Flight Qualified Pulsed Electric Thruster for Satellite Control

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A solid fuel pulsed plasma thruster (PPT) has been designed, built, and flight qualified for the LES-8/9 program (due to be launched in March 1975). The satellite attitude control system will contain six PPTs for orbit acquisition, east-west stationkeeping, three-axis attitude control, and station changes. Each thruster has fuel for 7320N-S (1645 lb-sec) total impulse and at 25 w generates 300 μN (67 μlb) thrust at 1000 sec specific impulse. Two prototype thrusters have passed flight qualification shock and vibration tests and operational lifetime ($>$34 million discharges or 10,460 N-sec). Important thruster components are discussed such as the design, fabrication, and testing of an 11 joule/kg (5 joule/lb) energy storage capacitor which has an extrapolated life of 100 billion discharges in thruster operation. Capacitor reliability at 41 joule/kg (18.8 joule/lb) was also tested and the results are given here. The spark plug design and its effect on thruster performance is examined. The plug causes a "periodic" variation in thrust and specific impulse.

I. Introduction

IN 1968 MIT Lincoln Lab. demonstrated its interest in electric propulsion by flying four solid Teflon pulsed plasma thrusters (PPTs) aboard its LES-6 communications satellite[1] and by initiating a program of PPT research and development. The result of that program gave a more thorough understanding of the electrical and plasma processes that affect thruster performance[2-6] and led to the development of thrusters with greatly improved thrust-to-power ratios.[7,8] From this program followed the design, fabrication, and flight qualification at Lincoln Laboratory of a PPT for the LES-8/9 mission. The development of that thruster will be discussed in this paper.

The two LES-8/9 communications satellites are scheduled for launching in Nov. 1975. In conjunction with new ground terminals they constitute an experimental system for a new mode of space communications. In addition to up- and down-link capability, this system will have the flexibility of crosslink communications between satellites. Each satellite weighs 454 kg (1000 lb) and has an operational lifetime of 5 yr.

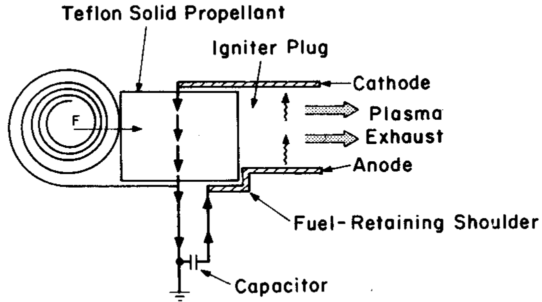

Fig. 1 Schematic of pulsed plasma thruster.

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Spacecraft propulsion will be provided solely by six PPTs, three located on the east face and three on the west face. Their duties include initial orbit acquisition, east-west stationkeeping, three-axis attitude control, and station changing. The impulse bit (I_{bit}) is 300 μN-sec (67 μlb-sec) and specific impulse is 1000 sec. The thruster weighs 6.6 kg (14.5 lb) and has a total impulse capability of 7320 N-sec (1645 lb-sec) although only 5560 N-sec (1250 lb-sec) are required for the mission. The mission requirement corresponds to 18.7 million thruster discharges which is well below the predicted 100 billion discharge life of the energy storage capacitor.

There are two modes of operation. In the low power mode (25 w for stationkeeping and attitude control) the thruster pulse rate is 1 pps and thrust is 300 μN (67 μlb). In the high-power mode (150 w) all three thrusters on one side operate at a combined rate of 6 pps (thrust $= 6 \times I_{bit} = 1790$ μN or 400 μlb) during orbit acquisition or station changes. As will be explained later, the thrust vectors are canted 30° to the satellite velocity vector. Thus, effective satellite thrust is reduced by the cos 30° from the thruster value.

II. Thruster Description and Function

Thruster Operation

The operation of the solid Teflon PPT has been described elsewhere[2] but it will be briefly repeated here. Referring to Fig. 1, the terminals of an energy storage capacitor are connected through a strip line to the electrodes in a discharge chamber. A Teflon fuel bar forms the back wall of the chamber and is fed by a negator spring against a fuel retaining shoulder. A 6 v trigger signal initiates a low energy spark plug discharge ($<$0.5 joule) in the vicinity of the fuel. This causes the electrode gap to break down and the energy storage capacitor discharges its energy across the Teflon. A portion of the fuel is ablated, ionized, and expelled by gas dynamic and electromagnetic forces producing thrust. The thrust level is given by the discharge rate times the momentum (impulse bit) of each discharge. The negator spring pushes the fuel forward as it is consumed.

Detailed Thruster Description

A LES-8/9 prototype thruster is shown in Fig. 2. For purposes of attitude control, its two nozzles are inclined 30° to either side of the thruster axis (see Fig. 3). Inclination is accomplished by

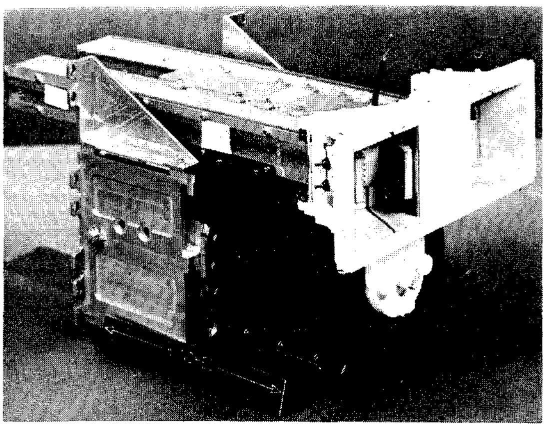

Fig. 2 Flight qualified LES-8/9 pulsed plasma thruster. The energy storage capacitor is located below the two fuel housings and the electronics is behind the capacitor. Cabling on this particular unit is incomplete.

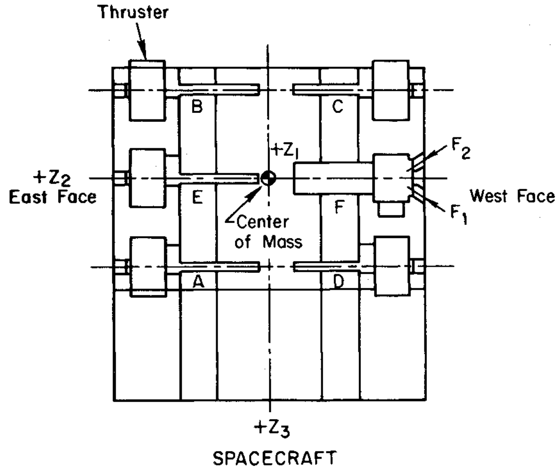

Fig. 4 Thruster locations on the satellite.

feeding the fuel bars parallel to the axis but cutting their faces 60° to it. The discharge chamber formed by the fuel face and electrodes makes a 30° angle to the axis and so does the thrust vector. The fuel face angle is maintained throughout the lifetime of the thruster. This scheme is based on a design developed at Fairchild Hiller[9] and tested at Lincoln Lab.

A single 17 μF oil-filled capacitor is connected to both discharge chambers through a low inductance (several nh) strip line. The capacitor is charged to 1538 v (20 joule) and is discharged by that spark plug which receives a trigger signal. Each chamber has two spark plugs in the cathode electrode placed equidistant from the Teflon face for even fuel erosion. The plugs are fired alternately, one at a time, and 28.5 μg of fuel is ablated for each 20 joule discharge. The current peaks at $\sim$18,000 amps during the 12 μsec discharge and the average momentum or impulse bit of each slug of ejected plasma is 300 μN-sec (67 μlb-sec). All necessary power conditioning and discharge initiating circuitry is located in two boxes behind the capacitor.

The fuel bars are 26.7 cm (10.5 in.) long $\times$ 2.3 cm (0.913 in.) in cross section. Fuel consumption is monitored by a slide wire in each fuel housing consisting of a 25.4 cm (10 in.) long, 6KΩ wire wound resistance strip (Evanohm wire), and a gold plated beryllium copper spring contact attached to the rear of the fuel. Fuel position is monitored by reading the resistance of the slide wire potentiometer and resolution is better than 10 mils which corresponds to a movement due to $\sim$11,000 capacitor discharges (out of a total of 9.4×10^6 per fuel bar).

A complete thruster weighs 6.6 kg (14.5 lb). The breakdown is as follows: 0.91 kg (2 lb) for electronics (power conditioning and discharge initiating circuitry), 0.750 kg (1.65 lb) for fuel, 1.93 kg (4.25 lb) for the capacitor, and 3 kg (6.64 lb) for structure.

III. Thruster Electronics

The PPT power conditioner uses the so called flyback type converter which transfers energy via storage in an inductor. The frequency of operation is constant and the peak inductor current is held constant thus producing a constant power system. Efficiencies are above 80% at 60 w levels while operating at 20 kHz to keep size and weight low. The only power needed is unregulated 15–30 v.

Digital inputs from either of two independent sources control which of the two nozzles will fire. Half or full charge rate is available. The charge rate is determined by the source system that triggered the converter. While the converter runs, it ignores other inputs. When the output voltage reaches 1538 v the converter is shut down and a spark plug is fired.

Two d.c. outputs are provided: 1538 v to charge the main storage capacitor, and 625 v to supply the discharge initiating (d.i.) circuitry. Internal circuitry automatically alternates spark plugs each time a discharge is initiated.

The d.i. circuitry simply places a 2 μf capacitor, initially charged to 625 v, across the appropriate spark plug, thereby initiating the mass discharge.

IV. Attitude Control and Stationkeeping

The attitude control system on LES-8/9 provides three-axis stabilization and will control angular orientation autonomously to $\pm 0.1°$ in pitch and roll and $\pm 0.6°$ in yaw. Axis stabilization is provided by a gimballed-momentum-wheel which is periodically "dumped" by the six PPTs.

Figure 4 shows the layout of the six PPTs. The thrust vectors in units A, B, C, D, and E are in a plane perpendicular to the paper whereas those of thruster F are in a plane parallel to the paper. Because the thrust vectors are canted at 30° to the thruster axis, controlled torque about any axis (Z_1, Z_2, or Z_3) can be realized by special combinations of nozzle firings. Table 1 lists these combinations and Fig. 5 shows the thruster reactions on the satellite. For example, if nozzles A_1 and A_2 are fired a positive torque about the Z_1 axis and a force in the negative Z_2 direction are produced.

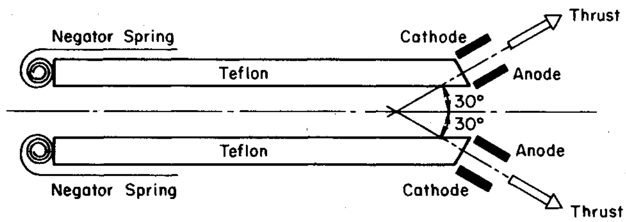

Fig. 3 Schematic showing canted thrust vectors.

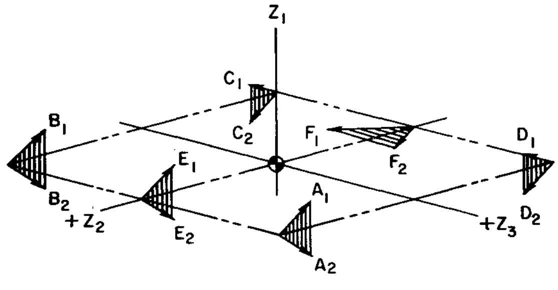

Fig. 5 Thruster reactions on the satellite.

Other combinations produce thrust in the east or west direction. Note that effective satellite thrust is reduced by the cos 30°. Stationkeeping accuracy is $\pm 0.15°$ in longitude. Should a thruster fail or fuel consumption become unequal, the nozzle combinations can be changed by ground command.

V. Key Thruster Components

The key components of the PPT are: 1) the energy storage capacitor, 2) the igniter plugs, and 3) the strip line and its insulation in the vicinity of the discharge chamber. These are described in detail in this section.

Energy Storage Capacitor

1) Requirements

It was realized early in the program that a proven capacitor that could meet the LES-8/9 PPT requirements did not exist. The capacitor had to have an energy density >8.8 joule/kg (4 joule/lb) with a minimum lifetime of 25 million discharges but preferably 100 million at peak currents up to 20 ka and operating temperatures from 25°C to 50°C. Dry film mylar capacitors, the type used on LES-6, shorted after 20 million discharges in 20 joule thruster operation. A silicon oil-filled mylar capacitor developed by Sprague Electric for Fairchild-Hiller[10] was tested in a 20 joule thruster at Fairchild-Hiller and Lincoln Lab. for a combined total of >27 million discharges with no trouble. Oil-filled capacitors seemed the only solution.

In mutual cooperation Capacitor Specialists, Inc. (CSI) and Lincoln Laboratory designed and laid out stringent assembly and test procedures for a 20 joule capacitor. Prototype units and eventually flight capacitors of an Aroclor oil-mylar design were built at CSI in cooperation with Lincoln Lab. personnel.

2) Assembly

The key steps in the capacitor assembly were: 1) all assembly procedures were performed in a clean tent with class 100 filtered air, 2) sample material was tested for dielectric strength, 3) the bushing-can assembly was helium leak tested, 4) extraordinary welding procedures were employed to protect against leaks and burning of capacitor insulation, and 5) the final seal off was under oil and at the lowest expected temperature, -20°C, to insure positive oil pressure and no voids at the higher operational temperatures. Thorough impregnation of the mylar layers was aided by the wicking action of alternate layers of paper and was observed by monitoring capacitance during the vacuum-pressure cycles.

Table 1 LES-8/9 attitude control system. Thruster nozzle combinations

		A_1	C_2	B_1	D_2	B_2	D_1
A_2	X	$+T_1$ $-f_2$	$+T_1$ $-f_1$	$-T_2$ $-f_2$	$-T_2$ $-f_1$	$+T_3$ $-f_2$	$+T_3$
C_1		$+T_1$ $+f_1$	$+T_1$ $+f_2$	$-T_2$ $+f_1$	$-T_2$ $+f_2$	$+T_3$	$+T_3$ $+f_2$
A_1				$-T_3$ $-f_2$	$-T_3$	$+T_2$ $-f_2$	$+T_2$ $+f_1$
C_2				$-T_3$	$-T_3$ $+f_2$	$+T_2$ $-f_1$	$+T_2$ $+f_2$
B_1						$-T_1$ $-f_2$	$-T_1$ $+f_1$
D_2						$-T_1$ $-f_1$	$-T_1$ $+f_2$

Symbols:
$T_{1,2,3}$ = Torque about $Z_{1,2,3}$ Axis
$f_{1,2,3}$ = Force in $Z_{1,2,3}$ Direction

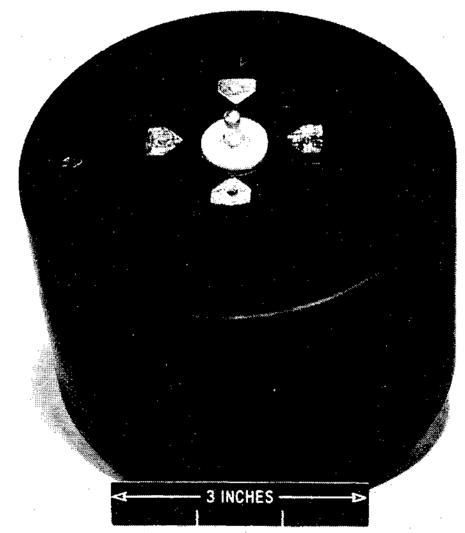

Fig. 6 Energy storage capacitor. The positive terminal is in the center surrounded by a concentric ground ring.

3) Physical description

A PPT energy storage capacitor is shown in Fig. 6. It is 12.7 cm (5 in.) in diameter, 8.9 cm (3.5 in.) long, and weighs 1.93 kg (4.25 lb). It consists of a single winding (aluminum foil-mylar-paper-mylar-aluminum foil) wrapped in an extended foil configuration on a plastic core and impregnated with Aroclor 1016 oil. The positive terminal, at the center of the top, is connected directly to the upper foil. The grounded foil at the bottom end is brought electrically through the can to a ground pick-off ring up front concentric with the positive stud. This provides for the lowest possible inductance path (measured less than 15 nh). Internal resistance is less than 10 mΩ.

The can was hydroformed at Bomco, Inc., out of 18 mil 304 stainless steel and the back lid out of thinner 12 mil 304. This affords a lightweight, uniform capacitor enclosure which has only one seam. The thin back lid acts as a bellows during the thermal expansion and contraction of the oil. Ceramaseal, Inc., built a custom silver brazed capacitor bushing which was induction brazed to the can at the same time as the ground ring. This assembly, along with the brazed fill hole collar on the lid was helium leak tested.

Capacitor Lifetime

Testing has shown that, for a variety of capacitors, lifetime (no. of discharges) vs voltage can be plotted as a straight line on a log-log plot.[11,12] Other factors that affect lifetime (lifetime decreases as they increase) are voltage reversal, temperature, and peak current, although the latter's effect is considered insignificant below 50 ka. A PPT capacitor life curve was generated at Lincoln Lab. by testing two to three capacitors at each of several selected voltages. The discharge circuit consisted of a capacitor in series with a mechanical switch and a 0.25 Ω load. The distributed inductance and load resistance were designed to give the same voltage reversal (30%) as seen in thruster operation. Samples were run at temperatures corresponding to the low (25°C) and high (50°C) thrust modes of operation. A straight line was then drawn through the lowest point (regardless of temperature) at each voltage tested (3 kv to 5 kv) and was extended to 1500 v. The resultant plot is shown in Fig. 7. The extrapolated life at 1538 v (20 joule) is ~ 100 billion discharges, 4000 times greater than the minimum required. Since CSI data indicates that a straight line extrapolation is a conservative estimate for capacitor life at the lower voltages (the line should curve upward) and since all of our data fell on or above our straight line extrapolation the probability of obtaining 25 million discharges at 1538 v is $\gg 99\%$.

Next, two capacitors were tested separately in thruster operation at 1538 v. Neither capacitor ever failed and both

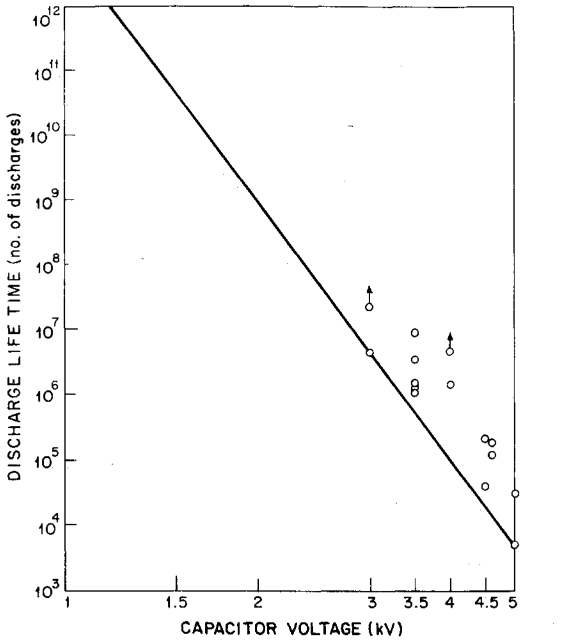

Fig. 7 Capacitor life curve at 25°C–50°C with 30% voltage reversal.

accumulated more than 34 million shots before it was decided to stop their respective tests. Capacitor temperatures were controlled to correspond to low and high thrust modes of operation.

Igniter Plugs

1) Description

The igniter plugs are made by the Bendix Corporation. One is shown in Fig. 8. It consists of an outer shell or electrode of Inconel which is separated by a concentric ring of semiconductor material from the inner electrode, also made of Inconel. The igniter plug is pressed into the cathode of the discharge chamber and the outer shell is held at ground potential. A spark or "sliding" vacuum discharge is generated when a positive voltage of ~700 v is applied to the inner electrode. The semiconductor is necessary for the vacuum discharge probably because it liberates electrons as a result of the strong fields present.

Several plugs were life tested in thruster operation and survived. The first plugs had a stainless steel outer shell and eroded quite badly.[10] The erosion was much less severe when the material was changed to Inconel.

2) Effect on thruster performance

A series of experiments showed that thruster performance is dependent on the location of the spark along the circumference of the igniter plug or, equivalently, spark distance from the fuel. This dependence is shown in Fig. 9 where impulse bit, fuel mass ablated per discharge, specific impulse and thruster efficiency are plotted as a function of distance. The data was obtained by grinding down the face of a spark plug so it could only fire at one spot on the semiconductor ring. The distance of the spot from the fuel was varied by rotating the spark plug.

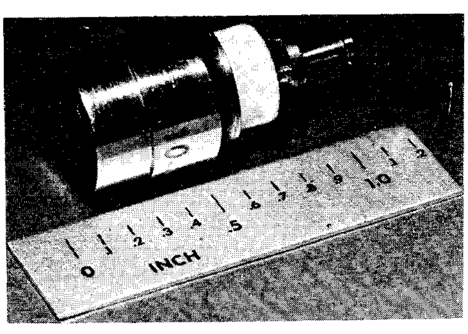

Fig. 8 Igniter plug.

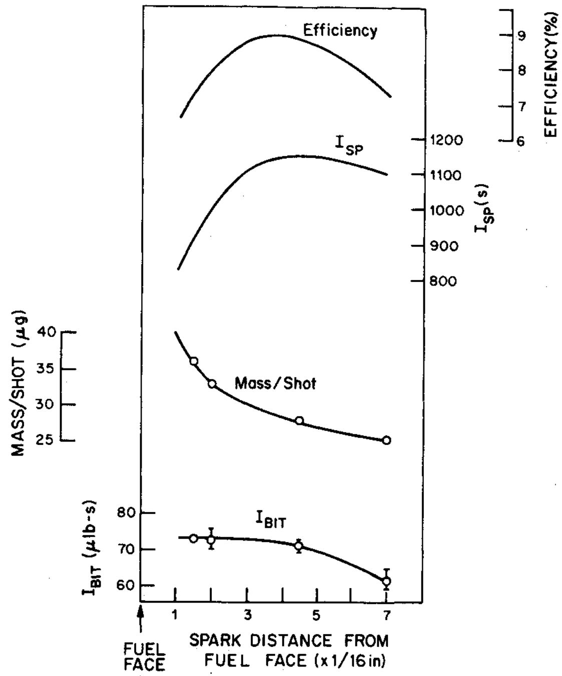

Fig. 9 Thruster performance as a function of spark distance from the fuel.

Analysis of capacitor voltage discharge waveforms showed that thruster inductance and resistance increase as the spark distance from the fuel (and from the current return path) increases. The dependence of impulse bit and mass per shot on these circuit parameters has been given in the literature.[4]

According to Fig. 9, impulse bit and specific impulse can be expected to vary 20% and 35%, respectively, from their minimum values. Average long-term performance is calculated by assuming an equal probability of the spark occurring anywhere on the igniter plug and averaging the curves of Fig. 9. This process gives 307 μN-sec (69 μlb-sec), 1100 sec, 28.5 μg per discharge, and 8% thruster efficiency. The average mass per shot measured after a 34 million discharge life test was found to be 28.3 μg, confirming the mass prediction. A second life test (described in Sec. VI) confirmed the "periodic" variation in impulse bit (see Fig. 10). The average I_{bit} was 297 μN-sec (66.7 μlb-sec) and the average mass consumption 30 μg per discharge. Both values were close to the predicted numbers.

Strip Line Insulation

The most important area of electrical insulation is in the throat of the discharge chamber where the fuel bar passes through the strip line. At the inside corners of the anode electrode, 1538 v looks directly at the ground strip across a gap of only a few mils of mylar. This area is less than 0.64 cm (0.25 in.) from the main discharge and is subjected to intense

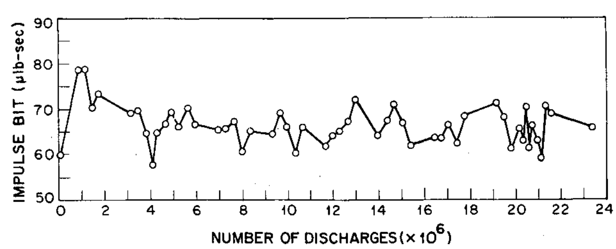

Fig. 10 Impulse bit variation. The average impulse bit, as calculated from the area under the curve, is 66.7 μlb-sec.

neutral and charged particle bombardment. A short here would short circuit the capacitor.

To insure that this cannot happen, the edges of the anode and cathode strips are covered with Kapton tape and hi-pot tested. Then the edges are completely shielded and insulated from the discharge by a seamless frame of Mykroy, a glass-bonded mica material which has a high arc and radiation resistance.

VI. Flight Qualification Tests

Three prototype LES-8/9 PPTs have successfully passed flight qualification shock and vibration tests (Titan III-C launch vehicle). The tests included random vibration about three orthogonal axes and shock pulses up to 775 g for <1 msec about three axes.

One of the prototype thrusters which went through qual testing was placed in a lifetime operational test (>34 million discharges) and passed without a problem of any kind. The test was run at 4pps with the electronics package outside the chamber. The PPT was qual tested again, this time on the satellite, and is still operational.

A second life test was conducted at Fairchild-Hiller with another qual tested thruster. The PPT was operated at 4 pps and on a thrust stand so that thrust could be monitored daily without breaking vacuum. The results confirmed the prediction that thrust would be variable (see Fig. 10). The thruster ran for 23.4 million discharges before the test was concluded. The thruster is still operational.

A third life test is in preparation at MIT Lincoln Lab. The thruster will operate at the flight pulse rates of 1 and 2 pps and the test will take one year to complete. A flight electronics package will be on this thruster and all thruster-satellite interfaces will be included. All flight thrusters are expected to be assembled and tested at Lincoln Lab. by the middle of 1974.

VII. Operation at Increased Energy

It is interesting to note that the performance of this same thruster with the same amount of fuel is improved when operated at 3000 v or 80 joule/discharge instead of 20 joule. Operating at 25 w (one discharge/4 sec) the thrust level is up 25% to 375 μN (84 μlb), specific impulse is up 45% to 1450 sec, and the total impulse is increased to 9940 N-sec (2230 lb-sec) per thruster. It should be noted that these are not long-term average performance figures as in the case at 20 joule. The average could be higher or lower than the numbers quoted here. The conservative discharge life curve shown in Fig. 7 shows that the LES-8/9 energy storage capacitor can meet the required mission lifetime (3.72 million discharges) when operating at this higher voltage, i.e., at 41 joule/kg (18.8 joule/lb). Presently, three of these capacitors connected in parallel are being life tested at 41 joule/kg (18.8 joule/lb) in thruster operation at Fairchild-Hiller. They are still operating and have passed the 2.75 million mark.[13]

VIII. Summary and Conclusions

The LES-8/9 PPT has a thrust level of 300 μN (67 μlb) and a 1000 sec specific impulse at 25 w. As power increases thrust increases proportionately and specific impulse remains constant. The thruster weighs 6.6 kg (14.5 lb) and has a total impulse capability of 7320 N-sec (1645 lb-sec).

The above performance figures were for operation at 20 joule per discharge. However, the energy storage capacitor can meet the LES-8/9 mission requirements at 80 joule per discharge which corresponds to a capacitor energy density of 41 joule/kg (18.8 joule/lb). Preliminary tests indicate that thruster efficiency is increased 82% under these conditions.

The thruster design has been flight qualified. It has passed qualification shock and vibration tests and lifetime operation of >34 million discharges or 10,500 N-sec (2350 lb-sec) total impulse. Major components such as the energy storage capacitor and spark plugs have been life tested more than once.

Circular spark plugs cause thruster performance to vary (Fig. 9); therefore, a linear plug (parallel rail electrodes) which maintains an equal spark distance from the fuel is desirable and should be developed.

Flight thruster parts are now being fabricated by Lincoln Lab. and assembly will be complete by the middle of 1974. Launch will be in Nov. of 1975.

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