Solid Propellant Pulsed Plasma Propulsion System Design

William J. Guman*
Fairchild Republic Company, Farmingdale, N. Y.

Fundamental definitions, a few semiempirical correlations of experimental data, and two design constraints of solid propellant-pulsed plasma thrusters are used to illustrate the design analysis of such an electric propulsion system. The semiempirical relations presented have been generated from thruster data covering impulse bits extending from 2.7 dyne-sec (6μ lb-sec) to 31 mN-sec (7 mlb-sec) and a specific impulse up to 5100 sec. They are descriptive to within about 8%.

Basic Considerations

A PULSED plasma thruster utilizes the rapid discharge of energy E from an energy storage capacitor to accelerate a small quantity of mass of plasma to a high discharge velocity.[1] The ejection of this mass produces an impulse bit I. If the thruster is operated at a fixed pulse frequency f, an equivalent steady state thrust T is generated

$$T=fI \quad (1)$$

where any consistent metric or engineering units can be used. The corresponding equivalent steady electric power P delivered to the thruster nozzle by the capacitor is then

$$P=fE \quad (2)$$

If a power conditioner of efficiency η_p is used to charge the capacitor the required bus power will be

$$P_b=fE/\eta_p \quad (3)$$

The relationship between the propellant mass m consumed per thruster discharge and its equivalent steady flow rate $\dot{m}$ is

$$\dot{m}=fm \quad (4)$$

The specific impulse I_{sp} is therefore

$$I_{sp}=T/(\dot{m}g)=I/mg \quad (5)$$

with $\dot{m}g$ denoting the weight flow rate of propellant. The thrust efficiency η_t is

$$\eta_t=T^2/(2\dot{m}P)=I^2/(2mE) \quad (6)$$

If the power conditioner is included, the system efficiency η_s becomes

$$\eta_s=\eta_p\eta_t \quad (7)$$

A given pulsed plasma thruster is unique because its thrust is varied at constant specific impulse and efficiency. Variable thrust is realized by merely varying the pulse rate. The electric power requirements are then directly proportional to the pulse frequency.

Presented as Paper 75-410 at the AIAA 11th Electric Propulsion Conference, New Orleans, La., March 19-21, 1975; received March 19, 1975; revision received July 28, 1975. The experimental data correlations presented summarize the results obtained in several programs[1-3] sponsored by the Air Force and the National Aeronautics and Space Administration over the period of 1967-1975.

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*Manager of Electric Propulsion. Associate Fellow AIAA.

The specific thrust (P/T) is also independent of pulse frequency

$$P/T=E/I \quad (8)$$

The performance capability of a thruster is valid as long as the initial conditions of an individual pulse are repeated with each discharge. In the event initial conditions are changed (i.e., the capacitor is charged to a different initial voltage, or capacitance is either added or removed), one obtains a new performance data point in a plot of thrust efficiency as a function of specific impulse. Since either the initial voltage or the capacitance can be changed easily, it is possible to encompass a relatively broad range of performance with a given thruster. This broader performance capability appears as a number of additional data points which can be defined by a curve in a plot of efficiency as a function of specific impulse. The semiempirical relations presented describe this broader performance capability.

Experience[2] has shown the specific thrust (power/thrust ratio) to be primarily a function of the Teflon propellant geometry inside the electrode nozzle. For example, early breech-fed thrusters with a planar propellant face at the breech end of the nozzle generated a specific thrust of 56.2W/mN-64 W/mN (250 W/mlb-285 W/mlb). Changing the propellant geometry to a V-shaped configuration[2] reduces the power requirement for a given thrust level. Depending upon the included angle that is selected, one finds the specific thrust to vary from 42.3 W/mN-37.1 W/mN (188-165 W/mlb). For thruster nozzle configurations in which the propellant is fed from the sides of the nozzle,[3] one finds the specific thrust to vary from 32.6 W/mN-24.5 W/mN (145-109 W/mlb).

For applications it would appear that one should always select the propellant geometry which requires the lowest power to realize a particular thrust level. However, other considerations, such as system weight or total number of required thruster discharges may show that a thruster requiring a higher power to be a preferred approach by the satellite auxiliary propulsion designer.

Example

The design analysis for determining the preferred approach can be illustrated by an example. Consider the case where a thruster is required for an application requiring a thrust level T of 1 mlb (4.46 mN) and a total impulse (I_t) of 20,000 lb-sec (89,280 N-sec).

Performance Considerations

Impulse Bit Amplitude: From Eq. (1) one can calculate and tabulate the range of impulse bits I that could be used to generate the required thrust level T when the thruster is operated at a pulse frequency f. The range of pulse frequencies that has been used to date includes $0.15<f<4$Hz. The calculated values are presented in Table 1.

Table 1 Example: thrust—1 mlb, total impulse—20,000 lb-sec

Frequency	Impulse bit	Pulses	Breech-fed $I/E = 4\mu$lb-sec/j		V-shaped $I/E = 6\mu$lb-sec/j		Side-feed $I/E = 9\mu$lb-sec/j	
(Hz)	(μlb-sec)		E (Joules)	Isp (sec)	E (Joules)	Isp (sec)	E (Joules)	Isp (sec)
4	250	(80×10^6)	—	—	—	—	—	—
3	330	(61×10^6)	—	—	—	—	—	—
2	500	(40×10^6)	—	—	—	—	—	—
1.25[a]	800	25×10^6	200	(3363)	133.3	1171	88.9	412
1	1000	20×10^6	250	(3844)	166.7	1338	111.1	471
0.5	2000	10×10^6	500	(5829)	333.3	2027	222.2	713
0.35[a]	2820	7.1×10^6	705	(7162)	470	2494	313.3	877
0.25	4000	5×10^6	1000	(8834)	666.7	(3075)	444.4	1081
0.2	5000	4×10^6	1250	(10,097)	833.3	(3516)	555.5	1236
0.15	6667	3×10^6	1667	—	1111.2	(4177)	740.7	1470

[a] Values calculated utilizing the two design constraints.

The total number of thruster capacitor discharges n to generate the required total impulse I_t is

$$n = I_t / I \tag{9}$$

This information is also presented in Table 1. Presently, the state-of-the-art of thruster firings demonstrated is about 2.5×10^7. As a first constraint, any pulse frequency and impulse bit of operation which requires more than 2.5×10^7 pulses to realize the required total impulse should be deleted from further consideration (i.e., $f \leq 2.5\times10^7 T/I_t$ or 1.25 Hz for this example).

Capacitator Energy: For each impulse bit calculated one can evaluate the required capacitor discharge energy E from the relation

$$E = I/(I/E) \tag{10}$$

The impulse bit/energy ratio I/E is a function of propellant nozzle geometry. For a design analysis one can use the following state-of-the-art ratios: a) $I/E \approx 7.78$ dyne-sec/J (4μ lb-sec/J) for a breech-fed configuration;[4] b) $I/E \approx 2.67$ dyne-sec/J (6μ lb-sec/J) for a V-shaped configuration;[4] c) $I/E \approx 4.00$ dyne-sec/J (9μ lb-sec/J) for a side-feed configuration. The calculated energy is also presented in Table 1.

Power Requirement: The power P into the capacitor can be calculated for each of the three propellant geometries from the relation

$$P = T/(T/P) = T/(|I/E|)$$

The capacitor power for the three propellant configurations of Table 1 are: 250 w, 166.6 w, 111.1 w, for the breech-fed, V-shape and side-feed propellant configurations, respectively. The spacecraft bus power is found from the relation $P_b = P/\eta_p$ where η_p is the power conditioning efficiency. A representative state-of-the-art value is about 0.8.

Specific Impulse: The specific impulse I_{sp} in seconds can be calculated from the semiempirical relations[4] applicable to each of three propellant geometries: a) a breech-fed geometry: $II_{sp} = 560E^{1.6}$; b) V-shaped geometry: $II_{sp} = 373E^{1.6}$; c) side-feed geometry: $II_{sp} = 251^{1.6}$. In these relations the impulse bit is expressed in microlb-sec and the energy in joules. Even though a specific impulse up to 5100 sec has been experimentally realized,[3] as a second design constraint present system designs are usually limited to about 2500 sec to avoid the relatively heavier capacitor weight of the higher specific impulse configurations. The calculated specific impulse is presented in Table 1 and it is seen that a breech-fed thruster would not be considered applicable in this example. From a plot of calculated specific impulse as a function of energy, one finds for this example a discharge energy of about 470 J to correspond to the 2500 sec design constraint for the V-shaped propellent geometry.

Weight Considerations

Propellant Weight: The weight of Teflon propellant is calculated from the relation

$$W_{prop} = I_t / I_{sp}$$

Because of the low vapor pressure of Teflon, it is stored directly in the vacuum environment without tankage. A very light weight fuel track is provided to guide the solid propellant. This weight is negligibly small and considered part of the structural weight. Propellant weight and general volumetric constraints determine whether or not the propellant should be stored in the form of a straight rod,[4] a circular segment,[4] or a helical coil.[4] The helical approach is the preferred approach for applications in excess of a 89,000 N-sec (20,000 lb-sec) total impulse.

Capacitor Weight: Energy storage capacitors have been life tested at an energy density of up to 35 J/kg (16 J/lb). Presently 88 J/kg (40 J/lb) capacitors are being developed. This latter energy density will become available for life testing late 1975.

Power Conditioner Weight: Experience has shown that the power conditioner weight is reasonably well defined by the relations: a) $W_{pc} = 500$ gr + 11 gr/w < 200 w bus power. b) $W_{pc} = 500$ gr + 5 gr/w > 200 w bus power. With the power being the spacecraft bus power. For a power conditioning efficiency of 0.8 one finds the power conditioner weight for the three propellant configurations of Table 1 to be: 2.06 kg (4.55 lb), between 1.54 kg (3.4 lb) and 2.79 kg (6.16 lbs), 2.03 kg (4.47 lb) for the breech, V-shaped and side-feed propellant configurations, respectively. The best estimate for the V-shaped configuration is found to be 2.04 kg (4.50 lb) obtained from a plot of weight as a function of power using the breech and side-feed configuration data.

Discharge Initiating Circuit Weight: The circuit required to initiate a thruster discharge has a fixed weight of about 0.23 (0.5 lb) independent of thruster size or power.

Structural Weight and Electrode Nozzle: The structural weight is more difficult to present in a simple manner. Mission, environmental (i.e., shock, vibration, thermal) and mounting requirements must be considered. The structural weight varies from a little over 0.45 kg (1.0 lb) for microthrusters to about 3.1 kg (6.8 lb) for a 37,000 lb-sec total impulse laboratory thruster. The 6.8 lb figure is probably an upper value for the example under consideration.

Final Selection Considerations

The system weight of a single nozzle system (see Ref. 5 for design aspects of a dual nozzle system) at each calculated discharge energy is found by adding the propellant weight, capacitor weight, power conditioner weight, discharge initiating circuit, and structural weight. Figure 1 presents the

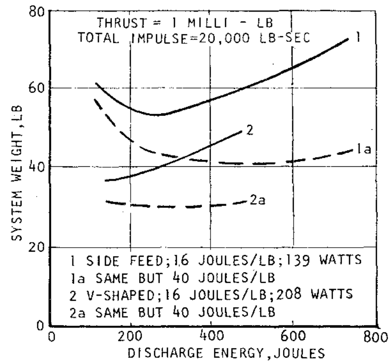

Fig. 1 Weight summary (for example).

system weight for the example as a function of discharge energy for the side-feed and V-shaped configurations. Both the 16 J/lb and 40 J/lb capacitor energy density data are presented. The energy range for which the system weight is at a minimum is evident. In this example, the spacecraft designer can consider either the V-shaped configuration which is lighter but requires more power and more thruster firings, or the side feed configuration which is heavier but requires less power and fewer firings. Since no weight has been allocated for the electric power source, the overall weight difference between the two configurations will not be as large if a power source weight is charged to the propulsion system. The 40 J/lb capacitor energy density system, which should be fully life tested by the end of 1976, allows substantially lighter systems, to be realized. Furthermore at the latter energy densities minimum weight extends over a broader range of discharge energies. It should be noted that the minimum weight system does not occur at the highest specific impulse which the pulsed plasma propulsion system is capable of. Once a discharge energy E has been decided upon, the pulse frequency to provide the required thrust level is evaluated from the relation $T=fE(I/E)$. This pulse frequency provides the time (τ) between pulses which then allows the bus current to be evaluated.

Spacecraft Bus Current: The power conditioner of a pulsed plasma thruster draws a constant current from the spacecraft power source of voltage V. Current is only required while the thruster capacitor is being charged. Because of the instant start-stop feature of the thruster, the system can be deactivated when not required. The average current i_a is evaluated from the relation:

$$E=\eta_p V i_a \tau$$

Where E is the discharge energy selected, V the source voltage, η_p the power conditioning efficiency, and τ the time between pulses. The peak current I_p will exceed the average current if the time τ_c to charge the capacitor is less than the time τ between pulses. The peak current is evaluated from the relation:

$$E=\eta_p V i_p \tau_c \quad (\tau_c<\tau)$$

In this latter case the peak bus power will exceed the average bus power. The peak bus power is equal to the product of the source voltage and the peak current.

Reliability: The pulsed plasma propulsion system has been qualitatively ranked to be the most reliable electric propulsion system.[6] A total system reliability of 0.92 and 0.98 for 5-yr missions has been calculated for the SMS[7] and TIP-2[8] propulsion systems, respectively.

Conclusions

The material presented describes the design of a thruster to meet a specific performance level and also provides the spacecraft designer with a methodology to evaluate the suitability of a solid propellant-pulsed plasma propulsion system to meet specific mission requirements. Several flight qualified pulsed plasma propulsion systems have been designed and built. Reference 9 presents some of the features of these systems as well as more details of pulsed plasma propulsion technology. Future developments will include reducing the specific thrust below 100 w/mlb, increasing the capacitor energy density above 40 J/lb, increasing the power conditioner efficiency to the upper limit of 92%, and designing multi-nozzle configurations.

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