle with propulsive capabilities of 1,000 kN of thrust and specific impulse of 2,000 seconds and electrical generation capabilities of this magnitude, the vehicle considered in the time frame of 2025 to 2050, could have weapons and defensive capabilities such as beam weapons and pulsed-train plasmoid weapons that would allow future military space vehicles to operate in near-Earth space, as well as cis-lunar space and beyond.

NOMENCLATURE

DPF – dense plasma focus
USAF – United States Air Force
MHD – magnetohydrodynamic
Q – Fusion energy/capacitor energy

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