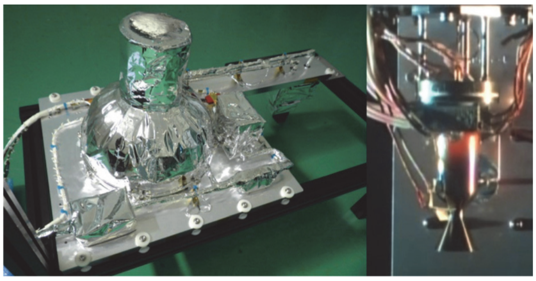
Green Propulsion Systems for Satellites - Development of Thrusters and Propulsion Systems using Low-toxicity Propellants -



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With satellite applications becoming increasingly common in recent years, the propulsion systems that control the orbit or attitude of spacecraft are expected to offer "better performance," "easier handling" and "lower cost." To replace current propulsion systems using hazardous propellants, Mitsubishi Heavy Industries, Ltd. (MHI) is developing a new system that use low-toxicity propellants ("green propellants") known as the green propellant reaction control system (GPRCS). GPRCS was selected as one of the mission equipment items for the Innovative Satellite Technology Demonstraion-1 of the Innovative Satellite Technology Demonstration Program by the Japan Aerospace Exploration Agency (JAXA) and the GPRCS we have developed will be used for the on-orbit demonstration in the program. The satellite is to be launched by the end of fiscal 2018. The on-orbit demonstration period of the GPRCS is about one year.

1. Introduction

As satellite applications have become increasingly common in recent years, commercial competition in this regard has intensified across the globe. To take the lead in such a competitive environment, it is essential to achieve low cost, higher performance and shorter lead times. For the propulsion systems that control the orbit or attitude of spacecraft such as rockets, satellites and space probes, the realization of "better performance (i.e., less consumption of propellants)," "improved workability or easier handling" and "lower cost" is hoped for. Of these factors, in this report we focus on the "improvement of workability/ease of handling." Low-toxicity propellants known as "green propellants" instead of the hazardous ones are expected to adopt the next-generation prolusion system.[(1)]

Under the Japanese Ministry of Economy, Trade and Industry, our joint research project with JAXA and Japan Space Systems (JSS) is under way to develop thrusters using propellants including hydroxylammonium nitrate (HAN) as fuel, which is also used in the reprocessing of spent nuclear fuel.[(2)] GPRCS was selected as one of the mission equipment items in the Innovative Satellite Technology Demonstration Program for the RAPid Innovative payload demonstration Satellite 1 (RAPIS-1) with a planned launch in fiscal 2018, and we have since developed a GPRCS by incorporating our 1N class HAN-based thruster.

This report describes the characteristics of green propellants, the development of HAN-based thrusters and the design/production results of the GPRCS for the RAPIS-1.

2. Green propellant comparison

The green propellants that have been developed so far are mainly divided into four types: HAN-based, ammonium dinitramide (ADN)-based, hydrazinium nitroformate (HNF)-based, and hydrogen peroxide. HAN-based propellants can be classified into four subgroups depending on the included solvent. Our GPRCS adopts a propellant called SHP163, which contains HAN, ammonium nitrate (AN), water and methanol.[(1)] Of the HAN-based propellants, the strong point of SHP163 is a low freezing point, high density, and high specific impulse. When it comes to spacecraft system applications, these properties provide significant advantages, such as the low power consumption for heaters are a result of the low freezing point, space saving due to the high

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density, and the reduction of the propellant mass because of the high specific impulse. **Table 1** compares the performances of these green propellants. **Figure 1** shows the relationship between the density specific impulse and the theoretical specific impulse, as well as the fact that SHP163 has a higher specific impulse than any other green propellant.

Table 1 Green propellant performance comparison

	Propellant currently in use	HAN[1]-based propellant					ADN[2] -based	HNF[3] -based	Hydrogen peroxide
	Hydrazine	LP1846	SHP163	LTHG[4]	HAN/ HN[5] -based	AF-M315E	LMP-103S		
Freezing point [°C]	2	-100	≤-30	-35	-35	-22	-7	n/a	-6
Density [g/cm^3]	1.0	1.4	1.4	1.3	1.4	1.5	1.3	1.4	1.4
Theoretical specific impulse [s]	239	262	276	191	210	266	255	260	182
Density specific impulse [g/cm^{3}s]	241	376	396	254	294	390	332	354	256
Adiabatic flame temperature [K]	1183	2171	2401	1251	1455	2166	2054	2218	1154

[1] NH_3OHNO_3, hydroxyl ammonium nitrate
[2] $NH_4N(NO_2)_2$, ammonium dinitramide
[3] $N_2H_5C(NO_2)_3$, hydrazinium nitroformate
[4] Low temperature HAN/glycine
[5] $N_2H_5NO_3$, hydrazine nitrate

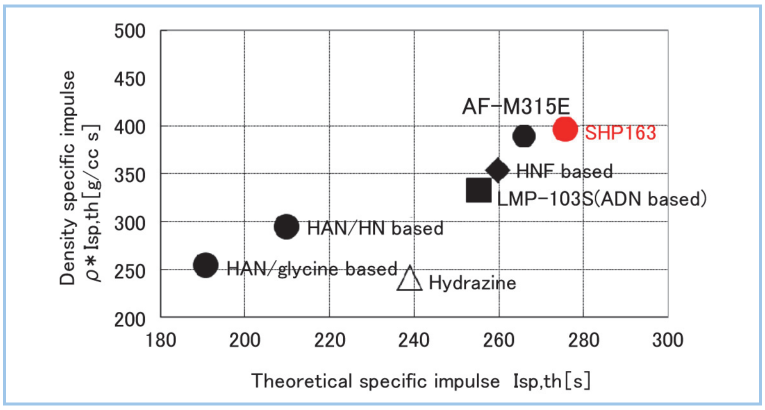

Figure 1 Green propellant performance comparison

Figure 2 shows the toxicity of propellants including hydrazine. The x-axis represents the oral median lethal dose (LD50, the dose of a test substance required to kill half the subjects when administered to animals under specific conditions), and the y-axis represents the probability of cancer development according to the International Agency for Research on Cancer (IARC). Figure 2 shows that SHP163 used in our GPRCS has low carcinogenicity and low acute toxicity and is one of the green propellants with the lowest impact on the human body.

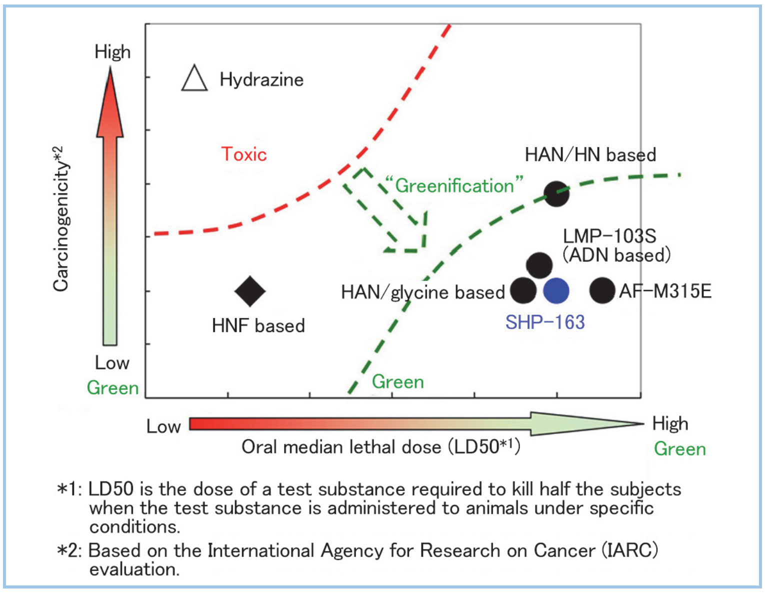

Figure 2 Toxicity assessment of green propellants

3. Development of thrusters

One of the challenges in the GPRCS project is to develop a 1N-class thruster. It is the critical component in the propulsion system.

We have been developing the 1N-class thruster as follows. The thruster for RAPIS-1 has reached STEP 1 status.

STEP 1: Realize low-cost production by keeping the combustion gas temperature low and adopting low cost materials. Maintain a specific impulse of approximately 200 seconds, which is as high as current hydrazine thrusters. Aim at applying to small satellites after on-orbit demonstration. Use S405 used in hydrazine monopropellant thrusters as a catalyst.

STEP 2: Develop new catalysts and apply a heat-resistant design to achieve a specific impulse of 240 seconds. The goal is to apply the technology to medium to large-sized satellites.

From 2014 to 2017, we have developed the 1N-class thruster according to STEP 1. The performance and characteristics of the developed thruster were confirmed through the qualification testing (QT) below.

- Thruster continuous characteristic confirmation test (continuous firing test)
- Mechanical environmental test
- Pulse characteristic confirmation test (pulse firing test)
- Life test (cumulative firing time and the total number of firings)

A thruster for QT is shown in **Figure 3**. **Table 2** lists the specification requirements of the QT (i.e., thruster continuous characteristic confirmation test, mechanical environmental test, and pulse characteristic test). These requirements are based on past spacecraft.

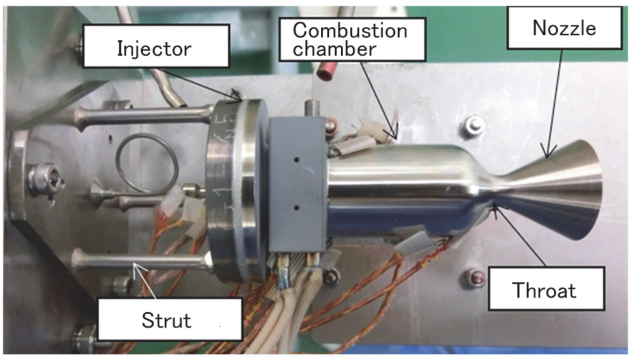

Figure 3 Exterior view of the test thruster for QT

Table 2 Firing tests and mechanical environment test – specification requirements

No.	Test	Requirements	
1	Continuous firing	Specific impulse	Specific impulse of 200 s at 1N
		Test conditions	Firing time: 30 s each Dimensionless pressure: 1.00, 0.80, 0.65, 0.40 Thrust: 1.0 N, 0.8 N, 0.7 N, 0.5 N
2	Mechanical environment	Random vibration	Overall: 17.0 Grms Duration time: 80 s
		Sinusoidal vibration	20 G at 5-100 Hz Sweep rate: 2 oct/min
		High-frequency shock	1000 G at 800-4000 Hz
3	Continuous firing	Performance	Firing time: 30 s Thrust: 1N ± 0.15 N Make sure that there is no significant drop in the specific impulse from the level before mechanical environment testing
4	Pulse firing	Minimum ON time	100 ms or longer
		Test conditions	Dimensionless pressure: 1.00 ON time: 0.1-1.0 s Cycle: 0.12-10.00 s Number of pulses: 38-100

Figure 4 shows the results of the thruster characteristic confirmation test (in terms of thrust and specific impulse), with the x-axis representing the dimensionless inlet pressure (the inlet pressure to the thruster at a thrust of 1N is supposed to be 1) and the y-axis representing the thrust or specific impulse. It has been demonstrated that the specific impulse at a thrust of 1N is approximately 200 seconds.

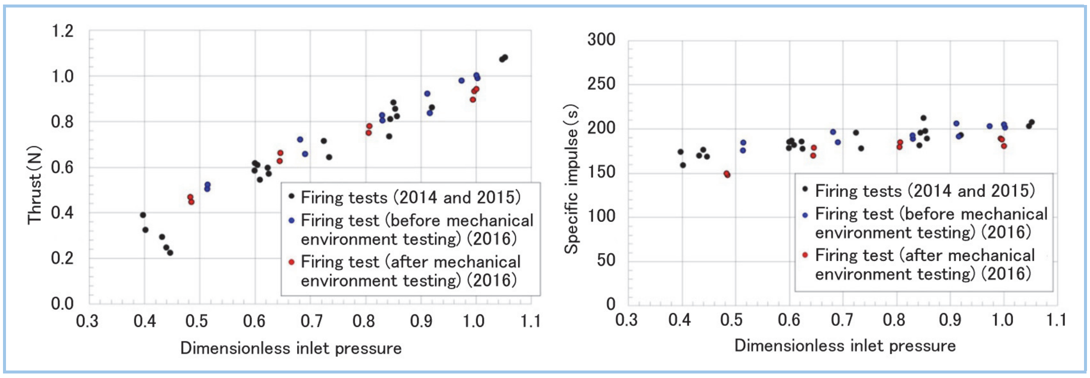

Figure 4 Firing test results (left: thrust, right: specific impulse)

As the results of pulse characteristic confirmation test, **Figure 5** shows the applicable range under pulse-mode, in which the x-axis represents the pulse ON time per shot and the y-axis represents the firing duty (i.e., pulse ON time over 1 firing cycle). The blue-shaded area in Figure 5 indicates the operable range of the pulse-mode. On the other hand, the red-shaded areas correspond to the non-operable ranges for the thruster developed at STEP 1, because the temperatures of the injector and catalysts are elevated beyond the permissible heat-resistance levels of the materials used at STEP 1.

To evaluate the lifetime of the thruster, firing tests on total firing cycle and total firing time were conducted. The total firing time was evaluated using the results of the continuous firing test under both high and low inlet pressure conditions. The total firing cycle was evaluated using the results of the pulse firing test under both high and low inlet pressure conditions. The firing duty was fixed during the pulse firing test. After 5,000 seconds and 10,000 firing cycles, the thruster performed almost as well as under the initial conditions.

Therefore, based on the QT results, we determined that the STEP 1 thruster could be supplied for the on-orbit demonstration and small satellites.

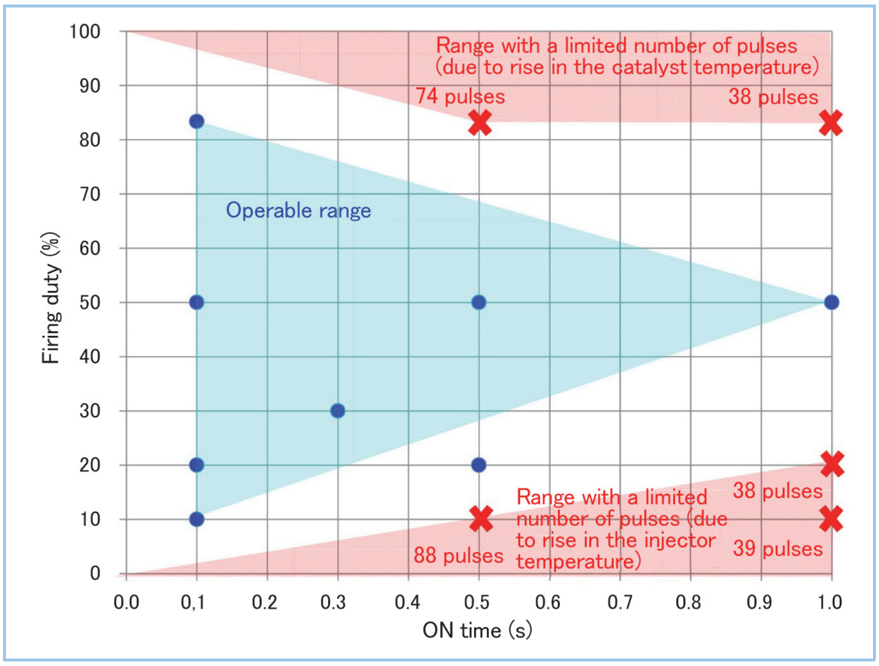

Figure 5 Pulse-mode firing operable conditions

4. Development of GPRCS for on-orbit demonstration

The on-orbit demonstration will be conducted using a GPRCS equipped with the STEP 1 1N-class thruster. **Figure 6** shows a system diagram of the GPRCS for the RAPIS-1 of the Innovative Satellite Technology Demonstration Program. **Table 3** shows a summary of the GPRCS specifications. The GPRCS is composed of the minimally required elements for on-orbit demonstration and has a blowdown propulsion system with a single 1N-class thruster. Although RCS is generally used to control the satellite attitude or orbit, the GPRCS for RAPIS-1 is mission equipment and therefore will not be used for attitude or orbit control. The evaluation of 1N-class thruster performance is the purpose of this GPRCS.

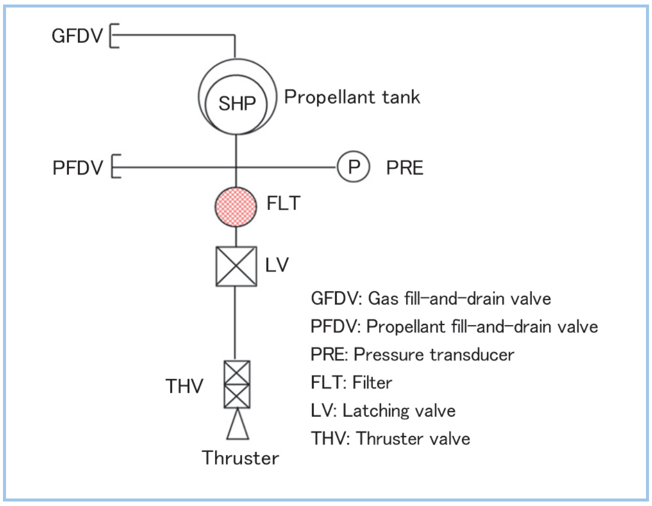

Figure 6 GPRCS piping system

Figure 7 shows the 3D model of the GPRCS. The propellant tank is placed in the center of the panel. The electrical and mechanical instruments, valves and thruster are installed around the tank.

The components, except the thruster, are flight-proven in hydrazine propulsion systems. The materials of the flow path passed the test for the compatibility with SHP163. As the maximum expected operating pressure (MEOP) is 0.95 MPa (which is under 1 MPa), the GPRCS is not subject to the High-Pressure Gas Safety Act of Japan.

All the components of the flight model (FM) passed leak and functional tests, as well as the mechanical environmental test required for RAPIS-1, before being assembled in the GPRCS. The

GPRCS passed the following tests. Therefore, we determined that the GPRCS could be supplied for RAPIS-1.

- Proof pressure test
- Leak test
- Functional test
- Thruster alignment inspection

Table 3 GPRCS specifications outline

Item		Specification
Number of thrusters		1 unit
Pressure system		Blowdown
Thruster specific impulse		≈200 s
On-board propellant amount		≈3 kg
Mass (excl. the panel)	Dry	≈5 kg
	Wet	≈8 kg
Electric power	On standby	≈ 15 W at 20°C constant temp. ≈7 W at 5°C constant temp.
	In operation	Max. 33 W (incl. raised temperature of catalyst layer)
Pressure	MEOP	0.95 MPa

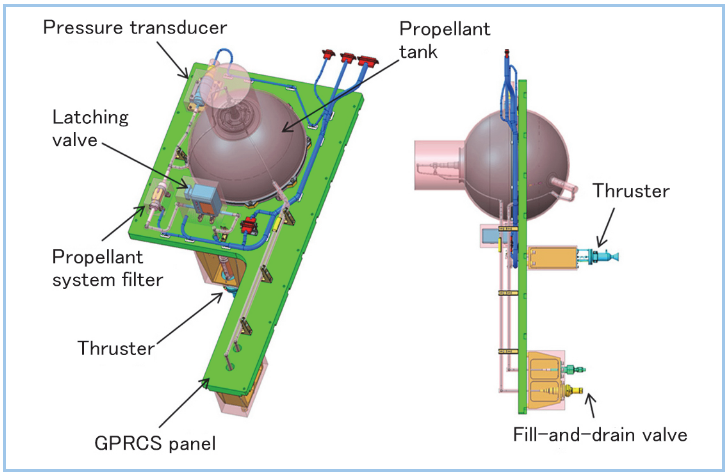

Figure 7 GPRCS outfitted system diagram

Figure 8 shows a photo of the GPRCS. All the components are covered with a multi-layer insulator, and are thermally insulated from the satellite system.

After the GPRCS was installed into the satellite system of RAPIS-1, the interface test and functional test on the RAPIS-1 system were conducted for the GPRCS. After SHP163 is filled at the rocket range, RAPIS-1 will be launched as a payload of the Epsilon-4 rocket. SHP163 is filled through the GPRCS fill-and-drain valve at the rocket range without wearing a SCAPE suit (which is necessary when filling hydrazine) because of its low toxicity. If green propellant (i.e., SHP163) is filled into tank of the satellite, in case of emergency, it is not required to urgently reduce the pressure and discharge the propellant. Such information is shared among the organizations involved.

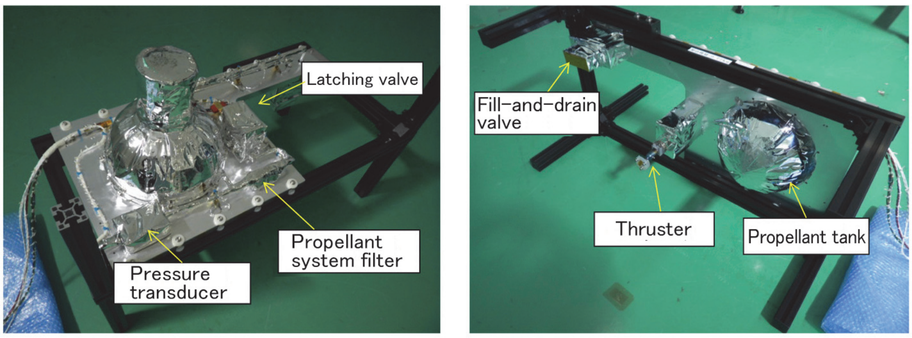

Figure 8 GPRCS exterior view

5. On-orbit demonstration plan

After the Epsilon-4 rocket is launched and the initial operation of the satellite system is checked, the experiments with the mission equipment items will be carried out for about a year, including our GPRCS on-orbit demonstration.

As the GPRCS on-orbit demonstration plan, we will examine how the GPRCS operates by monitoring the telemetry data from the satellite. **Table 4** presents the data lists.

To evaluate the operation of the GPRCS, the data obtained in orbit will be compared with the data obtained on the ground such as the firing test results, in terms of the thrust and specific impulse.

Specifically, the thrust calculated using the velocity increment estimated from the orbit, the satellite mass, and the thruster operation time will be compared with the one that is estimated from the propellant tank pressure based on the thrust-inlet pressure characteristics obtained through the ground-based firing tests.

The specific impulse will be evaluated based on the thrust and the average propellant flow rate. The average propellant flow rate is calculated from the propellant consumption estimated from the propellant tank pressure drop and the thruster operation time. The specific impulse will be compared to the firing test results on the ground.

In this demonstration, in addition to the evaluation of thrust and specific impulse, we will conduct the cumulative firing time of 3,000 seconds and a total of 10,000 pulses. **Table 5** lists the target values.

Table 4 Telemetry data

	Item
GPRCS data	Tank pressure
	Temperatures (tank, valves, pipes)
	Catalyst layer temperature
	Latching valve monitoring
	Cumulative firing time
	Total number of firings
Satellite system data	Orbit data
	Attitude data

Table 5 Demonstration targets

Thrust	1N (nominal value, ≥0.8 N at BOL)
Specific impulse	200 s (nominal value, ≥180 s at BOL)
Cumulative firing time	≥3,000 s
Total number of pulses	≥10,000
Firing pattern	Continuous firing: ≥20 s Pulse firing patterns (examples): 100 ms ON/200 ms cycle 500 ms ON/1 s cycle

6. Conclusion

This report described the development of a HAN-based thruster for GPRCS application and the results of the GPRCS that will be on board RAPIS-1. By conducting an on-orbit demonstration using the GPRCS, we will accelerate its commercial application to small satellites. We will also develop thrusters with further improved performance using SHP163 as a propellant (STEP 2).

References

(1) Matsuo. T., et. al., Development of HAN-based Liquid propellant thruster, 7th ISICP (2007)
(2) Oka N., et. al., Development status of GPRCS (Green Propellant Reaction Control System) for demonstration in Space, 61st Space Sciences and Technology Conference(2017)