A Micro Pulsed Plasma Thruster (PPT) for the "Dawgstar" Spacecraft

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Abstract—The AFOSR/DARPA sponsored University Nanosat program aims to produce a small fleet of nano- satellites in the 10 kg class. This challenging project has resulted in a variety of concepts from the student design teams. Among the most ambitious is the "Dawgstar" from the University of Washington. It proposes to use micro-PPT thrusters to formation fly with two other student built satellites in a constellation known as ION-F. At 10 to 20 kg, it will be the smallest spacecraft ever to fly with a propulsion system.

The design challenges of building a propulsion system for such a small satellite are described in the paper, along with the propulsion trade study conducted by the students at the University of Washington. PPTs were selected because they lend themselves well to very small satellites due to their solid state nature. The PPT also offers a very high specific impulse compared to other candidate microthrusters. Typically its specific impulse (Isp) has been between 800 - 1200 sec, although a scaled down version for Dawgstar is expected to achieve ~500s. The fundamentals of the PPT propulsion system are described and a preliminary layout of the concept is explained. Achieving the goals of the Dawgstar spacecraft requires scaling the PPT down to a smaller size than current designs. The results of some preliminary tests of scaled configurations will be presented.

Among the areas that must be scaled are electronics that charge the main discharge capacitor and fire the individual thrusters. Current designs weigh more than 2 kg, including the energy storage capacitor. The paper will describe work underway to miniaturize the electronics in the PPT to make its overall size and mass consistent with the targets of the nano-satellite effort. A jointly supported UW/Primex grant from the Washington Technology Center is being used to perform this work. Design analyses and preliminary testing of electronics breadboards will be described.

Dawgstar is planned for launch in 2001 with the other university nanosats. It provides a useful technology testbed for future micro- and nano-sat efforts such as the AF TechSat 21 and DARPA ASTRO programs. By pushing to meet the Dawgstar flight opportunity, we hope to have an advanced micro-PPT farther along in development for these future missions.

TABLE OF CONTENTS

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1. INTRODUCTION

Pulsed Plasma Thruster (PPT) systems are completely self contained propulsion modules, each containing its own thruster, propellant, propellant feed, and power processing. PPTs are capable of micro-Newton-second (μN-s) impulse-bit precision spacecraft control. The PPT employs solid Teflon™ propellant and requires only 28V power input, analog command/telemetry lines, and a mechanical hardpoint for mounting. The use of solid Teflon™ propellant eliminates the expense, reliability concerns, and mass of propellant feed system components such as tanks, valves, and heaters, as well as the safety requirements associated with pressurized propellants. The envelope of a state-of-the-art PPT with 2 axis thrust capability is only approximately 5300 cm^3, including propellant. The integrated system can be built and assembled fully fueled and placed on the shelf for an indefinite period until needed. This capability was amply demonstrated in 1994 at Primex when a LES 8/9 PPT was pulled out of a box after 20 years of uncontrolled storage, and fired reliably with the application of command signals and power.

A PPT can produce variable thrust depending on firing frequency up to approx. 1.5 milli-Newtons (mN). Its Isp of 800 - 1200 sec makes it attractive for missions which require a larger amount of delta V than feasible with cold gas systems. The minimum impulse bit can also be varied from approximately 10 μN-s to more than 800 μN-s by increasing the voltage applied to the energy storage capacitor. Because there are no moving parts, the use of PPTs for spacecraft ACS can result in a much lower jitter environment than reaction wheels. PPT systems capable of up to 15,000 N-s have been developed for flight.

PPT Physics Overview

The PPT is an electric propulsion device which uses electric power to ionize and electromagnetically accelerate a plasma to high exhaust velocities, which provides the high specific impulse levels. Figure 1 shows the basic elements of the PPT system.

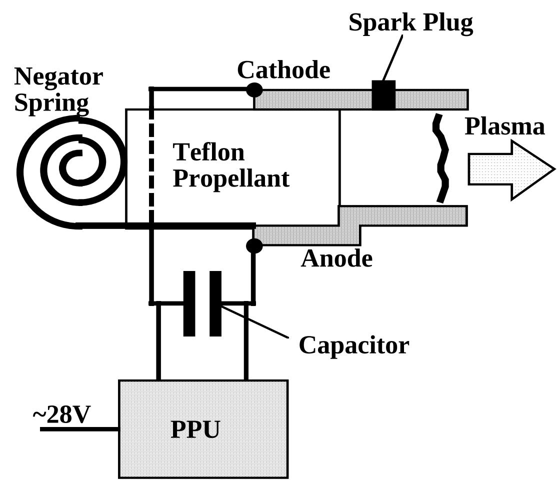

Figure 1 Elements of the PPT System

The thruster consists of a bar of Teflon™ propellant pressed against a shoulder between two electrodes by a negator spring (which is the only moving part). The negator spring serves to continually replenish the propellant as it is consumed. A power processing unit (PPU) charges a capacitor to voltages from 500-2000 V using unregulated power from the spacecraft bus. The PPU also supplies a high voltage pulse to a spark plug, which is used to trigger the discharge. Once the discharge is ignited, the energy stored in the capacitor (5-50 J) powers a high current / short duration plasma discharge (up to 30 kA, ~5-10 us). This discharge ablates and ionizes a small amount of Teflon™ from the face of the propellant bar and accelerates it to high exhaust velocities using the Lorentz force. The Lorentz force is a body force generated by the interaction of the current and the self-imposed magnetic field. The j X B interaction accelerates the neutral plasma to approximately 4000 m/s. A second component of the thrust arises from the thermal expansion of non-ionized Teflon™ vapor which results in a much lower exhaust velocity. The combined effect results in an effective Isp of 800 – 1200 sec.

PPTs in Application – Heritage

Pulsed Plasma Thruster technology has a long history of reliable space-flight operation. The PPT was first conceived in the 1950's by groups in the United States, Europe, and the Soviet Union. The first PPT to fly in space was aboard the Soviet Zond-2 spacecraft in 1964. In the United States, the PPT development work for the present solid state Teflon™ devices began in the early 1960's. In 1966, the MIT Lincoln

Laboratories began technology development of a Teflon™ PPT microthruster. This led to the first US flight of the PPT in 1970 aboard the LES 6 spacecraft.[1] This flight unit was a breech-fed design, and provided 26 µN of thrust at an Isp of 312 s. The system performed flawlessly in an East-West stationkeeping role for the 5-year satellite life of the LES-6 satellite.

The success of the LES-6 application lead to consideration of the PPT for other missions.[2] In particular, PPTs were found to be well suited to provide drag compensation for the Navy's NOVA navigation satellites. Three NOVA spacecraft were launched between 1981 and 1988.[3] Two PPT systems per spacecraft provided drag make-up propulsion for 7 years on each of the three NOVA spacecraft in LEO orbits.

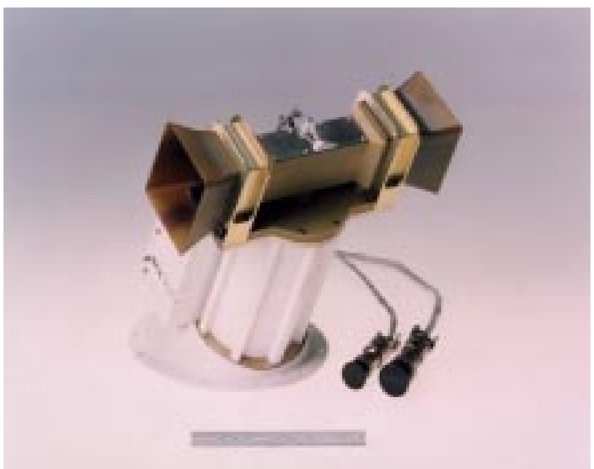

Figure 2 The EO-1 Pulsed Plasma Thruster System

In 1995, NASA Lewis Research Center initiated a program with Primex Aerospace Co. to develop, fabricate, and flight qualify a PPT that improved significantly on the then current state of the art. The result of that program is the Earth Observer-1 (EO-1) PPT, which is scheduled to fly on the EO-1 spacecraft in February of 2000. As is evident from Table 1, this design significantly improved on that of the previously flight qualified thrusters.[4,5]

The existing EO-1design, shown in Figure 2, provides a good baseline from which the miniature PPT configuration can evolve. The EO-1 PPT was designed to provide pitch axis attitude control.

The main features of the EO-1 PPT system are as follows:

- Two electrode pairs, each with a 9.65 square cm fuel face, opposing each other on one capacitor
- A single fuel feed housing that is shared between the two fuel bars
- A total impulse capability of 1560 N-sec (limited by available fuel)
- Impulse bit dynamic range is <100 µN-sec - 900 µN-sec
- 40 µF main capacitor, with a demonstrated life of over 25 million pulses at 43 joules
- Conical mounting bracket that supports the PPT cluster at a 30^{o} angle with the outside of the spacecraft
- Operates on a 28 V power bus (22-34 V unregulated)
- One power connector, one command/ telemetry connector

Table 1 Comparison of PPT Capabilities

Parameter	**PRIMEX EO-1 Design**	**LES 8/9**	**NOVA**
Maximum Ibit	>750 µN-sec	300 µN-sec	378 µN-sec
Minimum Ibit	<100 µN-sec	300 µN-sec	378 µN-sec
Pulse to Pulse Throttleability	Yes	No	No
Isp	1150 sec	1075 sec	~300 sec
Efficiency *(note 1)*	9.8%	~ 7%	~ 3%
Mass	5 kg *(note 2)*	7.33 kg *(Measured)*	6.35 kg
Thrust/Mass Ratio	306 µN/kg	82 µN/kg	53 µN/kg
Maximum Thrust	1.4 mN	600µN	378 µN
Total Impulse Capability	15,000 N-sec *(note 3)*	7,300 N-sec	2,224 N-sec

Note 1: Efficiency is defined as the thruster efficiency, PPU efficiency not included
Note 2: EO-1 mass driven by solar array torque environment
Note 3: EO-1 was fuel limited to 1,500 N-sec, however, key components demonstrated life to 20 million pulses ($20x10^{6}$ * 750mN-sec = 15,000N-sec)

2. PPTs for Smallsats/Nanosats

PAC has recently teamed with the University of Washington (UW) to develop a miniature PPT for use on the UW "Dawgstar" nanosat.[6] The Dawgstar spacecraft is targeted to be ~15 kg total mass, including the propulsion system and all propellant, making it the smallest spacecraft ever to fly a propulsion system. The enabling feature is the self-contained solid-state PPT. An innovative design of the PPT might be to integrate it into the structure of the top and bottom panels of Dawgstar's hexagonal bus. In this way the PPT serves as both a structural stiffener and a propulsion device once on-orbit. The PPT will impart to the spacecraft approximately 70 μN-s impulse bits with each firing.

The PPT was chosen as the result of an extensive trade study conducted by the students at the UW. Two propulsion system candidates were compared: micro-PPTs and cold gas thrusters. The micro-PPT design was assumed to be a scaled version of the larger EO-1 system. A baseline Isp of 500 sec was assumed due to the unknown performance effects of the scale-down. The energy stored in the capacitor was assumed to average 5 J. The cold gas thruster chosen for comparison was the Moog model 58E135, developed for the Pluto Fast Flyby program at JPL. The cold gas propulsion system meeting Western and Eastern Test Range requirements was specified with an average Isp of 65 sec over the life of the mission was assumed. Table 2 shows the results of the comparison.

While both systems were capable of compensating for the expected disturbance environments, the micro-PPT was selected because of its lower overall mass and higher reliability due to concerns about cold gas propellant leakage.

3. Miniature PPT Development

The technology baseline for development of a miniature PPT is the EO-1 system described previously. As noted above, the major components of the EO-1 PPT system are the energy storage capacitor, the on-board electronics, and the fuel feed and electrode assembly. A key challenge for development of a miniature PPT is the development of components that enable size and mass reductions of the overall PPT system. For example, the Maxwell Technologies oil-filled capacitor used on EO-1 has a mass of 1.5 kg. On internal funding, PAC has developed a modular test unit (MTU) for PPT development. The MTU, shown in Figure 3, allows testing of a variety of electrode configurations to assess their feasibility and performance capability. This is key to scaling the electrode dimensions to a size appropriate for a miniature PPT. The MTU also allows testing with various capacitor types to assess their applicability to PPT systems. PAC and UW recently completed a demonstration test using the MTU of four energy storage capacitors, a prototype miniature spark plug built by Unison Industries, and three thrusters electrode configurations, including one representing the flight design for Dawgstar.

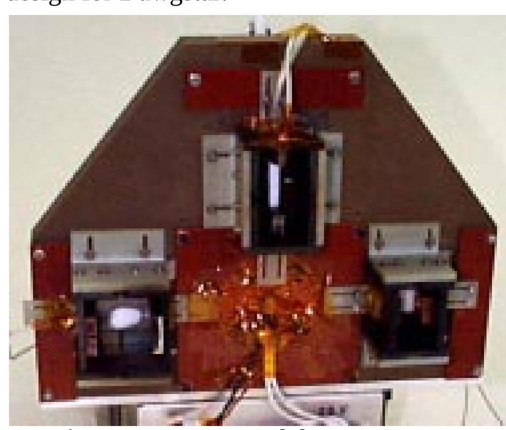

Figure 3 Primex Modular Test Unit PPT

Table 2 Comparison of μPPT and cold-gas propulsion systems (single thruster performance)

Propulsion System Type	Total Mass (kg)	I_{sp} (s)	I_{bit} (μNs)	T (mN)	Propellant Mass per ΔV (g-s/m)	ΔV Time Duration (s^2/m)	Energy per ΔV (J-s/m)	Peak Power (W)
μPPT †	**3.80**	**500**	**70**	**0.14**	**2**	**1.43×10^5**	**17.9×10^6**	**12.5**
Cold-gas	**4.58**	**65**	**100**	**4.5**	**16**	**2.22×10^3**	**$1\text{~}5\times10^4$ ‡**	**10.1**

† The performance of the μPPT was analyzed assuming a 1 Hz firing frequency.

‡ The energy per ΔV requirement for a cold-gas thruster depends on the firing mode, pulsed or continuous.

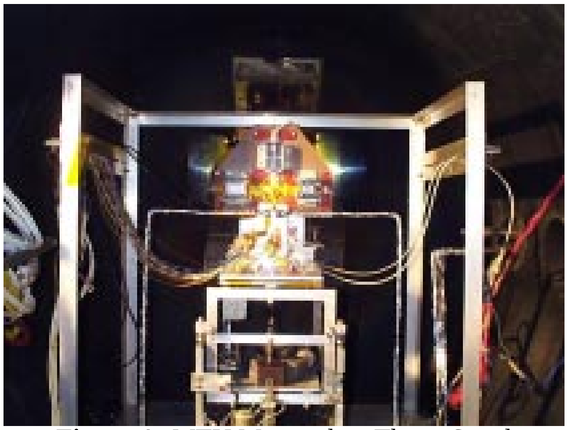

Figure 4 MTU Mounted on Thrust Stand

Figure 4 shows the MTU installed on the thrust stand in the test chamber. The test verified that the electrode configuration chosen for Dawgstar, shown in Figure 5, discharged normally. The dimensions of the Teflon™ propellant bar were 0.76 cm x 3.05 cm. This is a dramatically scaled propellant bar from the EO-1 heritage of 2.54 cm x 3.8 cm. The copper cathode electrode shown in Figure 5 includes the integrally mounted miniature sparkplug provided by Unison Industries for this test.

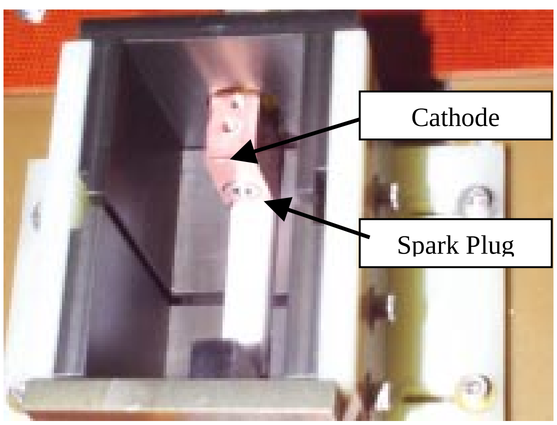

Figure 5 Dawgstar PPT Electrode Configuration

A second important result was that the capacitors tested all provided sufficient discharge current for the PPT. Preliminary discharge current waveforms for each of the capacitors tested are shown in Figure 6.

The PPT requires very short duration, high amplitude current pulses to achieve the Lorentz electromagnetic and concentrated electrothermal acceleration. Only one of the four capacitor types tested had ever been used to discharge into a plasma load before.

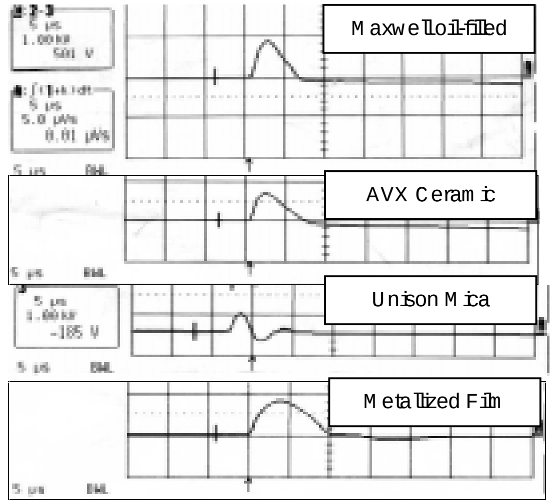

Figure 6 Current Waveforms

The waveforms in Figure 6 are the integrated outputs of the Rogowski coil used to measure current from the storage capacitor to the electrodes for each of the capacitors. While these traces do not yet have a calibration, they used the same Rogowski coil and are on the same scale. The time scale is 5 µs/div. These traces show that at the 5 J energy level, all capacitors are discharging in under 10 µs.

Figure 7 Energy Storage Capacitors Tested

Figure 7 shows the four capacitors tested. They included (left to right) the baseline Maxwell oil-filled capacitor, an off-the-shelf AVX stacked ceramic capacitor, a Unison Industries mica-paper/foil capacitor, and a metallized film capacitor provided by the Center for Space Power and Advanced Electronics at Auburn University. Note that the capacitors are all sized for various energy capabilities and their relative size does not indicate true scaling for a 5 J discharge design. The very fact that they all successfully fired the PPT was a significant result.

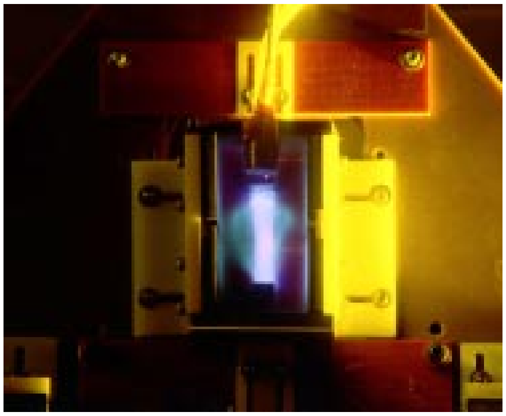

Figure 8 PPT Firing in Dawgstar Configuration

Another critical development area is the miniaturization of the PPT on-board electronics. Essentially the electronics provide two functions: charging the storage capacitor to voltages from 500 to 2000 V and firing the sparkplug. Currently, the EO-1 design accomplishes these functions with a single printed wiring board (PWB) of approximately 13 cm x 17 cm. Height and volume of the enclosure is driven by the main high voltage transformer, which is approximately 4 cm tall. This results in an overall electronics volume of 884 cm^3 per thruster pair, much larger than Dawgstar can tolerate.

UW and PAC teamed to win state funding under a Washington Technology Center grant to work the problem of miniaturizing the PPT electronics. UW will bring researchers working on cutting-edge new electronics technologies to bear on the problem. PAC will provide the problem definition and guidance on critical space product issues, such as radiation tolerance. This work is just getting underway in November 1999. The team is planning to investigate technologies such as planar magnetics, surface mount components, and possibly even integrated electronics and structure.

4. Conclusions

Micro-Pulsed Plasma Thruster systems present a very good propulsion alternative for nano-satellites. They are simple, solid-state devices with inherent high reliability. The performance, both in terms of minimum impulse bit and specific impulse are also well suited to nano-satellite needs. The UW Dawgstar team is working to demonstrate their use on their flight in late 2001/early 2002. Preliminary test results show that the selected electrode configuration will work and that a variety of capacitor types are available to select from. These encouraging results provide a good basis to continue the development with smaller electronics that will make a package appropriately sized for small satellites.

5. References

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6. Biographies

Joe Cassady *is a Senior Manager of Business Development at Primex Aerospace Company. He has been a Development Engineer and Project Manager in Electric Propulsion since 1981 at the Air Force Rocket Propulsion Laboratory, Rocket Research Company, Olin Aerospace, and Primex. He has recently been involved in several teams planning future NASA and Air Force technology directions, including the Space Propulsion Synergy Team, the New Millennium Modular and Multifunctional Systems Team, and the Integrated High Performance Rocket Propulsion Team.*

Andrew Hoskins *is a Principal Development Engineer at Primex Aerospace Company and the team leader for PPT efforts there. He has worked in Electric Propulsion research at Primex since 1989, including extensive work in arcjets, Hall Effect thrusters, ion engines and diagnostic development. He has a BS from Yale University in Physics and an MSE from Princeton in Mechanical and Aerospace Engineering.*

Mark Campbell *is an Assistant Professor in the Department of Aeronautics and Astronautics at the University of Washington. He received his Ph.D. from MIT in 1996, and continued at MIT as a Research Associate/Lecturer. While at MIT, Dr. Campbell developed space based model uncertainties, and designed 250 robust controllers implemented on-orbit for MACE, a dynamics and control laboratory flown on Space Shuttle Endeavour in 1995. Dr. Campbell's current research interests are in multiple satellites and autonomous systems such as aircraft and spacecraft, and actively controlled structures. Dr. Campbell has over 30 publications in the areas of dynamics, smart materials, control, and is co-authoring an interdisciplinary book to be published in 2000 by Cambridge University Press titled "High Performance Structures: Dynamics and Control."*

Christopher Rayburn *is a graduate student in the Department of Aeronautics and Astronautics at the University of Washington. Previously he was a student at Boston University where he worked as a research assistant at the Center for Space Physics. While there he provided engineering support for the Magneospheric Mapping Mission, Boston University's nanosatellite. He is currently working on the propulsion system development and integration for the Dawgstar satellite.*