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F.S. Gulczinski III, M.J. Dulligan, J.P. Lake, and
G.G. Spanjers

USAF Research Laboratory
Propulsion Directorate
Electric Propulsion Laboratory
Edwards AFB, CA

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MICROPROPULSION RESEARCH AT AFRL

Frank S. Gulczinski III*, Michael J. Dulligan†, James P. Lake*, and Gregory G. Spanjers*
Air Force Research Laboratory, Propulsion Directorate
Electric Propulsion Laboratory
Edwards AFB, CA 93524

ABSTRACT

There is an increased requirement for microsatellites to support such future missions as formation-flying space-based surveillance, space control, and on-orbit satellite servicing. Devices that can provide precise impulse bits in the 10- μ N range may be enabling for a new fleet of 25-kg class spacecraft supporting these missions. In response to this need, the Air Force Research Laboratory is developing a miniaturized propulsion unit: the Micro-Pulsed Plasma Thruster (Micro-PPT). Like a standard PPT, the Micro-PPT uses a surface discharge across the face of a solid Teflon™ propellant to create and accelerate a combination of plasma and neutral vapor. The Micro-PPT substantially differs from the standard design by using a self-igniting discharge, eliminating the separate igniter circuit from the thruster. This simplification enables order-of-magnitude reductions in the thruster size and operational power level. A technique for accurately measuring the performance of microthrusters has also been developed. Proof-of-concept performance measurements have been performed that indicate a non-optimized Micro-PPT has a thrust-to-power ratio that is approximately half that of LES-8/9 with a 60X reduction in mass.

INTRODUCTION

The Micro-Pulsed Plasma Thruster (Micro-PPT) is a simplified, miniaturized version of the Pulsed Plasma Thruster (PPT) designed primarily for stationkeeping and primary propulsion on microsatellites. The primary attractive features are the use of a solid inert propellant (Teflon™), expected high- I_{sp} due to the use of electromagnetic acceleration, and a simple, lightweight design based largely on previously flight-qualified electronic components. Prototype Micro-PPTs have been fabricated and several designs have demonstrated extended lifetime in laboratory tests. Thus, the Micro-PPT is believed to be a near-term design that could be made available for flight with a modest amount of engineering.

For 100-kg class microsatellites, such as the Air Force TechSat 21 flight, the Micro-PPTs can provide propulsive attitude control and a portion of the stationkeeping¹. For 25-kg class or smaller satellites, the Micro-PPTs can provide all stationkeeping and attitude control. The Micro-PPT can also provide maneuvering propulsion for these microsatellites;

however the trip durations may be excessively long depending on the specific mission.

Background

While the Micro-PPT retains some design similarity with the standard PPT, it is fundamentally different in critical areas that enable the required reductions in mass, size, and power. For the LES-8/9 PPT² (flight qualified in the 1970's), shown schematically in Figure 1, a DC-DC converter charges an integrated capacitor from the 28-V spacecraft bus to 1500 V. A second DC-DC converter similarly supplies 600 V to a smaller capacitor in the trigger circuit. Modern flight units operate in a similar regime³. The PPT discharge is initiated by a TTL pulse applied to the semiconductor switch in the trigger circuit. The trigger discharge fires a sparkplug embedded in the cathode, providing enough surface ionization or seed plasma to initiate the main discharge across the Teflon™ propellant face. The solid propellant is converted to vapor and partially ionized by the electric discharge. Acceleration is accomplished by a combination of thermal and electromagnetic forces to create usable

* Research Scientist, AFRL Electric Propulsion Group, Member AIAA

† Senior Scientist, ERC Inc., Member AIAA

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thrust. As the propellant is consumed over some 17 million discharges, a negator spring passively feeds the 25-cm-long propellant bar forward between the electrodes.

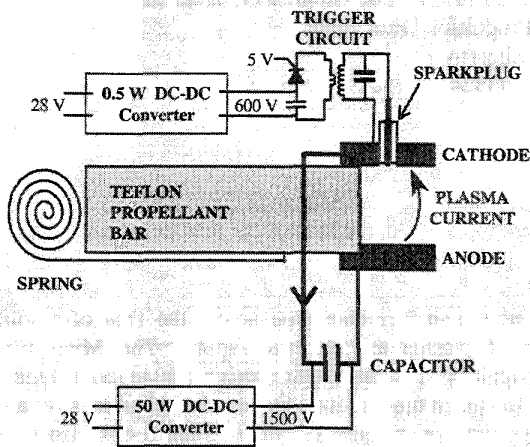


Figure 1: Schematic of a standard Pulsed Plasma Thruster

The Micro-PPT retains the use of a solid propellant from the standard PPT, which is beneficial towards reducing the thruster size, mass, and complexity. Although standard PPTs have used both rectangular and coaxial geometry, the coaxial geometry is used for the Micro-PPT since unwanted voltage breakdowns, due to edge effects, are expected to be more problematic as the scale size is reduced.

The primary difference between the standard PPT and the Micro-PPT lies in the electronics. The Micro-PPT uses only one circuit, and therefore one DC-DC converter. Two classes of electronics designs have been tested. A Triggered Micro-PPT uses semiconductor switches to create the pulsed discharge across the Teflon™ propellant. A Self-Triggering Micro-PPT applies the high-voltage charge directly to the propellant face. When the charge voltage exceeds the surface breakdown voltage, the discharge self-ignites. The self-triggering design is simpler and up to five times lighter than the triggered design, though inherent shot-to-shot variations in the discharge energy are expected to increase impulse-bit variation.

Similar to both designs is the propellant module. The coaxial geometry of the Micro-PPT consists of an inner conductive cathode and an outer conductive shell for the anode. The propellant is an annular rod of Teflon™ between the two concentric cylindrical electrodes. There is no equivalent to the sparkplug igniter used in the standard PPT. In both designs, the Micro-PPT discharge is ignited through an over-voltage at the propellant module tip. The breakdown initiates the surface discharge across the propellant face and the

concomitant propellant phase transformation and acceleration.

The Micro-PPT has some heritage in devices used as plasma sources, most notably the cable gun⁴. Indeed, some manifestations of the cable gun use the same semi-rigid cables used in Micro-PPT testing, although with diameters a factor 2 to 4 times larger and a graphite coating applied to the Teflon™ insulator face to act as the material source for the plasma. After about 20 discharges, the cable-gun coating has to be reapplied to avoid insulator (Teflon™) erosion and erratic operation⁴. Cable guns are generally energized using high voltage capacitor banks (0.6 μ F, 25kV, 188J) and switched with spark gaps switches. Working from the cable gun heritage, the design goals of the Micro-PPT are to:

- Directly use the Teflon™ insulator as the ablative material since reapplying a graphite coating is impractical for space applications.
- Reduce the voltage by a factor of 2 to 5.
- Eliminate the spark gap switch in favor of semiconductor switches more likely to meet lifetime and flight qualification requirements.
- Alternately, eliminate the switch entirely as is done in the Self-Triggering Micro-PPT design.
- Reduce the discharge energy about 100X to the range of 1 – 10 J.

MICRO-PPT DESIGN

Triggered Micro-PPT

A photograph of a prototype Triggered Micro-PPT is shown in Figure 2, detailing the propellant module, pulser box (containing the capacitors, switches, and a transformer), and transmission line connecting the two. The mass of the prototype unit is 600 g, more than a 10X reduction in mass from the 6 kg of an optimized standard PPT. The prototype was assembled to determine functionality, and was not optimized to minimize mass.

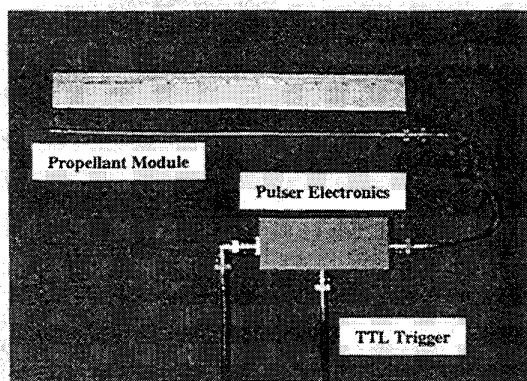


Figure 2: Photograph of a prototype Triggered Micro-Pulsed Plasma Thruster using a triggered design

The Triggered Micro-PPT is shown schematically in Figure 3. The device uses a circuit similar to the trigger circuit from the standard PPT to induce the surface discharge on the propellant module. A DC-DC converter (not shown in the photograph of Fig. 2) steps up the 28 V spacecraft bus voltage to charge the integrated capacitor. In the prototype unit a 2- μ F capacitor is charged to the 800 – 1000 V range (0.64 J to 1.0 J per discharge). The main capacitor is discharged using a semiconductor switch triggered with a simple TTL (5 V) pulse. Pulsed voltage amplification is accomplished using a 1:3 voltage step-up transformer. Charge is stored on the secondary using a 0.02- μ F peaking capacitor. Once the secondary voltage has increased to the surface breakdown voltage of the propellant module, the discharge commences.

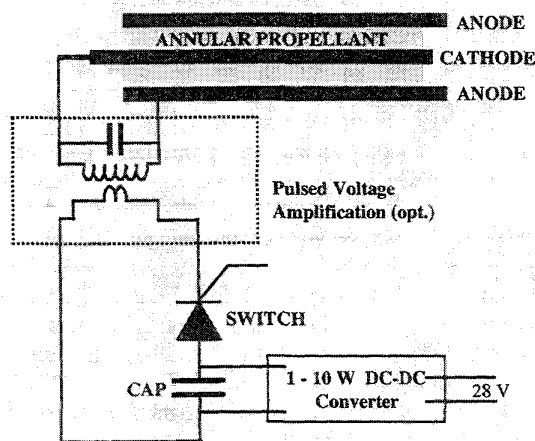


Figure 3: Schematic of a Micro-PPT using a triggered design

Pulsed voltage amplification is considered for the Triggered Micro-PPT in order to minimize the requirements (and mass) of the DC-DC converter, and still achieve sufficient voltage at the propellant face to

ignite the surface discharge. The amplification can be accomplished using several techniques. A 1:3 transformer is used in the prototype, however different step-up ratios may optimize the system mass and complexity. Alternative voltage amplification techniques include capacitive (Marx) and inductive stacking. The optimized voltage amplification technique must also be compared to the system mass achieved by simply using a more massive DC-DC converter and semiconductor switch to directly apply the surface breakdown voltage to the propellant module.

Self-Triggering Micro-PPT

A photograph of one configuration of a prototype Self-Triggering Micro-PPT is shown in Figure 4. The prototype includes a small DC-DC converter and is charged at the standard 28 V spacecraft bus voltage. Total mass for the non-optimized prototype is 100 g, a factor of 6 reduction from the Triggered Micro-PPT prototype and a factor of 60 reduction from a standard PPT.

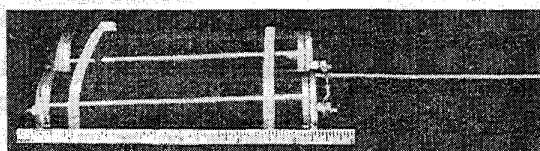


Figure 4: Photograph of a prototype Micro-PPT using a self-triggering design

The self-triggering design, shown schematically in Figure 5, is a further simplification of the triggered design. The semiconductor switch has been eliminated. The capacitor is directly charged by the DC-DC converter to a voltage sufficient to achieve the surface breakdown at the end of the propellant module. The mass of the DC-DC converter will be higher than that used in the triggered case since the required voltage is higher. An important tradeoff is whether this increased mass is offset by the decreased mass and added simplicity achieved through eliminating the switch and pulsed voltage amplification mechanism.

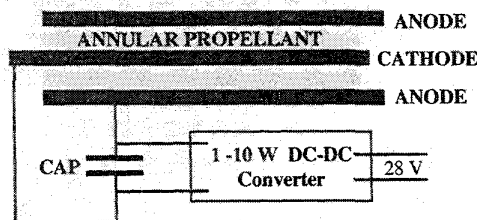


Figure 5: Schematic of a Micro-PPT using a self-triggering design

Propellant Module Designs

Common to both classes of Micro-PPTs is the propellant module, which consists of the electrodes and propellant. The module uses a coaxial geometry with an inner cathode and an outer conductive shell for the anode. The propellant is an annular rod of Teflon™ between the two concentric cylindrical electrodes.

During a discharge, the Teflon™ propellant ablates to create the bulk of the exhaust. Ablation over many discharges causes the face of the propellant to recede. In a standard PPT, the propellant bar is simply spring-fed back into the electrode region to circumvent this effect. For the Micro-PPT, where the dimensions and mass are severely limited, different approaches must be considered for feeding the propellant. Also to be considered is the effect of the electrode erosion. In a standard PPT, the electrodes are sufficiently bulky that the erosion causes no significant changes in performance over the mission life. For the Micro-PPT, either the electrode is made sufficiently robust to render erosion effects negligible as in the standard PPT, or the electrode is intentionally designed to ablate and recede with the Teflon™ propellant. The electrode recession can be enhanced by using easily ablated materials, increasing the wall current, or decreasing the electrode wall thickness. Two approaches, shown schematically in Figure 6, are being considered for the Micro-PPTs.

In Figure 6a, the module is designed so that the propellant face recedes back into the module as the material is ablated. The inner electrode also ablates with the propellant to prevent electrode shorting. The advantage of this design is that no mechanism is required to feed the propellant forward since the exit plane of the thruster, defined by the anode shell, remains fixed in position. A possible disadvantage may occur when the propellant has receded a considerable distance. When the exhaust must travel several centimeters to leave the thruster, wall effects may slow the thermal component and reduce the thrust. In Figure 6b, the entire propellant module is designed to ablate uniformly. Instead of designing a feed system to counter the recession, the module is positioned to protrude from the spacecraft. Although Micro-PPT modules have been tested in a configuration where outer electrode erosion is apparent, the uniform recession shown in Figure 6b has not been demonstrated in laboratory tests.

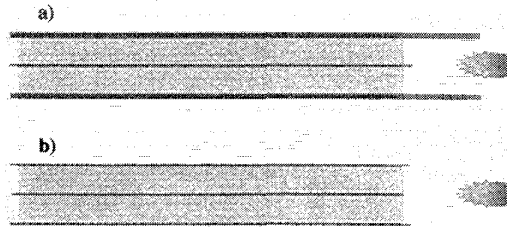


Figure 6: Two approaches for Micro-PPT propellant ablation characteristics

MICRO-PPT PROPELLANT ABLATION ISSUES

For typical microsatellite missions, the Micro-PPT will require propellant masses significantly less than the dry mass. Therefore, the greatest propulsion system mass reductions can be achieved through decreases in the dry mass. This is fundamentally different from standard kW-class electric propulsion research, which is directed toward decreasing propellant mass by improving thruster performance (typically specific impulse). The greatest dry mass reductions in the Micro-PPT can be achieved by decreasing the mass of the electronics.

The electronics requirements are dictated by the behavior of the propellant ablation. The primary requirement is that the voltage generated at the propellant face significantly exceeds the surface breakdown voltage, in order to reliably initiate the discharge. Also important is the energy discharged per pulse and propellant temperature. Insufficient discharge energy can lead to carbon deposits on the Teflon™ face, impacting performance and lifetime. High temperatures at the electrodes increase late-time vaporization of the propellant, impacting performance. Therefore, Micro-PPT development focuses heavily on the propellant ablation characteristics. The goal is to find a parameter space of propellant geometry, electrode material, discharge energy, voltage, and power that achieves acceptable performance and high reliability. Discharge voltage and energy must also be kept within reasonable limits for eventual space flight engineering. For high reliability from a propellant ablation standpoint, the design goal is to fire long enough to establish a steady-state cross-section shape at the propellant face that is free of deposits. Ideally, further firing will cause the propellant face to recede while maintaining the steady-state geometric profile.

The standard PPT suffers from very poor propellant utilization. As little as 10% to 20% of the propellant is converted to plasma and accelerated to high exhaust velocity, creating over 90% of the thrust⁵. The remaining propellant is consumed as late time neutral vaporization⁶ or particulate emission⁷. These

losses have been measured to continue for over 1 ms following the 10 μ s discharge pulse. A significant amount of PPT research and development has focused on eliminating this propellant loss, by either minimizing the vaporization and particulate emission, or accelerating it to increase thrust.

In contrast, the Micro-PPT relies on the late-time vaporization to achieve the uniform ablation of the propellant. The Micro-PPT discharge energy, voltage and rise-time are insufficient to create multi-channel discharge paths across the propellant face. Instead, what is observed experimentally is a discrete arc that ideally moves to various azimuthal locations during the thruster lifetime. Without late-time vaporization, a single discharge would locally ablate material. For the subsequent discharge, this local area would have slightly lower inductance and would become a preferential current path for all remaining discharges. This scenario is believed to lead to a "gouging" of the propellant in a localized azimuthal location that has been observed in some tests, most notably those at lower discharge energies. A localized pit forms between the inner and outer conductors at a localized azimuth and the discharge arc is restricted to this region. This is considered a failure mode for the Micro-PPT. Late-time vaporization and particulate emission are believed to be more dependent on the total energy deposition within the propellant, as opposed to being directly associated with the discharge arc itself. Clear support for this hypothesis lies in the observation that these effects continue for long after the arc discharge has dissipated. Since late-time vaporization and particulate emission consumes up to 9 times the propellant of the discharge arc, the Micro-PPT design relies on these effects to smooth out any preferential ablation in the location of the discharge arc, enabling smooth, steady-state propellant ablation characteristics.

MICRO-PPT EXPERIMENTS AND TESTS

Propellant Module Ablation Tests

As discussed in the previous section, understanding propellant ablation is critical to optimizing the Micro-PPT designs. To investigate the propellant ablation, a separate test apparatus is used where a series of fixed energy discharges are created across the propellant, triggered by an auxiliary sparkplug, independent of the specific Micro-PPT electronics design. Figure 7 shows the propellant face of a 6.35-mm diameter propellant module (1.70-mm cathode, 5.50-mm propellant diameter, and 0.43-mm anode wall) after 40,000 discharges at 5 J fired at 2 Hz. The propellant is clean with no significant conical shape. Instead, the propellant is observed to recess slightly slower near each electrode, possibly due to the heat transport

through the copper electrodes acting to cool the Teflon™. The inner electrode recedes at nearly the same rate as the propellant, with an approximately 3.18-mm protrusion past the propellant face in Figure 7. Further testing on the same propellant module increased the total discharges to 110,000. The propellant receded further into the anode shell, however the inner electrode protrusion past the propellant face remained constant. The propellant ablation rate during these tests was 8.7 μ g/discharge at 5 J. This rate, normalized to the discharge energy, is about 20% higher than that measured on standard PPTs operating at 20 J.

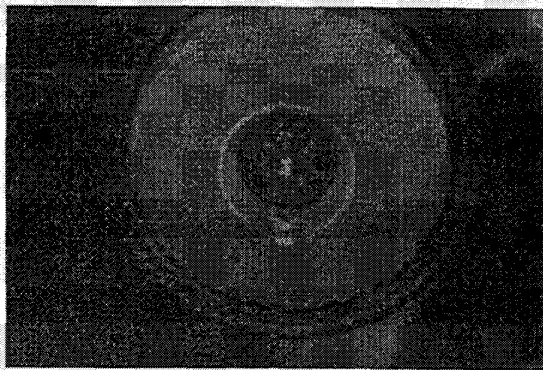


Figure 7: Photograph of a 6.35 mm diameter propellant module after 40,000 discharges at 5 J

The 6.35-mm propellant module tests display the behavior desired for the design shown in Figure 6a. However, designing Micro-PPT electronics and DC-DC converters with an acceptable mass that operate at voltages corresponding to these diameters (20 – 40 kV) is non-trivial unless a robust pulsed voltage amplification scheme can be developed with very high gain. These tests do suggest that the desired propellant ablation characteristics can be achieved in smaller propellant modules, with proper optimization of the discharge current and voltage, at more reasonable charge voltages.

Triggered Micro-PPT

The Triggered Micro-PPT was tested to determine lifetime and propellant ablation characteristics. The thruster tested had a propellant module with a 0.55-mm-diameter cathode, a 1.80-mm propellant outer diameter, and a 0.21-mm anode wall. It was freshly machined prior to the tests with a flat front face. It appears, in general, to achieve relatively long lifetimes, with approximately 500,000 discharges applied to a single propellant module without failure. These discharges were performed over a variety of conditions; however, there is no reason not to expect similar functionality in a controlled life test.

Following a large number of discharges, the propellant face began to exhibit signs of "gouging", where the bulk of the ablation occurs in a localized azimuthal region and the remainder of the propellant remains relatively pristine throughout the lifetime of the thruster. Thruster functionality continues, but it is clearly a waste of propellant mass and considered an overall failure for the thruster configuration.

Self-Triggering Micro-PPT

Similar lifetime and ablation tests were performed on the Self-Triggering Micro-PPT. Multiple configurations were built and tested. The variables in these configurations are the maximum charge voltage (set by the capacitor used), total capacitance, propellant diameter, and electrode material. Capacitors rated to accept charge voltages of 8 kV and 10 kV were used. Tests were conducted at total capacitances of 0.104 μF (one capacitor), 0.202 μF (two capacitors), and 0.303 μF (three capacitors). Two propellant sizes were tested: 3.58 mm diameter (0.9 mm cathode, 3.1 mm propellant diameter, 0.24 mm anode wall) and 2.21 mm (0.55 mm cathode, 1.80 mm propellant diameter, 0.21 mm wall). The electrode material was copper, except in one case where aluminum was used. The configurations tested are summarized in Table 1.

Thruster	Figure	V_{max} [kV]	C [μF]	E_{max} [J]	d [mm]	Material	Firing Time [s]	Discharges	Failure Mode
A	8	8	0.104	3.3	3.58	Cu	23076	27308	High Current Discharge
B	9	10	0.202	10.1	3.58	Cu	9096	6599	High Voltage Holdoff
C	10	10	0.202	10.1	2.21	Cu	4287	4414	High Voltage Holdoff
D	11	10	0.303	15.2	3.58	Cu	5203	8252	High Voltage Holdoff
E	12	10	0.202	10.1	2.21	Al	11225	12340	High Voltage Holdoff
F	13	10	0.303	15.2	2.21	Cu	16121	14801	None Found

Table 1: Parameters of Self-Triggering Micro-PPTs examined in endurance tests

Figures 8 through 13 show the propellant breakdown voltage for the Self-Triggering PPT configurations, measured with a Fluke 80k-40 1000-to-1 high voltage probe. The black line represents a moving average based on 200 breakdowns. When possible, a photograph of the propellant face at end-of-life is shown. Charge current was adjusted to maintain a discharge rate generally between 0.5 and 2 Hz. In all cases, there is typically a "burn-in" period during which the thruster operates at high current and low voltage. The duration of this period varied from test-to-test and it is associated with the removal of initial impurities on the propellant face. Following the short burn-in period there is generally a longer period of increasing surface

breakdown voltage. This is associated with the discharge path length increasing as the propellant face adjusts to a slightly curved profile. Ideally, this will be followed by a steady-state period, where the breakdown voltage and the propellant face shape remain relatively constant while receding into the anode shell. Once the steady-state shape is characterized, it is expected that this shape would be preformed, in order to minimize transient phases during flight.

Figure 8 shows Case A with 8 kV maximum charge voltage, 0.104 μF capacitance (max energy = 3.33 J), and 3.58-mm propellant diameter. The breakdown voltage increased over the course of the first 6000 s of operation to an average of approximately 3 kV. The thruster continued operating in this manner for another 9000 s. At this point, and several times afterward, the capacitors would charge to the maximum voltage without immediate breakdown. The voltage was held off for periods ranging from a few seconds up to several minutes before breakdown occurred. Several of these events would occur over a short period, before the thruster returned to an average discharge of 3 kV. This behavior occurred until 22000 s, when the thruster began operating in a high current, low voltage mode again, leading to the termination of the test. As shown in Figure 8, the propellant module shows signs of charring and preferential ablation near the electrodes. It is believed that insufficient energy was being supplied to provide for uniform ablation at the propellant face.

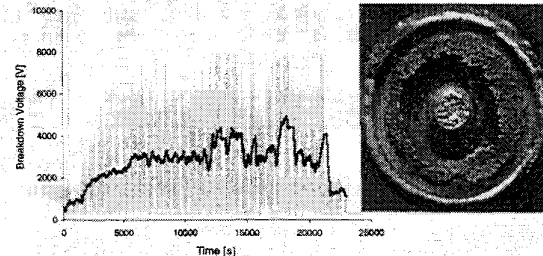


Figure 8: Voltage breakdown variation in time for the Self-Triggering Micro-PPT with a maximum charge voltage of 8 kV, capacitance of 0.104 μF , and diameter of 3.58 mm with photo of thruster at end of life

Figure 9 shows Case B with 10 kV maximum charge voltage, 0.202 μF total capacitance (max energy = 10.1 J), and 3.58-mm propellant diameter. The average breakdown voltage increased to approximately 6 kV, at which point the capacitor began charging to 10 kV and holding off the voltage before discharging. Testing continued until the thruster held off the voltage for 5 minutes without discharging, at which point the test was terminated. Examining the post-test photograph, the propellant bar is much cleaner and

more evenly parabolic, with areas of charring pushed out toward the anode. This shows that an increase in the discharge energy can reduce charring. However, the inner electrode did not recess with the propellant face, forcing the electron emission to come from the smooth curved surface on the outside of the inner electrode. This reduction in electron field emission is believed to have led to an increase in the breakdown voltage past the design constraint for the test. When the inner electrode recedes with the propellant, the electron emission can occur at the sharp protrusions near the tip, resulting in acceptable breakdown voltages.

Based on these tests, the design constraints for the propellant are to increase the ratio of the discharge energy to surface area sufficiently to avoid deposits on the propellant face. Furthermore, the current density on the inner electrode must be sufficient for the electrode to recede at a rate commensurate with the propellant ablation rate. The inner electrode erosion can be controlled through diameter, discharge energy, and material choice.

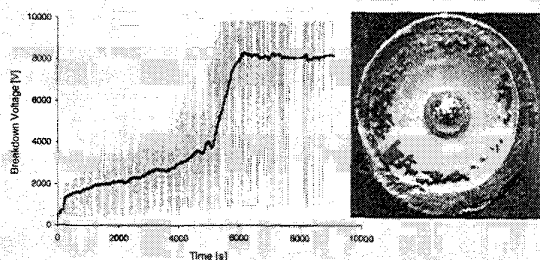


Figure 9: Voltage breakdown variation in time for the Self-Triggering Micro-PPT with a maximum charge voltage of 10 kV, capacitance of 0.202 μF , and diameter of 3.58 mm with photo of thruster at end of life

Figures 10 through 12 show additional configurations tested to find a regime where the propellant face remained clean and the inner electrode receded with the propellant. Figure 10 shows the effect of decreasing the propellant diameter while maintaining the energy of Case B (Figure 9). Case C (Figure 10) uses a 10 kV maximum charge voltage, 0.202 μF total capacitance (max energy = 10.1 J), and 2.21-mm propellant diameter. Case D (Figure 11), with 10 kV maximum charge voltage, 0.303 μF total capacitance (max energy = 15.2 J), and 3.58-mm propellant diameter, shows the effect increasing the discharge energy compared to Case B (Figure 9). Case E (Figure 12) shows the effect of aluminum, rather than copper, electrodes (Case C is used for reference). In general, test configurations with higher energy-to-diameter ratios maintained cleaner surfaces, but resulted in shorter lifetimes. The aluminum fuel bar shown in

Figure 12 shows greater lifetime than the similar configuration in copper in Figure 10, possibly due to the lower melting temperature and higher ablation rate of aluminum. However, this may also result in the greater variation in shot energy observed for the aluminum fuel bar.

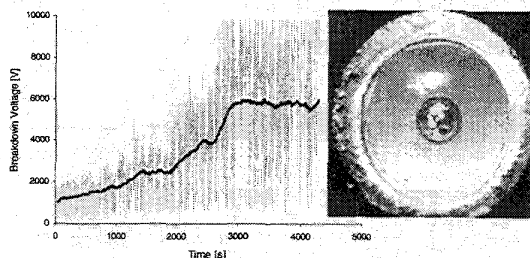


Figure 10: Voltage breakdown variation in time for the Self-Triggering Micro-PPT with a maximum charge voltage of 10 kV, capacitance of 0.202 μF , and diameter of 2.21 mm with photo of thruster at end of life

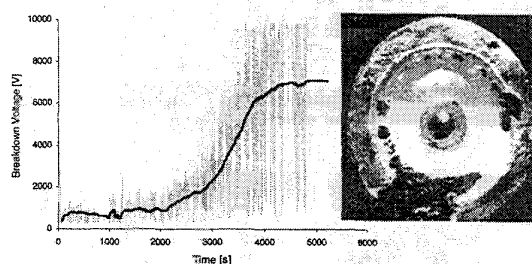


Figure 11: Voltage breakdown variation in time for the Self-Triggering Micro-PPT with a maximum charge voltage of 10 kV, capacitance of 0.303 μF , and diameter of 3.58 mm with photo of thruster at end of life

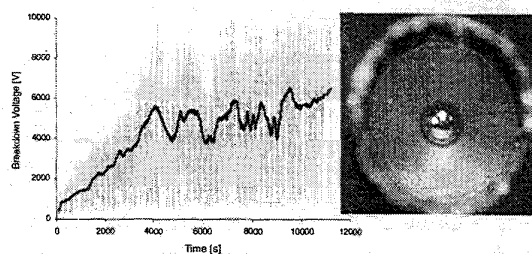


Figure 12: Voltage breakdown variation in time for the Self-Triggering Micro-PPT with a maximum charge voltage of 10 kV, capacitance of 0.202 μF , and diameter of 2.21 mm (aluminum) with photo of thruster at end of life

Figure 13 shows Case F with 10 kV maximum charge voltage, 0.303 μF total capacitance (max energy

= 15.2 J), and 2.21-mm propellant diameter. This was the most successful configuration tested. It was fired through 16000 s with no life-ending failures. Upon examination of the fuel bar, it was found that in this case the inner electrode had recessed back with the face of the Teflon™. It appears that in this configuration, there is sufficient energy to cause recession of the inner electrode, maintaining sharp points critical to field enhancement. Over the course of this test, the propellant and inner electrode recessed 5 mm relative to the outer electrode. Due to this recession, it was not possible to take a post-run photograph as was done for the other tests. Subsequent mass measurements performed on this configuration indicated ablation rates of 1.3 $\mu\text{g}/\text{discharge}$ and energy expended of 2.4 J/discharge. These are average rates over the entire test, including the burn-in period. This is approximately 40% of the ablation of LES-8/9 at 20 J, 28 $\mu\text{g}/\text{discharge}$.

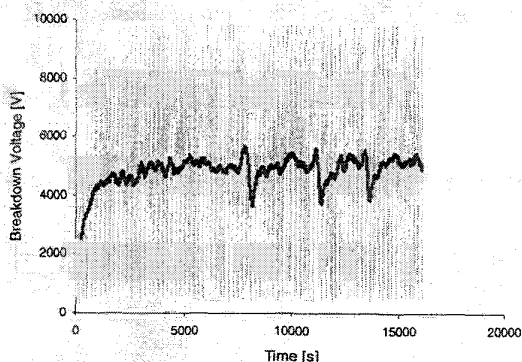


Figure 13: Voltage breakdown variation in time for the Self-Triggering Micro-PPT with a maximum charge voltage of 10 kV, capacitance of 0.303 μF , and diameter of 2.21 mm

Plume Tests

To enable an early assessment of potential spacecraft contamination issues specific to the Micro-PPT, a short series of plume measurements were performed. Figure 14 shows an intensified image of the plume from the 5 J, 6.35-mm propellant diameter tests. Figure 14a shows a well-directed plume with the image integrated over the first 15 μs of the discharge. Figure 14b shows the broadband emission with a 100 μs shutter time starting 50 μs after the discharge. The characteristic PPT particulates are observed as expected using the Teflon™ propellant⁷. The particulate traces are all forward-directed in sharp contrast to the standard PPT, where particulates are observed travelling all directions including back towards the spacecraft⁷. The

coaxial Micro-PPT geometry appears to be self-shielding, with the closed nature of the acceleration region blocking particulates from trajectories in the rear-plane of the thruster. Thus, the Micro-PPT may realize additional mass savings by not needing the auxiliary nozzles the standard PPT uses to minimize spacecraft contamination.

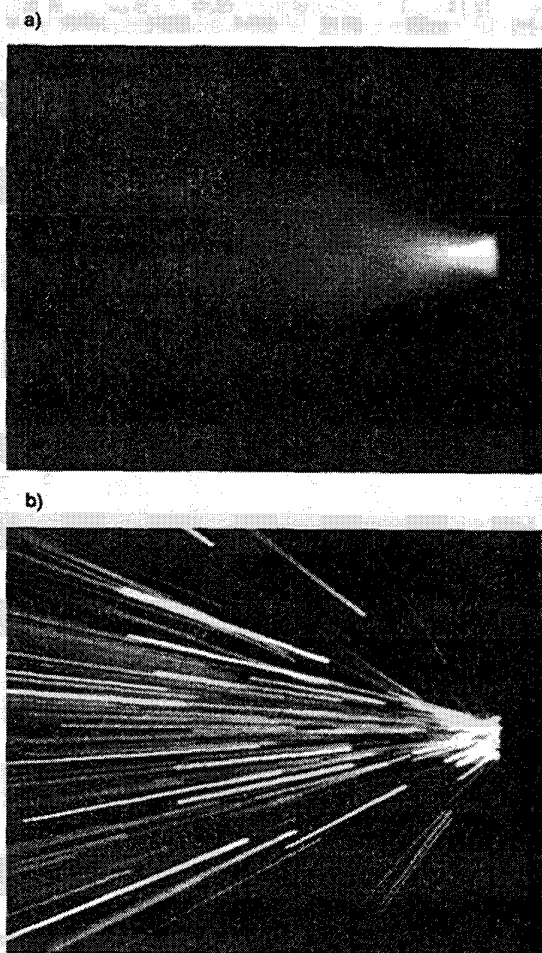


Figure 14: Intensified images of the exhaust plume from a 6.35 mm diameter propellant module discharged at 5 J

Performance Measurements

Prior to this study, a notable gap in Micro-PPT research and development was the lack of performance measurements. This is a common problem for microthruster research in the 10 μN thrust regime. As currently operated, state of the art thrust stands^{8,9,10} have ultimate resolutions near $\pm 10 \mu\text{N}$, primarily limited by facility effects such as thermal drifts and vibrations. In this mode, oscillations are magnetically damped, resulting in very small deflections for a given

thrust. These deflections are of the same order as those that result from thermal drift and vibrations. Attempts to increase the sensitivity of the thrust displacement measurement have inevitably resulted in more accurate measurements of vibration and drift effects, with no increase in thrust measurement accuracy.

For the study of Micro-PPT performance, a method was developed similar to that used to measure performance of the LES-6 PPT¹¹, whereby the thruster is fired in synchronization with the motion of an undamped thrust stand. By repetitively applying a small force, such as firing a thruster or loading a calibration mass, on only a half period of the oscillation, a large amplitude deflection may be obtained. The system responds as a forced resonant oscillator, significantly increasing the oscillation amplitude. The steady-state oscillation amplitude is a balance between the resonantly applied force and the inherent restoring force of the thrust stand, and is appreciably larger than a deflection obtained from the non-resonant, damped method. Forces such as vibrations and drift, which act upon the thrust stand over a full period of oscillation, produce a negligible net change in the measured deflection. This is in strong contrast to the adverse effect these forces have on non-resonant damped methods of measuring force.

Calibration was performed by picking up and dropping known masses of permanent magnets using an electromagnet attached to the thrust balance. Figure 15 shows steady-state oscillations for three masses (31.7, 50.0, 96.4 μN) from the resonant method. Shown underneath, on the same vertical scale, are the corresponding displacements for the traditional non-resonant, damped method. A LEM Servogor 111 strip chart recorder was used to record the LVDT output to measure the thrust balance deflections. The thrust stand period is 6.6 s and the weights were manually loaded and unloaded in 3.3 s intervals. Under identical conditions, the amplitude of the resonant method is nearly 40 times greater than that from the non-resonant, damped method. The robustness of the calibration was checked by observing the steady-state oscillation amplitude starting from two initial conditions: (1) initiating translation with the thrust stand at rest; and (2) initiating measurements from an amplitude beyond steady-state conditions then allowing the damping to bring it back to steady state. Both conditions ultimately result in the same steady-state oscillation. The bumps on the profiles in the resonant method of Figure 15 occur when the oscillations are electronically driven to amplitudes larger than steady-state. Note that the data in Figure 15 are shown for illustrative purposes and that longer times than shown are required to guarantee equilibrium has been achieved.

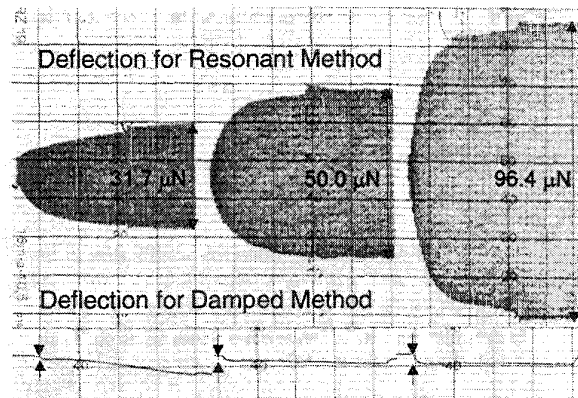


Figure 15: Comparison of Deflection Magnitude for Resonant and Damped Methods

Typical calibration data are shown in Figure 16. The dominant source of uncertainty in these measurements is the sensitivity of the measurement to thrust stand inclination. Small changes in inclination, on the order of 0.0072 arc seconds, are detectable. During operation, pitch control was used to keep the inclination within ± 0.036 arc seconds, resulting in an uncertainty on the order of ± 5 μN . This is considered an upper bound, since it will be relatively easy to reduce this uncertainty through active feedback control of inclination. The oscillation amplitude from day-to-day is highly reproducible for a given calibration mass, as long as pitch control is employed to match thrust stand inclination. A second major source of uncertainty lies in the manual operation of the application of force. The calibration masses and thruster operation were cycled on and off by hand. The result of irregular timing in the application of force causes variations in displacement of about 0.5%. This uncertainty will be minimized by using computer control to switch the power to the thruster or calibration electromagnet when the time derivative of the displacement changes sign. Upgrades to the thrust stand to include inclination feedback control and automated firing control are currently in progress at AFRL.

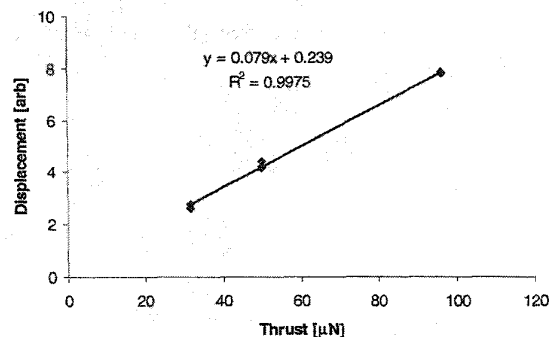


Figure 16: Typical Thrust Stand Calibration Curve

Proof-of-concept performance tests were carried out on Self-Triggering Micro-PPTs with 3.58-mm and 2.21-mm diameter fuel bars, each with a capacitance of 0.415 μF . These are similar to the thrusters shown in Figures 11 and 13. The larger value for capacitance was chosen based on the availability of off-the-shelf vacuum rated capacitors. As in all other tests, the Micro-PPTs were prepared such that the Teflon™ was initially flat and flush with both the inner and outer electrodes. The thrusters were fired in a vacuum tank with a pressure of 5×10^{-5} Torr. Approximately 14 and 8 discharges per period were put on the 3.58-mm and 2.21-mm diameter Micro-PPTs, respectively.

Typical power levels ranged from 2 to 10 W and thrust ranged from 20 to 80 μN . The thrust-to-power ratio as a function of firing time for the two Micro-PPTs is shown in Figure 17. By way of comparison, the fully optimized, flight qualified LES-8/9 had a thrust-to-power of about 13.5 $\mu\text{N/W}$ (270 μN at 20 W into the thruster)⁵. Though the average observed Micro-PPT thrust-to-power is slightly less than half that of LES-8/9, the thrusters are not optimized and have 1/60 the mass.

The observed decrease over time in thrust-to-power is noted and correlates with a decrease in discharge energy (averaged each 100 discharges) shown in Figure 18. This indicates that higher discharge energy results in better performance, as is generally true for all PPTs⁵.

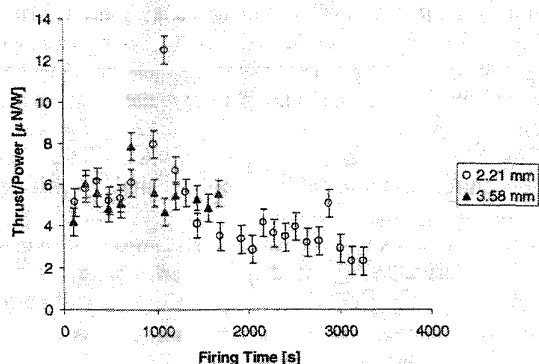


Figure 17: Thrust-to-Power over the lifetime of two Micro-PPTs

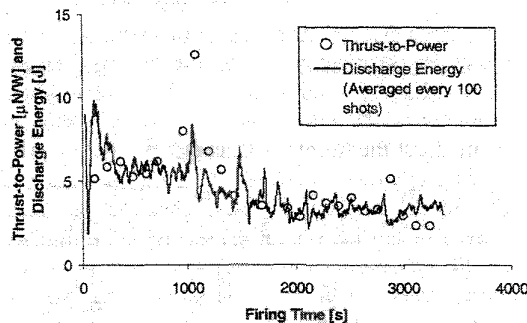


Figure 18: Comparison of Thrust-to-Power ratio and Discharge Energy

The thruster efficiency and specific impulse were not determined during this test series. The purpose of this initial effort was to develop a technique for accurately measuring Micro-PPT thrust levels. Test conditions were varied during the course of thruster operation and the majority of discharges were at power levels significantly above the intended design of about 1 W. Though thruster temperature was not measured, the thrusters probably operated at much higher temperatures than desired, significantly increasing the late time vaporization of the Teflon™.

Now that the basic technique for measuring Micro-PPT thrust levels has been demonstrated, AFRL efforts will focus on validating the technique and optimizing performance of the Micro-PPT. This technique should also be applicable to any thrust stand that normally operates in a damped mode in order to achieve increased sensitivity for microthruster performance measurements.

DISCUSSION

Comparing the Triggered and Self-Triggered designs, it is seen that a fundamental issue, other than the clear difference in mass and complexity, is the dominant failure mode. For the Triggered Micro-PPT, presuming that the capacitors are correctly sized for the proposed mission, the dominant failure is the semiconductor switch (SCR). However, SCRs are commonly used in space applications including, for example, the trigger circuits of flight-qualified standard PPTs. With correct design and testing, an SCR should be able to survive a Micro-PPT mission life provided the current and voltage limitations imposed by the switch do not unacceptably limit the thruster performance. For the Self-Triggering Micro-PPT the dominant failure mode is an increase in the surface breakdown voltage past the charging capability of the DC-DC converter or the voltage rating of the capacitor. In laboratory tests, these voltage increases are found to

be primarily due to changes in the geometry of the propellant face and the inner electrode. Tests have indicated that the ablation characteristics can be controlled through a judicious choice of geometry, materials, and discharge energy.

A key issue regarding the Micro-PPT is the variability in impulse bit. Standard PPTs have impulse bit repeatability in the range of $\pm 11\%$ (LES-6)¹² to $-10\% / +19\%$ (LES-8/9)⁵. Statistical analysis of the Self-Triggering Micro-PPT shows a larger variation of $\pm 74\%$ based on the assumption that impulse bit is proportional to discharge energy. Therefore, to maintain average impulse bit stability over a given period it will be necessary to fire the Self-Triggering Micro-PPT at higher frequencies and lower energies.

For the module designs shown in Figure 6, the propellant modules possess reasonable rigidity, which decreases during the mission life as the propellant and electrodes are consumed. This makes the Micro-PPT an attractive propulsion option for self-consuming satellite designs¹³. The modules would serve as structural elements during launch, and would then be used for propellant during flight. This is especially true for larger-diameter propellant modules.

Thinner modules ($d < 2.5$ mm) have a flexibility that can also be used to advantage. A servo placed at the end of the propellant module can make the required corrections to the thrust vector, with reduced mass and complexity over the standard gimbal system. Designing the propellant module for additional flexibility may also enable a single Micro-PPT to access all three thrust vectors required for attitude control at one corner of the spacecraft. In this fashion, a single Micro-PPT and servo can replace three thrusters and likely reduce the mass of the attitude control system.

SUMMARY AND CONCLUSIONS

Micro Pulsed Plasma Thrusters have been developed and tested in two basic designs. The Triggered Micro-PPT uses a pulse of energy at the face of a coaxial TeflonTM propellant module to create a surface discharge leading to vaporization, ionization and acceleration. The Self-Triggering Micro-PPT applies the high voltage on a slow time scale directly to the propellant face. The transition to a surface discharge is through a surface breakdown due to overvoltage. The Triggered Micro-PPT offers a thruster mass reduced by a factor of about 10 from a standard PPT. The self-triggering design offers about a 60X mass reduction.

The Triggered Micro-PPT has been observed to exhibit long lifetimes with no fundamental failure modes. The dominant failure is damage to the SCR switch, which can be avoided through judicious choice

of the circuit energy, voltage, and current. One flaw in the triggered design is the occasional tendency for the propellant to gouge out in a localized region, which is believed to be a result of insufficient energy per propellant face area. Although this flaw is expected to lead to superfluous propellant mass, and not to preclude subsequent firings, it is still considered a failure mode for test purposes.

The Self-Triggering Micro-PPT, with the inherent engineering advantages of simpler electronics and lower mass, is the primary focus of the Micro-PPT research and development. Propellant ablation tests have suggested design criteria required to achieve the desired steady-state propellant ablation characteristics. The ratio of average discharge energy to surface area must be sufficient to prevent deposits forming on the propellant face. Further, the current density at the inner electrode must be sufficient that the it recedes with the propellant face. The engineering of the Micro-PPT propellant then becomes a trade-off between propellant area, inner electrode diameter, electrode material, discharge energy, and voltage. A set of parameters shown to exhibit relatively long-term functionality (16000 seconds) used a 10 kV maximum charge, 15.2 J maximum energy discharge applied to a 2.21 mm propellant diameter.

A thrust measurement capable of resolving performance at the microthruster level has been developed. Proof of concept measurements have been made for Self-Triggering Micro-PPTs. They indicate thrust-to-power ratios for non-optimized Micro-PPTs are approximately half those measured for LES-8/9 at a much lower mass.

Current research has moved into custom fabrication of the propellant modules at AFRL. The capability to, for example, decrease the inner electrode diameter while maintaining propellant surface area will be exploited in an attempt to reduce the discharge energy and voltage. These designs will be part of the performance optimization study that uses the thrust measurement technique detailed herein.

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