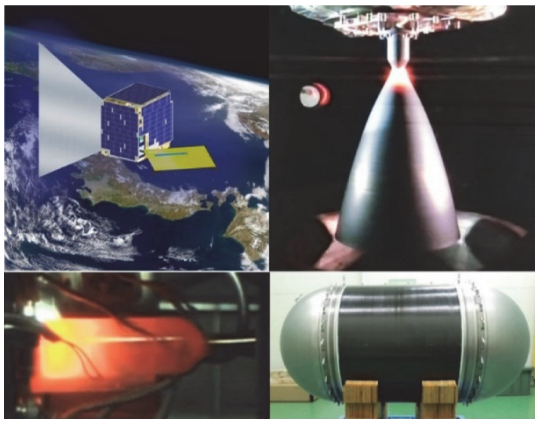
Development of 100 kg Class Small Satellite, Green Propellant Reaction Control System (GPRCS) and Thruster/Tank for Moon Lander (SLIM)



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Mitsubishi Heavy Industries, Ltd. (MHI) is working on the development of small satellites in addition to launch services and efforts related to space stations and international space exploration, which make up our main business. We have recently received an order from the Japan Aerospace Exploration Agency (JAXA) for development and operation of the RAPid Innovative Payload Demonstration Satellite 3 and are proceeding with the development of this satellite to ensure reliability within the constraints of low-cost and short-term development. In addition, for the development of a propulsion system for small satellites, we have completed the development of a green propellant propulsion system and on-orbit demonstration and plan to enter the small satellite market in the future. Furthermore, we have received an order from JAXA for the main thruster and propellant tank for the Smart Lander for Investigating Moon (SLIM) and are currently carrying out development. We also plan to apply them to future space exploration using small satellites or explorers.

1. Introduction

As for artificial satellites, in addition to large and medium-sized satellites that have been developed conventionally, the recent trend of small satellites and small satellite constellation systems is rapidly expanding. Early small satellites were mainly developed by universities, research institutes, etc., but as small and high-performance on-board equipment that can withstand practical missions has become readily available at a low cost and more affordable launch methods have emerged, the small satellite industry is expanding, such as through the entry of private industry. The missions of small satellites are expanding to the fields of space science and exploration, in addition to their use in communications and earth observation. Although the basic functions of small satellites are not significantly difference from those of large and medium-sized satellites, there are major differences in terms of cost and development period, which is one of the development issues.

Most of the early small satellites did not have a propulsion system and only their attitude was controlled using reaction wheels. In recent years, however, there has been increasing need for a propulsion system even for small satellites due to the diversification of missions and to prevent satellites from becoming space debris. For large and medium-sized satellites, propulsion systems using hydrazine-based fuels, which are highly toxic and difficult to handle, were the mainstream due to their high specific impulse and good reactivity. However, for small satellites in particular, a safe propulsion system that can be filled with fuel by a small number of workers and can be handled even at a launch site that is not equipped with facilities for handling poisonous and deleterious substances is desired. We have succeeded in developing a propulsion system that uses a low-toxicity propellant (a so-called Green Propellant). In addition, through the development of the SLIM small moon lander,

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we have acquired technology to compactly mount the propulsion system, such as integrating the fuel and oxidizer tanks and making the main thruster multifunctional (blowdown and pulse operation). We plan to apply these technologies to small satellites to be used for scientific missions such as low orbit missions, geostationary orbit missions and lunar exploration in the future.

2. RAPid Innovative Payload Demonstration Satellite 3

The RAPid Innovative Payload Demonstration Satellite 3 is a 100 kg class small satellite for on-orbit demonstration of parts and components in the JAXA Innovative Satellite Technology Demonstration Program. This program provides private companies and universities with opportunities to utilize small satellites for on-orbit demonstration experiments of key components of space systems and new elemental technologies. Satellite 3 is equipped with seven demonstration theme devices selected through a public call for submissions by JAXA and aims to acquire on-orbit data of each theme device during 13 months of satellite operation. **Table 1** is a list of the demonstration theme devices. Satellite 3 is being developed by MHI, which was selected through a public call for proposals in fiscal 2020, with the aim of launching in 2022. **Figure 1** shows the external view and specifications of Satellite 3 and **Figure 2** depicts its system configuration. The features of this small satellite development are (1) short-term, low-cost development (spring 2021 to summer 2022) and (2) introduction of MBSE (Model Based Systems Engineering).

Table 1 Demonstration theme devices for Rapid Innovative Payload Demonstration Satellite 3

Theme name	Organization
On-orbit demonstration of 920 MHz band satellite IoT platform utilizing satellite MIMO technology	Nippon Telegraph and Telephone Corporation
Software receiver using flexible development method	NEC Space Technologies, Ltd.
On-orbit evaluation and model base development of consumer GPU	Mitsubishi Electric Corporation
On-orbit demonstration of ultra-compact integrated propulsion system using water as propellant	Pale Blue Inc.
On-orbit demonstration and performance evaluation of pulsed plasma thruster (PPT) for small satellites	Advanced Technology Institute, LLC.
On-orbit demonstration of membrane-deployed deorbit mechanism for ultra-small satellites	Axelspace Corporation
Demonstration of lightweight membrane-deployed structure with power generation and antenna functions for Society 5.0	Sakase Adtech Co., Ltd.

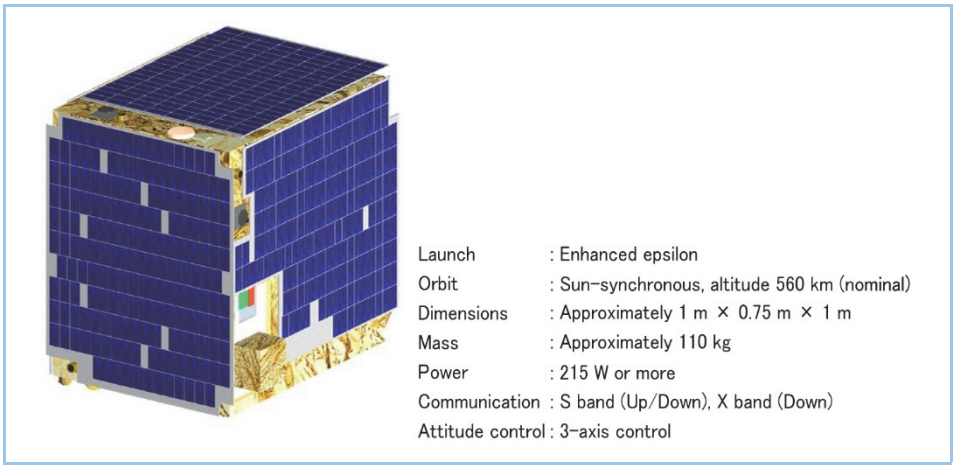

Figure 1 External view and specifications of RAPid Innovative Payload Demonstration Satellite 3

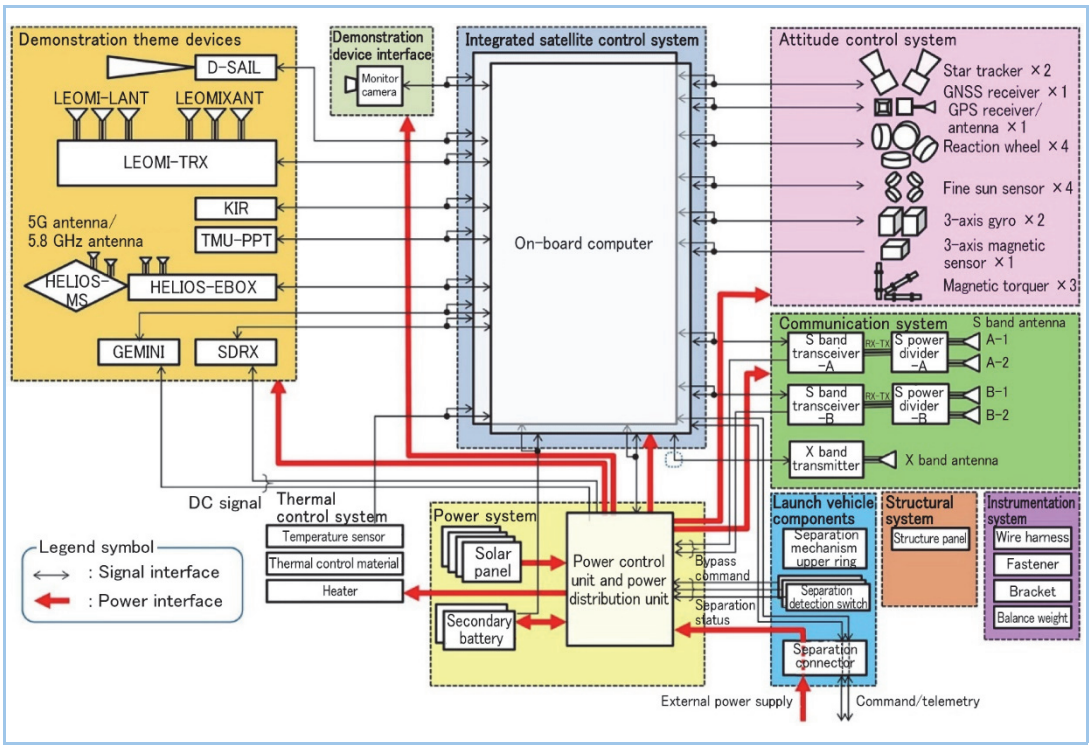

Figure 2 System configuration of Rapid Innovative Payload Demonstration Satellite 3

2.1 Short-term, low-cost development

For the Innovative Satellite Technology Demonstration Program, which is a program that conducts on-orbit demonstrations every two years, the satellite to be used is required to be developed in a short term of less than two years and also at a low cost, unlike general large satellites, which are developed over about 5 to 10 years. On the other hand, the satellite system needs to ensure reliability so that data from each demonstration theme device can be reliably acquired. Therefore, achieving both short-term, low-cost development and ensuring reliability is an important issue.

As an approach for solving this issue, we decided to adopt products that have already been proven in other satellites, or customized products based on those, for most of the satellite system equipment in order to shorten the period of new design and verification tests, suppress development costs and reduce risk. For the onboard computer (OBC), which is the key to satellite control, we adopted the OBC installed in the Hodoyoshi satellite that we developed in the past. This OBC is characterized by being equipped with a highly radiation-resistant space CPU (SOISOC2) developed by MHI and being able to utilize past assets in software development, which can ensure reliability and realize short-term development. For the structural design and thermal design among the development of the satellite system, it was planned to apply design methods proven in the past to reduce development risk and to manufacture test pieces for each design verification of structural design and thermal design and conduct their tests in parallel, in order to realize short-term development.

For low-cost development, we devised various methods in the development system, work assignment and coordination with customers and interfacing counterparts. Regarding the development system and work assignment, key persons for the development were gathered from among management members across the organization to form a small development team to increase the speed of decision-making. In addition, document optimization was examined within the team (design, manufacturing, quality assurance) to minimize work. For communication with the outside, shared folders were set up after ensuring internal security and used for reporting and information sharing.

2.2 Introduction of MBSE

MBSE (Model Based System Engineering) is a design system that applies a model (digital) to a series of processes including the design study, development, system requirements in operation, design, etc., to ensure consistency. MBSE, which has been applied to various fields and industries, was introduced to the development of Satellite 3 and its effectiveness was evaluated, in order to

improve the efficiency of spacecraft development with digital development. First, we are trying to partly apply and utilize MBSE for environment construction, model creation and design/traceability/examination committee for Satellite 3. Following this, it is planned to fully apply MBSE to subsequent satellites. Specifically, as shown in **Figure 3**, we conduct model creation and design for part of the development using the MBSE design tool and thus enhance traceability and the efficiency of review operations using the model sharing tool on the web—including those outside the company. These are realized by building an environment that ensures the security of the in-house network.

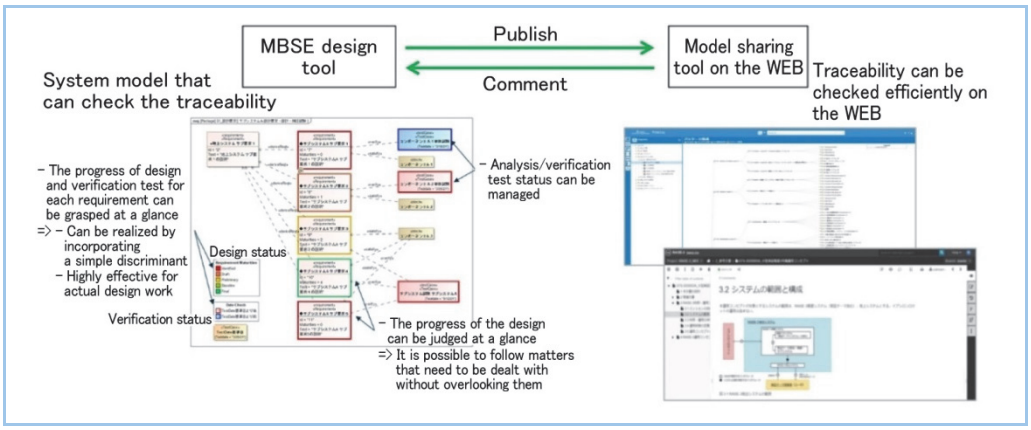

Figure 3 Example of MBSE installation for Rapid Innovative Payload Demonstration Satellite 3

3. On-orbit demonstration results of Green Propellant Reaction Control System (GPRCS)

3.1 Outline specifications

For the propulsion system for controlling the orbit and attitude of spacecraft such as artificial satellites, it is desirable to enhance the performance (reduce the propellant consumption), improve the workability and handleability and reduce the cost. Among these, we focused on improving the workability and handleability and developed the Green Propellant Reaction Control System (GPRCS), a propulsion system that uses Green Propellant which is low toxic propellant, instead of toxic propellants[(1)] and conducted its on-orbit demonstration through joint research with the JAXA Institute of Space and Astronautical Science and JSS (Japan Space Systems), etc., under the jurisdiction of the Ministry of Economy, Trade and Industry of GPRCS had been carried out as one of the mission devices of the RAPid Innovative Payload Demonstration Satellite 1 (RAPIS-1) of the JAXA Innovative Satellite Technology Demonstration Program, which achieved the world's first on-orbit firing of a propulsion system using the propellant SHP163.

Figure 4 shows an external view of the GPRCS demonstrated with RAPIS-1. The Green Propellant used was a propellant (SHP163) containing HAN (Hydroxyl Ammonium Nitrate)[(1)]. The GPRCS mounted on RAPIS-1 had the minimum configuration required for the on-orbit demonstration. The propellant filling work at JAXA Uchinoura Space Center was executed under relaxed safety conditions by workers wearing cleanroom work clothes instead of a scape suit that is essential for handling the current toxic propellant in order to confirm the improvement of the workability and handleability, which are advantages of this propellant as a Green Propellant.

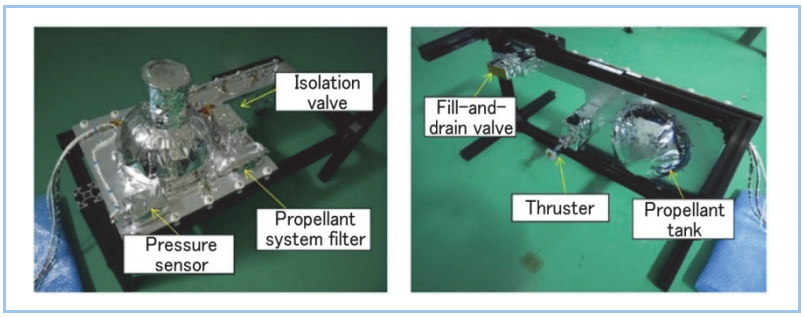

Figure 4 External view of GPRCS

3.2 On-orbit demonstration result

The on-orbit demonstration of the GPRCS mounted on RAPIS-1 was performed for about one year from February 2019 to February 2020 and all the success criteria were achieved as listed in **Table 2**. In orbit, pulse thrust of the thruster for 0.1 to 1 second and continuous thrust for a maximum of 30 seconds were performed. The evaluation was performed by calculating the thrust from the change in the orbit and by calculating the specific impulse from the thrust and the amount of consumed propellant that was calculated based on the decrease in tank pressure. **Figure 5** is a graph comparing the on-orbit thrust and specific impulse with the results of the ground firing test. Considering the estimation accuracy of the thrust and consumed propellant, the evaluation used the average value of continuous thrust performed in orbit. As a result, it was concluded that the same performance as in the ground firing test was attained.

Figure 6 presents the thrust history. A total thrust time of 4 635 seconds and a total thrust count of 13 660 were observed and the full success criteria, which were set as 3 000 seconds or more and 10 000 pulses or more, were achieved. In addition, it was confirmed that the thrust was possible until the 2.85 kg of propellant loaded in the tank was exhausted based on the decrease in tank pressure and the behavior of the pressure and the catalyst layer temperature during thrust.

Table 2 Achievement of success criteria

	Success criteria	Achievement
Minimum success	Confirmation of GPRCS performance	Achieved
Full success	Confirmation of following items - Thrust: 0.8 N or more - Specific impulse: 180 seconds or more - Total thrust time: 3 000 seconds or more - Total thrust count: 10 000 pulses or more	Achieved - 1.1 N - 209 seconds - 4 635 seconds - 13 660 pulses
Extra success	Firing is possible until the propellant is exhausted.	Achieved

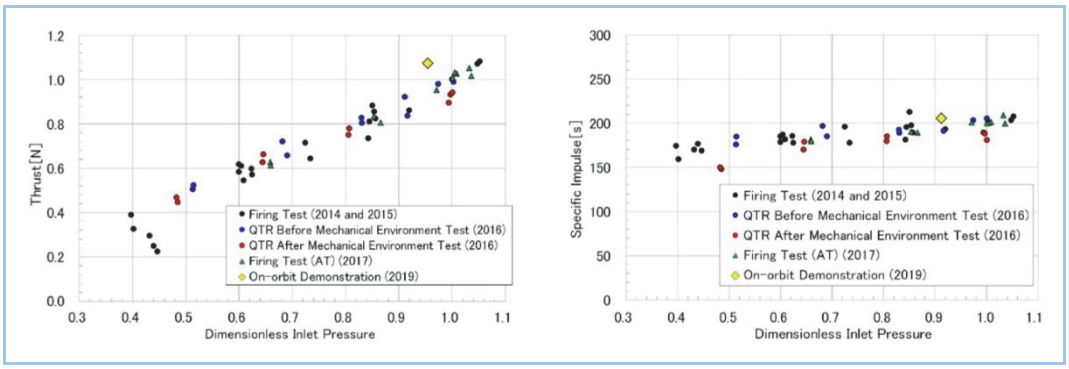

Figure 5 Comparison between on-orbit demonstrated performance and ground firing tested performance (Left: Thrust, Right: Specific impulse)

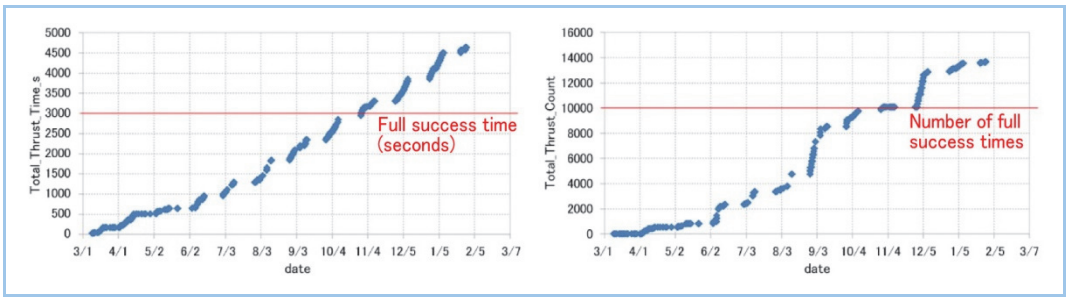

Figure 6 History of total thrust time (left) and total thrust count (right)

3.3 Future development

The GPRCS was demonstrated on-orbit using RAPIS-1. Currently, focusing on the demand for the cost reduction of the propulsion system for satellite systems, we are carrying out examinations so that more satellites can use the GPRCS through the reduction of cost in development tests and development by applying a modular design, as well as the suppression of manufacturing cost by developing AM (additive manufacturing) and low-cost components.

4. Development of main thruster and propellant tank for Smart Lander for Investigating Moon (SLIM)

4.1 Overview of SLIM

SLIM (Smart Lander for Investigating Moon) is a small lunar landing demonstrator being developed by JAXA with the aim of a technological demonstration of a high-precision soft landing on gravitational objects required for future lunar and planetary exploration and developing a lightweight explorer system that enables lunar and planetary exploration. **Figure 7** is an external view of SLIM. We were in charge of developing the main thruster and propellant tank.

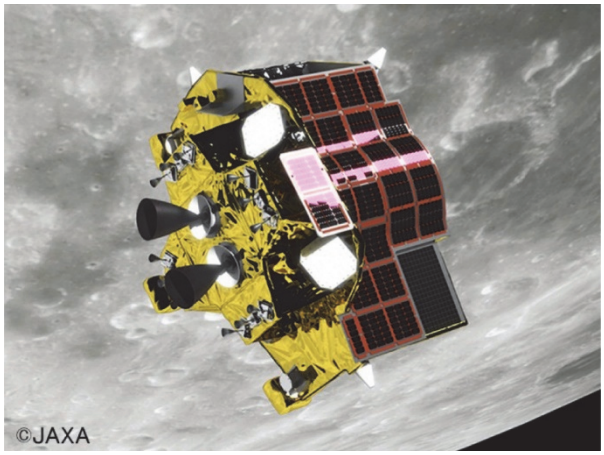

Figure 7 External view of SLIM

4.2 Main thruster

The main thruster (Orbit Maneuvering Engine: OME) used by SLIM is a bi-propellant thruster that uses hydrazine as a fuel and MON-3 as an oxidant. This thruster is the only one in the world that uses silicon nitride (Si_3N_4) ceramics for the combustion chamber[(2)(3)]. Therefore, as its main features, the heat resistance temperature is 1 500°C, which is about 200°C higher than that of commonly used thrusters made of niobium metal, so the firing temperature can be raised to improve the performance. In addition, since no oxidation-resistant coating is required, there are no life restrictions. **Figure 8** is an external view of the OME (during a firing test).

The OME is required to ensure a large ΔV and thrust in the sequence from the separation of the launch vehicle to moon landing and is operated in a wide thrust range from 630 N to 330 N because of the blowdown operation for weight reduction of the explorer. In addition, one of the major features is that the pulse operation required for landing on the moon is possible. **Table 3** lists the main specifications of OME.

In order to satisfy the aforementioned operation requirements, it is necessary to solve various technical problems such as high-frequency/low-frequency firing vibration and ignition impact, so

various types of verification tests have been conducted in the process of development. Among them, in the qualification test (QT), an operation test simulating the actual operation sequence was performed to confirm the feasibility of the operation including the control method and internal environment. As a result, we confirmed the appropriateness of stable firing performance in a wide thrust range and flexible pulse operation that can freely combine ON time and OFF time. **Figure 9** presents the operation results in the sequence simulation test. Currently, all development processes, including the acceptance test (AT), have been completed. In the future, we will proceed with examining the optimization of application suitable for explorers utilizing the flexible operability obtained in the development of SLIM so that adoption for more planetary explorers, etc., can be realized.

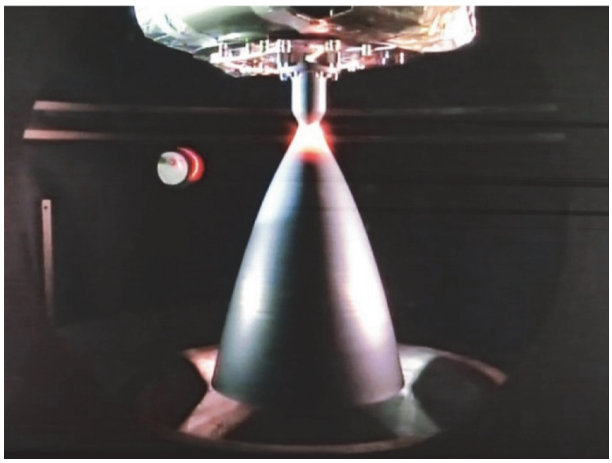

Figure 8 External view of OME (during firing test)

Table 3 Main specifications of OME

No.	Item	Specification
1	Function	Bi-propellant thruster made of ceramic (silicon nitride). Operated with blowdown supplied propellant.
2	Number of units	2
3	Propellant	Fuel: Hydrazine, Oxidizer: MON-3
4	Pressurized gas	Helium gas
5	Pressure upstream of propellant valve	1.723 MPaA to 0.750 MPaA
6	Thrust	630 [N] (Beginning of life)/330 [N] (end of life)
8	Specific impulse	322 seconds or more on average (Average in blowdown operating range (Thrust: 330 N to 630 N, Mixing ratio: 0.725 to 0.875))
9	Mixing ratio	0.8±0.075
10	Overall length of thruster	490 mm (From injector mounting plate to nozzle end face)
11	Mass	Approximately 5 kg
13	Pulsed thrust	330 N or more and 430 N or less

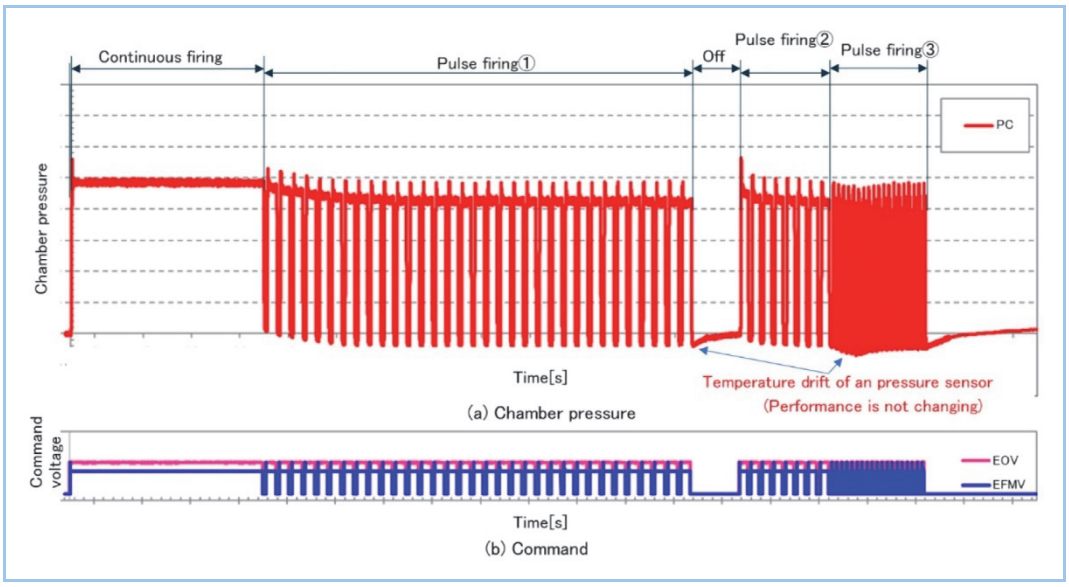

Figure 9 Operation results in sequence simulation test

4.3 Propellant tank

In order to reduce the weight of the explorer, the propellant tank of SLIM is designed to also act as the main structure of the explorer body. **Figure 10** depicts the shape of the fuel/oxidizer integrated tank of SLIM and **Table 4** lists its main specifications. The fuel and oxidizer compartments are separated by a common metal bulkhead and the propellant is pressurized with gas via the diaphragms installed on the fuel side and the oxidizer side and is supplied to each thruster through the propulsion system piping. Titanium alloy is used as the propellant tank material and a hoop-wrapped structure, in which the cylindrical part is wrapped with CFRP, is adopted in order to reduce the wall thickness and weight of the cylindrical part while ensuring the pressure resistance. As a result, the dry mass including the internal device could be reduced to about 40 kg.

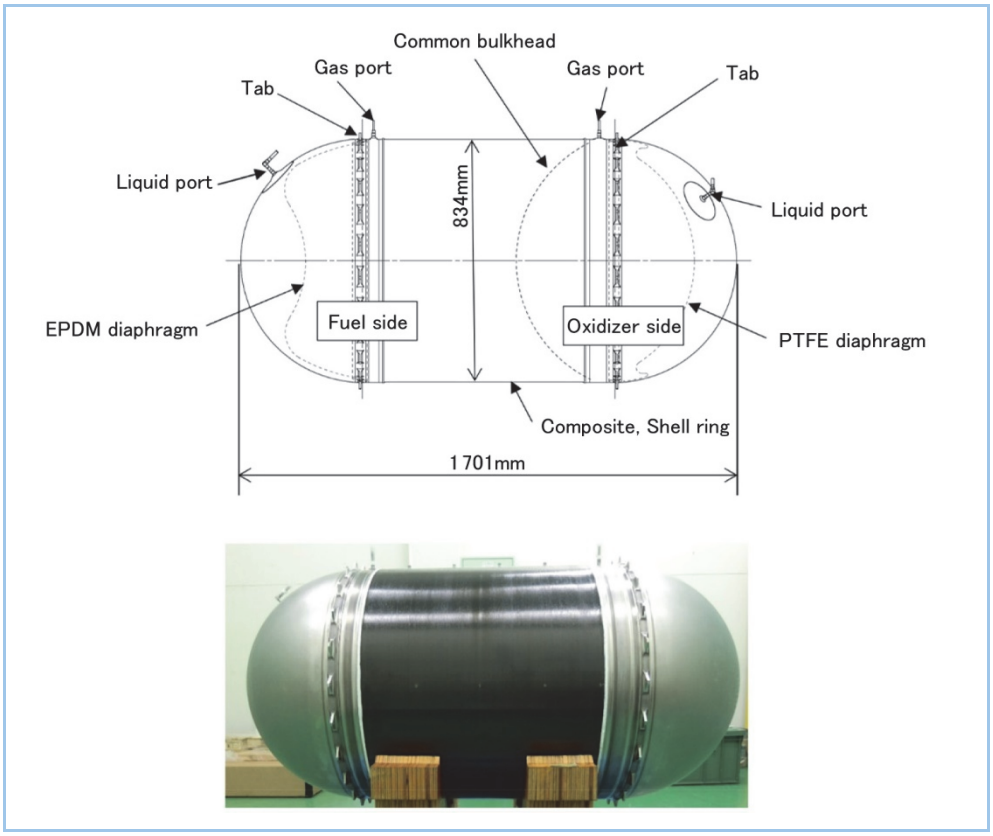

Figure 10 SLIM tank structure

Table 4 Main specifications of SLIM tank

No.	Item	Specification
1	Gas-liquid separation method	Diaphragm method (Hydrazine: EPDM, MON-3: PTFE)
2	Size	φ834 mm × 1 701 mm
3	Volume	769.0 liters (Hydrazine: 493.2 liters, MON-3: 275.8 liters)
4	Propellant mass capacity	534.0 kg (Hydrazine: 296.7 kg, MON-3: 237.3 kg)
5	Maximum operating pressure	2.20 MPa
6	Guaranteed pressure	2.75 MPa
7	Burst pressure	3.30 MPa
8	Material	Ti-6Al-4V/CFRP
9	Mass	42 kg

Table 5 shows the QT items. It was confirmed that there were no problems with the tank design by conducting a sine wave test to check resistance to the environment at launch, a static strength test (**Figure 11**) to check resistance to loads applied to the tank during launch and landing, etc. Currently, the AT has been completed, and explorer assembly work and system tests are underway toward the launch in FY2022.

Table 5 SLIM tank QT items

Test item	Test conditions
Pressure resistance test	Tank body: 2.75 MPa, Common bulkhead: 0.625 MPa
Airtightness test	Tank body: 2.20 MPa, Common bulkhead: 0.50 MPa
Sine wave vibration test	Pressure: Fuel side 0.6 MPa, Oxidizer side 0.7 MPa Sweep rate: 2 oct/min Equipment axial direction / Equipment axially orthogonal direction 5.0-7.0 Hz 12.7 mmDA / 5.0 Hz 4.4 m/s^2 7.0-30 Hz 12.3 m/s^2 / 5.8-6.5 Hz 6.1 m/s^2 30-50 Hz 30.6 m/s^2 / 6.6-18 Hz 8.6 m/s^2 50-100 Hz 9.8 m/s^2 / 19-90 Hz 7.4 m/s^2 91-100 Hz 5.1 m/s^2
Static strength test	Pressurization and load application on tab. Tested for yield and ultimate conditions. [Yield conditions] (1) Launch Pressure: 2.20 MPa Load: Compression side: Equipment axial direction 49 200 N, Circumferential direction 24 336 N Tension side: Equipment axial direction -7 608 N, Circumferential direction 6 480 N (2) Main landing gear, At landing Pressure: 1.10 MPa Load: Equipment axial direction -17 755 N, Circumferential direction 2 919 N (3) Front auxiliary landing gear, At landing Pressure: 1.10 MPa Load: Compression side: Equipment axial direction 7 440 N, Circumferential direction 48 000 N Tension side: Equipment axial direction 13 472 N, Circumferential direction 48 000 N [Ultimate conditions] (1) Launch Pressure: 2.75 MPa, Load: 1.2 × yield load (2)(3) Landing: 1.375 MPa, Load: 1.14 × yield load
Pressurized cycle test	Tank body: 4 MDC (1 MDC = Withstanding pressure 5 times (2.75 MPa) + Airtight pressure 10 times (2.2 MPa)) Common bulkhead: 4 MDC (1 MDC = Withstanding pressure 5 times (0.625 MPa) + Airtight pressure 10 times (0.50 MPa))
Burst pressure test	(1) Tank body: 3.30 MPaG (= 1.5 × airtight pressure) (2) Common bulkhead (differential pressure): 0.75 MPaD (= 1.5 × airtight pressure) Common bulkhead (back pressure): -0.02 MPaD (3) Fuel side (EPDM) diaphragm: 1.65 MPaG (gas side pressurization) Oxidizer side (PTFE) diaphragm: 1.65 MPaG (gas side pressurization)

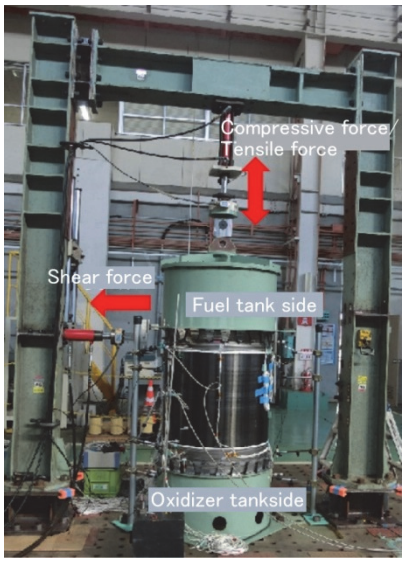

Figure 11 Static strength test of SLIM tank

5. Conclusion

This report described the development status and approach to issues of the Development and Operation of RAPid Innovative Payload Demonstration Satellite 3 ordered by JAXA, which is one of our efforts for the development of small satellites. We are focusing on the development of the satellite body toward the launch in fiscal 2022. In addition, the development status of the Green Propellant propulsion system—a propulsion system applicable to small satellites—and the main thruster and propellant tank for the JAXA lunar landing demonstrator were also presented. We will continue to contribute to space development and the space industry by acquiring and refining these technologies.

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