Research and Development of Electrothermal Pulsed Plasma Thruster Systems onboard Osaka Institute of Technology PROITERES Nano-Satellites

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Abstract: The Project of Osaka Institute of Technology Electric-Rocket-Engine onboard Small Space Ship (PROITERES) was started at Osaka Institute of Technology (OIT) in 2007.In PROITERES, a nano-satellite with electrothermal pulsed plasma thrusters (PPTs) was successfully launched by the Indian PSLV C-21 launcher on September 9th, 2012. The main mission is to achieve powered flight of a nano-satellite by an electric thruster and to observe Kansai district in Japan with a high-resolution camera. Just now, the PROITERES satellite is under operation; that is, the special FM command of PPT firing is transmitted to the satellite from the ground station at OIT. Furthermore, the project of 2nd PROITERES was started in 2010. The 2nd PROITERES satellite aims at powered flight with longer distance, i.e. changing 200-400 km in altitude on near-earth orbits, than that of the 1st PROITERES. We are developing high-power and high-total-impulse PPT systems. In this paper, we introduce the research and development of PPT systems for PROITERES satellite series at OIT.

I. Introduction and 1st PROITERES Overview

THE Project of Osaka Institute of Technology Electric-Rocket-Engine onboard Small Space Ship (PROITERES), as shown in **Fig. 1**, was started at Osaka Institute of Technology (OIT) in 2007[1-7]. In PROITERES, a nano-satellite with electrothermal pulsed plasma thrusters (PPTs) was successfully launched by the Indian PSLV C-21 launcher on September 9th, 2012 as shown in **Fig. 2**. The main mission is to achieve powered flight of a nano-satellite by an electric thruster and to observe Kansai district in Japan with a high-resolution camera. **Figure 3** and

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Table 1 show the specification and photo, respectively, of the flight model (FM) of the PROITERES satellite. Just now, the PROITERES satellite is under operation; that is, the special FM command of PPT firing is transmitted to the satellite from the ground station at OIT.

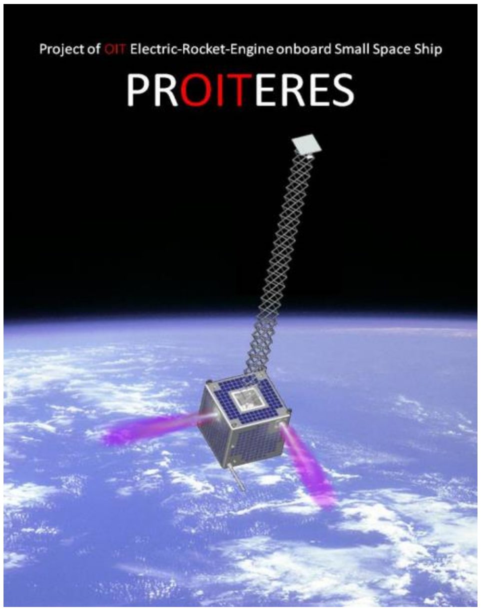


Figure 1. PROITERES satellite on orbit.

Figure 2. Launch of PSLV C-21 rocket.

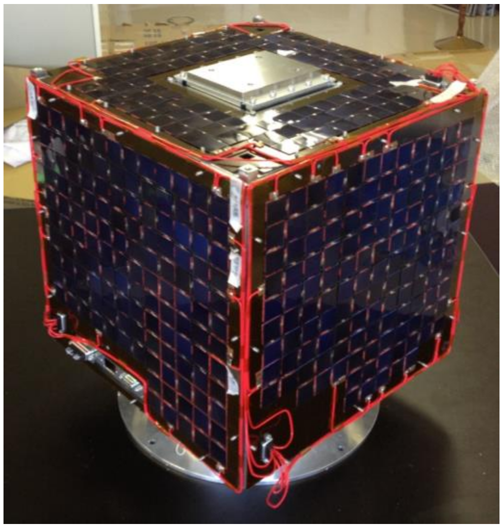


Figure 3. PROITERES satellite flight model.

Table 1. Specification of PROITERES satellite.

Mass	14.5kg
Outside dimension	290mm×290mm×290mm (Without extension boom)
Orbit	Orbital inclination: 99.98[deg], Eccentricity：0
Altitude	670km
Commencing time	April, 2007
Life time	1-2 years
Rocket	PSLV(India)
Launch	9.Sept.2012
Attitude control	Magnetic attitude control Gravity-gradient stabilization

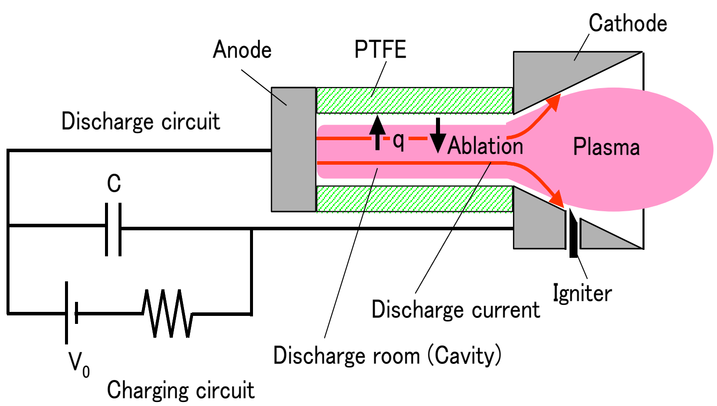


Figure 4. Electrothermal pulsed plasma thrusters.

Pulsed plasma thrusters, as shown in **Fig. 4**, are expected to be used as a thruster for small/nano satellites. The PPT has some features superior to other kinds of electric propulsion. It has no sealing part, simple structure and high reliability, which are benefits of using a solid propellant, mainly Teflon® (poly-tetrafluoroethylene: PTFE). At Osaka Institute of Technology, the PPT has been studied since 2003 in order to understand physical phenomena and improve thrust performances with both experiments and numerical simulations. We mainly studied electrothermal-acceleration-type PPTs, which generally had higher thrust-to-power ratios (impulse bit per unit initial energy stored in capacitors) and higher thrust efficiencies than electromagnetic-acceleration-type PPTs. Although the electrothermal PPT has lower specific impulse than the electromagnetic PPT, the low specific impulse is not a significant problem as long as the PPT uses solid propellant, because there is no tank nor valve for liquid or gas propellant which would be a large weight proportion of a thruster system.

At OIT, the project of 2nd PROITERES was started in 2010. The 2nd PROITERES satellite aims at powered flight with longer distance, i.e. changing 200-400 km in altitude on near-earth orbits, than that of the 1st PROITERES. We are developing high-power and high-total-impulse PPT systems, in which conceptual designs of PPT system and initial performances are investigated for high-power and high-total-impulse operations. In this paper, we introduce the research and development of PPT systems for PROITERES satellite series at OIT.

II. Thrust Measurement System

Figure 5 shows a thrust stand in a vacuum chamber for precise measurement of an impulse bit. The PPT and capacitors are mounted on the pendulum, which rotates around fulcrums of two knife edges without friction. The displacement of the pendulum is detected by an eddy-current-type gap sensor (non-contacting micro-displacement meter) near the PPT, which resolution is about ±0.5 μm. The electromagnetic damper is used to suppress mechanical noises and to decrease quickly the amplitude for the next measurement after firing the PPT. It is useful for a sensitive thrust stand because it is non-contacting. The damper consists of a permanent magnet fixed to the pendulum and two coils fixed to the supporting stand. The control circuit differentiates the output voltage of the displacement sensor and supplies the current proportional to the differentiated voltage to the coil. Accordingly, the damper works as a viscosity resistor. The damper is turned off just before firing the PPT for measurements without damping, and turned on after the measurement to prepare for the next measurement.

Figure 6 shows a typical signal of displacement in measurement of impulse bit. Sensitiveness of the thrust stand is variable by changing the weight mounted on the top of the pendulum as shown in **Fig. 7**. A calibration of the thrust stand is carried out by collisions of balls with various masses to the pendulum from various distances corresponding 15-1400 μNs.

Figure 8 shows a vacuum chamber 1.25 m in length and 0.6 m in inner diameter, which is evacuated using a turbo-molecular pump with a pumping speed of 3,000 l/s. The pressure is kept below 1.0×10^{-2} Pa during PPT operation.

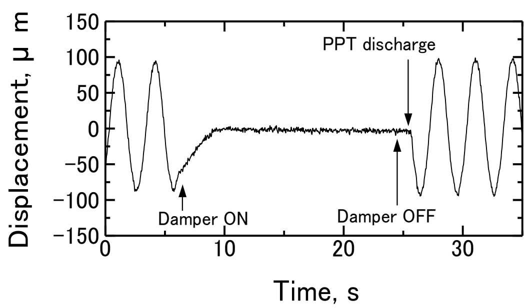


Figure 5. Typical signal of displacement in measurement of impulse bit.

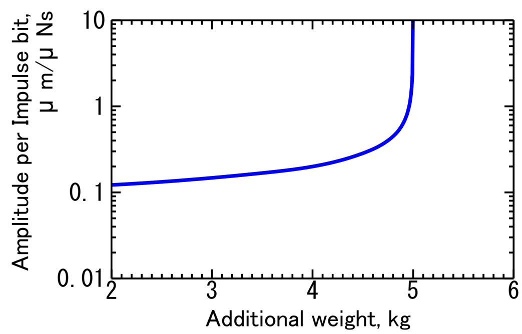


Figure 6. Sensitiveness of thrust stand vs top weight.

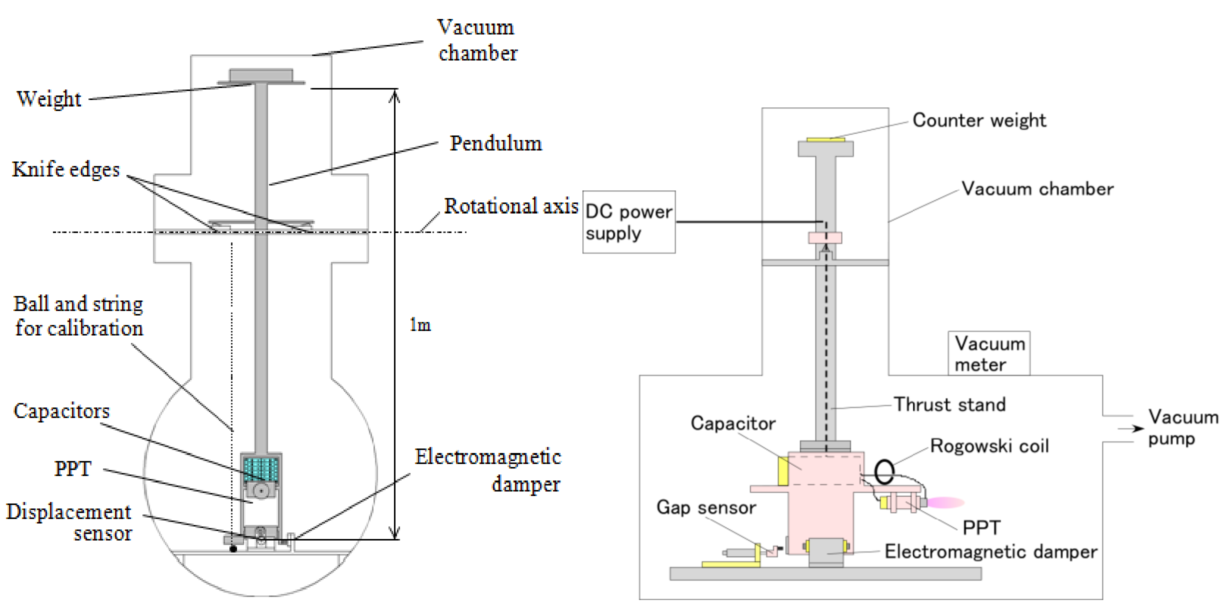


Figure 7. Thrust stand installed in vacuum chamber.

Figure 8. Vacuum chamber.

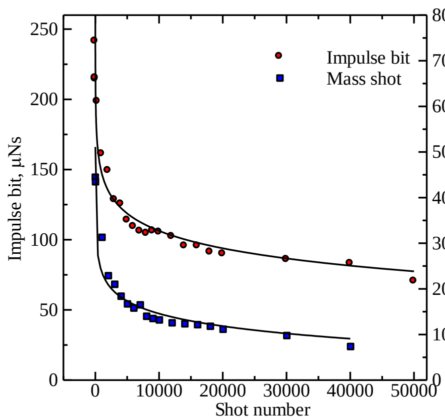
III. PPT of 1st PROITERES

Figure 9 shows the shot-number history of impulse bit, mass loss, specific impulse and thrust efficiency with operational conditions of 2.43 J/shot and 1 Hz. Both the impulse bit and the mass loss, as shown in **Fig. 9(a)**, rapidly decrease with increasing shot number[8-10]. Specially, the impulse bit decreases from 250 μNs at initial condition to 75 μNs after about 50,000 shots. Although a few miss fires occurred around 53,000-shot, a total impulse of about 5 Ns was achieved. As shown in **Fig. 9(b)**, the specific impulse increases with increasing shot number, and the thrust efficiency is around 0.2 during the repetitive operation.

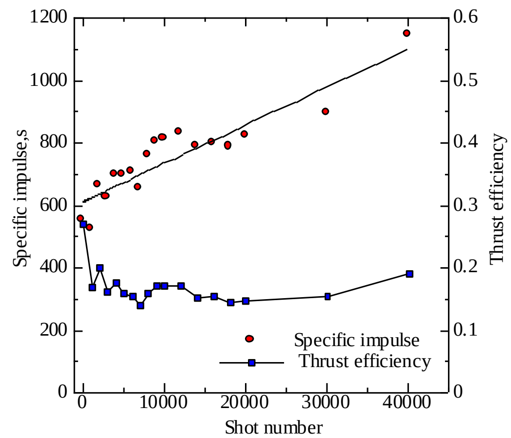
The cavity diameter, as shown in **Fig. 10**, increases from 1.0 mm to about 6.0 mm of the anode diameter after 50,000 shots. The discharge feature, as shown in **Fig. 11**, changes from a long plasma plume with intensive emission light at 1-10,000 shots to a very short plume with weak emission. This is expected because of lowing pressure and ionization degree in the cavity when enlarging cavity diameter.

We designed the flight model of a PPT head and its system[10]. **Figures 12 and 13** show the structure, illustrations, and photos. The PPT head has a simple structure, and two PPT heads are settled on the outer plate of the 1st PROITERES satellite. As shown in **Fig. 13**(b), the power processing unit and the 1.5-μF capacitor are mounted in the satellite. The final endurance test of the PPT system was successfully finished with operational condition shown in **Tables 2-4**.

Accordingly, 2-head PPT system will be operated with a practical scheme shown in **Fig. 14**.



a)



b)

Figure 9. Results of endurance test.
a) Impulse bit and mass shot, b) specific impulse and thrust efficiency.

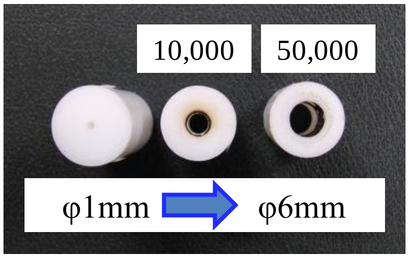
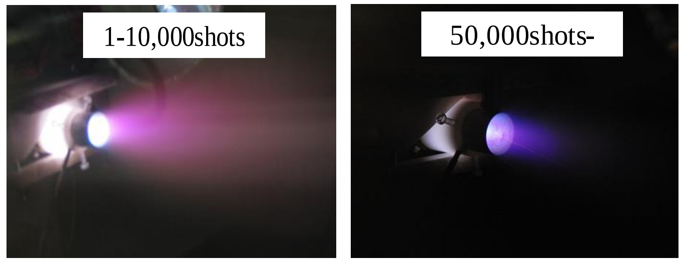


Figure 10. Change of cavity diameter before and after 50,000-shots.



a) b)

Figure 11. Feature of plasma plume. a) 1-10,000 shots, b) 50,000shots.

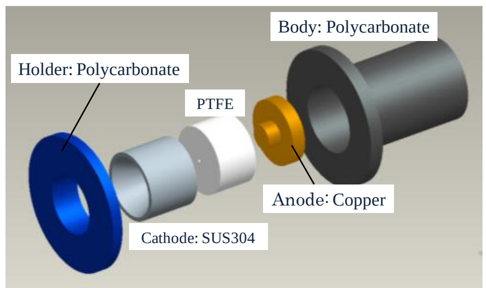
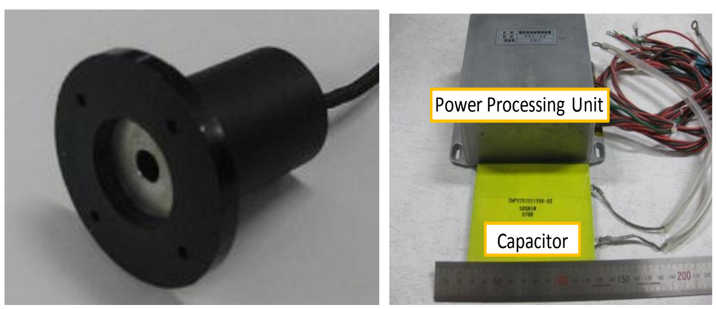


Figure 12. Inner structure of PPT head.



a) b)

Figure 13. PPT flight-model parts.
a) Photos of PPT head, b) power processing unit and 1.5-μF capacitor of flight model of PPT.

Table 2. Specification of PPT head FM.

Items	PPT
Mass	138 g
Size	30(h) x 50(w) x 40(d) mm
Cavity length	10 mm
Cavity diameter	1.0 mm
Ignitor hole diameter	3.0 mm
Ignitor hole position	3.0 mm
Nozzle length	19 mm
Nozzle diameter	5.7 mm
Nozzle half angle	20 deg
Material propellant	PTFE
Material anode	Cu
Material cathode	SUS304
Material body	Polycarbonate

Table 3. Specification of power processing unit FM.

Items		PPU
Mass		710 g
Size		100 x 100 x 50 mm
Power Consumption		5 W
Input Voltage		DC 12 V±10 %
Charge Time		1.0 sec
Output Voltage	to CAP	1.8 kV
	to Ignitor	2.25, 2.7 kV
Operating Frequency		Optional

Table 4. Specification of capacitor for PPT system FM.

Max Voltage	Capacitance	Mass	Inductance
4.0 kV DC	1.5 μF	188 g	44.0 nH

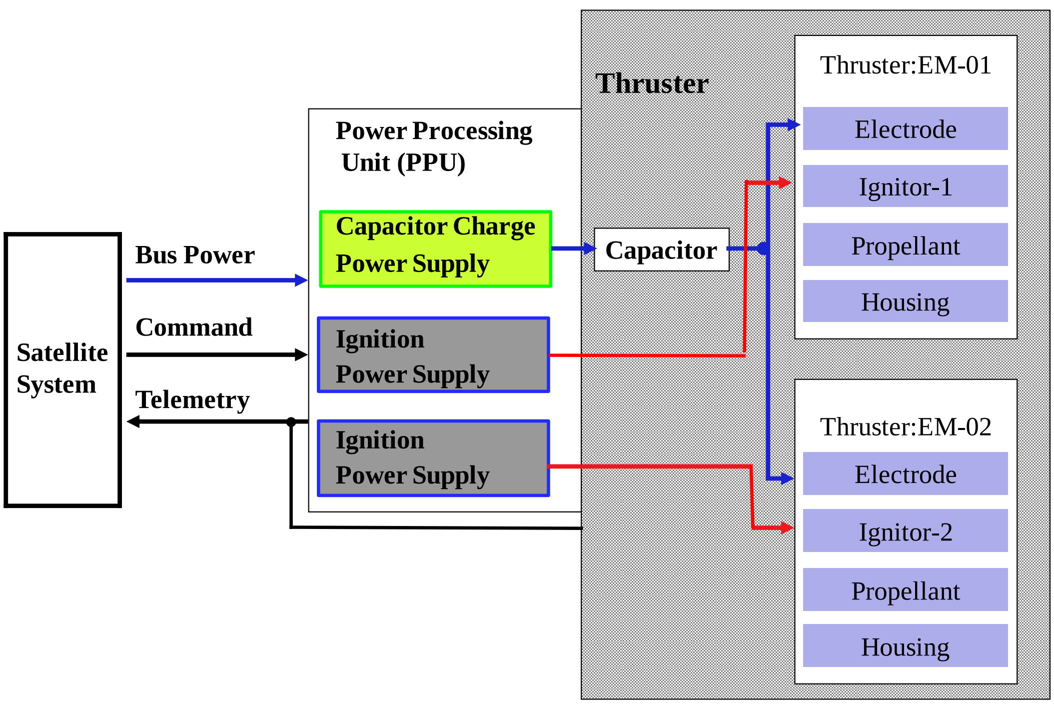


Figure 14. Operational diagram of PPT system FM.

IV. PPT of 2nd PROITERES

The research and development of the 2nd PROITERES[11-13] satellite with high-power and large-total-impulse PPT system are introduced. The image of the satellite is shown in **Fig. 15**, and the specification is shown in **Table 5**. The 2nd PROITERES satellite is a practical satellite for earth observation. The mass of the satellite is 50 kg, and the shape is a 500-mm cube; the electric power is 62 W.

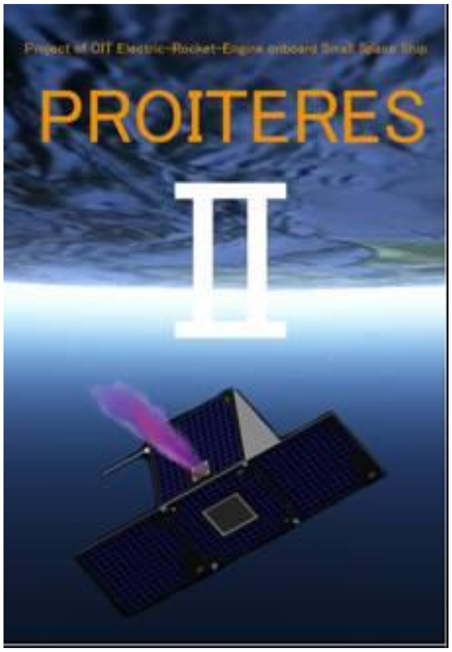


Figure 15.Illustration of 2nd PROITERES.

Table 5. Specification of 2nd PROITERES satellite

Specifications	Value
Mass	50kg
Dimensions	Cube, 500mm on a side
Electrical power	62W
Development period	3year
Life time	More than one year
Launching due date	The second half of 2015-2016

In the 2nd PROITERES satellite, a large orbital change of 400 km in distance or long-time orbital keeping on super low-earth orbits is planned for de-orbit and high-resolution observation. A total impulse of 10000 Ns is required for these missions. Therefore, we cannot use the PPT system onboard the 1st PROITERES satellite; that is, the charging energy must be enlarged to 32.4J from 2.43J. The changes are shown in **Table 6**. Furthermore, because the total impulse obtained from one cavity (one discharge room) is about 120 to 150 Ns, a new PPT system with which a long-term operation is possible is needed for 400 km orbital transfer. In order to establish a long-term operation, a fuel-supplying-type PPT, as shown in **Fig. 16**, was made in this study. When the PPT head has an electric discharge room with two Teflon (PTFE) bars; that is, a propellant of Teflon is supplied from both sides. However, when the inner surface of a discharge room (Teflon tube) was eroded axially-unevenly, the air-tightness of the discharge room collapsed, and an outer-flow of plasma occurred. Therefore, this structure and system of propellant supply is unsuitable for long operation. Accordingly, we designed a new PPT system with multi-electric discharge rooms[14,15]. The schematic view is shown in **Fig. 17**, and the structure is shown in **Figs. 18 and 19**.

Table 6. Changes of PPT system.

	1^{st} PROITERES	2^{nd} PROITERES
Capacitance [μF]	1.5 μF	20.0 μF
Stored energy [J]	2.43 J	32.4 J

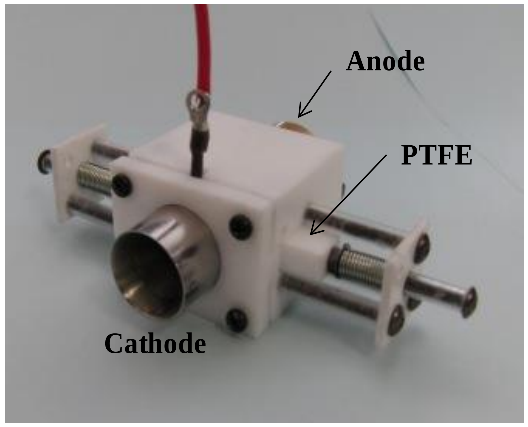


Figure 16. Fuel-supplying- type PPT.

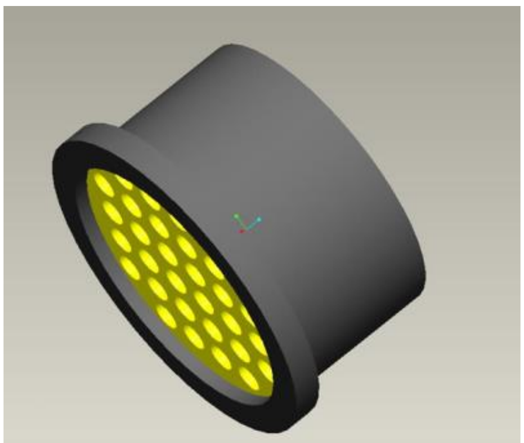


Figure 17. PPT with multi-discharge room.

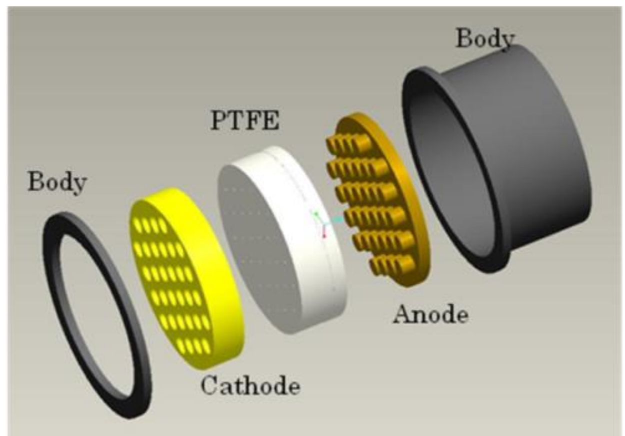


Figure 18. Structure of multi-discharge-room PPT.

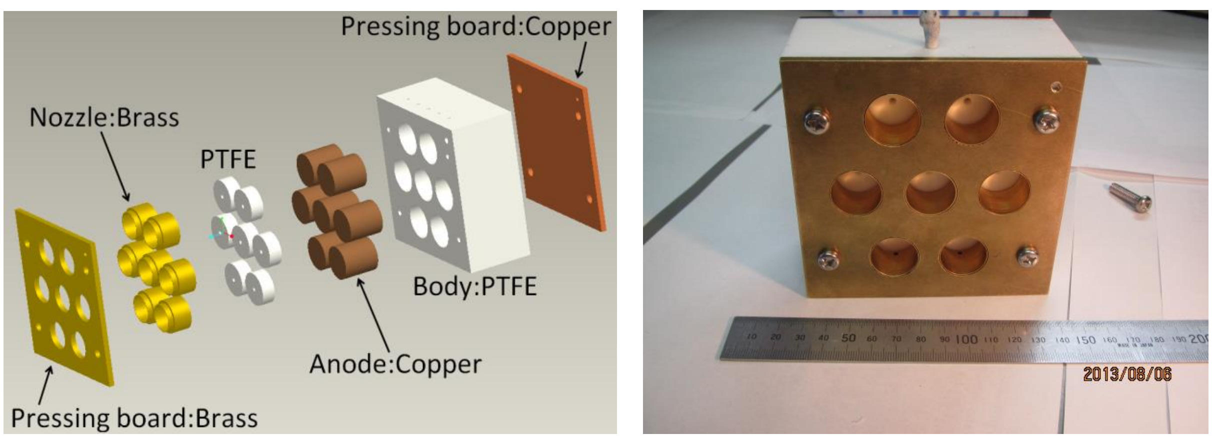


Figure 19. Structure of laboratory-model multi discharge-room PPT.

In order to design multi-discharge-room-type PPTs, it is necessary to optimally design only one electric discharge room. For that reason, discharge-room shape was changed, and initial performance characteristics were investigated. **Figures 20 and 21** show impulse bit and specific impulse, respectively, as a function of cavity length (discharge room length) with cavity diameters of 3, 4 and 5 mm.

We measured the initial performance with 350 shots. When discharge room diameter was 2mm or less, operation of 350 shots did not succeed. This is expected because a tube hole was blocked with eroded Teflon during 350 shots. Finally, we selected 4.0 mm in diameter and 25 mm in length as a preferable structure of discharge room; that is, the highest impulse bit was 1912 μNs, with a specific impulse of 385 sec.

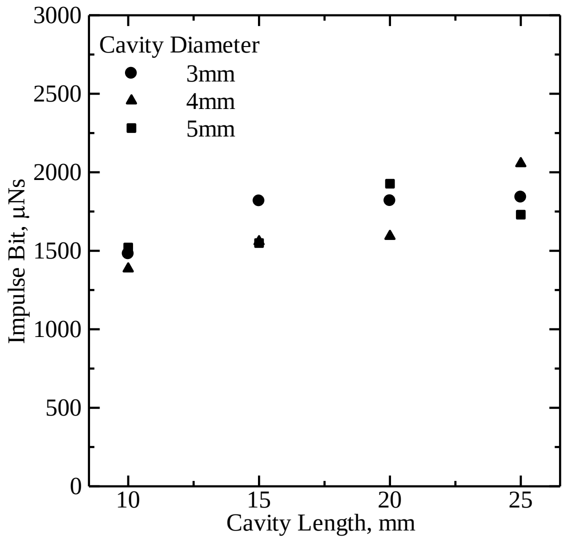


Figure 20. Impulse bit vs cavity length.

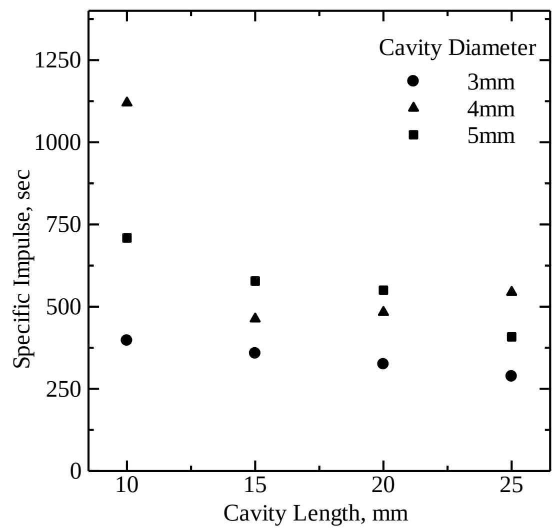


Figure 21. Specific Impulse vs cavity length.

V. Conclusion

The Project of Osaka Institute of Technology Electric-Rocket-Engine onboard Small Space Ship (PROITERES) was started at Osaka Institute of Technology (OIT) in 2007. In PROITERES, a nano-satellite with electrothermal pulsed plasma thrusters (PPTs) was successfully launched on September 9th, 2012 by Indian PSLV C-21 launcher. The main mission is powered flight of nano-satellites by electric thrusters. From endurance tests with the two PPT head FMs connecting the PPU FM, the total impulse of each PPT head reached 5.0 Ns with no miss-firing. Just now, the PROITERES satellite is under operation; that is, the special FM command of PPT firing is transmitted to the satellite from the ground station at OIT.

Furthermore, the development of the 2nd PROITERES satellite with high-power and large-total-impulse PPT system is under way. The 2nd PROITERES satellite is a practical satellite for earth observation. The mass of the satellite is 50 kg, and the shape is a 500-mm cube; the electric power is 62 W. In the 2nd PROITERES satellite, a large orbital change of 400 km in distance or long-time orbital keeping on super low-earth orbits is planned for de-orbit and high-resolution observation. A total impulse of 10000 Ns is required for these missions. A PPT system with multi-discharge-rooms was designed, and the initial performance was measured. According, a preferable structure of the PPT system was determined for the 2nd PROITERES satellite.

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