

Overview of NASA's Pulsed Plasma Thruster Development Program

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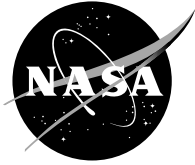
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NASA's Pulsed Plasma Thruster Program consists of flight demonstration experiments, base research, and development efforts being conducted through a combination of in-house work, contracts, and collaborative programs. The program receives sponsorship from Energetics Project, the New Millennium Program, and the Small Business Innovative Research Program. The Energetics Project sponsors basic and fundamental research to increase thruster life, improve thruster performance, and reduce system mass. The New Millennium Program sponsors the in-orbit operation of the Pulsed Plasma Thruster experiment on the Earth Observing-1 spacecraft. The Small Business Innovative Research Program sponsors the development of innovative diamond-film capacitors, piezoelectric ignitors, and advanced fuels. Programmatic background, recent technical accomplishments, and future activities for each programmatic element are provided.

I. Introduction

The National Aeronautics and Space Administration's (NASA's) Pulsed Plasma Thruster (PPT) Research and Development program consists of elements supported by the Energetics Project, the New Millennium Program, and the Small Business Innovative Research Program. The Energetics Project is formerly an element of the Aerospace Technology Enterprise's (Code R) Mission and Science Measurement Technology theme, which is being transitioned to the Human & Robotics Technology theme in the new Office of Exploration at NASA Headquarters. The Energetics Project addresses the technology development through an improved understanding of the fundamental physics and the identification and resolution of design challenges to advance the technology. Current activities include investigating the challenges of improving performance, extending life, and miniaturizing designs. The New Millennium Program has been supporting the flight demonstration of an experiment on the Earth Observing-1 satellite. Recent demonstrations have included the interrogation of the impacts of PPT operation on communications signals, optics sensors, and other spacecraft payloads. The next phase of the demonstration would be planning operations during deorbit maneuvers. The Small Business Innovative Research Program is providing opportunities for small business to develop novel component technologies for future generations of PPTs, including diamond film capacitors, piezoelectric igniters and advanced solid fuels.

II. Energetics Project

A. Programmatic Background

The objectives of the PPT task sponsored by the Energetics Project are to investigate innovative thruster concepts and components which will enable the advancement of PPTs for potential application to a range of spacecraft control functions. These function include attitude control and translation propulsion, momentum management, drag make-up/orbit raising on power limited spacecraft and large space structure dynamic control. The long-term objective of this task has been to advance the PPT state-of-art to effect increased placement in spacecraft systems on NASA, commercial, and military satellites. The efforts have focused on three technology goals for multi-thruster PPT systems, high-efficiency single-axis PPT systems, and micro-PPT concepts. The roadmap for these technology goals is shown in figure 1.

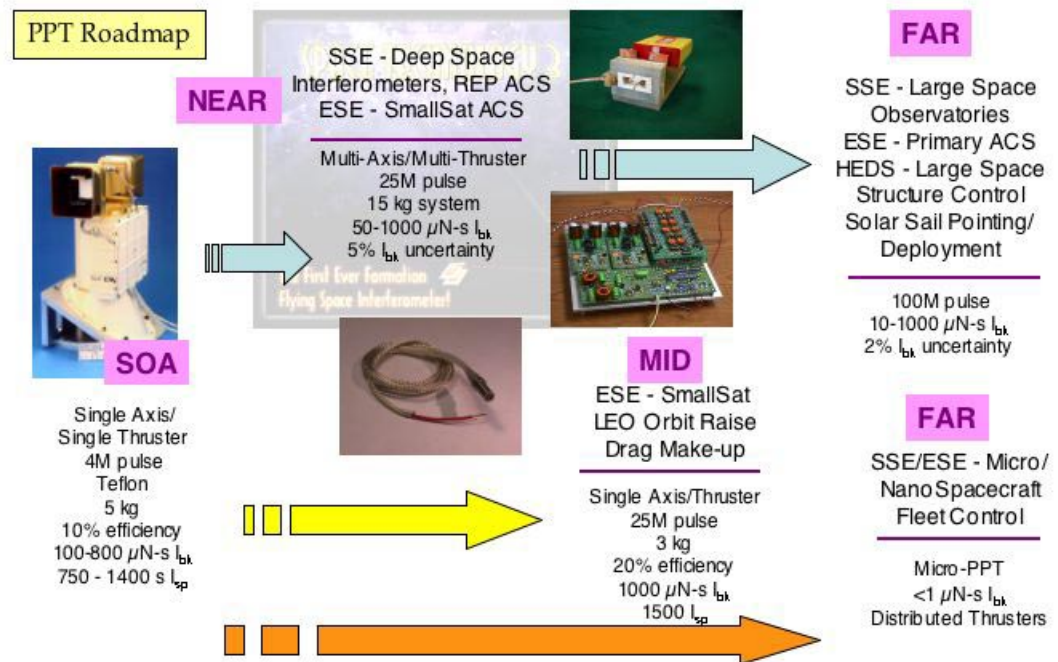


Figure 1.—Roadmap of NASA’s Pulsed Plasma Thruster Development Program

Recent technical accomplishments toward these goals under the Energetics Project include:

- the continued life evaluation of breadboard components (energy storage unit, spark plug, discharge initiation unit, and multi-channel power processor unit), which were developed under contract with Unison Industries, Aerojet, and C.U. Aerospace,
- an evaluation of PPT micropulsing as a means to minimize capacitor mass and volume through variable frequency and variable energy PPT operation,
- advanced numerical simulations of a coaxial inverse pinch PPT concept,
- a performance evaluation of alternate propellants in a PPT,
- peer-reviewed publication of PPT plume plasma characterizations, and
- selection as an attitude control system for a concept radioisotope electric propulsion mission.

A detailed description of each of the technical accomplishments is listed in the following section.

B. Recent Technical Accomplishments

1. Breadboard Component Life Demonstration

Future applications of pulsed plasma thrusters will include longer-life, higher-precision, multi-axis thruster configurations, used for applications such as three-axis attitude control systems or high-precision, formation-flying systems. Advanced components, such as a “dry” mica-foil capacitor, a wear-resistant spark plug, a discharge initiation module, and a multi-channel power processing unit (shown in fig. 2) were developed under contract with Unison Industries, General Dynamics, and C.U. Aerospace¹. These components offered many advantages over the Earth Observing–1 PPT hardware and were evaluated extensively at NASA Glenn Research Center². In order to demonstrate the anticipated life of these components, a life test was initiated at NASA Glenn in the fall of 2001. The breadboard components were

integrated into a two-nozzle, parallel-axis, laboratory PPT. The laboratory PPT was mounted inside a 1.52-m diameter by 3.05-m tall vertical vacuum chamber, which was evacuated by an isolatable cryogenic pump. The duration of the test runs were limited by many factors including the amount of fuel that can be loaded into the laboratory PPT and the total pumping capacity of the cryogenic pump. These interruptions required that the facility be vented to atmospheric conditions to replace the fuel bar or regenerate the pumping surface. Although the microprocessor in the power processing unit was locking up frequently early in the test phase adjustments to software, filtering, and grounding permitted longer test periods.

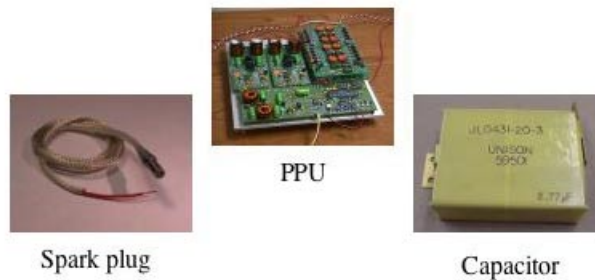


Figure 2.—Composite photograph of breadboard components undergoing life evaluation.

The breadboard component life test has had mixed results. To date the energy storage unit (mica-foil capacitor), discharge initiation module, and the power processing unit have successfully been operated for an accumulated 38 million pulses, which exceeds the near-term life requirements for deep-space interferometry demonstrator missions. The rated life for the energy storage unit was anticipated to be 45 million pulses. The spark plug has not been as successful. Presently the spark plug life has been limited typically to 1 to 4 million pulses. Several concurrent phenomena have bounded spark plug life. To remove fluorocarbon soot formation on the surface of the spark plug, an operation called pulse clearing was performed. Pulse clearing offered some life extension, however, the test hardware ultimately needed to be cleaned mechanically after the accumulation of about 1 to 2 million pulses. Although the mechanical cleaning process did not rigorously test the components in a manner consistent with space operations, it has revealed a concurrent life-limiting issue with the spark plugs, which was significant erosion of the nickel outer electrode. It should be noted that the iridium inner electrode has survived the same operation without erosion. As a result of this observation, a spark plug with both electrodes made from iridium, has been designed, fabricated, and implemented into the life test.

2. Micropulsing Evaluation

In order to reduce mass and volume, the breadboard component designs lowered discharge energy and increased the pulse repetition rate range. Although this maintained the same thruster power levels, there was an underlying assumption that there would be no penalties in thruster performance. An evaluation of the impact of micropulsing on thruster performance has been investigated³. The test matrix included variation in discharge energy, capacitance, and pulse repetition rate to cover the thruster power throttling range. Thruster performance was quantified via power, propellant mass loss, and thrust measurements. When capacitance is varied the impact on impulse bit is shown for each discharge energy level in Figure 3. The trend was different for efficiency and specific impulse. When the thruster power was held constant, both efficiency and specific impulse decreased as the capacitance was lowered.

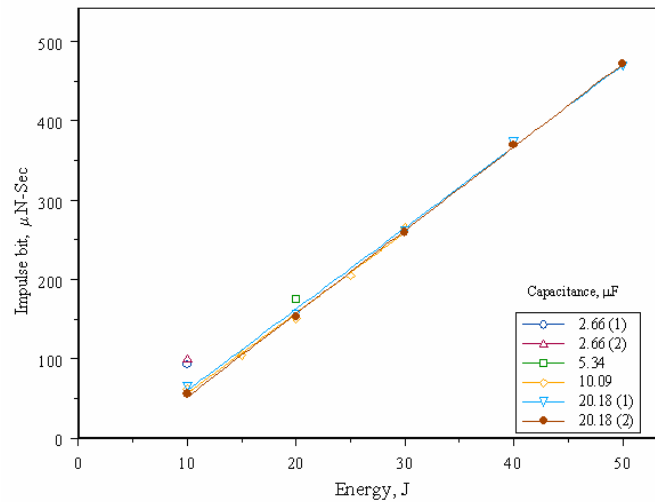


Figure 3.—Impulse bit as a function of discharge energy for various capacitances.

3. Coaxial Inverse Pinch PPT Numerical Simulations

Coaxial inverse-pinch PPT numerical simulations indicated that an axisymmetric discharge current distribution on the polytetrafluoroethylene (PTFE) surface permitted the attainment of high peak currents while limiting PTFE surface temperatures below the decomposition temperature. This limited post-pulse evaporation and macro-particle evolution.^{4,5,6} Recent numerical simulations using the MACH2 code were performed to interrogate the effects of background pressure and PTFE temperature boundary conditions on the magnitude of ablated mass. In general, results indicated that operating at a low background pressure (less than 0.01 mTorr) caused elevated temperatures in the PTFE solid in comparison with higher background pressures, and as such may initiate macro-particle evolution from the propellant surface. Figure 4 shows the MACH2 8-block computational domain and current contours at peak temperature for a coaxial inverse-pinch PPT operating with a background pressure less than 0.01 mTorr at 20 joule.

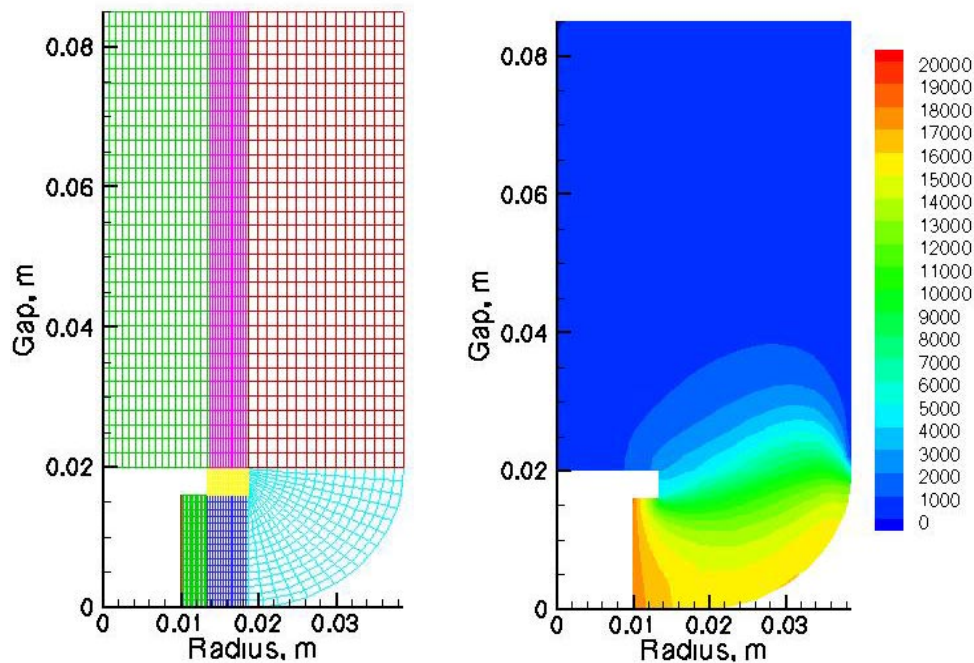


Figure 4.—MACH2 computational domain and simulation results of current contours at 20 joule.

4. Alternate Fuel Evaluation

Additional in-house research has focused on the performance evaluation of additives to PTFE propellants. Research indicates that small amounts of carbon added to PTFE significantly reduced propellant ablation rates, while marginally changing thrust. The improvements over nominal PTFE depended on several factors including discharge energy⁷, electrode geometry⁸, and propellant composition⁹. For discharge energies ranging from 40 to 140 joules, the propellant ablation rates were about 20 percent lower for 2%-carbon PTFE as compared to nominal PTFE with no change to the impulse bit generated. The net result was a 3 percent improvement to thruster efficiency and a 26% to 33% improvement to specific impulse in these cases as shown in figure 5. For discharge energies ranging from 5 to 60 joules, the propellant ablation rates were about 20 percent lower for 2%-carbon PTFE as compared to nominal PTFE with no change to the impulse bit generated. The net result was an improvement up to 6 percent to thruster efficiency. For discharge energies between 5 and 10 joules, a high thrust-to-power configuration (large gap to length ratios) demonstrated that a 50 percent reduction in propellant ablation rates could be achieved with the addition of 2% carbon to PTFE. The net result was 50% increase in specific impulse for the conditions tested.

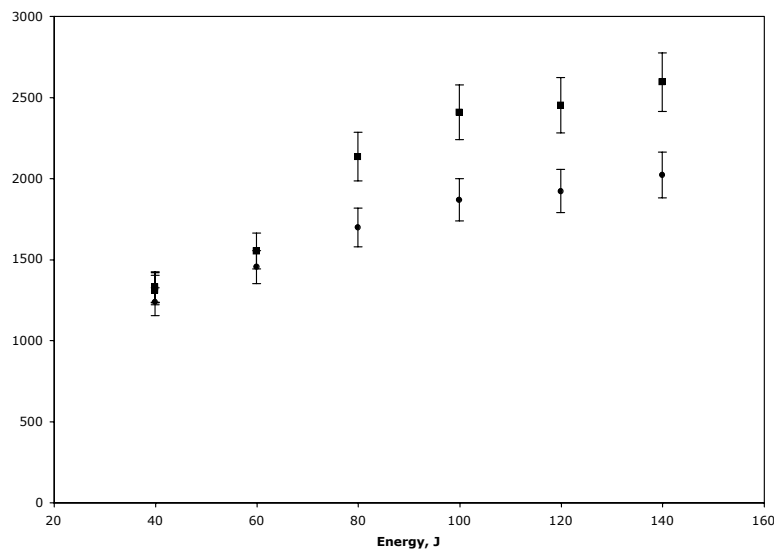


Figure 5.—Specific impulse comparison of 2%-carbon PTFE to nominal PTFE.

5. PPT Plasma Characterization

A current-mode quadrupole and triple langmuir probe methods were developed and used to measure electron temperature, electron density, and the ratio of ion speed to most probable thermal speed in a PPT plume¹⁰. The novel approach of measuring the currents in the biased probe leads increased signal to noise significantly during the first few microseconds of the PPT discharge. Also the issue of voltage fluctuations due to pickup of electromagnetic emissions on the ungrounded probe leads was eliminated. The theory for the current collection method was developed in detail¹¹. The experimental results of the plasma characterization include the insight that electron temperatures ranged in excess of 10 electron volts during the rise of the discharge current, but typically less than 5 electron volts for the rest of the pulse. Representative plots of probe/discharge currents, electron temperature (T_e), electron number density (n_e), and ratio of ion speeds (S_i) are shown in figure 6. In addition electron density maps across the plume were collected at several discharge energies.

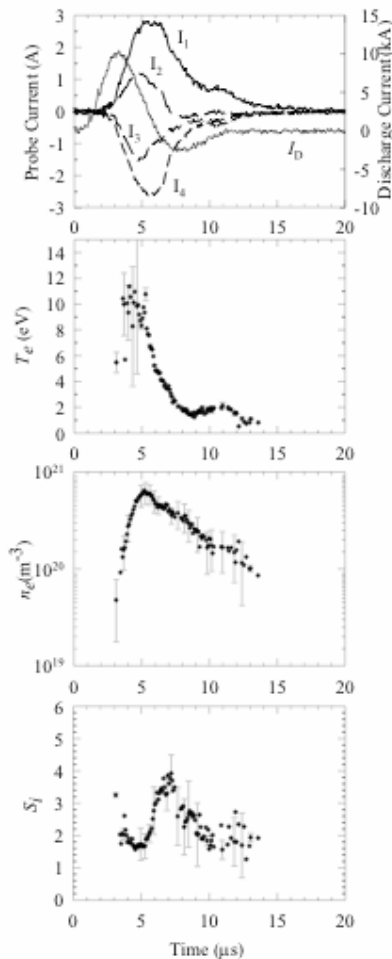


Figure 6.—Discharge current, quadrupole-Langmuir-probe currents and resultant plasma properties.

6. Attitude Control Systems for Radioisotope Electric Propulsion Missions

A design study of Radioisotope Electric Propulsion (REP) missions to Neptune orbiters was conducted¹². The spacecraft concept design is shown in figure 7. A comparison was made to solar electric propulsion (SEP) stage/aerocapture scenarios. The REP approach increased power available for scientific instrumentation after primary ion thruster operation with comparable trip times as compared to the baseline approach. The attitude control system (ACS) of this REP design was constrained to last over 14 years and use less than 100 W of power. PPTs met the design constraints, provided reasonable roll-control and as a result were selected as the baseline ACS. The Energetics Project PPT task provided definition of the PPT ACS subsystem to the spacecraft concept study.

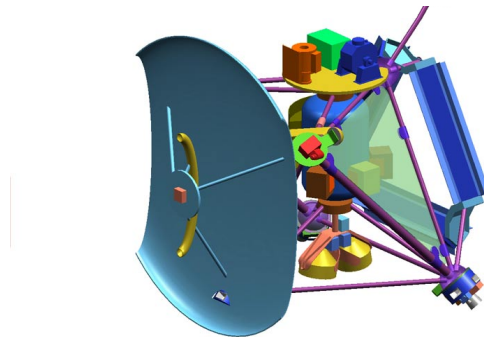


Figure 7.—REP spacecraft conceptual design using PPTs as the baseline attitude control system.

C. Future Activities

The basic research and development activities conducted under the sponsorship of the Energetics Project will not continue beyond FY04. Alternate sources of funding are being sought in Space and Earth Science Enterprises.

III. New Millennium Program's Earth Observing 1 PPT Flight Demonstration

A. Programmatic Background

The Earth Observing-1 PPT experiment was implemented by the New Millennium Program to demonstrate advances in PPT technology¹³. Advances in materials, electrical components, and circuit card technologies provided potential to significantly reduce thruster dry mass from prior flight thrusters. A flight experiment was designed to incorporate those advances in a protoflight thruster and demonstrate pitch axis control and momentum management on a small, low Earth orbit science spacecraft¹⁴. Results of this flight experiment have validated usage of PPT technology in spacecraft systems.

B. Recent Technical Accomplishments

The Pulsed Plasma Thruster (PPT) mounted on the Earth Observing-1 spacecraft was operated successfully in orbit in 2002¹⁵. The two-axis thruster system is fully incorporated in the attitude determination and control system and is being used to automatically counteract disturbances in the pitch axis of the spacecraft.

Since the first successful functionality demonstration, the impacts of thruster emissions on communication systems have been interrogated. X-band and S-band communications data packages were transmitted during thruster operation and analyzed for data corruption. A summary of the results from these tests is listed in table 1. The analysis has verified that there was no measurable increase in bit error rates during thruster operation. The benign interactions reduce user concerns and pave the way for electric propulsion applications on future earth imaging satellites¹⁶.

Table 1.—Results of EO-1 Communications Compatibility Test.¹⁶

Pass	Time (DOY:HH :MM)	Ground Station	Band	PPT Control	Bit Error Count	Comments
1	246:06:23	PF1	X&S	No	123	
2	246:08:01	AGS	S	No	456	
3	246:16:36	LGS	X	No	789	
4	246:18:14	LGS	X	Yes	789	Multiple files. Sequence break on 1st image (pre-image dark calibration)
5	246:19:47	AGS	X&S	Yes	444	Multiple files. 6 sequence breaks on the 3rd file (image), 1 sequence break on the 4th file (image) and 3 sequence breaks on the 6th file (post-image dark calibration)
6	246:21:26	PF1	X&S	Yes	666	Multiple files, no breaks
7	246:23:04	PF1	X&S	Yes	777	Multiple files, no breaks
8	247:02:16	AGS	S	No	898	
9	247:05:41	PF1	S	No	676	
10	247:13:12	HGS	X	No	666	Multiple files, no breaks
11	248:02:49	LGS	X	No		

C. Future Activities

Although no near-term activities have been defined for the EO-1 experiment, additional tests are being planned during spacecraft deorbit. As a spacecraft nears the end of its useful life, "high risk" maneuvers such as rolling the spacecraft about its pitch axis as a means to calibrate thruster performance

against ground test data, can become acceptable risk events to spacecraft operators. Additional tests will be defined as the spacecraft nears the end of its useful life.

IV. Small Business Innovative Research (SBIR) Program

A. Programmatic Background

Opportunities for small business exist under the SBIR Program to develop future generations of PPT components. Examples of these efforts include the development of diamond film capacitors, piezoelectric ignitors, and advanced PPT fuels. The following section outlines recent accomplishments under these development contracts.

B. Diamond Film Capacitors

Titan Industries (formerly Jaycor Industries), in collaboration with Vanderbilt University and Aerojet, has developed diamond film capacitors under a Phase II contract to the NASA Small Business Innovative Research Program. The purpose of the contract is to develop high energy density capacitors using chemical vapor deposited (CVD) diamond films as the dielectric material. It is expected that the diamond film capacitor would by a factor of ten, decrease the discharge time, decrease the heating and increase the useful lifetime of the capacitor. These capacitors offer advancements in packaging over conventional capacitor technologies. The targeted operating characteristics of the capacitor developed in Phase II are as follows:

Table 2.—Diamond film capacitor operating characteristics

Operating Voltage	4,000 volts
Repetition Rates	> 1000 cycles/sec
Operational Temperature	–70 to 155 °C
Energy Density	> 1 J/g or > 3.5 J/cm ³
Capacitance	0.125 microfarads
Energy Storage	1 Joule
Lifetime	30 years

In addition Vanderbilt University has successfully fabricated diamond dielectric with high resistance on both silicon and molybdenum. The resulting leakage currents are similar to or lower than comparable commercially available capacitors. Figure 8 shows a sample diamond dielectric film capacitor.



Figure 8.—Sample diamond dielectric film capacitor.

C. Piezoelectric Ignitors

Face Electronics, Inc. is investigating the manufacturing and development of piezoelectric materials for application to ignition circuits in a pulsed plasma thruster. During Phase I Face Electronics demonstrated the feasibility of developing a high voltage initiation circuit able to deliver sparks up to 15 kV and over 5 W in power. The ignition scheme utilizes piezoelectric based ignition schemes. The breadboard electronics are shown in figure 9 (a quarter provides the scale). In Phase II, Face Electronics plans to optimize the circuit design for PPT propulsion systems used in small satellites which weigh less than 20 kilograms, integrate controller circuitry with the power processing circuitry, optimize booster circuit output, integrate the components into a single housing unit, which would integrate with an appropriately sized PPT.

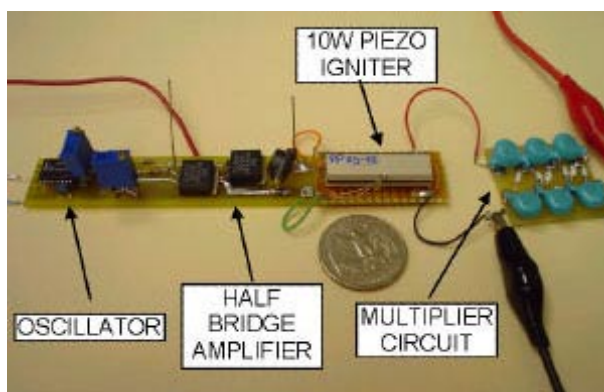


Figure 9.—Breadboard piezoelectric ignition system.

D. Advanced PPT fuels

ET Materials, LTD, is working under a Phase I SBIR contract to investigate innovative formulations of electrically ignitable materials, which may offer advantages over existing PPT fuels. ET Materials has developed several formulations under its Phase I contract and has completed performance tests on a thrust stand at Aerojet. The advantages that these formulations offer are under evaluation at present, but could include fuel decomposition to non-condensing constituents and improved electrothermal thrust component generation.

E. Future Activities

Like with any SBIR development contract, other sources of funding (non-SBIR) will be investigated for advancing these components to a higher Technology Readiness Level for future generations of PPTs.

VI. Summary

The Pulsed Plasma Thruster development program by NASA GRC during recent years under the sponsorship of the Energetics Project, New Millennium Program, and the Small Business Innovative Research Program was described. Programmatic background, recent technical accomplishments and future activities were provided. Under the sponsorship of Energetics, basic and fundamental research was conducted to evaluate the life of the advanced breadboard components, to evaluate the effectiveness of micropulsing, to understand coaxial inverse pinch thruster operation through numerical models, to evaluate the performance of alternate propellants, and to understand plume expansion through the plasma characterization. Inputs to a conceptual spacecraft design of a radioisotope electric propulsion Neptune orbiter led to the PPTs being selected as the baseline configuration for attitude control system. Under the sponsorship of New Millennium Program, EO-1 flight operations have demonstrated benign interactions with other spacecraft systems, adding to an extensive database for future applications. The SBIR program is investing innovative concepts, like diamond-film capacitors, piezoelectric ignitors, and advanced fuels, which promise reductions in system mass and volume in future generations of PPTs.

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