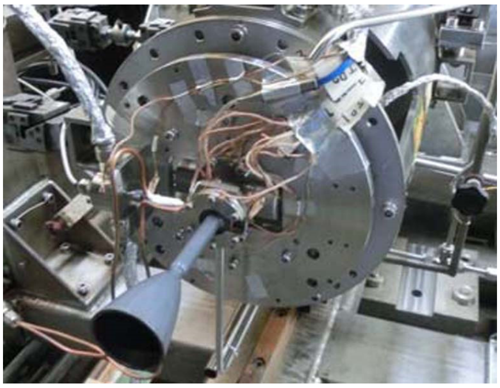
Development of Low-thrust Thruster with World's Highest Performance Contributing to Life Extension of Artificial Satellites



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A low-thrust thruster is a small liquid fuel rocket engine with a thrust of 1 N to 20 N used for attitude control and orbit control of artificial satellites. In recent years, as the life of artificial satellites has been extended, the improvement of their propellant consumption and operability is strongly required. We are developing a 10 N bi-propellant thruster for next-generation commercial satellites while improving thruster performance by applying silicon nitride ceramics with high heat resistance to the combustion chamber, and have obtained the prospect of achieving high performance that exceeds conventional thrusters through firing tests of actual thrusters. This paper reports the summary of the low-thrust thruster that is under development and the test results, and presents the future development plan.

1. Introduction

In recent years, there have been an increasing number of geostationary satellites, such as communication satellites, the operational period of which is 10 years or longer in terms of economic efficiency. The service life of a satellite is determined by that of the power system equipment and the propellant quantity that can be used to maintain the orbit. One approach to the improvement of the latter includes increasing the propellant loading amount by enlarging the satellite and reducing propellant consumption by using high performance thrusters.

In addition, since the required control accuracy of the attitude and position (trajectory) of a satellite has become stricter to increase the number of satellites in geosynchronous orbit, the need for 10 N-class thrusters capable of fine control in comparison to 20 N-class thrusters conventionally used for attitude control is on the rise.

Therefore, we are developing a 10 N bi-propellant thruster that can realize a highly-robust propulsion system due to improved operability in addition to high performance and low cost. A firing test using a ground test model resulted in the achievement of a specific impulse higher than comparable thrusters of our competitors and allowed us to obtain technical prospects for the practical application of 10 N bi-propellant thrusters. This paper reports an overview and the development results of the 10 N bi-propellant thruster that is under development and presents our future development plan.

2. Overview of low-thrust thruster

2.1 Thruster structure

Types of thrusters include a chemical propulsion thruster that generates thrust by generating high-temperature and high-pressure gas by the catalytic decomposition or combustion of propellant and an electric propulsion thruster that generates thrust by ionizing propellant and accelerating it electrostatically or electromagnetically. In many cases, current satellite propulsion systems use chemical propulsion thrusters. Our 10 N bi-propellant thruster under development is a thruster utilizing a combustion reaction, and is called a bi-propellant thruster because it uses two kinds of

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propellants, fuel and an oxidizer.

Figure 1 shows the structure of a bi-propellant thruster. The thruster consists of three components: the propellant valve that controls the supply of propellant, the injector that injects and mixes the propellant, and the combustion chamber that combusts the injected propellant and accelerates the generated gas.

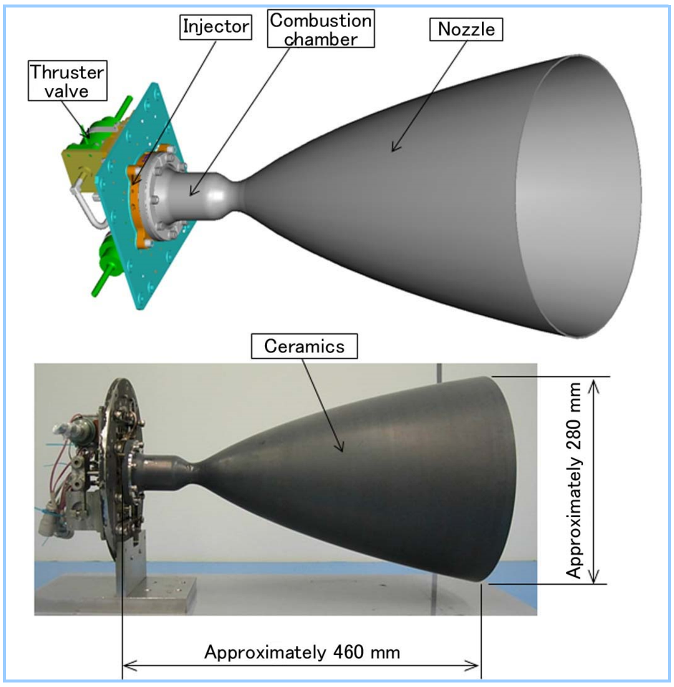


Figure 1 500 N ceramic thruster

Our bi-propellant thruster characteristically uses an integrally-formed part made of silicon nitride monolithic ceramics for the combustion chamber that is subject to high temperature. We have been developing a 500 N bi-propellant thruster for the orbit changing engine of the Akatsuki Venus orbiter[1, 2] since 2001, and succeeded in operating the world's first ceramic thruster in space in June 2010. **Figure 2** is a photograph of the 500 N bi-propellant thruster installed on the Akatsuki Venus orbiter. The ceramic combustion chamber used in this thruster has a length of about 460 mm and an outlet diameter of about 280 mm, the world's largest monolithic ceramic part.

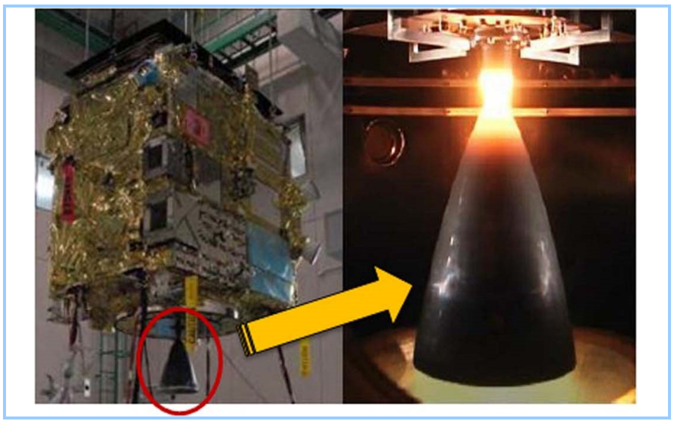


Figure 2 500 N ceramic thruster installed on Akatsuki

2.2 Characteristics of silicon nitride ceramics

Since the combustion gas temperature of the bi-propellant thruster exceeds 2000°C, a niobium heat-resistant alloy was used in the past. A niobium heat-resistant alloy needs oxidation resistant coating because its oxidation resistance is low at high temperature. Even when film cooling is applied by flowing part of the propellant along the wall surface of the combustion chamber to cool the wall surface, the practical heat-resistant temperature is limited to about 1300°C. For this reason, the performance, cost, and reliability are largely restricted, which has been a bottleneck in the improvement of the thruster. Therefore, several kinds of ceramics and precious metals shown in **Table 1** were examined, and as a result, silicon nitride ceramic material, which is a high-strength and high-toughness ceramic structural material and does not require coating, even though the heat-resistant temperature is as low as 1500°C and film cooling is required, was selected as the combustion chamber material.

Table 1 Examination of combustion chamber material

	Niobium ally	**Silicon nitride**	C/C composite	CMC (silicon carbide)	Pt/Rh	Ir/Re
Density $[kg/m^3]$	8870	**3400**	1500	Approximately 3000	19800	Ir:22650 Re:21020
Bending strength @1200°C [MPa]	150	**600**	140	350	120	520
Fluctuation of strength	○	△	△	×	○	○
Thermal conductivity [W/mK]	42	**52**	35	60	Pt:72 Rh:150	Ir:147 Re:48
Oxidation resistance	× (Requires coating)	○ **(Requires no coating)**	× (Requires coating)	× (Requires coating)	○	× (Ir requires coating)
Airtightness	○	○	×	×	○	○
Cost	High	**Low**	High	Low	High	High

Silicon nitride is a kind of non-oxide ceramic, and was developed and used as a gas turbine component or an engine component. When compared to other ceramic materials such as silicon carbide, silicon nitride has a lower heat-resistant temperature, but its oxidation resistance and toughness are higher and the fluctuation of its strength is smaller. Therefore, it can be used for a relatively large structural member. In addition, its high-temperature strength is 468 MPa@1500°C, which is sufficiently high in comparison to the 76 MPa@1370°C of the niobium alloy used in conventional bi-propellant thrusters.

In terms of the cost, noble metals (Iridium, platinum, etc.) with high heat-resistant temperatures are used for the combustion chamber of some thrusters, while silicon nitride ceramics are cheaper. In addition, because silicon nitride ceramic material is made in Japan, the delivery time is shorter than that of niobium alloys that are procured from overseas. In this way, silicon nitride is also superior in terms of stable supply.

2.3 Required performance of 10 N bi-propellant thruster (development target)

Table 2 shows the required performance of the 10 N bi-propellant thruster.[3, 4] The required performance was set based on interviews with satellite system manufacturers and on the benchmark of the existing thruster. While the maximum specific impulse of the products of our competitors on the market is 290 seconds, our 10 N bi-propellant thruster targeted the specific impulse of 300 seconds. This specific impulse enhancement of about 10 seconds corresponds to a propellant amount that can extend the operation of the geostationary satellite by roughly 1 to 2 years, and brings significant benefits to the satellite operator. A continuous firing time of 4 hours is the required performance for firing the 10 N bi-propellant thruster for a long time to prepare a backup of a 500 N bi-propellant thruster used for orbital transformation. The operational range of the supply pressure for continuous firing is set based on the blowdown operation requirement.

Table 2 Required performance

No.	Item	Development target
1	Nominal thrust (N)	10
2	Propellant	MMH/MON-3
3	Mixing ratio O/F	1.0 to 2.1 (nominal: 1.6)
4	Supply pressure Pv (MPa)	0.69 to 2.76 (nominal: 1.52)
5	Continuous specific impulse (s)	295 (target: 300)
6	Pulse specific impulse (s)	250 (duty: 50%) and equal to or higher than the products of our competitors
7	Continuous firing time (h)	4 or more
8	Cumulative firing time (h)	15 or more (target: 30)
9	Total number of pulses	1000000 or greater
10	Firing pattern	Not restricted
11	Re-ignition count	700 or more

3. Development of 10 N bi-propellant thruster

3.1 Thruster for ground testing

Figure 3 shows an external view of the thruster manufactured for ground testing. The combustion chamber of this thruster is made of silicon nitride ceramics. The thruster is flange-joined with the injector, and uses a metal C seal to maintain the airtightness. The injector is installed with a heater and a temperature sensor to prevent the propellant from freezing.

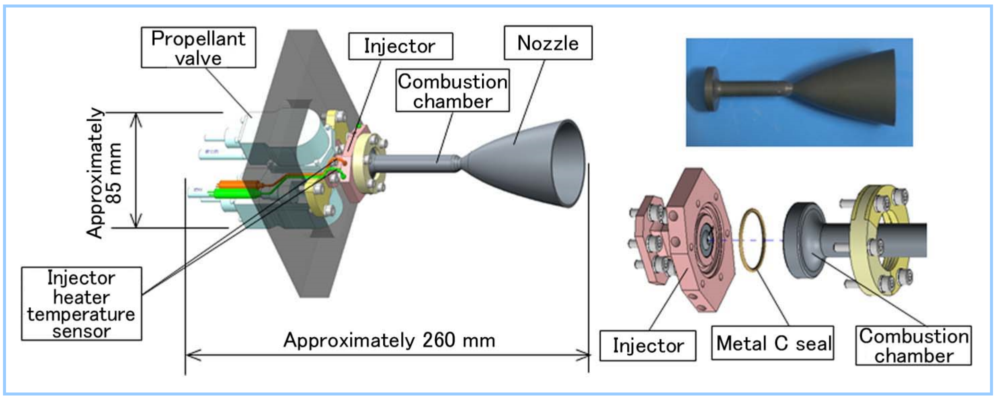


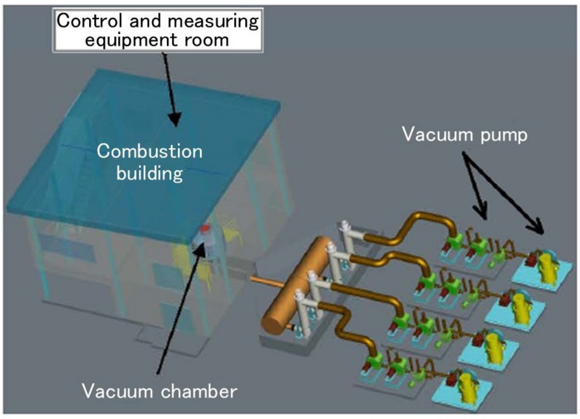
Figure 3 External view of 10 N-class ceramic thruster

To acquire operational characteristics such as pulse firing, the torque motor-type integrated propellant valve that is assumed to be used on the actual thruster is used.

This thruster is a prototype for ground tests, but adopts a satellite joining interface, etc., close to the actual equipment so that the evaluation of its performance and thermal characteristics can be performed in high-altitude firing tests simulating the actual operating conditions.

3.2 High-altitude firing test

As can be seen in **Figure 4**, the high-altitude firing test facility[1] is placed in a vertical position, and uses four units each consisting of a water-sealed vacuum pump and three roots pumps (mechanical boosters). This is a facility that can conduct tests simulating firing in outer space. The exhaust capability allows thrusters of up to 500 N class to fire for a long time with a back pressure of 1 Torr or less. **Figure 5** shows the setup and firing conditions of the 10 N bi-propellant thruster.



(a) Schematic diagram of firing test facility

(b) Vertical vacuum chamber

(c) Vacuum pump

Figure 4 High-altitude firing test facility

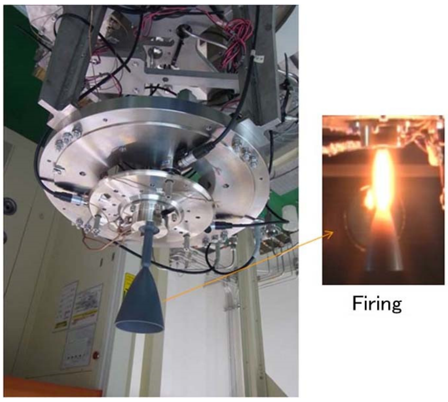


Figure 5 Setup of 10 N thruster

3.3 Firing test results[3, 4]

(1) Continuous firing characteristics

The resulting continuous specific impulse under nominal conditions was as high as about 300 seconds, and the prospect of realizing the world's highest-performance 10 N bi-propellant thruster was obtained. **Figure 6** compares the specific impulse between our 10 N bi-propellant thruster and the thrusters of our competitors. The specific impulse of the thrusters of our competitors with actual flight experience is 290 seconds for 10 N class and 302 seconds for 20 N class. The continuous specific impulse of our 10 N bi-propellant thruster, about 300 seconds, was obtained using a combustion chamber with an expansion ratio of 180. However, the specific impulse is expected to be improved by about 5 seconds by expanding the expansion ratio to 300, which may surpass the 20 N-class thrusters of our competitor’s.

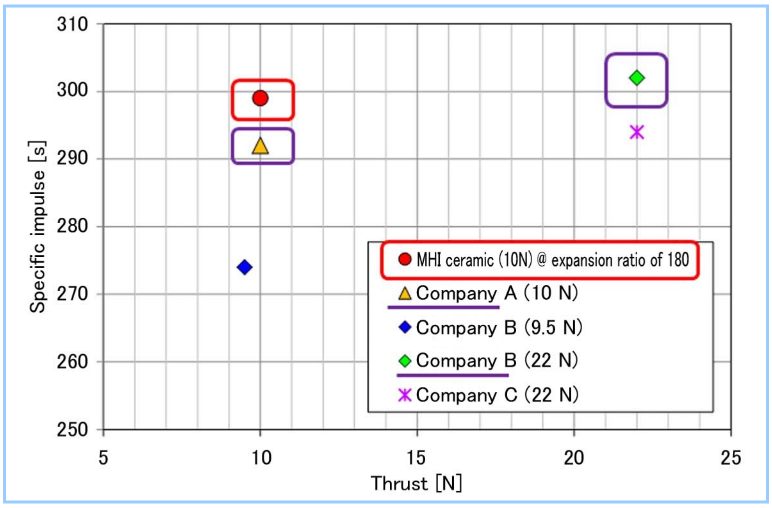


Figure 6 Performance comparison with competitors

Figure 7 shows the operational record of continuous firing. As a result of the test, it was confirmed that continuous firing operates successfully in the operating range required for low-thrust thrusters. The combustion chamber temperature in the operating range is 1200°C or less, which has a sufficient margin against the allowable temperature limit of silicon nitride ceramics of 1500°C. **Figure 8** shows the relationship between the mixing ratio and the specific impulse. A specific impulse of about 300 seconds was achieved under nominal conditions (at a mixing ratio of 1.6).

The resulting continuous combustion was 10800 seconds (3 hours) at the longest. The required continuous combustion is 14400 seconds (4 hours), and this result confirmed that the 10 N bi-propellant thruster has the possibility of backing up a 500 N-class orbital conversion engine by performing continuous firing for several hours.

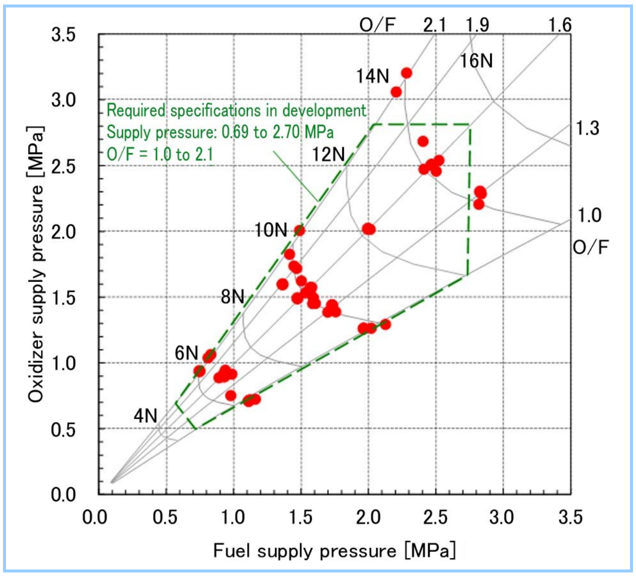


Figure 7 Operational results

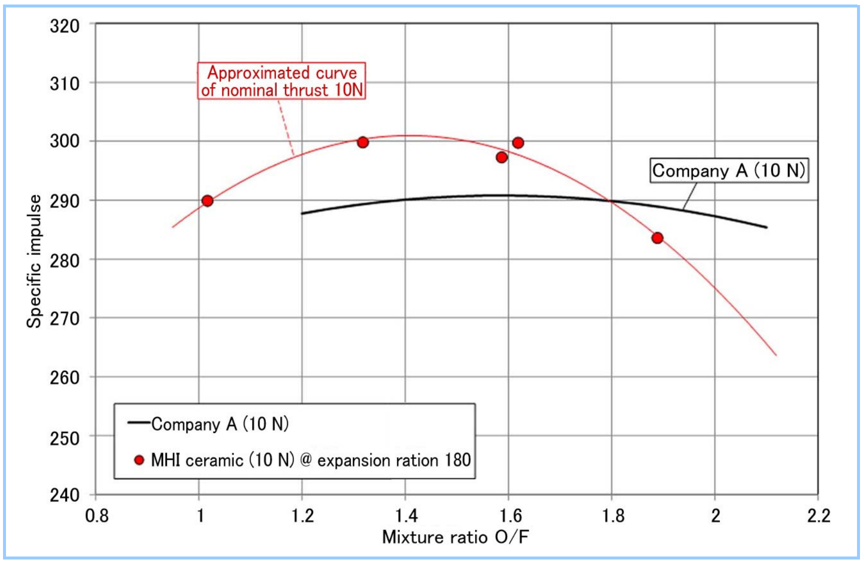


Figure 8 Continuous specific impulse

(2) Pulse firing characteristics

Figure 9 presents the results of the firing pattern of pulse combustion. It was confirmed that the pulse combustion operated without problems in the typical firing pattern expected to be used in actual equipment. **Figure 10** shows the relationship between the specific impulse and the impulse bit. It was verified that the specific impulse was almost equal to that of the thrusters of our competitors (and superior in small impulse bits).

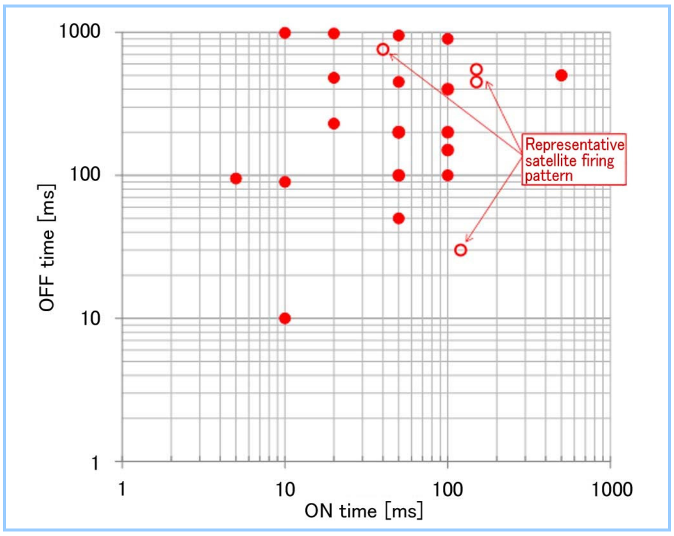


Figure 9 Firing pattern of pulse combustion

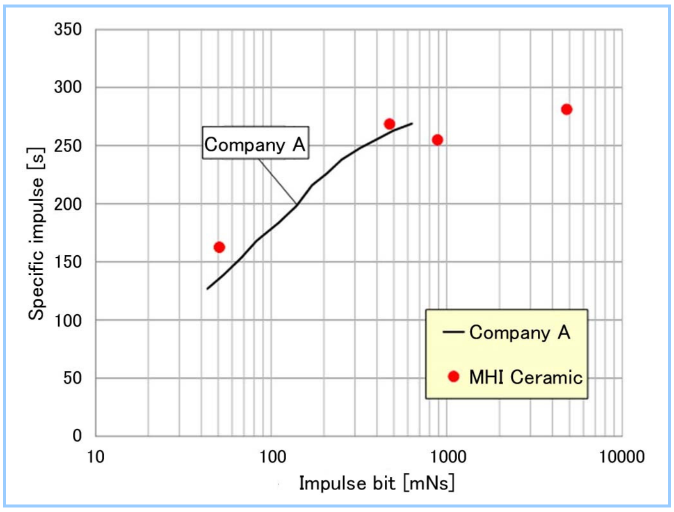


Figure 10 Relationship between specific impulse and impulse bit

Generally, after thruster operation, a heat soak back phenomenon where the heat of the combustion chamber is transmitted to the upstream side causes the injector temperature to rise and the propellant to be gasified, resulting in the impossibility of firing, so a rest for a certain period of time is necessary. On the other hand, for the efficient operation of the satellite, it is favorable that the combination of the thruster firing pattern (continuous operation or pulse operation) is not limited. To confirm the operational restriction range of this thruster, a compound pulse test under the severe temperature conditions shown in **Table 3** was carried out. As a result, it can be confirmed that both the injector temperature and the propellant valve temperature were suppressed to sufficiently low temperatures and the thruster operated normally. This means that this thruster has a wide operational range and there may be no need to impose operational restrictions.

Table 3 Compound pulse pattern

No.	Time	Firing pattern
1	0 to 180 s	Continuous 60 s → Rest 120 s
2	180 to 400 s	500 ms ON per 1 second cycle x 100 pulses → Rest 120s
3	400 to 620 s	100 ms ON per 1 second cycle x 100 pulses → Rest 120s
4	620 to 840 s	50 ms ON per 1 second cycle x 100 pulses → Rest 120s
5	840 to 1060 s	20 ms ON per 1 second cycle x 100 pulses → Rest 120s
6	1060 to 1190 s	10 ms ON per 0.1 seconds cycle x 100 pulses → Rest 120s
7	1190 to 1320 s	5 ms ON per 0.1 seconds cycle x 100 pulses → Rest 120s
8	1320 to 1380 s	Continuous 60 s

(3) Re-ignition test

To evaluate the durability of the metal C seal adopted as the airtight holding structure between the ceramic combustion chamber and the metal injector, a joint durability evaluation test simulating a temperature cycle that applies the maximum load to the C seal was carried out. This test assumed that north-south control is performed once every 1 to 2 weeks during the 15-year operational period of a geostationary satellite and set the number of temperature load cycles applied to the thruster to 700 (700 thruster re-ignitions). Then the load was applied to the joints using actual firing.

Figure 11 shows a typical temperature history of the joint durability evaluation test. **Figure 12** presents the history of the combustion pressure, mixing ratio and combustion chamber temperature. In this test, a total of 704 firing cycles were conducted. The resulting combustion pressure, mixing ratio, and combustion chamber temperature were nearly constant and stable, and there was no performance degradation in the performance confirmation combustion test after the firing test. Accordingly, it was verified that the joint was durable.

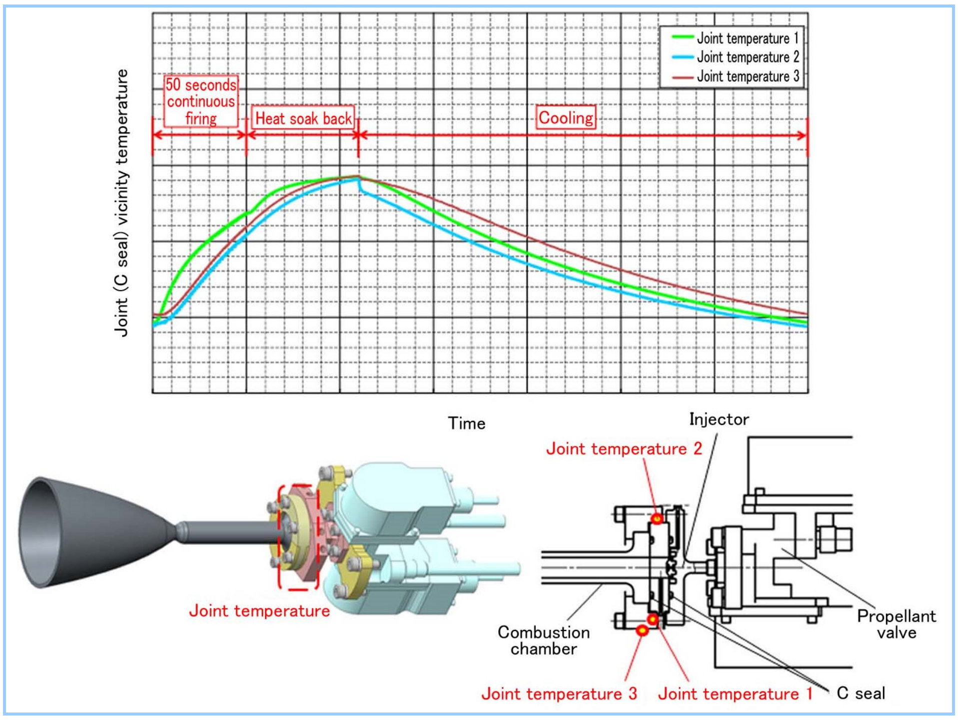
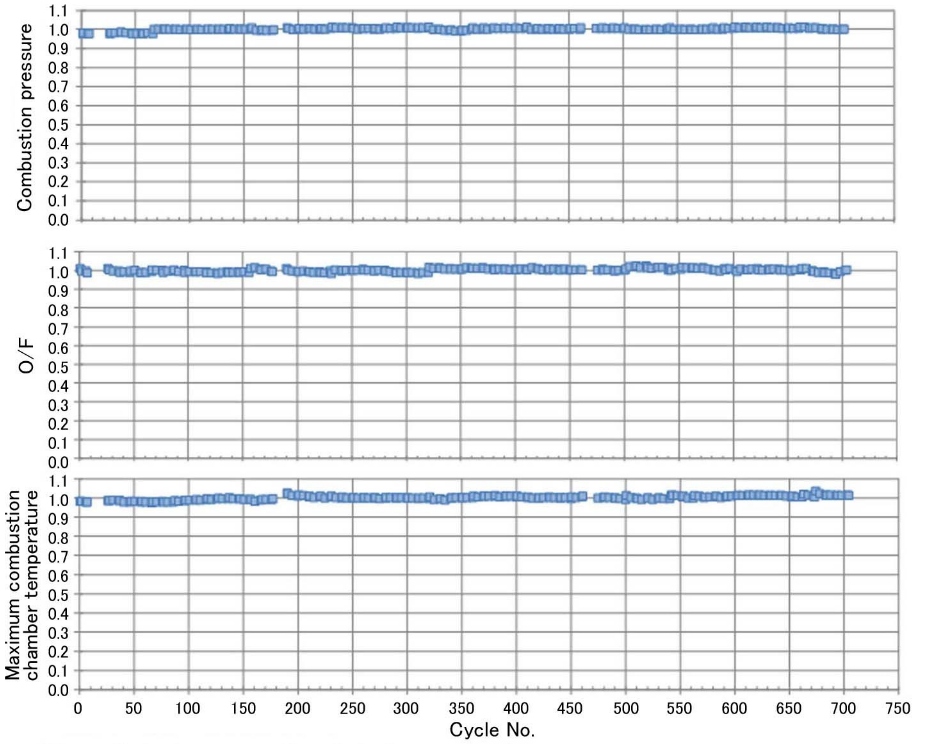


Figure 11 Temperature cycle history in joint evaluation test



*The vertical axis expresses the ratio to the average value.

Figure 12 Joint durability test results

3.4 Future development plan

As a technical prospect for the development of the 10 N bi-propellant thruster was obtained, we plan to confirm the machine environment resistance and the life (the cumulative firing time is 15 hours or more and the total number of pulses is more than 1 million times) as a qualification test, and verify that the required performance listed in Table 2 is satisfied.

To further improve the reliability of the 10 N bi-propellant thruster, we are proceeding with the research of the joining technology of the ceramic combustion chamber and a metal injector that is more reliable than the current mechanical joint (C seal).[5]

4. Conclusion

This document reported an overview and the development results of our 10 N bi-propellant thruster that is under development and presented the future development plan. In a combustion test of a thruster for ground testing, we obtained a technical prospect for realizing the world's-highest-performance 10 N bi-propellant thruster that exceeds competitive products from overseas. In the future, we will carry out qualification tests and accelerate the development of the bi-propellant thruster, targeting installation on commercial satellites.

References

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