Pulsed Plasma Thrusters: a worldwide review and long yearned classification

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Molina-Cabrera P.,* Herdrich G.,† Lau M.,‡ Fausolas S.§
University of Stuttgart, Stuttgart, 70569, Germany

Schoenherr T.¶
and Komurasaki K.‖
University of Tokyo, Tokyo, 7-3-1, Hoongo, Bunkyo, Japan

Since first launched in 1964 by the Soviet Union aboard Zond-2, Pulsed Plasma Thrusters (PPTs) have come a long way to currently enjoying the heritage of eleven successful flights and about fourteen active R&D laboratories around the world. Renewed interest in PPTs has been kindled by the growing microsatellite industry due to their performance at low powers, precise impulse bit, throttling capability, simplicity, and robustness. For the purpose of mission planning, the field of PPTs is plagued with various, often contradicting, naming schemes. It is imperative for the community to agree in a certain classification scheme. The present work presents a suitable classification to the immense variety of electrode geometries, feed-mechanisms, propellant state of matter, ignition-mechanism, and energy ratings . It was found PPTs could be classified via energy input in much the same way as microsatellites are classified according to their mass and power. Furthermore, an extensive PPT data base amassed over the years at IRS allows large-scale performance comparisons between PPT geometries and other EP technologies revealing important patterns for mission design.

Nomenclature

ACS	= Attitude Control Systems
EM	= Electromagnetic
EP	= Electric Propulsion
ET	= Electrothermal
h	= height
I_{sp}	= Specific Impulse
I_{bit}	= Impulse bit
PET	= Pulsed Electrothermal Thruster
PPU	=Power Processing Unit
PPT	= Pulsed Plasma Thruster
$PTFE$	= Polyetrafluoroethylene, C_2F_4,Teflon ®
RRP	= Rail-Rectangular-Parallel geometry
m_{bit}	= Mass bit
μ_o	= Permeability of free space

*Masters Student - Space Studies, International Space University, pedro.molina@masters.isunet.edu
†Research Associate, Head of Plasma Technology, Institut fur Raumfahrtsysteme,herdrich@irs.uni-stuttgart.de
‡Doctorate Student, Institut fur Raumfahrtsysteme, lau@irs.uni-stuttgart.de
§Director Space Transportation Technologies, Insitut fur Raumfahrtsysteme, fausolas@irs.uni-stuttgart.de
¶Doctorate Student1, Arakawa and Komurasaki Laboratory, tony.schoenherr@googlemail.com
‖Professor , Arakawa and Komurasaki Laboratory, komurasaki@al.t.u-tokyo.ac.jp

I. Introduction

With the increased interest in micro-satellite technologies, the bulky cold gas mono/bipropellant thrusters and conventional reaction-wheel attitude control systems are being replaced for lighter and more capable electric thrusters serving all kinds of purposes from attitude-control, drag make-up, to primary propulsion depending on the application. Pulsed Plasma Thrusters (PPT), the first EP technology to ever fly in space currently enjoys the heritage of over ten successful spaceflights.[14,16,43] After a twenty-year period between 1980 and 2000 where no PPTs were flown, the constraining budgets drove a wave of miniturization that rekindled the interest in this technology. PPTs' high specific impulse I_{sp} per unit power (with the concominant propellant savings), low mass, simplicity, and robustness make them competitive for low power and low mass applications. Nowadays, there are nearly fourteen laboratories around the world actively working in PPTs. In spite of the nearly fifty-year heritage, there has been no attempts to reconcile an appropriate naming scheme. The mini and micro[3] prefixes have been adapted to the PPT acronym without consulting similarities or contrasts with other akin efforts and their respective namings. It is therefore of great importance to settle an appropriate PPT classification to ensure mission planners have a comprehensive palette of options when deciding upon one or another PPT family. A clear division has the potential to increase PPT interest revealing the flexiblity and full potential of PPT technologies.
The present publication commences by justifying the PPT effort based in the increased interest in microsatellites. The classification problem is then addressed from both the physical and energetic perspectives. Section 3 presents fruitfull data analysis patterns along with theoretical explanations of such behaviour. Section 4 presents comparisons between PPt geometries and other EP devices. Lastly potential applications and future recommendations encourage future PPT R&D.

II. Faster, cheaper, smaller?

After the ludicrous budgets of the space race of the sixties and seventies, scarcity of funding has encouraged the exploration of cost-reduction strategies on every single phase of space projects. The pinnacle of the cost dropping approach was NASA's former administrator Goldin's mantra: faster, better, cheaper. However, the failure of the twin Mars probes in 1999 and the Columbia Accident discouraged the further use of the FBC term in the industry.[8] Space, following the trail of parallel industries, has recently seen an increased emphasis in advancing miniaturization. Mini and micro satellites and their compact payloads continue to improve their predecesors in both performance and cost savings. A large number of limited microspacecraft in formation demonstrate superior performance than a single large spacecraft. Moreover, big space players such as EADS Astrium and QinetiQ have recently purchased Surrey Satellite Technology and Verhaert (respectively) in order to ensure a competitive position in the growing micro-satellite industry.[28]

Figure 1 *numerically* demonstrates the steady increased interest minisatellites in the last decade. For the purposes of the graph below, minisatellites are defined as spacecraft with 500kg of mass or less. Figure 1 was generated using the launch database of[25] registering the number of dedicated, shared, or piggy-back launches that included satellites of masses below 500kg. It does not include classified launches or unknown masses of Chinese and Russian spacecraft which might fall under 500kg; otherwise, it is believed accurate to within 2 launches every year. It was impressive to find that the renewed interest in PPTs sparked in the year 2000 is exactly when higuest amount of minisatellites was ever launched. This figure also shows that the decision to work in PPT R&D is practical given the number of minisatellite launches has remained more or less stable in the last decade and apears to be increasing with time (see linear fit to percentage of launches above).

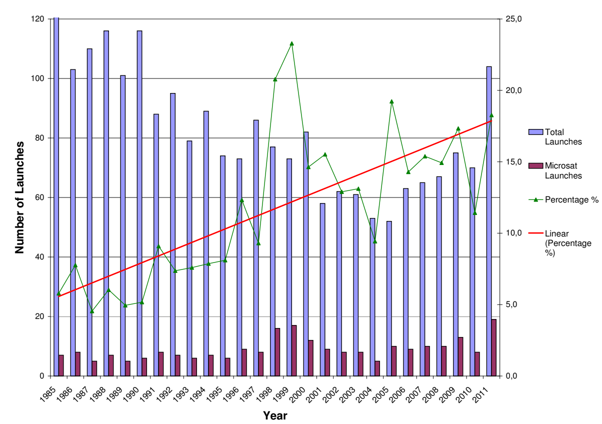

Figure 1. Number of mini, micro, and nano satellite (m¡500kg) launches compared with total launches over the last 25 years

III. The classification problem

The name: 'Pulsed Plasma Thruster' is already extremely vage straight off-the-bat. It attempts to uniquely define a thurster that works by propelling plasma, while both electrostatic and electromagnetic thrusters are concretely plasma thrusters as well. Also the term 'pulsed' simply implies unsteady operation. However, since the early days of plasma accelerator development, the term PPT was used to classify ablative Lorentz-force plasma accelerators. Over the years propellant-feed mechanisms, chamber geometries, and energy levels have varied. Various attempts to improve performance have led teams to use gas,[7] liquid[23] propellants, laser[15] and/or high-pressure gas[26] ignition over the standard configurations. Unfortunately, thus far, a common classification scheme is non-existent. Worse even, there has been conflicting naming schemes where certain groups have called a given PPT geometry "micro" PPT[22] while others consider *micro* anything bellow 500 Isp.[39] American PPT developments beyond 500J have been simultaneously called milipound[41] and High Energy PPT.[19] Russian R& D have called their PPTs *ablative* all along without observing rail or coaxial geometric variations[1].[21] Moreover, Stuttgart's IRS' PPTs have been extensively termed *i-MPDs* in contrast with the rest of the community. Coaxial PPTs working in the electromagnetic (EM) regime are essentially pulsed MPDs. However, the i-MPD term is not used anywhere else in the world. There is an obvious need to identify a certain PPT development from the rest. For the purposes of mission planning, an accurate classification scheme is paramount. A clear division would increase interst in PPTs by simplyfing decision-making to mission designers and revealing the true flexiblity and full potential of the technology.

A. Physical Classification

The physical layout of a PPT is the first logical categorization scheme that comes to sight. Apart from the original rail-accelerator PPT there have been a whealth of physical variations which can be divided in electrode geometry, propellant feed method, propellant state of matter, and ignition technology. All of these feature **must** be clearly identified to fully describe a PPT.

1. Electrode Geometry

Electrode geometry has been found to be divided in three main families (with their respective inner subdivisions):

1. Rail: Propellant is accelerated between two plates. Optimized empirically to the following
    - Shape
        - **R**ectangular
        - **T**ongue
    - Angle
        - **P**arallel
        - **F**lared: Angled plates between 0 and 20 degrees off the horizontal
2. Coaxial: MPD/Arcjet-like
3. Z-pinch: Nozzle-less coaxial designed to minimize propellant losses.[31]

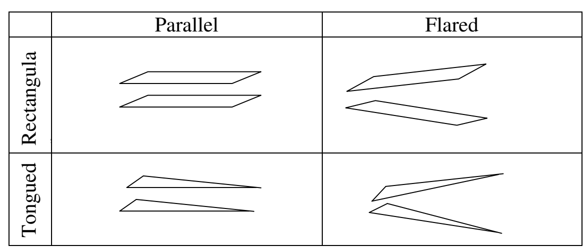

Figure 2. Rail-geometry electrode combinations

2. Propellant feed mechanism

Attempts at optimizing propellant surface area exposed to the arc have given rise to a rich variety of propellant feed-mechanisms:

- Breech-fed: Feeding propellant to the chamber from the rear-end (opposite to exhaust nozzle or aperture)
- Oblique-fed: Propellant injected from sides at a diagonal angles
- Side-fed: Propellant fed from sides at right angles to electrodes

- Erosion: Only applicable to Coaxial PPTs. The teflon bar forms part of the walls of the chamber where arcing takes place, and it is not continuously replenished but simply eroded over the life of the thruster[29]

Beyond the propellant feed geometries, the surface area shape input to the discharge chamber is also known to vary, for solid PPTs exclusively, as follows:

- Frontal: A single flat surface exposed to the arc,
- V-shaped: Two surfaces at a given angle between 0 and 90 degrees exposed to the arc,
- Parallel: Two surfaces at straight angles to the electrodes facing each other.

3. Propellant state of matter

All three kinds of electrode geometries have quite intricate propellant feed-mechanisms and could receive propellant in gas, liquid, or solid forms (solids being, by far, the most popular). Solid PPTs have mostly used Teflon®, but also Polyethylene and doped compounds (MoS_2)[36] thereof. Another innovative approach involves using no separate propellant (per say) and relying on the ablated electrode material during discharge.[27] In the case of liquid PPTs, water has been used sometimes doped with salts to decrease plasma resistance.[24] Lastly, gas-feed PPTs use mainly ammonia gas.[44]

B. Ignition Method

Throughout the present review, several ignition methods where found. The most widespread is the use of an ignitor spark plug, introducing electrons that drop the vacuum resistance between electrodes. Semiconductor, self-made, and airplane ignitor plugs are used.[33] However, given the lack of reliability and limited lifetime due to carbon deposition and erosion[26] some researchers have opted for alternative approaches:

- Laser Assisted: Originally proposed by researchers at Princenton University, IR monochromatic radiation could be used to induce under-voltage ignition.[2] Japanese researchers have also engaged in such work obtaining fairly good current results at low electrode voltages.[15]
- High Pressure: Kushari et al.[26] suggested that high vacuum pressures catalize ignition through the air gap once a given voltage is reached. The breakdown clears the energy from the capactior until it recharges and self-ignites again allowing the pulsed behaviour desired.

C. Energy classification

Power is a vital performance parameter in electric propulsion. Power does not only indicate the input electrical needs but also gives an idea of the EP engine's thrust and exhaust-speed performance. The capacitor energy in a PPT gives an indication of the size of the power conditioning unit, the main discharge capacitor, and the peak currents available to ionize propellant during discharge. Furthermore, research revealed that the energy is always quoted when referring to any PPT system.

The first step was to find all thruster energies and divide the energy spectrum in 'boxes' of about 2 joules each. Flight-qualified PPT models and experimental efforts with final mass and lifetime data were taken into account (see Appendix 1). This process revealed a large number of thrusters around the 30 +/- 10 J range and very few beyond 10,000J and under 2.5J. Figure 3 below shows results of the quantization. The second step was to investigate existing small-satellite naming schemes. Muller[32 6] presents the current microsatellite classification scheme based in mass and power where minispacecraft correspond to the 500-100kg/W range and microspacecraft (¡100kg ¡100W) are divided in three classes of 20-5, 5-1, and ¡1 kg/W respectively. In order to simplify naming by using existing standards, PPTs

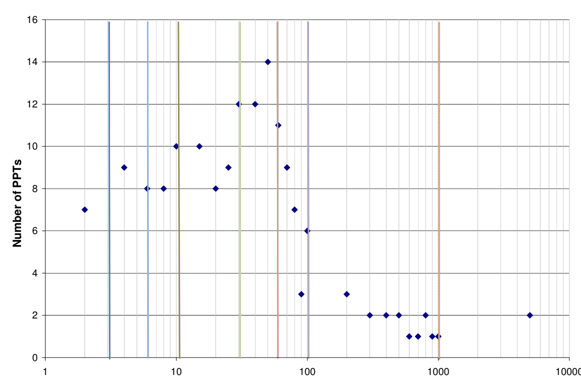

Figure 3. Classification of PPTs in energy boxes

were divided in energy classes that would serve the re-
spective microspacecraft classes. For example, a PPT suitable for a Class I microspacecraft should serve common Δ V needs of the class and not exceed either mass or power limits. This PPT would be named after the respective microsatellite class.

Based on an article about station-keeping by TUDelft ,[40] the average Δ V budget for orbit control and drag compensation for a LEO satellite (400-500 km) was quoted to be less than 25 m/s in average up to a maximum 100m/s. Furthermore, 3-axis attitude control costs between 2 and 6m/s per year. Due to the fact that the PPTs under classification have published mass and maximum-lifetime data, their Δ V performance aboard a given microsatellite class was easily derived with the rocket equation. Tables 4 and 5 show the result of the analysis. Appendix 1 shows the relevant PPTs (with either published lifetime or fligh performance data) used in the analysis.

		Satellite Class					
Proposed PPT Name	Energy, J	CLASS III (1kg - 1W)		CLASS II (5kg - 5W)		Nano (10kg-10W)	
		A/C (yr)	O/C (yr)	A/C (yr)	O/C (yr)	A/C (yr)	O/C (yr)
CLASS III	0 to 2	4.5	1	6	1	3	
CLASS II	2 to 5	Too heavy		1		12	1
Nano	5 to 10	Too heavy		Too heavy		29	1.7
CLASS I	10 to 20	Too heavy		Too heavy		Not enough power	

Figure 4. Energy Classification and naming proposed for PPTs serving satellites of less than 10kg mass

		Satellite Class					
Proposed PPT Name	Energy, J	CLASS I (20kg-20W)		Micro (100kg-100W)		Mini (500kg)	
		A/C (yr)	O/C (yr)	A/C (yr)	O/C (yr)	A/C (yr)	O/C (yr)
Nano	5 to 10	14	1	2.8		1	
CLASS I	10 to 20	30	2	7	0.5	1,3	
CLASS 0	20 to 50	Not enough power		20	1.6	5	0,3
Medium	50 to 100	Not enough power		70	4	14	0,9
High Energy	100 to 1000	Not enough power		Not enough power		17	1
Very HE	1000-100000	Not enough power		Not enough power		Not enough power	

Figure 5. Energy Classification and naming proposed for PPTs serving satellites of more than 10kg mass

In both tables 4 and 5, A/C and O/C(yr) refer to the number of years the *best* PPT performer of the given class could serve 3-axis zero-momentum attitude control and orbit control-drag compensation respectively. The term 'too heavy' states that the PPT mass is larger than the satellite's total mass. The term 'not enough power' indicates that the satellite's maximum power could not serve the respective PPT at the rated frequency - mostly at 1Hz. It is possible, however, to fire these PPTs at lower frequencies, but their performance at these frequencies was not published and therefore not considered.

These tables above present a naming scheme sharing great similarities with microsatellite classifications seen in Muller.[32] The newcommers are only *CLASS 0* and *Medium* PPTs wich split the 20-100J energy bank into 20-50 for CLASS0 and 50-100J for Medium. This further classification is necessary due to the large number of PPTs in this range as seen in figure 3. It is interesting to note that every PPT energy class is just enough to allow one year or more of orbit control and drag compensation to the given microsatellite class. Considering that PPTs used for this analysis had published lifetime performance data, these tables demonstrates PPTs are competitive solutions to serve the LEO market.

IV. Experimental data and theoretical justifications

The extensive PPT data base amassed over the years at IRS allows large-scale performance comparisons between PPT geometries and other EP technologies revealing important patterns for mission design. Data analysis firstly revealed linearities between performance parameters. It turns out both impulse bit and mass bit are linear with energy. Even tough anything seems linear when plotted log-log with a thick marker, Figure 6 takes into account all PPT geometries and manufacturers and still shows an upward linear trend without significan departures from direct proportioonality with energy.

Theoretical justifications for these patterns were found. Thrust in PPTs can be divided in electrogmanetic and electrothermal components. The EM thrust component is derived in the basis of the $j \times B$ force with d, h, and, δ corresponding to electrode thickness, spacing, and plasma sheet tickness.

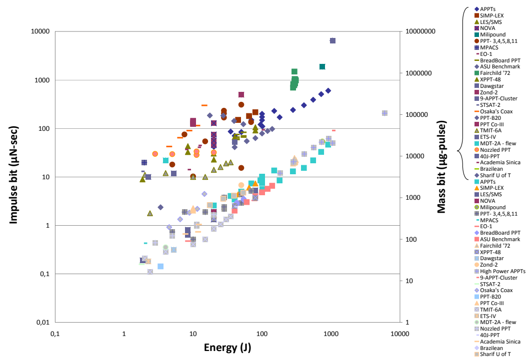

Figure 6. Linear Performance parameters with Energy Increase

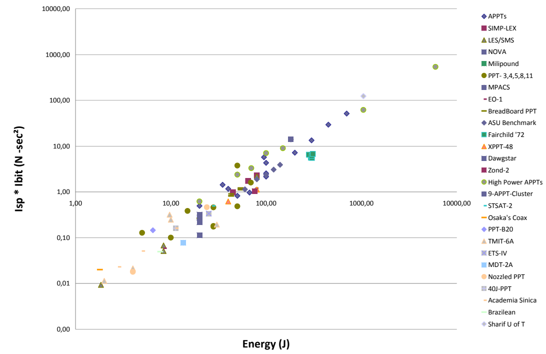

Figure 7. Linear trend of impulse bit times exhaust velocity with energy

$$T_{EM} = \int_h \int_d \int_\delta jxBdx \tag{1}$$

$$T_{EM} = h \cdot d \cdot j \int_\delta Bdx \tag{2}$$

$$T_{EM} = h \cdot d \cdot j \int (\frac{\mu_o i}{d} - \mu_o j \cdot x)dx \tag{3}$$

$$= \frac{1}{2}\frac{h}{d}\mu_o i^2 \tag{4}$$

$$\tag{5}$$

The current integral can be evaluated in the basis of the electrical circuit[42] and shown to be:

$$I_{EM} = \int T_{EM}dt \tag{6}$$

$$\int_0^\infty i^2 dt = I^2 = \frac{E_o}{R} \tag{7}$$

$$\therefore I_{EM} = \frac{1}{2}\frac{h}{d}\mu_o \cdot \frac{E_o}{R} \tag{8}$$

$$I_{EM} = \frac{1}{2}L' \cdot \frac{E_o}{R} \tag{9}$$

$$with R = 1.3\sqrt{\frac{C}{L_o}} \tag{10}$$

$$\tag{11}$$

Where L_o is found at t=0 from $L_o(di/dt) = V_o$. The term $dL/dx = L' = \frac{h}{d}\mu_o$ is termed the inductance per unit length, as it reveals that equation 8 is equivalent to taking the displacement derivative of energy stored in an inductor .[18] Burton[3] presents the same inductance per unit length above (which is for rail-type geometries) for coaxial geometries as well; therefore, equation 8 linearizes EM thrust with energy independant of electrode geometry. Vondra[42] shows, through integrating the momentum of the current sheet, that the electrothermal contribution to the thrust is of the form:

$$I_{ET} = m_{ablated} \cdot U_o^* \tag{12}$$

$$m_{ablated} = \frac{\sigma_o \delta}{\lambda}\frac{d}{h}\left(R_p^2 + \frac{L_p^2}{LC}\right)\frac{E}{R} \tag{13}$$

Where U_o^* refers to an 'effective' velocity which accounts for an ablated-propellant exit velocity and pressure contributions, σ_o refers to the conductivity, δ to the thickness of the sheet, λ to the latent heat of vaporization, and R_p and L_p to the plasma resistance and inductance respectively. The ablated mass expression assumed that the mass ablated per shot is proportional to the energy dissipated over the solid propellant. Taking 8 and 13, the total impulse bit is thus found to be:

$$I_{bit} = \left(U_o^* \frac{\sigma_o \delta}{\lambda} \frac{d}{h} \left[R_p^2 + \frac{L_p^2}{LC} \right] + \frac{1}{2} \frac{h}{d} \mu_o \right) \frac{\mathbf{E}}{1.3} \sqrt{\frac{L_o}{C}} \tag{14}$$

Equation 14 supports the linear relationship between energy and impulse bit shown in 6. However, assumptions made in the electromagnetic thrust derivation above are based on rail, rectangular, paralllel electrode geometries. Only the mass bit derivation of 13 does not assume any particular geometry. Literature review has failed to find a closed-form derivation of electromagnetic thrust in the coaxial PPT from first principles without using inductance-per-length assumptions. Unfortunately, not all derivations of I_{bit} in literature show linear relationships with energy. For example,[3] shows the electrothermal contribution proportional to the square-root of energy. In this case, the energy relationship is more complex and contains a linear and a square-rooted term, which disagrees with the pattern observed in figure 6. Furthermore,[12] show a relationship between Electrothermal I_{bit} and current integral to the power of $2/n$, where n is experimentally determined. Unless n is found to be exactly 2, then this expression also questions figure 6. It is possible that the ET contribution is so small when compared to the EM that whatever scaling of ET thrust with energy is irrelevant; however, this discrepencies must be adddressed by theoreticians in the community. Fortunately for the sake of agreement,[12] shows the ablated mass to be directly proportional to Energy with a completely different derivation.

$$T = m_{ablated} * v_{exhaust} \tag{15}$$

$$I_{bit} = \int T = v_{exhaust} \int_0^{\tau} m_{ablated} \tag{16}$$

$$I_{bit} = m_{bit} v_{exhaust} \cdot f \tag{17}$$

$$I_{bit} = m_{bit} I_{sp} g f \tag{18}$$

$$I_{sp} = \frac{I_{bit} g}{m_{bit} f} \tag{19}$$

$$\therefore I_{sp} \cdot I_{bit} = \frac{I_{bit}^2 g}{m_{bit} f} \tag{20}$$

Where f is the pulse frequency and $m_b it$ is the mass ablated in every shot. If I_{bit} and m_{bit} both linearly depend on energy, then Equation 20 should have energy squared in the numerator and one energy term in the denominator leaving a linear relationship of $I_{bit} \cdot I_{sp}$ with E as shown confirmed below in figure7.

Another interesting pattern for mission designers is the scaling of thruster efficiency. In PPTs thruster efficiency takes into account the energy stored in the capacitor and the energy of the expelled propellant, as given in Burton.[4] In general, in PPTs thruster efficiency is seen to increase with input power, which shows that scaling energies might be the way forward towards improving efficiency. Even tough, a clear relationship with energy has not been experimentally observed 8, [33] argues there is linear relationship between thrust efficiency and I_{sp} applied below in figure 9

Even tough the latter figure cannot be perfectly linear because no energy level could give efficiencies beyond 100%, it is seen to very roughly agree with Nawaz's expression where $\mu_T = 10^{-4} I_{sp}$. Considering the log-log axis, the agreement is at best rough. Some algebra reveals that theoretical expressions support this linearity:

$$\eta_t = \frac{[I_{bit}]^2}{2mE_o} \tag{21}$$

$$given - I_{bit} = m_{bit} g I_{sp} \tag{22}$$

$$let - I_{sp} = I_{bit}/m_{bit} g \tag{23}$$

$$\therefore \eta_t = \frac{I_{bit} I_{sp} g}{2E_o} \tag{24}$$

$$\tag{25}$$

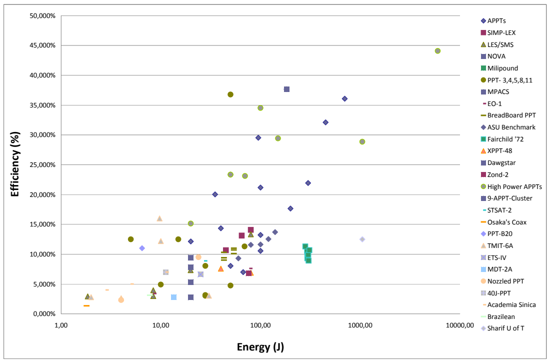

Figure 8. Thrust efficiency scaling with capacitor bank energy

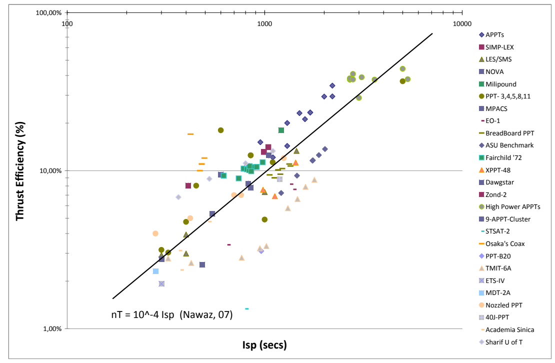

Figure 9. Thrust efficiency scaling with exhaust velocity

The following section continues profiting from the large data base by comparing PPT electrode geometries and these with other EP technologies.

V. Geometrical Comparisons

The current section is devoted to empirically compare PPTs both with each other and other EP devices, and it begins by comparing PPT performance over differing geometries. It is hoped the patterns drawn here would reveal the niches of specific geometries so further PPT development is more efficiently tailored to specific mission requirements. The first pattern shown below in figure 10 compares I_{bit} performance.

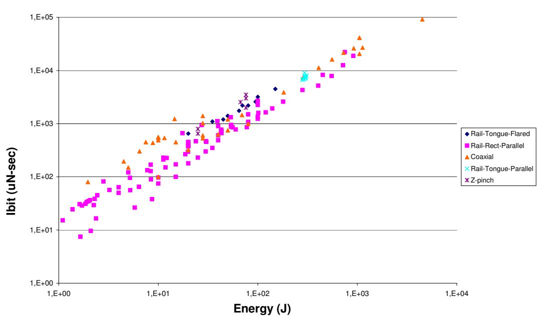

Figure 10. Geometrical comparison of I_{bit} performance

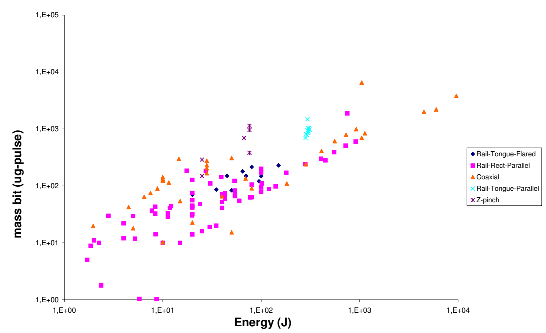

Figure 11. Geometrical comparison of m_{bit} performance

Figure 10, in addition to reinforcing the statements above in Equation 14, reveals that coaxial and tongue-flared PPTs give higher I_{bit} per energy than RRP PPTs. Coaxial PPTs are likely to have an increased electrothermal component due to the increased propellant surface area, closed breakdown chamber, and supersonic nozzle (in most cases). Figure 11 reveals that the mass bit ejected is also increased in coaxial PPTs. Flared rail-type electrodes are a result of experimental geometrical optimization[33] and their superior thrust and mass bit performance is explained in the basis of more efficient electromagnetic plasma-sheet acceleration through increased current-sheet density, decreased natural plasma expansion, and decreased sheet canting.

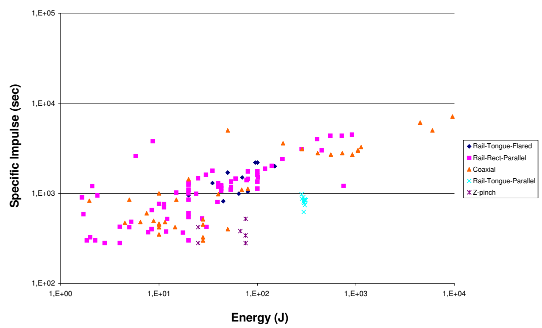

Figure 12. Geometrical comparison of I_{sp} performance

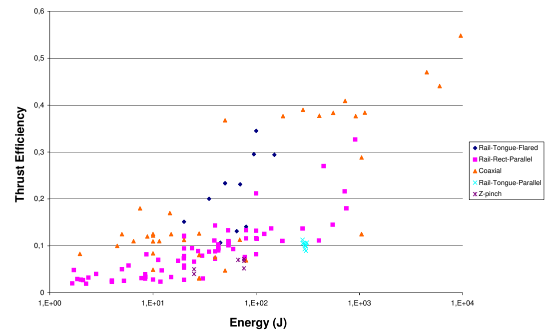

Figure 13. Geometrical comparison of thrust efficiency performance

Figure 13 shows that rail-type PPTs are also not as thrust efficient as coaxial or z-pinch types. Then, it is questionable why rail-type PPTs are so widely developed? Figure 12 shows that RRP PPTs have higher Isps per unit power than most other geometries. Since the $j \times B$ force is the main source of acceleration, figure 12 demonstrates that the acceleration process is most efficient in simple rail-rectangular-parallel type electrodes. In coaxial PPTs, since pressures are higuer and the plasma is confined to a cylinder, the plasma sheet has higher density which introduces losses through collisions. In tongue-flared electrodes, the peak currents driving the acceleration of the plasma sheet drop as the electrode tickness decreases and the plasma arc size and resistance increases down the electrodes. Therefore, the exhaust velocities at a given energy are not as high as with *RRP* electrodes. Once PPTs have been compared with each another, the logical step is to compare the whole body of PPTs with other electric propulsion technologies too see where PPTs really fit in the big picture of EP.

VI. Comparisons with other EP devices

With the contribution of data acquired by IRS' Doctorate student Birk Wollenhaupt, PPT performance was compared with other electric propulsion technologies. Figure 14 compares PPTs in terms of thrust efficiency (defined as the ratio of exhaust energy VS energy input).

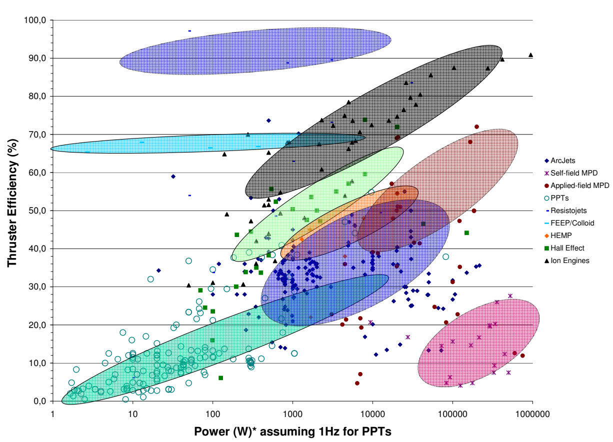

Figure 14. Efficiency comparison among different EP technologies

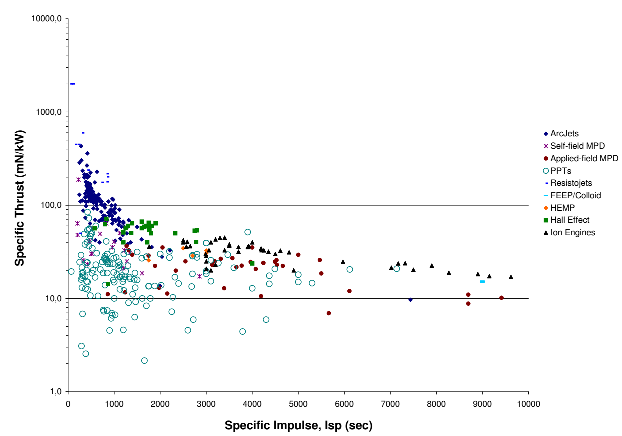

Figure 15. Specific Thrust over specific impulse: Thrust cost and Isp compromise

Figure 14 shows that most PPT developments lie on the low power and low thrust efficiency left corner of the graph. Other propulsion technologies such as Ion, FEEP, and arcjets are much more efficient at similar power levels. Figure 15 reveals a decaying exponential relationship between specific thrust and Isp. When a higher Isp is required, the 'power' cost of producing a unit of thrust goes up. The figure shows that most PPTs have low thrust per unit power in general, that is, thrust is expensive in PPTs. Arcjets (widely developed at IRS) performance seems to broadly outperform PPTs in specific thrust, yet specific impulse seems to be more flexible in the PPT front. Figure 15 has revealed another PPT weakness: low specific thrust (or high thrust cost). Hopeful still to find the PPT niche, figure 16 shows thrust over energy input for the family of electric propulsion engines.

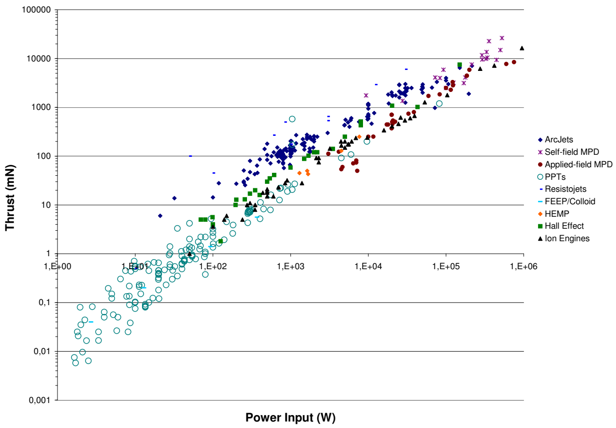

Figure 16. Thrust over Energy

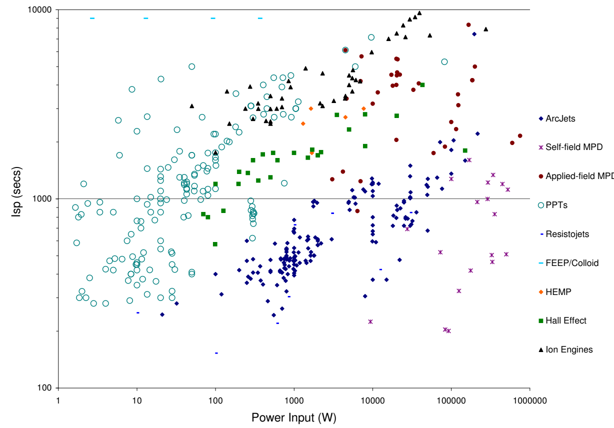

Figure 17. Exhaust velocity over Energy

Figure 16 reveals that PPTs give also a relatively low thrust per unit energy over a wide energy spectrum. The thrust produced at a given energy is similar in average to FEEP/Colloidal thrusters, HEMP, and ion engines. However, for the most part, PPTs are again poor performers. If an application calls for the ability to throttle over large energy ranges and/or produce small impulse bits well below 1mN, PPTs seem to enjoy wide heritage and flexibility. Figure 17 shows Isp over Energy for various EP devices, finally revealing a PPT strength! PPTs display a relatively higuer I_{sp} per unit power than most EP technologies. They seem superior than arcjets and hall effect engines, only to approach Ion-engine performance at high energies. Therefore, PPTs are good accelerators per energy input. When modest powers are available, PPTs ensure the higuest possible exhaust velocity is achieved.

VII. Potential PPT applications

As shown above, PPTs are very versatile thrusters. PPTs were mainly used for station keeping and spin-axis control during the 70s (see Appendix 1) and mainly for attitude control since 2000. The first application in 1964[43] used them only for orienting the solar panels of the Mars Probe Zond-2. When low powers are available, we have seen in figure17 and 14 in 10, PPTs give very good Isp bang for the power buck.

IRS has considered PPTs for two of their small satellite missions: PERSEUS and Lunar BW1.[11] PERSEUS would be a technology demonstrator envisioning flight qualification of student-built Arcjet and PPT thrusters. The Lunar BW1 mission plans to use a combination of arcjet and PPT (i-MPD) to raise the orbit of a 250kg satellite from LEO to lunar orbit. This transfer would be achieved through the cooperation of both PPT and Arcjet thrusters: The arcjet's higuer thrust (envisioned around 100s of mN) would be used when going through the high-risk Van Allen belt region, while the PPTs would constantly burn for the remainder of the trip. In this application, PPTs act as part of the *primary propulsion* systems. This is because in these low-power application, long burning times are acceptable. Furthermore, it calls for an affordable, simple, and robust system with plenty of flight heritage that could be built by students during their Master's or Doctorate degrees.

The energy classification investigation in chapter 2 shows that PPT families can comfortably serve LEO orbit control and drag maintenance as well as 3-axis zero-momentum attitude control applications. The small impulse bits (I_{bit}) (produced specially by rail-type PPTs) could prove advantegeous in precision pointing and constellation maintenance applications.[17] argues that with the increased interest in micro and nanospacecraft(addressed in section II), the ability of producing very small impulse bits at high enough I_{sp} levels to keep acceptably low system-masses enjoys great interest today. When applied to attitude control systems(ACS), PPT brings significant mass savings over conventional torque-rods and momentum-wheel solutions, which potentially drove the PPT reinassance of the 2000s. According to Spanjers et al.,[39] PPTs can provide attitude control on 150-kg (mini-spacecraft) using 1/5th the dry mass of conventional systems. Moreover, Cassady[5] further proves that as the satellite mass increases, the mass of momentum wheels scales linearly upwards, but PPT-based ACS' mass increases at a much smaller rate that gives the apparence of remaining constant in comparison.

PPT's small impulse bits and high thrust costs (see figure 15); however, make them unsuitable for missions requiring high slew rates, rapid ΔV maneouvers, and/or large drag makeups. Only when long burn times are acceptable, such as in the Lunar BW1 mission, PPTs could be used for primary propulsion.

Launched back in 2006,[25] the NEW HORIZON's Pluto-Kuiper Belt mission spacecraft hopes to reach Pluto by 2015 with the muscle of both a Jovian fly-by and 16 hydrazine thrusters. Ziemer[45] proved that PPTs could have increased 100% in scientific payload mass if implemented instead of the hydrazine propulsion system. Thus, interplanetary missions are also a target for PPT technology.

VIII. Power Processing Unit mass

During the PPT workshop discussions last March in Stuttgart, it was deemed important for mission designers to know precisely the mass of the power processing units (PPU). Research revealed only five publications where a detailed mass breakdown of PPT thrusters was presented[37 13],[9],[3].[17] Guman directly[10] analyzed PPUdevelopment and provided a linear model for PPU specific mass (Table6, pg65) ([45] might be considered the former's simplification) supported by the manufacturer Willmore shown below in figure 18

$$Power < 200W \rightarrow Mass = 500g + \frac{11g}{W} \tag{26}$$

$$Power > 200W \rightarrow Mass = 500g + \frac{5g}{W} \tag{27}$$

$$Ziemeret.al. \rightarrow Mass = \frac{11g}{W} \tag{28}$$

$$Empiricalfit \rightarrow Mass = 400g + \frac{15g}{W} \tag{29}$$

$$\tag{30}$$

Figure 18 shows a fair agreement with Willmore's model and a weak linear R-square of 0.87. Given the variety of manufacturers and countries taken into account, this plot should give mission designers a good idea of the mass implications of growing PPT energies.

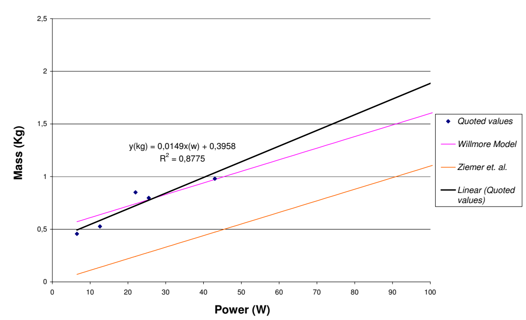

Figure 18. PPU specific mass including Wilmore's and Ziemer's models

IX. Recommendations and Research Voids

Throughout the present study, various proposed improvements were reviewed. It is interesting to summarize these insights for the benefit of future PPT developments. Firstly, electrode geometry and electric circuit optimization techniques[34],[3] successfully realized in various institutes, should be taken into account to ensure state-of-the-art performance and under-performing configurations are not repeated. Refer to Burton[3] for a full account of these.

Further emphasizing the minituarization pattern in chapter 1, PPT work should be oriented towards decreasing both mass and size. The present small power niche in ACS would only be further secured if PPT minituarization goes forward.

Another important gap found is that most PPT developments are quoted at the operation frequency of 1Hz exclusively. Very little data is available at higher frequencies. There are concominant performance decrements when PPT are ran at higuer frequencies involving higuer electrodes operational temperatures and increased erosion, but the ability to throttle using frequency modulation could increase peak thrust and has not been throughly investigated. Peak thrust increase would add I_{bit} flexibility to a given PPT design. The concern is not the operability of PPTs at higuer frequencies, but the lack of published experimentation in such regard. One of the reasons why PPT researchers are not driving their thrusters at higher frequencies is the lack of electrode erosion rate data. Much work has been published in the erosion rates of ion and hall effect surfaces, but[30] argues there remains a need for erosion rates using a variety of materials, temperatures, and current levels.

Moreover, section V revealed there is a lack of consistent single-laboratory geometrical comparisons that would truly establish the strengths and weaknesses of each geometry. It was clearly shown that coaxial PPTs give higuer mass and impulse bits at smaller Isp than rail-type PPTs (details on the theoretical reasons for this are addressed in V). However, within rail-type PPTs there was no data from a single group comparing rectangular to tongue or parallel to flared configurations using the same ignitor, charging PPU circuit, and experimental conditions. Insights gained by such experiments would help the community ensuring the best geometry is used tailored to specific mission requirements.

Furthermore, the physical electrode arrangment, propellant state of matter and feed-mechanism freedom were observed to allow a wide variety of rich combinations. The possible combinations where analysed and checked against the reviewed literature. It turns out, all liquid and gas PPT efforts have only been breech-fed so far[7].[24] It is possible to increase m_{bit} or I_{bit}, by attempting oblique/side feed methods as seen in solid PPTs development. This method could provide another *knob* to and should be investigated in future work.

Another interesting gap revealed by this review was the severe lack of rail-type PPT development at high powers above 700J.[20] Coaxial PPTs have been tested above 80KJ showing efficiencies as high as 44%. While significant improvements have been performed over the years in rail PPTs, no high-energy data is available to systematically argue their ultimate performance limits.

Yet another void in the main body of published experimental work is the lack complete lifetime measurements. Since electrode and propellant erosion is likely to affect performance (due to changes in inductances and resistances), the real operational data of a PPT thruster **must** include lifetime and degradation information. Table 19 shows all experimental thrusters and whether lifetime performance has been published or not.

In Table 19, the field *Experimental lifetime data* implies the thrusters were fired for a limited amout of shots over 10 thousand. That is, tests ran for long but they were stopped before the full thruster capabilities could be revealed through component or ignition-system failure.

No Lifetime data		Experimental Lifetime		Full Lifetime Data	
Thruster	Institution	Thruster	Institution	Thruster	Institution
(ADD)SIMP-LEX	IRS, Stuttgart	Advanced PPT	CUA, UIUC	Millipound	Fairchild
uPPT for Cubesats	Southamton	BreadBoard	Primex	PPT-8	CUA, UICI, AFRL
Benchmark	Arizona State U	PPT-COIII	Tokyo Metro U	Proof-concept	LACP-Brazil
XPPT-48	UCV, AFRL	9-APPT	Kurchatov	APPT 35-150	RIAME
AZPPT 2-4	Princenton, UM			EPPT Coax	Osaka Uni
HEPPT	NASA Glenn, QSS			PPT-B20	Tokyo Metro IT
High Power PPTs	Kurchatov				
Rail-type PPT	Sharif UoT				
TMIT 5 - 6A	Tokyo Metro IT				
Laser Assisted PPT	Tokai, U of Tokyo				
Liquid PPT	Kyushu IT, U of Tokyo				
Nozzled PPT	Shangai JiaoTong U				
40J PPT	GUCAS				
Geom-varying PPT	Academia Sinica				
High Pressure PPT	Indian IT, Singapour				

Figure 19. Full-lenth, experimental, or non-existant lifetime performance data from different laboratories

Lastly, another research gap is the lack of agreeing theoretical expressions for I_{bit}, m_{bit}, or I_{sp} for all combinations of geometrical and component parameters. There are closed-form formulae for rail geometries, but (as shown in section IV in page 5) I_{bit} expressions were found in contradiction. Also, for flared and tongue-shaped electrodes, there has only been published data and no effort to reconcile these improvements analytically. For co-axial geometries; furthermore, there has been no direct derivation of such formulae. Burton[3] showed that the impedance in the EM-force component had an applicable coaxial analog. However, no efforts have been made to find a close-form expression of coaxial electrothermal contributions from first principles. It is highly likely that inspiration towards such expressions could be found in MHD, Arcjet, or Resistojet electrothermal thrusters. Furthermore, the review found many PPT developments attempting to derive their own semi-empirical expressions while there were already a whealth of analytical expressions as shown in section IV[33].[38] The PPT represents a particularly difficult modeling subject given the large number of physical processes involved: Lorentz forces, self-induced $\vec{B}$ fields, Joule heating, ablation, radiation losses, netural and ion collisions. Generating PPT codes is useful to understand the thruster, but without attempting a closed form expression derived from first principles, the coding effort remains much too specific to a certain thruster. The generation of additional codes is useful for educational purposes, but the community already counts with many serious developments.[3] Robust analytical expressions for each geometry have been found to be much more important than generating further computational models.

X. Conclusions

The growing microsatellite community has revived interest in low-power high-performance propulsion systems, dormant since conceptualized in the late 60s. Pulsed Plasma Thrusters are simple, robust, compact EP engines that using off-the-shelf technologies can bring significant mass, size, and cost savings. Renewed interest in this technology calls for a congrous classification scheme. The present work revealed that to fully identify a PPT: electrode geometry, propellant feed method, propellant state of matter, ignition mechanism, and energy class must be defined. Specifically, this work presents an energy classification scheme based in existing microsatellite class definitions. Also, an extensive

PPT database was used to draw the latest development and performance patterns. It was found that PPTs are one of the most highly developed EP technologies in powers under 10W. Even tough PPTs were found to have poor thruster efficiency, and high thrust cost, the precise impulse bit and high I_{sp} per unit power make them an attractive alternative for precision pointing, constellation maintenance applications, interplanetary missions, and even primary propulsion as long as lengthy ΔV manouvers are acceptable. Furthermore, PPT electrode geometries were compared revealing important patterns for mission design with higher efficiency, I_{bit}, and m_{bit} performance for coaxial and higher I_{sp} for rail PPTs. Lastly, recommendations and research voids important to future PPT R& D were addressed.

Appendix

The following tables show all the flight qualified(except from MightySat II which data were not available) and experimental PPT efforts analyzed during this review.

Table 1 below shows all PPT missions so far:

Year	Mission Name	Satellite Mass (kg)	Feed Type	Electrode Geometry	Sponsor/ Builder	Energy Family	Capacitor Energy (J)	Specific Impulse (secs)	Thrust Cost (μN/W)	Total Mass per Thruster (kg)	Thrust Efficiency	Total Impulse (N-sec)	Max ΔV (m/s)	Thruster function / Number of Thrusters	Reference
1964	Zond 2	925	E	C	USSR?	C0	50	410	40	5	8,04%	1608	1,74	Solar Panels Orientation / 4	(Zhurin,76)
1968	LES 6	163	B	RRP	Fairchild MIT Lincoln	C3	1,9	300	17	1,4	2,90%	320	0,82	East-West Station Keeping / 1	(Vondra,71)
1974	SMS	627	B	RRP	Fairchild MIT Lincoln	Nano	8,4	400	15-20	4,1	3-4%	1720	4,7	Spin-Axis Precession Control	(Guman, 73)
1975	LES 8 & 9*	454	B	RRP	MIT Lincoln	Med	20-80	1000-1450	15-19	6,7	7-13%	7300-42700	24	Attitude Control	(Burton, 98)
1975	TIP-II	170	B	RRP	John Hopkins University	C1	20	850	19	7,1	7,80%	4400	26	Drag Compensation / 2	(Burton, 98)
1981	NOVA	170	B	RRP	RCA Astro-Electronics	C1	20	543	20	6,8	5,31%	2450	14,4	Drag Compensation / 3	(McGuire, 96)
1984	ETS-IV	640	B	RRP	NASDA	C3	2,3	300	13	6,6	1,92%	8,83	0,02	Spin Rate Control / 4	(Hirata, 81)
1981	37min Parabolic	N/A	B	RRP	Academia Sinica	C2	4	280	16	2,8	2,30%	803	N/A	Experimental	(An, 81)
2000	EO-1	566	B	RRP	Primex Aerospace	Med	8,5-77,6	650-1400	10,7-11	4,95	3,4-7,6%	1500	2,65	Pitch-axis Attitude Control	(Zakrzwski, 02)
2005	STSAT-2*	100	B	RRP	Satellite Centre KAIST	C3	1,8	800	14	N/S!	1,34%	N/S!	N/S!	Attitude Control	(Shin, 2005)
2007	FalconSat-3	50	B	C	Air Force Research Lab	C3	1,96	827	40,8	1,7	8,40%	29	1,15	Attitude Control	(Busek, 2011)

Table 1. Flight qualified PPT versions

Latest Publication	Laboratory Name / Country	Name	Electrode Geom	Feed	Cap Energy (J) / Family	Energy Density (J/cm²)	Impulse bit (μNsec)	Specific Impulse (secs)	Specific Thrust (μN/W)	Thrust Efficiency	Max Number of Firings (shots)	TRL	Ref
2007	Raumtransport technologie IRS / Germany	SIMP-LEX	RTF	S-V	45-80 / Med	2,8 – 5	1200-2200	816-1043	27	10-14%	N/S	4-5	(Nawaz, 07)
2011	Mars Space Ltd U of Southampton / UK	CubeSat μPPT	RRP	B	1,71 / C3	2	29	585	16,8	4,48%	3000	4	(Gabriel,10)
1979	Fairchild / US	Millipound PPT	RRF	B	750 / HE	N/S	22300	1210	30	18,00%	100000	3-4	(Vondra, 82)
1998	U of Illinois Urbana Champaign / US	PPT 3,4,5	C	B	5-50 / C0	N/S	150-750	600-5000	30-15	5-36%	N/S	4	(Burton, 98)
2001	CU Aerospace U of Illinois Unison Industries / US	PPT 8	C	B	28-50 / C0	N/S	533-1208	325-400	19-24	3-5%	180000	4-5	(King,01)
2009	NASA Glenn / US	450J PPT	RRP	B	450 / HE	N/S	8259	3000	18,4	27,00%	1000	3-4	(Kamhawi,09)
1997	Primex Aerospace / US	BreadBoard	RRP	B-S	43-54 / C0	N/S	694-914	1059-1331	16-18	9-11%	10000	4	(Arrington,97)
2009	Arizona State University/ US	Benchmark	RRP	B	40-140 / C0-HE	4.1 – 14.5	490-1940	1211-2021	12-14	7-14%	N/S	3-4	(Henrikson,09)
1972	Fairchild, NASA Langley/ US	Sidefeed-Short Pulse	RTP	S-V	282-309 / HE	3.5-10.8	6640-9033	620-976	24-27	9-11%	N/S	6	(Palumbo,72)
2007	Uni of California Viterbi, AFRL / US	XPPT-48	C	B	20-80 / Med	N/S	320-1000	980-1440	13-16	7-11%	N/S	4	(Schillin,07)
2000	Primex Aerospace U Of Washington / US	Dawgstar	RRP	B	5.23 / Nano	2,27	56,1	483	11	2,50%	27000	6	(Rayburn,00)
2005	Princenton University U of Michigan / US	AZPPT 2,3,4	Z	E	25-67 / Med	3.5-17	650-3500	280-520	26-46	5-7%	2000	4	(Markusic,05)
2005	NASA Glenn Research Centre / USA	HEPPT (1b, 2)	RRP	B	100-700 / HE	7 - 48	1300-13200	1660-3900	13-19	10-36%	N/S	4	(Kamhawi,02)
2001	RIAME Moscow Aviation Insitute / Russia	MIPD-3	RRP	S-V	100 / Med	N/S	2250	1130	23	13,00%	N/S	4	(Antropov, 97)
2007	RIAME Moscow Aviation Insitute / Russia	New generation APPTs	RTF	S-V	20-150 / C0-Med	N/S	650-4500	950-2200	28-31	15-30%	15000000	5	(Popov, 07)

Table 2. Global PPT experimental efforts

Latest Publication	Laboratory Name / Country	Name	Electrode Geom	Feed	Cap Energy (J) / Family	Energy Density (J/cm²)	Impulse bit (μNsec)	Specific Impulse (secs)	Specific Thrust (μN/W)	Thrust Efficiency	Max Number of Firings (shots)	TRL	Ref
2000	RRC Kurchatov / Russia	High energy	RRP	B	101-911 HE	N/S	1600-18900	1500-4500	13-20	11-33%	N/S	5	(Antropov,00)
2009	RRC Kurchatov / Russia	Very High Energy	C	B	182-82000 / VHE	0.6-272	3883-1,120,000	3100-5300	21-15	29-44%	N/S	4	(Kazeev,09)
1997	RRC Kurchatov / Russia	9-APPT array	C	B	1050 / VHE	4.34	41.211	3000	39	13,00%	50000	4	(Antropvo, 97)
2010	Sharif U of T / Iran	Lab Benchmark	RRP	B	18-54 / C1-C0	1.8-5.6	660-1323	370-1100	38-25	7-13%	N/S	4	(Raeza, 10)
2006	Osaka IT / Japan	Coaxial PPT	C	S-P	5-15 / Nano-C1	3-10	200-1230	470-420	44-84	10-17%	11400	5	(Edamitsu,06)
2007	Tokio Metropolitan Uni	PPT-B20	RRP	B	3.4 / C2	N/S	22	960	6,6	3,10%	1000000	5	(Mukai,07)
2007	Tokio Metropolitan Uni	Co-III 3-12mm	C	E	10 / Nano	1.2-10	49-55	350-450	49-55	8.4-12%	10000	4	(Mukai,07)
2001	Tokio Metropolitan IT NASDA / Japan	TMIT-6A	RRP	B	2-35 / C3-C0	0.7-11.7	35-350	324-1790	6.7-18	2-8%	N/S	4	(Igarashi,01)
2001	Tokio Metropolitan IT NASDA / Japan	TMIT-5	RRP	B	2,37 / C2	4.7	17	945	7	3,30%	500000	5	(Igarashi,01)
1979	University of Tokyo	External B	C	B	30 / C0	N/S	456	423	15	3,00%	N/S	3-4	(Kimurai.79)
2005	Tokai University/ Japan	Laser Assisted	RRP	B	0.2-8.7 / C3-Nano	1.1-58	4-38	250-3800	25-4.4	3-8%	401	4	(Horisawa,05)
2004	Kyushu IT, U of Tokyo	Liquid Propellant	RRP	B	3.4-20 / C2-C1	7-41	25-120	850-4300	7-6	3-13%	N/S	3-4	(Kakami,04)
2007	Shangai JiaoTong U / China	Nozzled PPT	RRP	B	3-20 / C2-C1	0.2-1.6	82-392	280-1250	29-20	4-12%	N/S	3-4	(Hou,08)
2002	CSSAR Chinese Science Academy / China	40J PPT	RRP	B	40 / C0	N/S	605	1188	15,13	9,00%	N/S	3-4	(Hu,02)
1985	Academia Sinica / China	Geom-Varying	RRP	B	7.8-12 / Nano-C1	1.7-3	133-227	370-520	17-19	3-5%	N/S	3-4	(Kuang,85)
2010	India Inst. Of Tech and National U of Singapore	Self-ignited PPT	RRP	B	10-30 / C1-C0	-	30-350	1000-2400	3-11	1-11%	N/S	3-4	Kingsari,09
2003	Laboratorio de Combustao e Propulsao / Brasil	Benchmark	C	B	0,06 / C3	0.009	1,12	68	19,5	38,00%	1616400	3-4	(Init,03)

Table 3. Global PPT experimental efforts, continued

Table 1 shows all PPTs that have participated in missions. The stars next to LES 8-9 and STSAT-2 imply that even tough these 2 PPTs were readied for flight and integrated with their respective satellites, they did not fly on space. The LES 8-9 satellite constellation never flew and the STSAT-2 launch failed .[25] The field Electrode Geometry above classifies rail-type PPTs as in Section 1 in page 3 with shape first and angle later. For example, a rail-type PPT with rectangular and parallel electrodes is named **RRP**. Furthermore, table 1 field energy family shows the proposed PPT family classification of all flight-qualified thrusters.

The large number of laboratory efforts around the globe are shown in tables 2 and 3. These tables show the broad variety of efforts around PPTs, which further encourage interest in the technology through both international collaboration and competition. In tables 2 and 3 N/S refers to 'not specified' since certain publications do not specify all experimental details such as surface area of propellant exposed to discharge. The technology readiness level was derived based in.[35]

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