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A System Optimization Model for the Application of Ablative Pulsed Plasma Thrusters to Stationkeeping Missions*

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Abstract

We present a realistic and easy-to-apply model for the optimization of the design of an ablative pulsed plasma thruster (APPT) propulsion system for a given stationkeeping mission. By "optimization" we mean finding the design characteristics of the APPT module(s) that lead to minimum propulsion system mass for given satellite mass and mission specifications. We show that using an empirical relation for the mass production rate, an expression relating the optimal (minimum) propulsion system mass, for a given mission, to the APPT's most important scaling parameter E/I (where E is the discharge energy and I the impulse bit) can be found and, remarkably, is *independent* of the state of capacitor and power conditioning technologies (i.e. specific masses, conversion efficiency, etc.). This independence allows unfolding the relations between the propulsion mass, E/I, and the mission requirements in a single plot that is applicable for a wide range of Delta-v's and payload masses. The use of the model to characterize the optimal design of an APPT system is illustrated with the example of a 10-year north-south stationkeeping of a medium size commercial satellite at GEO. We show that even with off-the-shelf capacitor technology the use of an APPT system can result in propulsion mass fractions as low as 6.4%.

1 Introduction

With the prospect of the near-term deployment of small satellite constellations, the use of ablative pulsed plasma thruster (APPT) systems for stationkeeping may hold the promise of great mass savings. These mass savings, through the use of smaller launchers or the possibility of mounting multiple satellites on a single launcher, translate directly into cost savings.

We start in Section 2 with a general but realistic model for the optimal APPT system mass that includes four general types of masses: energy-dependent mass, power-dependent-mass, fixed mass and size-dependent mass. The optimized model is cast in terms of the most important scaling parameter E/I (where E is the discharge energy and I the impulse bit). In Section 3 we specialize the model with an empirical relation for the mass production rate and find that the mass of an optimized system as a function of E/I is *independent* of the state of capacitor and power conditioning technologies. This allows for a straightforward application of the model to a spectrum of mission requirements of current interest. In the following sections we illustrate the use of the model for the design of an APPT system optimized for specific mission requirements.

2 General Model

We can express the total. mass, M_{tot} of the satellite as

$$M_{tot} = N_m M_p + M_{satp} \qquad (1)$$

where M_{satp} is the mass of the satellite payload, M_p is the mass of one APPT propulsion module and N_m is the number of modules. Furthermore, M_p can be

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broken down into the following components:

$$M_p = M_{cb} + M_{pc} + M_{sp} + M_{fix} + M_{pack} \qquad (2)$$

Where M_{cb} is the mass of the capacitor bank, M_{pc} is the mass of the power conditioner, M_{sp} is the **mass** of the solid propellant, M_{fix} is a **fixed** mass (that indudes the mass of the electrodes and ignitor assembly) and M_{pack} is the **mass** of the packaging which can be expressed **as** a fraction ϵ of the total module mass

$$M_{pack} = \epsilon M_p \qquad (3)$$

The mass of the capacitor **bank** mass can in turn be expressed in terms of a the discharge energy E,

$$M_{cb} = \bar{m}_{cb} E \qquad (4)$$

where $\bar{m}_{cb}$ **is** the **specific mass** of the capacitors The **mass** of the power conditioning system can be written as the **sum** of **a fixed mass** and a power-dependent mass

$$M_{pc} = M_{pc_{fix}} + \bar{m}_{pc} P_b \qquad (5)$$

where $M_{pc_{fix}}$ is the power-independent mass of that system which we include, along with other fixed **masses** of the system, in M_{fix}. Also, $\bar{m}_{pc}$ is the specific mass of the **power** conditioning system and P_b is the power required from the spacecraft **bus. This** power is related to the discharge energy, the pulse frequency f and the power conditioning efficiency η_{pc} **by**

$$P_b = \frac{fE}{\eta_{pc}} \qquad (6)$$

Finally, **the** mass of the solid propellant can be expressed as

$$M_{sp} = N_p F(E_i) E \qquad (7)$$

where N_p is the number of pulses and $F(E_i)$ is the specific mass of ablated solid propellant per shot which has been shown **by** experiments to be a function of the ratio E_i of the discharge energy ***E*** to the impulse bit I:

$$E_i \equiv \frac{E}{I} \qquad (8)$$

A stationkeeping mission can be characterized in terms of a Delta-v which, for a certain satellite **mass,** would require a total impulse, I_t, from the pulsed propulsion system

$$I_t = N_m N_p I = M_{tot} \Delta v \qquad (9)$$

where I is the impulse bit. This equation carries the implicit assumption that the total mass does not change appreciably over the time of the entire mission which is equivalent to saying

$$M_{sp} \ll M_{tot} \qquad (10)$$

This assumption must therefore be checked a ***posteriori*** to validate the calculations.

Combining equations (1) to (9) we can write an expression for the mass of the **APPT** module

$$M_p = \frac{\Psi \frac{M_{salp}}{N_m} + M_{fix}}{1 - \epsilon - \Psi} \qquad (11)$$

where Ψ is ***a*** mass scaling parameter given by

$$\Psi = \frac{\Delta_v}{N_p} \left[\bar{m}_{bc} + \frac{f \bar{m}_{pc}}{\eta_{pc}} + N_p F(E_i) \right] E_i. \qquad (12)$$

With the above two equations, the APPT module **mass** is expressed as a function of the energy to im**pulse** bit ratio E_i which is an important parameter in scaling the **APPT** performance.

For a given state of the capacitor and power Conditioning technology, the parameters, $\bar{m}_{bc}$, **%o,** η_{pc} **and** the highest number of pulses N_p are fixed. Under such conditions there is for each value of E_i **an** optimal pulse frequency f^* for which M_p is minimum. We find this optimal condition by setting $\partial M_p / \partial E_i$ to zero and solving for f^* to obtain

$$f^* = \frac{\eta_p c}{\bar{m}_{pc}} \left\{ \bar{m}_{cb} + n_P \left[F(E_i) + E_i \frac{\partial F(E_i)}{\partial E_i} \right] \right\} \qquad (13)$$

The optimal discharge energy **is** then given by

$$E^* = \frac{M_p(1-\epsilon) - M_{fix}}{\bar{m}_{bc} + \frac{f^* \bar{m}_{pc}}{\eta_{pc}} + N_p F(E_i)} \qquad (14)$$

Since we have expressed the **mass** model in terms of E_i it is also convenient and straightforward to express the following quantities in terms of E_i:

the optimal specific impulse I_s^*

$$I_s^* = [E_i^* F(E_i) g]^{-1} \qquad (15)$$

the total system efficiency at optimal conditions is given by

$$\eta^* = \eta_{pc} \left[2 E_i^* F^2(E_i) g \right]^{-1} \qquad (16)$$

3 Model Specialized with a Mass Production Law

We now specialize the general model for a specific function $F(E_i)$ obtained experimentally. It was found in **ref.** [1] that the following empirical relation holds for the **mass** production of the propellant plasma

$$F(E_i) = E_i^{-4}/4\kappa \qquad (17)$$

where κ is an ablation constant that depends only on the propellant. For Teflon $\kappa = 4 \times 10^{-11}$ kg/J.

Using the above expression **for** $F(E_i)$ in Eq. (13) we obtain the following expression for the optimal pulsing frequency:

$$f^* = \frac{\eta_p c}{\bar{m}_{pc}} \left[\frac{3N_p}{4\kappa} E_i^{-4} - \bar{m}_{cb} \right] \qquad (18)$$

The optimal value for the mass scaling parameter becomes

$$\Psi^* = \frac{\Delta v}{\kappa} E_i^{-3}. \qquad (19)$$

It is interesting to from the above expression that Ψ^* becomes *independent* of all the specifications of the propulsion subsystem (specific **masses,** power conditioning efficiency, and number of pulses). This means that the optimal propulsion module **mass,** given by

$$M_p^* = \frac{\Psi^* \frac{M_{satp}}{N_m} + M_{fix}}{1 - \epsilon - \Psi^*} \qquad (20)$$

can **be** expressed **as** a function of E_i that depends only on the following four parameters: **A**$_m$, M_{satp}/N_m, M_{fix} and ϵ. The first two parameters are dependent on the mission and satellite requirements while the last two, the fixed **mas5** and the packaging coefficient, are independent of the capacitor and power conditioning technologies.

M_{fix} can be estimated from experience at Fairchild Republic[2] **as** the sum of the mass of the discharge ignitor **and** its circuitry (.23 **kg),** the mass of the electrodes and the associated assembly **(3 kg)** and the mass of the power independent part of the power conditioning system (.5 kg) **giving** M_{fix} = **3.73 kg.** While the packaging ratio, ϵ, for more **complex** electric propulsion systems, such **as** ion **and** MPD thrusters, **can** be **as** high **as** .5 ***(see* ref.** [3, 4]) APPT flight-ready prototypes have typically **a packaging** ratio of ϵ = .2 (see ref. [I]).

With fixed values of M_{fix} and e, equations (19) and (20) can be **used,** with Ψ^* **as** an intermediate parameter, to build a graph that allows finding M_p^* as a function of E_i with the mission requirements (M_{satp}/N_m and Δv) **as** parameters. This plot is shown in **Fig. (I)** for a typical range of these parameters. The use of this graph to design an optimal **APPT** system is illustrated below.

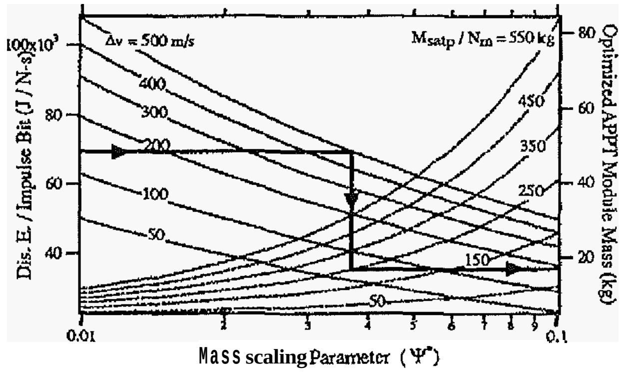

Figure I: Plot relating the optimized APPT module mass M_p^* to the ratio of discharge *energy* to impulse bit E_i for a range of interesting mission parameters. The mass scaling parameter Ψ^* **is** used as an intermediate parameter to unfold the information in Eq. (19) and Eq. (20) on the same plot. The arrows across the plot **show** how the curves are used for the case study in Section ***5.*** This plot is independent of capacitor and power conditioning technologies.

4 Model further Specialized with State of the Capacitor Technology

For a **given** state of the capacitor (and power conditioning) technology **a** series of curves **can** be drawn **using** the model above **that** give the relation between the desired average thrust and the required power from the spacecraft **bus** for a range of mission **re**quirements. For our model calculations here we **as**sume the state of capacitor (and power conditioning) technology to be **as** follows:

4.1 Capacitor Specific Mass, $\bar{m}_{cb}^{-1}$=50 J/Kg

Capacitor technology has made great advances since the early development time of the APPT's in the seventies. The capacitors with the highest energy density, $\bar{m}_{cb}^{-1}$, **that are** presently available **are** ah-minum electrolytic capacitors[5] with $\bar{m}_{cb}^{-1}$ **as** high **a**, ~ 99 J/kg but are currently deemed unreliable for long-term **space** applications[3]. The double-layer capacitor technology promises a two-order of magnitude improvement in the energy density but these capacitors are currently still in the research stage[6, 7]. Barium-

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strontium titanate and lead-zirconate titanate capacitors are being developed[8] with energy densities of 10^5 J/kg but have not yet been shown to be suited for long-term APPT applications. Ceramic capacitors are an off-the-shelf technology and offer a factor of 2 improvement on the energy densities of the capacitors used on early APPT systems. They have been recently chosen in a pulsed MPD propulsion system study[3] and are benchmarked at 50.3 J/kg for the ceramic Z5U capacitor[9]. For our current study we set $\tilde{m}_{cb}^{-1}$=50 J/Kg.

4.2 Power Conditioning (PC) Specific Mass and Efficiency, $\tilde{m}_{pc} = 8 \times 10^{-3}$ kg/W and η_{pc}=.8

The power conditioner (PC) for APPT systems is much simpler than that required for other EP systems and is not as critical as the capacitor bank. The power conditioner technology used at Fairchild Republic in in the mid-seventies[2] is still well suited for today's APPT applications and is characterized by a fixed mass of .5 kg (added to M_{fix} in the model above), a specific mass $\tilde{m}_{pc} = 8 \times 10^{-3}$ kg/W and an efficiency of η_{pc}=.8.

4.3 Number of pulses, $N_p = 3 \times 10^7$

The largest number of pulses demonstrated for an APPT system is in the 10^7 range and is limited mostly by capacitor failure. High energy density capacitors have not yet been demonstrated to exceed that range so we take $N_p = 3 \times 10^7$ for our present study.

The chosen technology parameters are summarized in the middle part of Table 1.

The plot in Fig. (2) gives the required bus power (which must not exceed the available bus power) as calculated by the model above for the optimal characterization of one APPT module at a desired average thrust level for the case of $M_{satp}/N_m = 250$ kg and a range of Δv of interest. For a chosen average thrust level per module and number of modules the plot gives the required bus power for a given Av. This will also specify the optimal value of E_i ($E_i = \eta_{pc} P_b/T$) which can be used in the plot of Fig. (1) to obtain the mass of the module. Finally, the optimal pulse frequency is given by the curves in Fig. (3) obtained from Eq. (18). We note that this plot is independent of the mission requirements (i.e. Δv, M_{satp} and N_m).

We illustrate the use of these plots with the sample case study below.

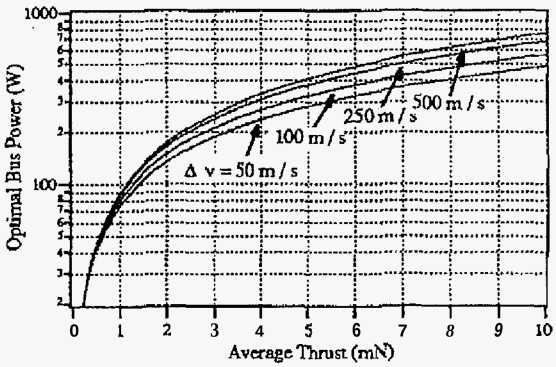

Figure 2: This plot gives the optimal bus power for a desired average thrust level and for a range of Δv. We set M_{satp}/N_m = 250 kg, $\tilde{m}_{cb}^{-1}$=50 J/Kg, $\tilde{m}_{pc} = 8 \times 10^{-3}$ kg/W, η_{pc}=.8 and $N_p = 3 \times 10$

5 Sample Case for the NSSK of a 500 kg Payload in GEO

A typical example from the spacecraft engineer's point of view is the case of the north-south stationkeeping of a 500 kg payload in GEO for 10 years. We assume that the maximum available bus power is 300 W. The particulars of the mission (stabilization scheme, pointing requirements, stationkeeping allotments, power budgeting, etc.) dictate the choice of the number of modules and the average thrust. We assume that 2 modules are needed and each of which must deliver an average thrust of 1.5 mN. These requirements are summarized in the upper portion of Table 1.

The worst-case changes in velocity required for stationkeeping at GEO are Δv_{MOON} = 36.93 m/s per year and Δv_{SUN} = 14.45 m/s per year which for 10 years yield a total of Av = 513.8 m/s. From Fig. (2) we find, for an average thrust of 1.5 mN, a required bus power of 130 W which is acceptable since the total power for the two modules (260 W) does not exceed the available power of 300 W. This yields an energy to impulse bit ratio of $E_i = 70 \times 10^3$ J/N-s. At this value of E_i (and for $N_p = 3 \times 10^7$) we find from Fig. (3) that, in order to insure the optimal conditions, the pulse frequency for each module must be .3 Hz. Furthermore, for that value of E_i and the required A v we find from the left side of the plot in Fig. (1) a mass scaling parameter Ψ^* =.04 which, from the right side of the same plot (with M_{satp}/N_m = 250 kg) yields an

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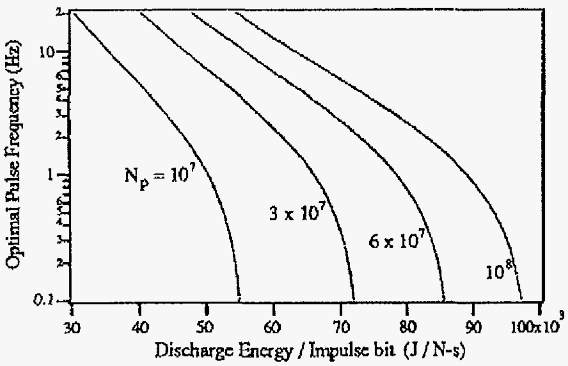

Figure **3:** Optimal pulse frequency as a function of E_i for a range of number of **pulses** N_p. **We** set $\bar{m}_{cb}^{-1}$=50 J/Kg, $\bar{m}_{pc} = 8 \times 10^{-3}$ kg/W and η_{pc}=.8. This plot is independent of the mission requirements (Δv, M_{satp} and N_m).

APPT module mass of about 17kg. The calculation is illustrated by the arrows drawn across that plot. The total propulsion system mass is thus *34* **kg.** This is 6.4% of the total spacecraft **mass.** Other pertinent system parameters can **be** calculated with the relations above and are shown in Table 1. In particular, we **find** the total. mass of required Teflon to be **5** kg which satisfies the assumption that $M_{sp} \ll M_{tot}$.

6 Thruster Design Considerations

By combining **fits** to experimental data obtained with **various** thruster designs at Fairchild Republic in the mid-seventies[2, 10] we **can** write the following approximate empirical expression that relates E_i to the exposed area *A* of Teflon in the thruster

$$A = E_i^{-1/n} \left(\frac{d}{c}\right)^{1/n} \tag{21}$$

where all units are in SI **arid,** $n = .585$, $d = 1.4511$ with *c* dependent on the **particular** feed **configuration**. In particular, $c \approx 2.49 \times 10^{-3}$ for a breech-fed geometry, $c = 1.659 \times 10^{-3}$ for a V-shaped geometry and $c = 1.116 \times 10^{-3}$ for a side-fed geometry. This relation is **plotted** in Fig. **(4)** for the three geometries.

The breech-fed geometry is preferable when the optimization yields a requirement of high **specific** im**pulse** which **is** the **case** for the sample calculation

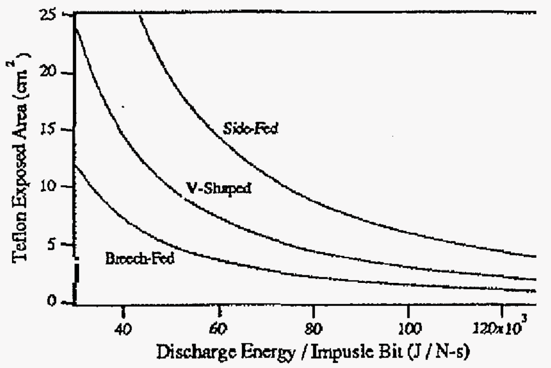

Figure **4:** Teflon exposed area **as** a function of E_i for the three **feed** geometries studied at Fairchild Republic[2, 10].

here. **For** that geometry, and **our** calculated value of $E_i \approx 70 \times 10^3$ J/N-s, the optimal exposed area is about **3** cm^2. Considering the uncertainty in the **ex**perimental database this value for the exposed area should be taken **only as** the starting point for iterat**ing** the design of ***a*** **thruster** that satisfies the optimal criteria calculated above. **The results** of this **sample** optimization calculation are **displayed** in Table 1.

7 Concluding Remarks

The **APPT is** the only plasma propulsion option that is currently in **use** on **actual** US spacecraft and many **APPT** systems **have** reached flight-readiness in the late-sixties and mid-seventies[11]. Most of these **sys**tems, however, **were** limited to operation at a **few tem** of **joules** of discharge energy. For **many** realistic stationkeeping requirements, **we** have shown above that optimal ***APPT operating conditions*** (which can ***lead*** to total mass fractions of a few percent for even the more requiring stationkeeping missions) are reached for discharge energies of a **few** hundred joules. The scaling towards higher energy systems, the integration **of** modern capacitor technology, along with other technical issues[11] should be the subjects of research aiming at the development of advanced **APPT** systerns that could **meet** the stationkeeping requirements of the upcoming constellations **of** commercial satellites.

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REQUIREMENTS

Satellite Payload Mass	500 kg
Mission Type	10-year-NSSK at GEO (Δv=513.8 m/s)
Number of Propulsion Modules	2
Available Bus Power	300 W
Average Thrust per module	1.5 mN

ASSUMED TECHNOLOGY PARAMETERS

Capacitor Energy Density	50 J/kg
Power Cond. Specific Mass	.5 kg +.08 kg/W
Power Cond. Efficiency	80%
Maximum Number of pulses	3×10^7
Fixed Mass	3.73 kg
Packaging Mass Ratio	.2

OPTIMIZED APPT MODULE CHARACTERISTICS

Required Bus Power	131 W
Impulse Bit	4.57 mN-s
Pulse Frequency	.33 Hz
Discharge Energy	321 J
Specific Impulse	5621 s
Total Efficiency	31%
Geometry	Breech-fed
Teflon Exposed Area	3 cm^2
Mass of capacitors	6.4 kg
Mass of Power Cond.	3 kg
Mass of Teflon	2.5 kg
Total Mass of APPT Module	17.1 kg

Table 1: Sample case study: requirements and optimization results.

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