Pulsed Plasma Thrusters

Rodney L. Burton

Department of Aerospace Engineering, University of Illinois at Urbana-Champaign Urbana, IL, USA

1 INTRODUCTION

The family of pulsed plasma thrusters (PPTs) covers a wide range of devices, propulsion performance, and level of development. Some devices have flown on spacecraft and others are still in the laboratory development phase. All PPT operate by ionizing a fraction of the propellant to create a current-conducting plasma.

2 BASIC CONCEPT OF THE PULSED THRUSTER

PPTs use energy storage to operate at a pulsed power level many times higher than the average power to the thruster. The basic concept (Figure 1) includes a prime power source such as a solar array, a power processing unit (PPU), an energy storage unit such as capacitors, a thruster with propellant feed system, transmission lines connecting the thruster to the energy storage unit, and a switch for repetitively closing the circuit to initiate the pulse.

In pulsed operation, the power source and PPU continuously feed energy to the storage unit. When the energy reaches the predetermined level E_0, after a time t_c, the switch is energized and the energy E_0 is transferred to the thruster in a pulse time t_p, delivering an average pulse power of E_0/t_p to

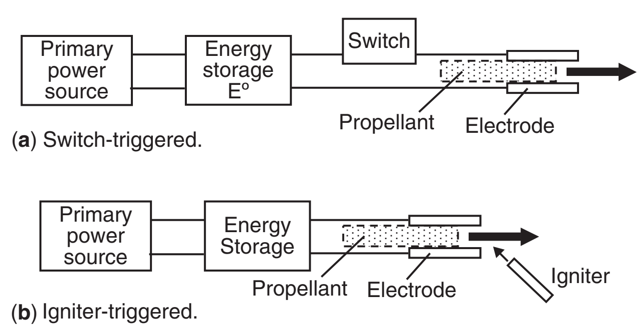

Figure 1. Pulsed plasma thruster schematics. (a) Switch-triggered; (b) igniter-triggered.

Encyclopedia of Aerospace Engineering, Online
This article was published in the *Encyclopedia of Aerospace Engineering* in 2010 by John Wiley & Sons, Ltd.
DOI: 10.1002/9780470686652.eae120

the thruster. After subsequent storage charging cycle times t_c, the cycle repeats, resulting in a thruster average power E_0/t_c. The time ratio of pulse length to charging time t_p/t_c is called the duty cycle. A variation of the pulsed mode used with some pulsed devices is the burst mode, for which the energy E_0 is delivered in a rapid sequence of pulses rather than a single pulse.

Pulsed thrusters operate using a basic circuit as shown in Figure 1.

In either case, the pulsing rate is determined by the firing rate of the switch or igniter. Typical pulsing rates are 1–20 Hz, although some pulsed thrusters operate at much higher rates of 1–50 kHz.

3 EARLY HISTORY

The earliest known pulsed thruster was developed in Russia in the mid-1930s. Looking similar to a solid propellant rocket, it used a pulsed discharge to evaporate plastic material that formed the inner wall of the thrust chamber, after which the heated gases exhausted through a conventional-looking nozzle. The first known space application was a PPT that flew on the Russian Zond 2 mission to Mars in 1964.

4 CLASSES OF PULSED THRUSTERS

Pulsed thrusters are characterized by unsteady operation of various types. A pulsed unsteady thruster is characterized by a pulse length of less than 10 μs, shorter than or comparable to the plasma acceleration time, so that the plasma conditions never reach steady state. A quasi-steady thruster uses a relatively long pulse, say 1000 μs and achieves steady-state acceleration conditions at high power for most of the pulse. Quasi-steady operation is used to achieve megawatt pulse power levels with relative small average power. In the burst mode, the energy storage may deliver several short pulses at a high rate (e.g., every 100 μs) and then delay to recharge before the next burst. Burst mode allows matching the pulse rate to the relatively slow operating time of a gas valve.

5 TYPES OF PULSED PLASMA THRUSTERS

The electrodes of the PPT are designed to conduct current, usually in the form of an arc, which evaporates and accelerates the propellant. The acceleration mechanism is either pressure, generated by the electric arc (electrothermal), or the force generated by the current and magnetic field (electromagnetic). Generally both forces exist in a PPT, but one or the other dominates. Various types of PPTs are shown in Table 1.

6 PERFORMANCE OF PULSED PLASMA THRUSTERS

The measurement of PPT performance, expressed in terms of specific impulse and efficiency, can be done either on an average or a pulsed basis, as shown in Table 2. Each individual pulse accelerates a propellant packet of mass m, with N pulses occurring over a time t_N, resulting in a pulse rate N/t_N. Each

Table 1. Types of pulsed plasma thrusters.

Type	Name	Typical propellant	Thrust type	Propellant feed	I_{sp} (s)	Efficiency (%)	Status
Teflon parallel plate	PPT	Teflon	$j \times B$	Spring, solid ablation	1500	17	Flight
Teflon coaxial	PPT	Teflon	$j \times B$	Spring, ablation	1300	13	Thrust test
Micro-PPT (coaxial)	μPPT	Teflon	$j \times B$	Ablation	1000	6	Lab
Gas-fed PPT	GPPT	Argon	$j \times B$	Gas injection	6000	8	Lab
Vacuum arc	VAT	Copper	Pressure gradient	Ablation	1000	10	Flight
Pulsed inductive (coaxial)	PIT	Nitrogen	$j \times B$	Gas injection	4000–8000	50	Thrust test
Gallium electromagnetic (coaxial)	GEM	Gallium	$j \times B$	Liquid gallium	2000	50	Lab
Marshall gun (coaxial)	MG	Hydrogen	$j \times B$	Gas injection	100 000	Unknown	Lab
Deflagration gun	DG	Argon	$j \times B$	Gas injection	Lab		
Pulsed electrothermal	PET	Water	Pressure gradient	Liquid injection	1400	50	Thrust test
Pulsed arcjet	—	Helium	Pressure gradient	Gas injection	300	50	Thrust test
Microcavity discharge thruster	MCD	Neon	Pressure gradient	Gas injection	150	50	Lab

Encyclopedia of Aerospace Engineering, Online © 2010 John Wiley & Sons, Ltd.

This article was published in the *Encyclopedia of Aerospace Engineering* in 2010 by John Wiley & Sons, Ltd.
DOI: 10.1002/9780470686652.eae120

Table 2. Pulsed thruster performance for N pulses in time t_N, mass m, and pulse length t_p.

	Average	Per pulse
Exhaust mass flow rate (kg s^{-1})	Nm/t_N	m/t_p
Thrust (N)	NmU_e/t_N	mU_e/t_p
Thrust impulse (N s)	NmU_e	mU_e
Specific impulse (s)	$T/\dot{m}g = U_e/g$	$mU_e/mg = U_e/g$
Thrust power (W)	$(1/2)NMU_e^2/t_N$	—
Thrust energy (J)	—	$(1/2)mU_e^2$
Thrust efficiency (η_t)	$\eta_t = (1/2)NmU_e^2/t_N/P_{term}$	$\eta_t = (1/2)mU_e^2/E_{term}$

mass packet is accelerated to a mean velocity U_e, imparting a momentum to the spacecraft mU_e, where mU_e is sometimes referred to as the impulse bit. The specific impulse I_{sp} is defined as the impulse bit per unit weight of propellant, so $I_{sp} = mU_e/mg = U_e/g$ (s). The thrust efficiency η_t is written as the thrust power, $(1/2)\dot{m}U_e^2 = (1/2)TU_e$, divided by the power to the thruster terminals, so $\eta_t = (1/2)TU_e/P_{term}$. The efficiency η_{PPU} of the PPU is accounted for by writing the total efficiency as $\eta = \eta_{PPU}\eta_t$. A more detailed discussion of efficiency is given below.

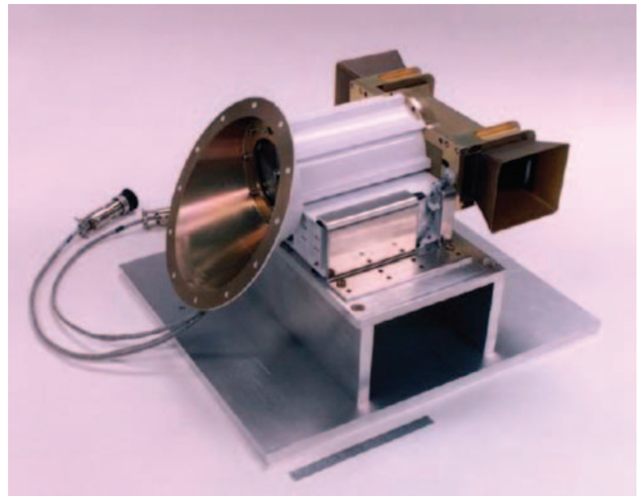

Figure 2. Rectangular Teflon pulsed plasma thruster, EO-1 satellite. Reproduced with permission from Meckel *et al*. (1997) © IEPC.

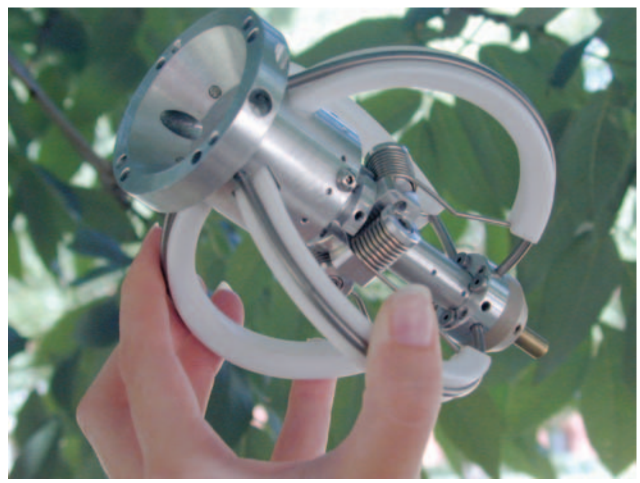

Figure 3. Coaxial Teflon pulsed plasma thruster. Reproduced with permission from Laystrom and Burton (2003) © AIAA.

6.1 Teflon pulsed plasma thruster (PPT)

The electrode arrangement of the PPT is either rectangular (Meckel *et al*., 1997), called parallel plate, or coaxial (Laystrom and Burton, 2003) accelerating propellant either by the $j \times B$ electromagnetic force (Figures 2 and 3). PPTs can operate in two modes: detonation or deflagration. The detonation mode is achieved when the propellant evaporates between pulses to fill the thruster with gas before ignition, and the pulse drives a shock wave into the gas, heating and accelerating it in a highly unsteady process. The second and more efficient acceleration method, called the deflagration mode, supplies the evaporating propellant gas from the rear (breech) of the thruster and accelerates it in a steady fashion during the pulse with limited heating. The thruster current pulse can be a single, nonreversing current pulse, or it can oscillate.

6.2 Micro-PPT (μPPT)

The micro-PPT (μPPT) is one of the simplest PPTs, consisting of a length of solid coaxial cable with a Teflon insulator and solid copper outer conductor, all within a diameter of 5–10 mm. The current pulse flows radially between the cable center and outer conductors, creating an axial electromagnetic body force on the plasma created by the discharge. Pulse energy and impulse bit are suitable for use in microsatellites. The device is fired with a high-voltage solid-state switch. If the propellant is not fed into the device, arc ablation occurs further from the exit with each firing, resulting in performance degradation during the life of the thruster. The μPPT benefits from simplicity, and low mass and volume, and is useful for tasks such as precision attitude control and positioning (Keidar *et al*., 2006).

Encyclopedia of Aerospace Engineering, Online © 2010 John Wiley & Sons, Ltd.

This article was published in the *Encyclopedia of Aerospace Engineering* in 2010 by John Wiley & Sons, Ltd.
DOI: 10.1002/9780470686652.eae120

6.3 Gas-fed PPT (GPPT)

The gas-fed PPT (GPPT) uses gaseous propellant with coaxial electrodes. In order to achieve high propellant utilization, the propellant gas injection must be timed synchronously with the current pulse. Because it is difficult to operate an injection valve on a time scale shorter than 1 ms, and because the current pulse is 10 s of microseconds, it is beneficial to deliver a burst of current pulses during each opening of the injection valve in order to accelerate as much propellant as possible. Each current pulse generates a current sheet that accelerates from the back of the GPPT to the exit plane, ionizing, compressing, and accelerating the propellant. The GPPT has not achieved high efficiency due to the high temperature and ionization state of the exhaust, which results in large frozen flow losses, and because the current sheet has an undesirable radial force component that drives some of the propellant into the electrode instead of out the exit (Ziemer *et al*., 1997).

6.4 Vacuum arc thruster (VAT)

The vacuum arc thruster (VAT) (Figure 4) operates in a high vacuum by evaporating a metallic cathode that can be made of nearly any metallic element (Schein *et al*., 2002). Success has been achieved with tungsten, copper, and titanium cathodes, which can be coaxial or rectangular. The VAT employs a simple, low-voltage inductive energy storage, and PPU, not unlike that employed in disposable cameras. To fire the VAT, a solid-state switch closes to drive battery current through an inductor, and the switch is opened to transfer current to the VAT electrodes in parallel with the switch. If the switch opening is sufficiently fast, a high-voltage spike is generated across the electrodes that generates breakdown through a thin film of metal deposited on the electrode insulator from previous shots. The main current pulse then flows to the cathode at localized micron-sized spots of high current density, creating a locally intense discharge. Propellant velocities up to 30 km s^{-1} can be achieved. Although the acceleration mechanism is not clear, the high velocities suggest an electromagnetic mechanism.

VATs for attitude control were launched on the University of Illinois ION 1 satellite in 2006, although the satellite did not reach orbit (Rysanek *et al*., 2002).

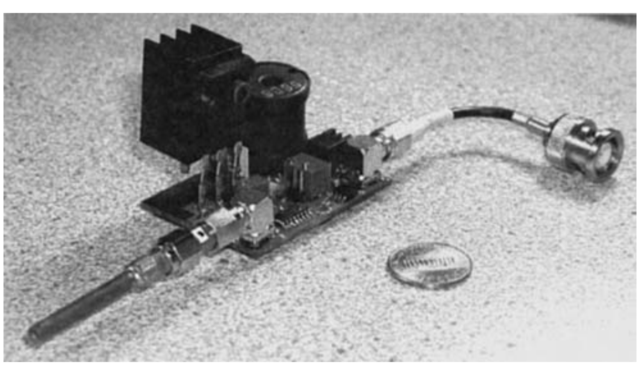

Figure 4. Vacuum arc thruster. Reproduced with permission from Schein *et al*. (2002) © American Institute of Physics.

6.5 Pulsed inductive thruster (PIT)

The pulsed inductive thruster (PIT) (Figure 5) is the only pulsed thruster to exploit the electromagnetic force from an azimuthal current (j_θ) and a radial magnetic field (B_r) to accelerate propellant (Lovberg and Dailey, 1982; Russell *et al*., 2004). The size and mass of the PIT, which was invented by C.L. Dailey in 1971, make it best suited for high power applications exceeding 100 kW. The thruster operates by radially injecting a pulse of cold gas from a central valve, usually ammonia or argon, onto the face of a large (typically 1-m diameter) disk-shaped insulated coil. With the gas flowing, a bank of switches is closed to produce a current pulse of a few microseconds duration in the coil, driven by a high-voltage (typically 35 kV) capacitor bank. The coil current induces a high electric field in the cold gas propellant, which breaks down, ionizes, and begins to conduct a high level of azimuthal current through itself, which in turn generates an induced magnetic field in the radial direction and an axial $j_\theta B_\mathrm{r}$ electromagnetic force. The coil magnetic field and the propellant magnetic field repel each other, pushing the propellant plasma away from the coil at high velocity in the axial direction.

The thrust efficiency of the PIT, which measures the stored electrical energy transferred to propellant kinetic energy, is typically 50%. The specific impulse varies from 2000 to 8000 s, depending on the mass and type of the injected gas. Losses occur in the coil and in the switches, which are typically high-voltage spark gaps. Because of concerns for switch life, particularly when pulsing the PIT at a rate up to 50 pulses per second (pps), it is advantageous to operate the PIT with solid-state switches. Losses also occur through failure of all the injected gas to ionize and be accelerated. Survival of the gas injection valve is also a concern when operating at 50 pps.

6.6 Gallium electromagnetic (GEM) thruster

The gallium electromagnetic (GEM) thruster, in the early stages of development, is a coaxial high current pulsed

Encyclopedia of Aerospace Engineering, Online © 2010 John Wiley & Sons, Ltd.

This article was published in the *Encyclopedia of Aerospace Engineering* in 2010 by John Wiley & Sons, Ltd.
DOI: 10.1002/9780470686652.eae120

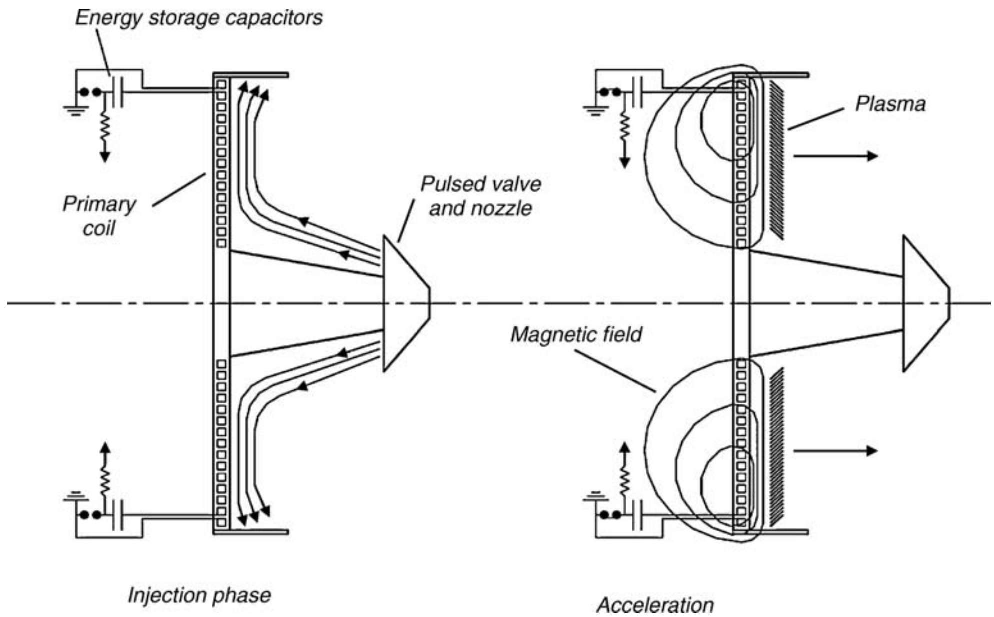

Figure 5. Pulsed inductive thruster schematic. Reproduced with permission from Russell *et al*. (2004) © AIAA.

thruster, distinguished because it injects propellant by evaporating a liquid gallium electrode. Gallium metal liquefies at 30 °C, evaporates at 2400 °C, and ionizes at low temperature, making it useful for thruster applications. Specific impulse is expected to be 2000 s at en efficiency greater that 50% (Thomas, Burton and Polzin, 2008).

6.7 Deflagration gun (DG) and Marshall gun

While not strictly speaking a plasma thruster, the deflagration gun (DG) is a high-efficiency, high current, coaxial electromagnetic accelerator that displays thruster-like properties (Cheng, 1971). The DG is important because it was one of the first devices to inject gas from the rear of the accelerator, maintaining relatively low temperature throughout the acceleration process. As such it was an improvement in efficiency over the Marshall gun as a space thruster, as the latter drives an electromagnetic shock wave through the gas to accelerate it, resulting in very high temperature and associated frozen flow losses (Marshall, 1960).

6.8 Pulsed electrothermal thruster (PET)

The pulsed electrothermal thruster (PET) uses extremely high pressure (hundreds of atmospheres) and high temperature to accelerate water vapor propellant in a conventional supersonic nozzle. Liquid water droplets are injected continuously, and the power is pulsed at a rate of 10 Hz at a level of several hundred watts, using a pulse of 10–20 μs. A capacitive energy storage unit is charged continuously, and the storage voltage rises until breakdown occurs, typically at 2 kV, which typically discharges 50 J to evaporate the droplets and heat the vapor. The discharge chamber is a long thin ceramic tube in radial compression, capable of withstanding high internal pressure. The pulse power is several megawatts, and the water is heated and ionized at a temperature and pressure of about 20 000 K and 100–1000 atm, after which it accelerates through a conventional supersonic nozzle (Burton *et al*., 1990; Burton and Wang, 1991). Approximately 33% of the pulse energy is lost to the walls by radiation and convection, so that peak efficiency is below 67%. Principle difficulties are electrode erosion and water boiling in the feedline.

6.9 Pulsed arcjet

Operation of the pulsed arcjet (Willmes and Burton, 1999) is similar to the PET. The propellant is helium, which is injected continuously into a 2.5-mm diameter by 10-mm-long ceramic discharge tube, connected to a low Reynolds number supersonic nozzle, and heated by a fast current pulse from a small 1–2 kV capacitor. The several hundred ampere nonreversing discharge of several microseconds duration is triggered by Paschen breakdown between the electrodes without using a switch, and the helium pressure is raised by the discharge energy to produce a thrust impulse. To reduce helium loss between pulses, the pulse rate is several kilohertz, and for a 100-W thruster the discharge energy is 20–100 mJ. This low

Encyclopedia of Aerospace Engineering, Online © 2010 John Wiley & Sons, Ltd.

This article was published in the *Encyclopedia of Aerospace Engineering* in 2010 by John Wiley & Sons, Ltd.
DOI: 10.1002/9780470686652.eae120

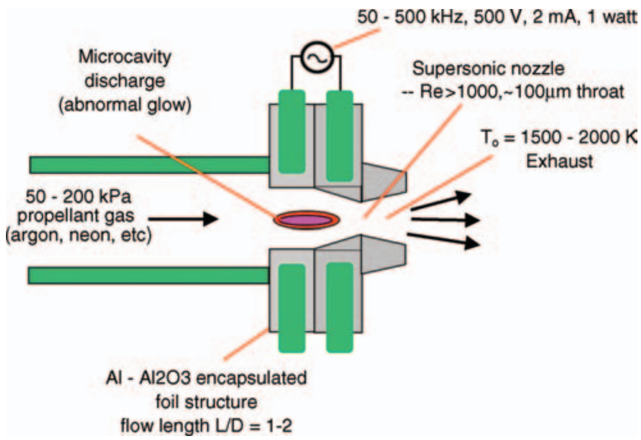

Figure 6. Microcavity discharge (MCD) electrothermal microthruster schematic.

energy has the benefit of reducing the size of the capacitor and also implies a small discharge chamber, typically 50 mm^3.

Maximum efficiency of the pulsed arcjet is 55% at 230 s specific impulse and reduces to 38% at 310 s. Operation is possible with heavier gases at reduced specific impulse and similar efficiency.

6.10 Microcavity discharge thruster (MCD)

The microcavity discharge thruster (MCD) (Figure 6) has some attributes of the pulsed arcjet. The propellant is a gas, typically neon that is injected continuously through a 100-μm diameter converging–diverging low Reynolds number supersonic nozzle made of aluminum oxide. The electrodes are buried in the aluminum oxide and are driven by a 10–100 kHz oscillating pulse train at 500–1000 V. An electric field is developed in the nozzle that is sufficient to break down and resistively heat the gas, which is accelerated by pressure in the nozzle. The plasma ionization fraction is less than 0.01%. The lack of electrode exposure to the discharge predicts a long life for this type of device.

Gas temperature has been measured up to 1500 K, which would result in a specific impulse for neon of 150 s. Efficiency is predicted to exceed 50%, based on low predicted heat, frozen flow, and nozzle losses for the device (Burton *et al*., 2009).

7 FACTORS GOVERNING SELECTION OF PULSED THRUSTERS

For many missions involving pulsed thrusters, as for chemical thrusters, high specific impulse is an important selection criterion. However, because PPTs tend to be low thrust systems, producing accelerations less than 10^{-3} g, other factors can also dominate.

7.1 Mission ΔV

For some small satellite missions (e.g., precision stationkeeping), the ΔV can be low, which means that the mass of a micropropulsion system is not necessarily dominated by the mass of the propellant. For such systems the specific impulse can be low without significantly raising the propulsion system mass. The system mass is then dominated by other components such as the PPU or the propellant tank.

7.2 Thrust efficiency

Just as specific impulse can be relaxed for low ΔV missions, in certain situations low thrust efficiency can be tolerated. In cases where the power requirement of the propulsion system is a small fraction of total satellite power, low thrust efficiency does not have a large impact on satellite mass.

7.3 Propulsion system simplicity

With some pulsed plasma systems the thruster is not the limiting factor determining system life. The 1964 Soviet Zond 2 mission (Bober *et al*., 1993) used a PPT with an efficiency of less than 10%. Auxiliary components such as a switch, neutralizer, or igniter plug can be first to fail before mission completion. Long missions benefit from simpler propulsion systems with fewer auxiliary components, influencing choice of propulsion type.

7.4 Propellant leakage

The Russian Zond 2 mission (Bober *et al*., 1993) was the first flight application of the PPT, chosen to avoid possible leakage of liquid or gas propellants. This thruster used a solid plastic propellant that satisfied the “no leak” criterion.

7.5 Propellant volume

In many cases the propulsion system is volume-constrained rather than mass-constrained. High propellant density and a propulsion system compatible with that propellant can be a deciding factor in the choice of thruster system.

Encyclopedia of Aerospace Engineering, Online © 2010 John Wiley & Sons, Ltd.

This article was published in the *Encyclopedia of Aerospace Engineering* in 2010 by John Wiley & Sons, Ltd.
DOI: 10.1002/9780470686652.eae120

7.6 Propellant geometry

For solid propellant systems such as those using Teflon, the geometry of the propellant constrains the total propellant mass and total thrust impulse. For large cylindrical satellites, Teflon can be arranged in a spiral around the outer diameter, and this geometry coupled with the high density of Teflon can result in a large propellant mass fraction. For small satellites the spiral arrangement may not be practical, and the propellant mass fraction may be too small to meet mission requirements.

7.7 Propellant condensation

Propellants such as metallics and those containing carbon can condense over time on satellite surfaces due to random collisions in the exhaust plume. Condensation can cause electrical shorts in the satellite power system and reduction in effectiveness of photovoltaic cells and optical sensors. Condensation effects are best determined by testing in a high vacuum system and can influence the choice of thruster propellant for a given satellite or mission.

7.8 Thrust noise

Pulsed systems inherently induce vibrations in the satellite structure, and this can be unacceptable for satellites with instrumentation susceptible to vibrations. In this situation pulsed systems cannot be used.

7.9 Thruster radiation

Pulsed discharges in pulsed thrusters produce electromagnetic radiation that can interfere with satellite instrumentation or communications and data handling. In these cases the propulsion system must be shielded, or if shielding is impractical for one type of thruster, a different type of thruster must be used.

7.10 Minimum impulse bit

Some applications of PPTs require extremely small momentum change per pulse, as when the satellite location must be known to a fraction of a millimeter. The minimum impulse bit capability of the thruster can be a deciding factor in thruster selection.

Table 3. Pulsed plasma thrusters used for attitude control systems (ACS).

Satellite	Thruster	Flight	Application
Zond-2	Teflon coaxial PPT	Yes	ACS
EO-1	Teflon parallel plate PPT	Yes	ACS – 1 axis
ION-1	Vacuum arc thruster VAT	Failed launch	ACS – 3 axes
Techsat-21	Micro-PPT	No	ACS – 3 axes

8 APPLICATION TO ATTITUDE CONTROL OF SATELLITES

Satellite attitude control is one of the most common applications of PPTs. Table 3 shows some examples. The Russian Zond 2 Mars mission used a solid propellant PPT to avoid propellant leakage. EO-1 demonstrated use of PPT pitch control on an earth satellite (Meckel *et al.*, 1997). Ion-1 was a 1 kg. CubeSat satellite with PPT attitude control. PPT missions are summarized in Burton and Turchi (1998).

9 BASICS OF PULSED THRUST PRODUCTION

The pulsed thruster is designed so that each pulse exhausts a propellant mass m at high velocity U_e, producing an increment of exhaust momentum mU_e, called the impulse bit. The exhaust velocity is often expressed in terms of the specific impulse, where $I_{sp} = U_e/g$. The total impulse is then the impulse bit times the number of pulses N, which can range from a few pulses up to $N = 10^9$ pulses, depending on the application. For a pulsed thruster with a pulse rate ν (Hz), the average thrust is $T_{ave} = mU_e\nu$ (N). For electromagnetic accelerators the instantaneous thrust is given by $(1/2)L'I^2$, where L' is the gradient of the inductance in the direction of thrust and I is the current. The impulse bit is the time integral over a pulse, or:

$$I_{bit} = \int \frac{1}{2} L' I^2 \, dt = \frac{1}{2} L' \Psi \quad (1)$$

where $\Psi \equiv \int I^2 \, dt$. (The electric current in amperes (A) is most commonly represented by the symbol I, both in standard electric circuit use and for most types of electric thrusters, although some pulsed thruster texts use J. Since J is also used in many texts to represent current density (A m^{-2}), the symbol I is used here for current, both to agree with common usage and to avoid confusion.)

This article was published in the *Encyclopedia of Aerospace Engineering* in 2010 by John Wiley & Sons, Ltd.
DOI: 10.1002/9780470686652.eae120

10 PULSED THRUSTER PROPELLANT

The requirement of minimizing the total propellant mass for a given impulse implies that the exhaust velocity U_e must be high, often in excess of 10 km s^{-1}. Achieving a mass velocity U_e of this magnitude requires either very high temperatures, above 10 000 K, or electromagnetic forces, which in turn implies that the propellant must be an electrically conducting gaseous plasma containing ions, electrons, and neutrals. Although conductive metal projectiles with masses of tens of grams per pulse have been proposed as a propellant, the storage of the required pulse energy in the megajoule range makes this impractical. The propellant in the PPT is often stored as a solid, sometimes as a liquid or gas, then evaporated ionized and accelerated by the pulse energy delivered to the thruster head.

The decision of how to store the propellant and what propellant to use is determined by spacecraft requirements. The most common propellant is Teflon$^{\mathrm{TM}}$, a polymer with molecular formula CF_2, which sublimates from solid to gas at approximately 800 K, dissociates into C + 2F and then ionizes. Attempts to find solid propellants other than Teflon have not been successful. Various gas and liquid propellants have been used in the laboratory but have not flown on spacecraft.

11 PULSED PLASMA THRUSTER PERFORMANCE

PPT performance refers to the thrust, exhaust velocity, and efficiency of the PPT system. Generally, the efficiency of the thruster includes that of the energy storage, switch and thruster head, while that of the prime power source (e.g., solar cell efficiency) and of the PPU are treated separately.

The average thrust of a steady electric thruster is given by $T = \dot{m}U_e$, and that of a repetitively pulsed thruster as $T = mU_e/t_c$, where m is the mass accelerated per pulse. The thruster efficiency is expressed in terms of the exhaust kinetic energy $mU_e^2/2$ and the stored energy: $\eta = mU_e^2/2E_0$. The specific thrust (thrust per unit power) is correspondingly $T/P = 2\eta/U_e$ for continuous thrusters. For pulsed thrusters the parameter of interest is impulse bit per joule, which also equals $2\eta/U_e$.

The performance of various types of PPT is plotted in terms of specific thrust (N W^{-1}) versus specific impulse I_{sp} (s) in Figure 3. Curves of constant efficiency are shown in Figure 3, and no PPT has an efficiency higher that 20%. An efficiency this small can be tolerated in a very low power thruster where $P < 100$ W, but not in a higher power system.

Table 4. Propellant acceleration mechanisms.

Acceleration mechanism	Thrusters using
Electromagnetic $j \times B = j_r B_\theta$	Coaxial Teflon PPT, μPPT, GPPT, GEM, DG
$j \times B = j_\theta B_r$	PIT
$j \times B = j_y B_z$	Parallel plate PPT
Gas dynamic pressure	PET, VAT, MCD

12 PROPELLANT ACCELERATION MECHANISMS

Several methods are used in general to accelerate propellant in a PPT, as summarized in Table 4.

For an electromagnetic device, the instantaneous thrust is given by $(1/2)L'I^2$ (N), and the impulse bit, integrated over one pulse length, is $I_{\mathrm{bit}} = \int_0^{t_p}(1/2)L'I^2\,\mathrm{d}t \equiv (1/2)L'\Psi$ (N s). In this expression, L' is the inductance gradient, where $L' = \mathrm{d}L/\mathrm{d}x$ (H m^{-1}) is the spatial derivative of inductance in the direction of the electromagnetic accelerating force.

For a pulsed electrothermal device, the flow is unsteady. The propellant is heated to high pressure and temperature while stagnating at the closed end of a duct and allowed to expand into a vacuum. Propellant exits at high velocity early in the process, but then achieves lower velocities as the remaining stagnated propellant cools due to the expansion process. The expression for the impulse bit per joule is then $I_{\mathrm{bit}} = (\gamma - 1)/a$, where γ is the ratio of specific heats and a is the sound speed.

13 THRUSTER LOSS MECHANISMS

The usual definition of thruster efficiency is given in terms of either energy or power. For a pulsed thruster, the thruster efficiency is the ratio of the exhaust kinetic energy to the stored energy:

$$\eta_t = \frac{(1/2)mU_e^2}{E_0} - \frac{I_{\mathrm{bit}}^2}{2mE_0} = \frac{(\int T\,\mathrm{d}t)^2}{2mE_0} \qquad (2)$$

where I_{bit} is the directed momentum $mU_e = \int T\,\mathrm{d}t$ generated per pulse, as measured on a thrust stand. Pulsed thrusters are notorious for their low thrust efficiency, which is a result of loss mechanisms in the plasma generation and acceleration processes.

The efficiency can be broken down into losses due to electrical resistance in the energy storage system, heat loss to the walls, unrecovered ionization and dissociation energy,

Encyclopedia of Aerospace Engineering, Online © 2010 John Wiley & Sons, Ltd.

This article was published in the *Encyclopedia of Aerospace Engineering* in 2010 by John Wiley & Sons, Ltd.
DOI: 10.1002/9780470686652.eae120

exhaust plume divergence, and the velocity distribution of the (nonmonoenergetic) exhaust plume. Thus:

$$\eta_t = \eta_{tr}\,\eta_{heat}\,\eta_{ff}\,\eta_{div}\,\eta_{dist} \tag{3}$$

where the subscripts on the right-hand side refer to efficiencies associated with energy transfer from the energy storage system to the thruster, heat loss from heated plasma to the thruster body, frozen flow, divergence and velocity distribution:

- Transfer efficiency: The biggest loss is usually in the internal resistance of the energy storage system, which is usually a capacitor. Because an efficient pulsed thruster has an impedance of $\sim$10 mΩ, the internal resistance associated with E_0 needs to be less than 1 mΩ to achieve $\eta_{tr} > 0.9$.
- Heat loss: This loss is associated with heat conduction from the arc discharge into the electrodes and stored propellant, which increase in temperature and radiate to space. This efficiency depends strongly on the thruster size and geometry, and typically $\eta_{heat} > 0.8$.
- Frozen flow: Efficient pulsed thrusters operate at high degrees of ionization, typically exceeding 50%, and this energy is not recovered in the acceleration process. The frozen flow efficiency is the ratio of the particle kinetic energy to the total energy, including kinetic and internal (thermal, dissociation, ionization). For fast ions (20–25 km s^{-1}) $\eta_{ff} \sim 0.7$, and for fast neutrals (10 km s^{-1}) $\eta_{ff} \sim 0.6$. However, for slow neutrals (3 km s^{-1}) $\eta_{ff} \sim 0.15$, so that an exhaust with a large fraction of slow neutrals has a low frozen flow efficiency.
- Divergence: Spreading of the exhaust beam causes a small loss of thrust and efficiency. For a divergence half-angle of 20°, $\eta_{ff} \sim 0.93$, so divergence is not a major loss factor compared to other factors.
- Velocity distribution: Velocity distribution includes both spatial velocity distribution, in which the center of the exhaust beam has a higher velocity than the edge due to viscous drag along the electrodes, and distribution in velocity space, because ions and double ions are accelerated to higher velocity than neutrals. Both types of distribution represent a departure from a monoenergetic beam and hence a loss of efficiency. As an example, suppose that 50% of the mass m is accelerated to $1.5U_e$, and the other 50% is accelerated to $0.5U_e$. Then the impulse bit is mU_e but the required energy is not $(1/2)mU_e^2$, but is $(5/8)mU_e^2$, resulting in a distribution efficiency $\eta_{dist} = 0.8$. Distribution efficiency is improved in general by operating at a high degree of ionization, reducing the number of neutrals, and at high average exhaust velocities, greater than 10 km s^{-1}, and is typically 0.7.

Typically, using the suggested values, $\eta_t = 0.9 \times 0.8 \times 0.4 \times 0.93 \times 0.7 = 0.19$, showing that high efficiency is difficult to achieve with these types of PPTs.

14 THRUST EFFICIENCY AND IMPEDANCE

PPTs as a class operate over a wide impedance range of eight orders of magnitude. The Teflon PPT can operate at a discharge voltage of 25 V, current of 2500 A, and impedance of 10 mΩ, and the MCD can operate at 1 kV, 1 mA, and an impedance of 10^6 Ω.

The significance of impedance is its relation to efficiency. A 10 mΩ thruster can easily incur an impedance loss Z_{ext} of $\sim$1 mΩ in the external power source and transmission lines, resulting in an efficiency drop of 10%. For a thruster impedance above 1 Ω this factor is negligible. Also, low impedance devices imply high current, sometimes tens of kiloamperes, which makes switching difficult in those devices requiring switching.

The impedance associated with propellant acceleration, as opposed to the impedance Z_R associated with resistive random thermal heating, is called the dynamic impedance and is given by $Z_D = (1/4)L'U_e$, where U_e is the exhaust velocity. For typical values of $L' = 0.4\,\mu$H and $U_e = 20$ km s^{-1}, $Z_D = 2$ mΩ, a value comparable to the impedance Z_D in the external circuit transmitting power to the thruster.

The thruster efficiency of electromagnetic thrusters can be expressed in terms of resistive and dynamic impedance as

$$\eta_{t,EM} = \frac{Z_D}{Z_D + Z_{ext} + Z_R} \tag{4}$$

Since $Z_D = (1/4)L'U_e$ is usually less than $Z_R + Z_{ext}$, and L' is dictated by the electrode geometry, high efficiency is achieved by operating at high U_e, by careful attention to the external circuit to reduce Z_{ext}, and by operating at high discharge energy to reduce Z_R.

15 ENERGY STORAGE AND SWITCHING

Energy storage is needed for any pulsed system, and must be able to deliver high power to the thruster. The two principal types are capacitive storage and inductive storage. Capacitive storage is closely coupled to the thruster to minimize external resistive losses. Capacitors can either be directly connected to the thruster electrodes, or connected through a switch to deliver energy to the discharge (Benson and Frus, 2001).

This article was published in the *Encyclopedia of Aerospace Engineering* in 2010 by John Wiley & Sons, Ltd.
DOI: 10.1002/9780470686652.eae120

There are several methods of switching capacitor energy:

- The capacitive store is directly coupled to the electrodes, and the voltage on the capacitors is allowed to rise until a Paschen breakdown occurs across the electrodes (Figure 1a). With this approach, the breakdown voltage and pulse energy can vary somewhat from pulse to pulse, depending on breakdown conditions, which include electrode geometry, ambient background gas pressure in the electrode gap, and electrode and insulator material, surface roughness, temperature, and cleanliness. This approach is useful and may be the only option at high pulse rates.
- The capacitive store is directly coupled to the electrodes, the voltage is allowed to rise to a set value, and a separate plasma source called an igniter is triggered, spraying the interelectrode gap with low-density plasma to initiate the discharge (Figure 1b). The difficulty with this method is that the igniter is subjected to the high velocity and temperature plasma and can be damaged over time. The advantage is that the pulse energy and pulse rate are precisely controlled.
- The capacitive store is directly coupled to the electrodes, the voltage is allowed to rise to a set value, and propellant is injected into the gap to trigger the discharge. This approach is difficult to implement with microsecond-length pulses, since gas injection valves are not available that can open in microseconds.
- The capacitor is coupled to the electrodes through a switch, which can be of various types. The capacitor voltage is allowed to rise to a set value, and the switch is triggered, precisely controlling the pulse energy and pulse rate. The switch types are: gas-injected switch, which can be operated in a manner similar to propellant injection described in Lovberg and Dailey (1982), except that the valve can operate on a millisecond time scale; vacuum spark gap, for which the breakdown voltage and hence pulse rate can be precisely controlled, and the spark gap suffers from short life at high energy; semiconductor solid-state switches of various types, which are precisely controlled and have long life, although they can be damaged if used for pulses with extremely fast risetimes (Frus, 1991).
- Inductive storage can also be used, although this is less common. Prior to the pulse, current is switched through a solenoid coil, storing energy in the magnetic field. Rapidly opening a solid state switch builds up a large voltage across the switch, which also appears across the thruster electrodes, causing a breakdown. Inductive storage works for low current discharges, since the size of the coil is small and the solid-state switch is not damaged by high current.

16 PULSE SHAPING

The most important pulse parameters are energy, peak power, and pulse rate. Some pulsed thrusters also require pulses with a specific current pulse shape.

For some thrusters, the efficiency improves if the pulse current is not allowed to oscillate, a pulse shape sometimes called unipolar. Unipolar operation can be created in several ways; through a matched pulse forming network (PFN), from operating an overdamped storage circuit, or by using a diode in parallel with the thruster, called a free-wheeling diode.

Some pulsed devices operate in a quasi-steady mode, meaning that plasma conditions remain constant during the pulse. This mode requires a rectangular constant current non-reversing pulse. Such a pulse is produced by a PFN, such as from a distributed capacitance and inductance (e.g., a length of coaxial cable) or by a series of discrete parallel capacitors L and series inductors C, called a lumped transmission line or L–C line. By selecting the proper discrete components, the line impedance $(L/C)^{1/2}$ can be set equal (matched) to the thruster impedance Z_t, producing a single unipolar pulse of constant current. By tailoring the distribution of L and C in the line, other desired pulse shapes can be created (e.g., a pulse where the current rises to a constant level for half the pulse) and then changes to a second level for the second half. Matching can also be achieved by operating N lines in parallel, for which the PFN impedance is $(L/C)^{1/2}/N$.

By using a critically damped or overdamped circuit, a non-reversing pulse is created that rises rapidly and falls slowly. Such a pulse is simpler to produce but does not produce quasi-steady conditions.

By connecting a diode across the thruster opposed to the initial current flow, current can flow through the thruster in one direction. If the current tries to reverse, the diode short-circuits the thruster, along the current to continue flowing in the same direction, producing a pulse with approximately the same shape as the critically damped case.

17 PROPELLANT FEED SYSTEM PROBLEMS

It is often the case that the propellant feed system presents the most difficult technology issue in developing a PPT. Solid, gaseous, and liquid propellants all present particular difficulties. Because the operating time scale of a pulsed injection valve is measured in milliseconds, and that of a high power current pulse in microseconds, matching the mass injection with thruster power is difficult. Solid propellants do not require valves but can be equally demanding geometrically,

This article was published in the *Encyclopedia of Aerospace Engineering* in 2010 by John Wiley & Sons, Ltd.
DOI: 10.1002/9780470686652.eae120

in terms of feeding a large volume of propellant into a small thruster. Liquid propellants such as water present additional difficulties with premature vaporization upstream of the injection nozzle. Designs for PPTs that present high propulsive performance can otherwise flounder on the mass feed system issue.

18 THRUST STAND MEASUREMENTS

Performance of PPTs is measured in vacuum on a thrust stand (Burton and Turchi, 1998). Most thrust stands operate either as a pendulum, or as a deflecting beam. Thrust can be determined in several ways. One is to measure a single impulse bit mU_e, by measuring the thrust stand oscillatory response to a single pulse after a suitable calibration. Multiplying the impulse bit by the pulse frequency ν gives the average thrust. The second method is to use a thrust stand with a natural frequency much lower than the pulse rate, so that the thrust stand deflection is a direct measure of average thrust T_{ave}. In this case the impulse bit is determined from T_{ave}/ν. A third method is to operate the thruster with a solenoid feedback system that opposes the thrust stand deflection, eliminating the deflection entirely. In this case the thrust or thrust impulse is determined by the current in the solenoid, calibrated against a known force in the thrust range of interest.

19 SUMMARY/CONCLUSION/ PERSPECTIVE

PPTs have proven to be versatile additions to the space propulsion arsenal. Despite their generally low efficiency and low specific impulse when compared to steady thrust propulsion systems such as ion and Hall thrusters, they are useful for applications such as satellite attitude control and propulsion for microsatellites and nanosatellites, for which reliability, functionality, system simplicity, and ability to operate at power levels below 10 W may be more important than high propulsion performance. As more miniaturized satellites are used in Earth orbit, it can be expected that PPTs will play an important propulsive role.

REFERENCES

Benson, S.W. and Frus, J.R. (2001) Advanced pulsed plasma thruster electrical components. AIAA Paper 2001-3894.

Bober, A., Maslennikov, N., Day, M., Popov, G. and Rylov, Y. (1993) Development and application of electric propulsion thrusters in Russia. International Electric Propulsion Conference, Paper IEPC-93-001.

Burton, R.L., Eden, J.G., Park, S.-J., Yoon, J.K., de Chadenedes, M., Garrett, S., Raja, L.L., Sitaraman, H., Laystrom-Woodard, J., Benavides, G. and Carroll, D. (2009) Initial development of the microcavity discharge thruster. Proceedings of the 31st International Electric Propulsion Conference, September, 2009, IEPC-2009-169.

Burton, R.L., Fleischer, D., Goldstein, S.A. and Tidman, D.A. (1990) Experiments on a repetitively pulsed electrothermal thruster. *J. Propul. Power*, **6**(2), 139–144.

Burton, R.L. and Turchi, P.J. (1998) Pulsed plasma thruster. *J. Propul. Power*, **14**(5), 716–735.

Burton, R.L. and Wang, S.Y. (1991) Initial development of a pulsed electrothermal thruster. *J. Propul. Power*, **7**(2), 301–303.

Cheng, D.Y. (1971) Application of a deflagration plasma gun as a space propulsion thruster. *AIAA J.*, **9**(9), 1681–1685.

Frus, J.R. (1991) Apparatus and method for providing ignition to a turbine engine, US Patent 5065073.

Keidar, M., Boyd, I., Antonsen, E., Burton, R. and Spanjers, G. (2006) Optimization issues for a micropulsed plasma thruster. *J. Propul. Power*, **22**(1), 48–55.

Laystrom, J.K. and Burton, R.L. (2003) Geometric optimization of a coaxial pulsed plasma thruster. AIAA Paper 2003-5025.

Lovberg, R.H. and Dailey, C.L. (1982) Large inductive thruster performance measurement. *AIAA J.*, **20**(7), 971–977.

Marshall, J. (1960) Performance of a hydromagnetic plasma gun. *Phys. of Fluids*, **3**(1), 134–135.

Meckel, N.J., Cassady, R.J., Osborne, R.D., Hoskins, W.A. and Myers, R.M. (1997) Investigation of pulsed plasma thrusters for spacecraft attitude control. 25th International Electric Propulsion Conference, Paper No. IEPC 97-128.

Russell, D., Poylio, J.H., Goldstein, W., Jackson, B., Lovberg, R.H. and Dailey, C.L. (2004) The Mark VI Pulsed Inductive Thruster, AIAA Paper 2004-6054.

Rysanek, F., Hartmann, J.W., Schein, J. and Binder, R. (2002) Microvacuum arc thruster design for a CubeSat class satellite. *16th Annual Utah State University Conference on Small Satellites*, Paper SSC02-I-2.

Schein, J., Qi, N., Binder, R., Krisnan, M., Ziemer, J., Polk, J.E. and Anders, A. (2002) Inductive energy storage driven vacuum arc thruster. *Rev. Sci. Instrum.*, **73**, 925–927.

Thomas, R.E., Burton, R.L. and Polzin, K.A. (2008) Preliminary development and testing of a self-injecting gallium MPD thruster, AIAA Paper 2008-5081.

Willmes, G.F. and Burton, R.L. (1999) The low power helium pulsed arcjet. *J. Propul. Power*, **15**(3), 440–446.

Ziemer, J.K., Cubbin, E.A., Choueiri, E.Y. and Birx, D. (1997) Performance characterization of a high efficiency gas-fed pulsed plasma thruster. AIAA Paper 1997-2925.

Encyclopedia of Aerospace Engineering, Online © 2010 John Wiley & Sons, Ltd.

This article was published in the *Encyclopedia of Aerospace Engineering* in 2010 by John Wiley & Sons, Ltd.
DOI: 10.1002/9780470686652.eae120

This article was published in the *Encyclopedia of Aerospace Engineering* in 2010 by John Wiley & Sons, Ltd.
DOI: 10.1002/9780470686652.eae120