

Status Of Pulsed Inductive Thruster Research

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Abstract. The TRW Pulsed Inductive Thruster (PIT) is an electromagnetic propulsion system that can provide high thrust efficiency over a wide range of specific impulse values. In its basic form, the PIT consists of a flat spiral coil covered by a thin dielectric plate. A pulsed gas injection nozzle distributes a thin layer of gas propellant across the plate surface at the same time that a pulsed high current discharge is sent through the coil. The rising current creates a time varying magnetic field, which in turn induces a strong azimuthal electric field above the coil. The electric field ionizes the gas propellant and generates an azimuthal current flow in the resulting plasma. The current in the plasma and the current in the coil flow in opposite directions, providing a mutual repulsion that rapidly blows the ionized propellant away from the plate to provide thrust. The thrust and specific impulse can be tailored by adjusting the discharge power, pulse repetition rate, and propellant mass flow, and there is minimal if any erosion due to the electrodeless nature of the discharge. Prior single-shot experiments performed with a 1-meter diameter version of the PIT at TRW demonstrated specific impulse values between 2,000 seconds and 8,000 seconds, with thruster efficiencies of about 52% for ammonia. This paper outlines current and planned activities to transition the single shot device into a multiple repetition rate thruster capable of supporting NASA strategic enterprise missions.

INTRODUCTION

Rapid access to any point in the solar system and beyond requires advanced propulsion concepts that can provide extremely high specific impulse, high specific power, and high thrust-to-power ratios. NASA's vision for the 21st century and beyond is challenging scientific and engineering communities to develop propulsion technologies which will enable ambitious exploration of the solar system and its interstellar neighborhood, commercialization of space, and eventual human colonization beyond Earth (Schmidt, 1998). Two technologies that synergistically offer tremendous potential for the immediate future are advanced electric propulsion and nuclear energy. Space nuclear systems have recently received a renewed interest due to their versatility, high-power density, and ability to support power-intensive missions (Borowski, 1998). The dualism of providing both propulsion and power, linked with the enormous energy available per unit mass of fission fuel, has significant benefits to future programs involving nuclear thermal rockets (Watson, 1994), efficient conversion systems, space-based nuclear reactors, and nuclear electric propulsion (Allen, 1995).

To date, only a few electric propulsion concepts can support the high power requirements for future missions. These are the magnetoplasmadynamic (MPD) thruster (Polk, 1999, LaPointe, 2000), the Variable Specific Impulse Magnetoplasma Rocket (VASIMR) (Chang-Diaz, 1995), advanced ion and Hall thrusters (Sankovic, 1999), and the pulsed inductive thruster (PIT) (Dailey, 1993). Because of its variable repetition rate and electrodeless design, the PIT appears to be an ideal candidate to support power intensive missions. Depending on the mission scenario/profile, this efficient electric propulsion device can be powered by solar or space nuclear power.

Research in the field of pulsed electromagnetic acceleration has been conducted since the early 1960s' resulting in a number of different devices capable of supporting space propulsion. These devices use either a pair of suitable

electrodes or electrodeless techniques to couple energy into plasma. In either case, strong cross-product interaction of plasma currents and magnetic fields governs acceleration mechanisms of the plasma. Two of the most prominent examples are the pulsed plasma thruster (PPT), a very low power device supporting missions which require small, precise impulse bits (Benson, 1999), and the pulsed inductive thruster (PIT), a multi-megawatt device potentially supporting human/robotic missions to Mars and interplanetary space.

The pulsed inductive thruster was primarily developed at TRW during the 1960s' with various government support and internal TRW research and development funds (Dailey, 1987, 1993). Preliminary thruster designs with coil diameters of 20 cm and 30 cm were first investigated for low power applications. Due to parasitic circuit and other losses, they achieved efficiencies of less than 20% and specific impulse stayed below 1500s (Dailey, 1971, 1973). TRW's extensive research efforts during the 1970s and 1980s established scaling laws that characterized thruster performance with respect to coil size and power input. With increased demand for power intensive missions during the 1980, especially those targeted by defense programs in space, Dailey and Lovberg evaluated the performance characteristics of a 1-m diameter PIT. This large-scale device was built and tested with additional funding from NASA Glenn RC in the late 80s and early 90s. The thruster operating predominantly in single-shot (non-repetitive) mode demonstrated significant performance improvements, reaching efficiencies of about 50% and specific impulse of over 7000 s. However, funding for high power electric propulsion subsided dramatically in the years to follow and compromised further PIT technology development.

With the recent advent of the NASA Human Exploration and Development of Space (HEDS) and Space Science enterprise missions to Mars and the outer planets, interest has once again turned to the pulsed inductive thruster as an efficient high power propulsion alternative. As a result, a collaborative effort was initiated in 1999 between TRW, Inc., the NASA Glenn Research Center, and the NASA Marshall Space Flight Center to develop and test a repetitively pulsed version of the PIT. This paper provides a status review of the collaborative effort, with particular emphasis on the preliminary design results for a solid state switching circuit and program plans for the development and testing of a high power, multiple repetition-rate version of the thruster.

PULSED INDUCTIVE THRUSTER

Operating Principle

The Pulsed Inductive Thruster (PIT) is characterized by μ -second, MW-power pulsed operation that can provide high thrust efficiency over a wide range of specific impulse values. The main components of the thruster are a flat spiral inductance coil covered by a thin insulator, a propellant injection nozzle that extends above the coil, and a pulsed power supply consisting of a capacitor array, switch assembly and pulse forming circuitry. The nozzle injects a puff of propellant covering the coil surface, while the pulse generator simultaneously triggers the discharge of the high-energy capacitor bank. The transient high current pulse passes through the coil, generating a rapidly changing magnetic field, which induces a strong azimuthal electric field in the region above the coil. The propellant breaks down due to this strong electric field, creating plasma with azimuthal currents proportional to the raising currents in the coil. The cross-product interaction of the plasma current and the magnetic field in the coil generates a Lorentz force accelerating the plasma axially away from the coil to produce thrust. The thrust and specific

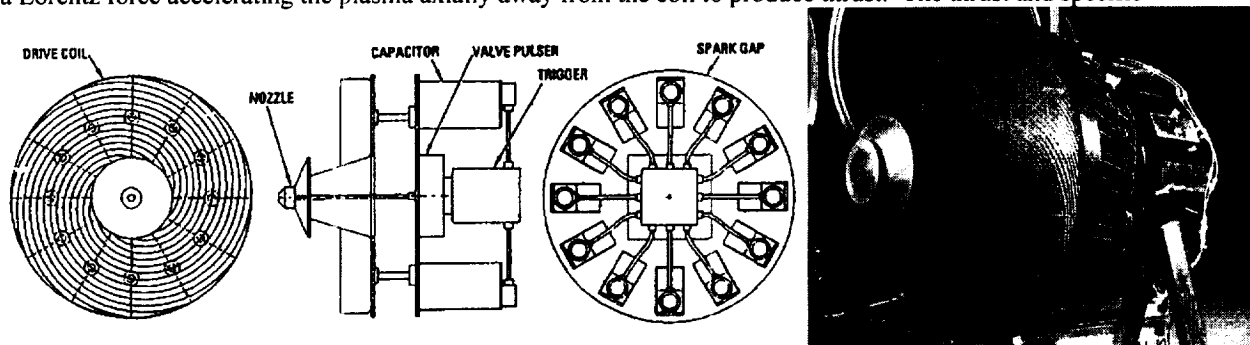


FIGURE 1. Pulsed Inductive Thruster Developed at TRW.

impulse can be tailored by adjusting the discharge power, pulse repetition rate, and propellant mass flow. There is minimal if any component erosion due to the electrodeless nature of the discharge. Figure 1 illustrates the PIT thruster as it was designed and tested at TRW.

Characteristic Performance Parameters

The push for large scale PIT thruster research in the late 1970's was embraced due to 1) the necessity for higher power, efficiency and thrust demanded for emerging power intensive space missions and 2) results of numerical analysis showing higher efficiencies with increasing coil size. In the most recent study sponsored by NASA Glenn Research Center evaluated the performance of a 1-meter diameter PIT thruster (Dailey, 1993). The coil of the thruster was supplied with energy stored in a Marx bank network of eighteen 20-kV capacitors. The bank configuration consisted of nine circuits in parallel and each circuit contained two capacitors. The Marx bank concept allows charging a capacitor array (consisting of n-number of units) in parallel and discharging the array in series connection. Thus, charging is accomplished at a much lower voltage, which is typically safer and requires simpler operating circuitry. Voltage multiplication due to the series connection of capacitor units furnishes the high operating voltage for discharging without the need for voltage converters or step-up transformers. With each capacitor having a capacitance of 2 μ F, the Marx bank configuration yielded an effective capacitance of 9 μ F. The total inductance of the circuit was 740 nH. The life rating was 10^4 pulses and the reversal capability was assessed at 40% when operated at their maximum design voltage. Charging the capacitors to less than 16 kV extended their life rating to approximately 10^5 pulses, but limited the total discharge energy of the bank to about 4.6 kJ. Performance characteristics were evaluated with a variety of propellants ranging from ammonia, hydrazine, and argon, to carbon dioxide. Table 1 summarizes typical performance parameters for charge voltages of 12-16 kV and propellant mass of 0.5-8 mg injected per pulse.

TABLE 1. PIT Performance for Various Propellants.

Propellant	Specific Impulse [s]	Efficiency
Ammonia	3,000 – 8,000	50%
Hydrazine	2,500 – 5,000	40%
Argon	1,000 – 2,000	20-30%
Carbon Dioxide	1,000 – 2,000	20-30%

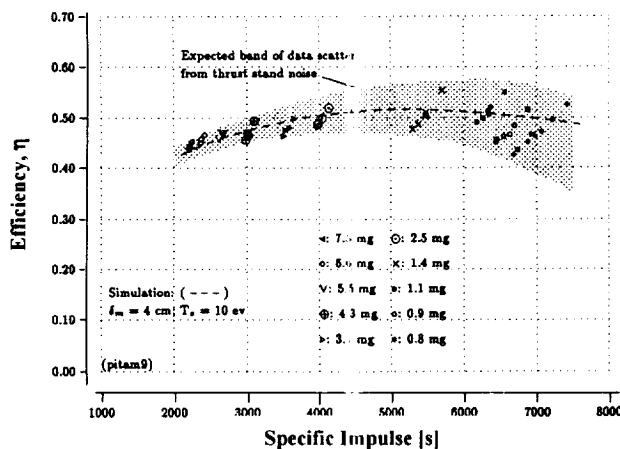


FIGURE 2. Efficiency as a Function of Specific Impulse for Ammonia at 15 kV

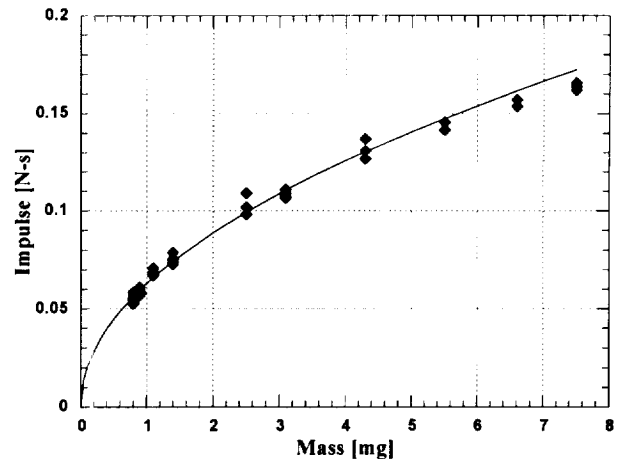


FIGURE 3. Impulse as a Function of Mass for Ammonia at 15 kV

To illustrate the potential capability of this thruster technology, Figure 2 and 3 depict test data achieved with Ammonia as propellant at a charge voltage of 15 kV. Figure 2 shows efficiency as a function of specific impulse and propellant mass injected per pulse. The efficiency remains about $50 \pm 5\%$ over a wide range of specific impulse (2,000-7,500 s) and injected propellant mass (0.8-7.5 mg). Varying the amount of injected propellant mass accomplishes significant throttle ability with very little deterioration of efficiency for a fixed capacitor voltage and propellant type. Even though specific impulse and efficiency are independent of frequency, the repetition rate is key

in determining generated thrust in a pulsed operating mode. Figure 3 illustrates impulse as a function of injected mass per pulse. The diagram provides another strong case for the conceivable abilities of the PIT.

For the new generation PIT, the projected repetition rate is 10 to 100 pulses per second. Ultimately, the amount of in-space power available to recharge the capacitor bank will determine the repetition rate. In the example below, the thruster could deliver a thrust between 0.5 and 17 N at a user-defined specific impulse of 2000-8000 s and an efficiency of about 50%. This performance parameter not only accentuates the throttle ability outlined above, but also illustrates the high level of propulsive capacity available to the spacecraft. This is a crucial factor for proposed planetary and interplanetary missions whose propulsion systems must accomplish a wide range of tasks. These propulsion demands can encompass high-thrust, low-specific-impulse operation to leave or enter gravitational effects induced by space objects and low-thrust, high-specific-impulse operation for coasting between destinations. The remarkable ability to provide variable specific impulse and thrust while maintaining a high overall thruster efficiency makes the PIT a unique device that is well suited for applications ranging from lunar and Mars cargo transport to future missions of planetary and deep space exploration.

Disadvantages Of Spark Gap Switches

PIT devices used in previous research efforts operated with high voltage spark gap switches to deliver current from the capacitor bank to the discharge coil. The discharge in a spark gap depends on a multitude of parameters such as electrodes (shape, gap distance, configuration, material), gas environment (kind, pressure), and power characteristics (AC/DC, voltage, rise time, power, etc.). Spark gap switches have limited lifetime and are difficult to use in a pulsed mode operating at high repetition rates. To support an interplanetary mission, required lifetime is about 10^{10} pulses (Dailey, 1993). Spark gap switches cannot achieve such a lifetime requirement predominately due to the erosion rate of the switch electrode material. At a nominal erosion rate of $10 \mu\text{g/C}$, the spark gap electrodes would erode more than one kilogram of tungsten over the life of the mission. This erosion has a significant impact on electrode separation, which is a crucial parameter for proper spark gap operation and performance. In addition, radiative destruction of the insulating materials within the gap will occur, ultimately leading to the deterioration of spark gap performance. In most cases, especially for very high voltage applications, these switches require a gaseous working medium to ensure the proper hold-off voltage at a given gap distance (Paschen Law) and to carry the main discharge. Typically, a trigger electrode is introduced to provide enough charge carriers enabling the main discharge. Hermetic sealing to ensure proper operating pressure and consequently to provide the designed breakdown voltage complicates space applications. Furthermore, a major difficulty employing a parallel array of spark gaps is the stringent requirement to fire all switches simultaneously. The slightest time difference separating two spark gaps could lead to the firing only one gap and removing voltage from the second spark gap before its trigger arrives. In this case the second spark gap would never fire at all, providing only partial discharge of the bank and poor thruster performance. For these reasons, solid-state switches capable of supporting high voltage and rapid current rise times are being considered for the next generation of pulsed inductive thruster hardware.

NEW GENERATION PIT

TRW, Inc., NASA Glenn Research Center (GRC), and NASA Marshall Space Flight Center (MSFC) have formed a collaborative research project to advance the state-of-the-art pulsed inductive thruster. The primary technical objectives of the research and development program are to address thruster design and performance issues, such as the development of a high rep-rate propellant-delivery system, improvements to the pulsed power network design, and physics-based modeling of high power thruster operation. The main goal of this combined research effort is to design, build and ground-test a repetitively pulsed inductive thruster serving as a transitional development device for future MW-class, flight-qualified engines.

Thruster Hardware

After years of research, the current PIT hardware (PIT-MkV) is unsuitable for further testing and must be replaced with new components better suited for repetitive pulsed operation. Under a recent 6-month NASA contract, TRW identified and designed several of the key components required for the next generation thruster hardware (Lovberg, 2000). The proprietary contractor report will be used as a guideline for fabricating and testing the PIT-MkVI thruster which will be operated at first in short bursts at low to moderate repetition rates and later transition to high

repetition rates. The new thruster hardware, which includes a 1-m diameter inductance coil, repetitively pulsed propellant valve, thrust balance, and support structures will be fabricated and tested at the TRW facility in Redondo Beach, CA. Although the basic appearance of the thruster will remain similar to the schematic shown in Figure 1, design modifications will be made to the MkVI model to support pulsed mode operation. The primary change is to replace the spark gap switches with high voltage, solid-state switches capable of sustaining high thruster repetition rates. The evaluation and incorporation of these solid-state switches into the PIT-MkVI design is the principle near-term focus of the collaborative effort, as discussed in the following section.

Solid-State Switches

Figure 4 depicts qualitatively and quantitatively a current waveform measured for an individual PIT circuit element. The peak current is approximately 15 kA, and initial rise time (di/dt) is on the order of 30 kA/ μ s. The near-term objective of the PIT-MkVI solid-state switch effort is to evaluate commercially available switch performance with regard to these two key parameters. To test candidate high-power solid-state switch technology, two independent LRC circuits were designed, each addressing one key parameter. The LRC circuits are significantly simplified and do not attempt to reproduce the actual current waveform as shown in Figure 4. Both circuits consist of LRC components connected in series. The capacitance is 2 μ F and the charge voltage is between 15 and 20 V in accordance to the energy storage requirement for the original Marx bank configuration. The boundary conditions dictate the resistance and the inductance values for the two circuits. Peak current testing requires a period of about 10-15 μ s and a current reversal of 50% for the second half cycle of oscillation. To test di/dt capability, the inductance is determined according to $L=V_0/(di/dt)$, where V_0 is the charge voltage of the capacitor, and resistance is calculated based on critical damping.

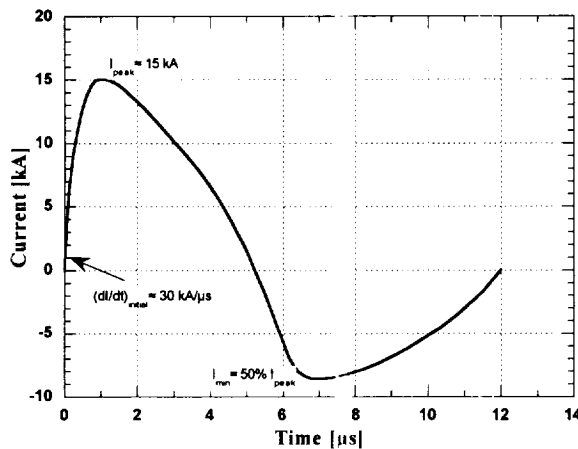


FIGURE 4. Current Waveform of one Circuit in Thruster Experiment

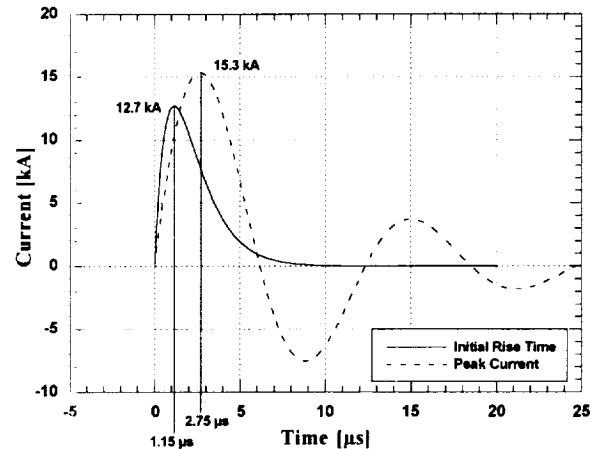


FIGURE 5. Analytical Results for Peak Current and Initial Rise time Testing

Figure 5 shows analytical results assuming a charge voltage of 20 kV for the two key parameters according to the discussed requirements. The component values for each LRC circuit are summarized in Table 2 for the expected voltage range. An industry survey is currently underway as a prelude to the acquisition and testing of suitable solid-state switches that can meet these requirements. Switch evaluations are expected to begin in FY01, with final component selection and in-depth performance testing to occur in FY02.

TABLE 2. Analytical Results

	Voltage [V]	Capacitance [μ F]	Inductance [μ H]	Resistance [Ω]
Peak Current Analysis	20,000	2	1.836	0.423
	16,000	2	1.27	0.35
Initial Rise Time Analysis	20,000	2	0.667	1.158
	16,000	2	0.533	

CONCLUSIONS

The pulsed inductive thruster is an efficient, versatile propulsion system that can enhance or enable a variety of missions. As in-space power capabilities evolve to meet even more demanding mission requirements, this thruster will be able to provide primary propulsion for lunar, planetary and deep space exploration activities. Unlike current electric propulsion devices, the PIT is an electrodeless system that can operate efficiently over a wide range of specific impulse. In addition, its electrodeless nature mitigates material and component erosion, and the development of solid-state switches in concert with commercially available long-life capacitors ensures thruster longevity. The average thrust provided by the PIT is determined by the pulse repetition rate, which in turn depends on the available in-space power required to charge the capacitors. As in-space power capabilities grow to encompass nuclear power, this highly efficient, variable specific impulse and high thrust device becomes an attractive option for planetary and deep space applications. A propulsion system, which can perform different segments of a mission due to these attributes decreases the specific mass α [kg/kW] due to fewer propulsion subsystems, and significantly reduces the complexity of a spacecraft. The combination of long life, high thrust, and variable specific impulse is unique among electric propulsion systems, making the PIT well suited for the challenging missions envisioned by NASA. To further develop this unique capability, TRW and NASA have teamed to develop the next generation of pulsed inductive thrusters, designated PIT-MkVI. Through a combined multi-year effort involving numerical simulation, component design, and breadboard thruster performance testing, it is anticipated that this next generation thruster will demonstrate the viability of efficient, high rep-rate operation in a simulated space environment, leading to the design and future deployment of flight qualified pulsed inductive thrusters.

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