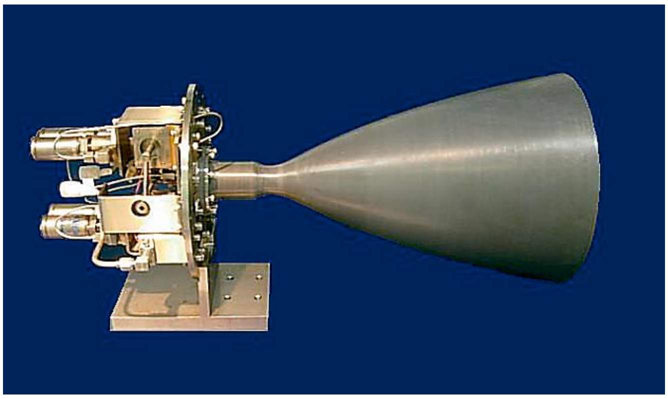


Development of 500N Ceramic Thruster for the PLANET-C Venus Explorer

TETSUYA MATSUO*1 KATSUSHIGE MORISHIMA*1
RYOHEI INOUE*1 YOSHINORI NONAKA*2

A conventional thruster for orbit maneuvers and attitude control of a satellite uses a niobium alloy combustion chamber coated with silicon. However, there are problems with the heat resistance (the allowable temperature limit is approximately 1300°C), lifetime, and handling of this type of thruster. The difficulty in obtaining niobium alloy combustion chambers coated with silicon in Japan is also a problem, because they are imported components. On the other hand, thruster performance improvement, cost reduction, and stable supply can be achieved by employing domestic ceramics for the combustion chamber, which have a 1500°C allowable temperature limit. Based on this background, Mitsubishi Heavy Industries, Ltd. (MHI), is now conducting qualification tests to evaluate the practical use of the world's first ceramic thrusters and we are viewing the prospect of using the ceramic thruster in the PLANET-C Venus explorer. In this paper, we discuss the status of the qualification testing and describe the combustion test facilities used in the firing tests.

1. Introduction

A thruster is a small rocket engine used for orbit maneuvers and attitude control of a satellite. Two types of thruster are currently used for space vehicles such as satellites. One type is the monopropellant thruster, which produces a thrust by generating high-temperature and high-pressure gas through the catalytic decomposition of the propellant. The other type is the bipropellant thruster, which produces a thrust by mixing the fuel and oxidizer and subsequently exhausting the combustion gas at high velocity by use of a nozzle.

However, the components installed in a satellite are required to be lightweight and to demonstrate high performance and reliability. This is especially true for the thrusters used for orbit maneuvers and attitude control of satellites. Improving the thruster performance can contribute to greatly reducing the total weight of the satellite.

A bipropellant thruster provides higher thruster performance than a monopropellant thruster, but it requires a special heat-resistant alloy to withstand combustion gas temperatures higher than 2000°C. Niobium alloy has been used for conventional bipropellant thrusters. However, its allowable temperature limit of approximately 1300°C imposes severe restrictions on performance and reliability, and an oxidation-resistant coating is required. For this reason, MHI has developed silicon nitride ceramics for the combustion chamber material. These ceramics are very strong and tough, and have an allowable temperature limit of 1500°C.[1, 2]

In this report, we discuss the status of the qualification testing currently underway to evaluate using this technology on board the PLANET-C Venus explorer, and describe the combustion test facilities used in the firing tests.

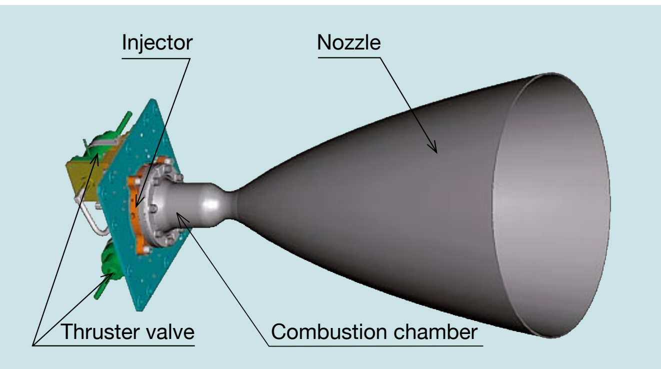


Fig. 1 Thruster configuration
The major components of the thruster are shown.

2. Ceramic characteristics

The configuration of the thruster is shown in **Fig. 1**. The thruster consists of four components: (1) a thruster valve to control the propellant supply, (2) an injector to supply the propellant to the combustion chamber and to mix it, (3) a combustion chamber to combust the propellant, and (4) a nozzle to accelerate the combustion gas. In a ceramic thruster, silicon nitride monolithic ceramics are used for the combustion chamber and the nozzle. Silicon nitride is a kind of non-oxidizing ceramic and it has high toughness and the high heat resistance of approximately 1500°C and it is superior in strength and thermal shock resistance at

*1 Nagasaki Shipyard & Machinery Works
*2 Nagasaki Research & Development Center, Technical Headquarters

Table 1 Characteristics of silicone nitride and niobium alloy (C-103)

		Silicone nitride Si_3N_4 (SN 282)	Niobium alloy (C-103)
Density	(kg/m^3)	3 400	8 870
Bending strength at room temperature	(MPa)	738	640
Bending strength at high temperature	(MPa)	468 (1 500 °C)	76 (1 370 °C)
Heat conductivity	(W/m·K)	64.0	41.9
Heat resistance temperature	(°C)	1 500	1 300
Oxidation resistant coating required?		No	Yes

high temperature. For this reason, it was developed for, and is used in, gas turbines and engine components. The major physical properties of silicon nitride monolithic ceramics are listed in **Table 1**. These ceramics have the equivalent or higher performance compared with the niobium alloy used in conventional bipropellant thrusters.

3. Outline of the combustion test facilities

A 1,000 second duration firing test is one of the qualification tests for the 500N ceramic thruster used in the PLANET-C Venus explorer. However, the firing test time is limited to 10 seconds at conventional combustion test facilities. Therefore, a conventional combustion test facility was renovated, as shown in **Fig. 2**. We are now able to test a 500N-class thruster for a long duration during a firing test at approximately 1 Torr back pressure.

The features of the test facilities are as follows:

- High vacuum (approximately 1 Torr back pressure is possible)
- Vertically-arranged vacuum chamber (combustion in the vertical direction)
- Reduced running costs

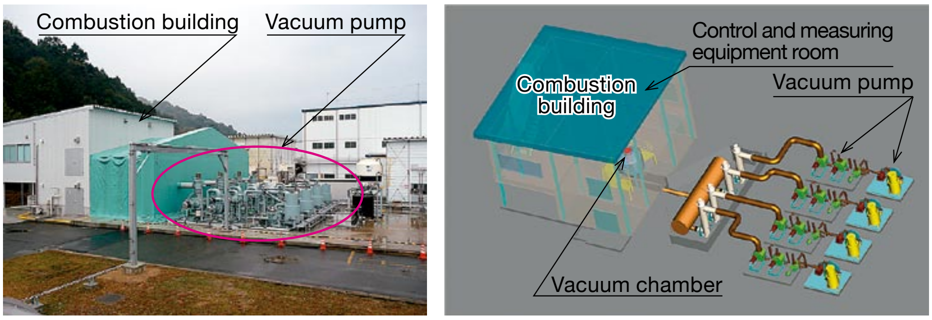
The major facility elements are shown in **Figs. 3** to **6** and are described below.

Vacuum pump

A vacuum system with a steam ejector is generally used in the high-altitude firing test stand, but the renovated facility uses a water-sealing vacuum pump. This makes it possible to reduce the running costs significantly. In the facility, four sets of a water-sealing vacuum pump with three Roots vacuum (mechanical booster) pumps are installed.

Vacuum chamber

A 2 m diameter vacuum chamber is located on the first floor of the combustion building. Unlike conventional combustion test facilities, the thruster installed in the vacuum chamber is combusted in the vertical direction in view of the gravity effect and the deflagration of unburned accumulated propellant within the thruster. For this reason,



(a) Combustion test facilities

(b) 3 dimensional view of the combustion test facilities

Fig. 2 Combustion test facilities

Fig. 3 Large-capacity vacuum pumps used for the combustion test facilities

Fig. 4 Vacuum chamber used for the combustion test facilities

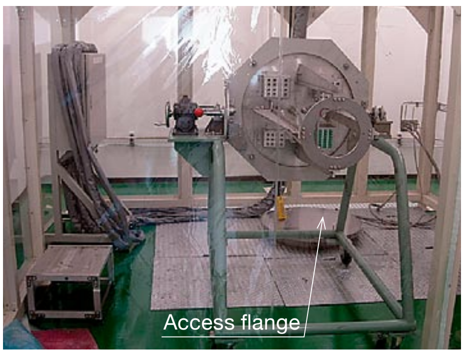


Fig. 5 Clean booth used for the thruster setting at the combustion test facilities

Fig. 6 Measurement and control systems used for combustion test facilities

access to the thruster is conducted from the access flange on the upper part of the vacuum chamber (second floor). To ensure cleanliness during assembly, a clean booth is installed at the access part of the thruster. Four small thrusters can be installed simultaneously on the access flange, making it possible to improve firing test efficiency. Windows for monitoring the test status, infrared transmissions for temperature measurements of the combustion chamber, access ports for pressure sensors and thermocouples, and cooling water ports are installed on the first floor of the vacuum chamber.

Control and measurement systems

Control systems are constructed based on a personal computer based system. The system makes it possible to measure the pressure, flow rate, and temperature, to record monitoring from the windows, to record thermographies, and to control valves. Measurements of the pressure and temperature are performed with Labview, a graphical programming software package for measurement and control. The system has the capability of recording 72 channels of pressure and/or other parameters and 26 channels of temperature. Remote operation and monitoring are possible for these measurements and control systems using an optic LAN.

4. Qualification test status for the PLANET-C 500N ceramic thruster

A flowchart of the qualification testing is shown in **Fig. 7**. First, thrust adjustment tests are conducted by repeating adjustment of the orifice size which is installed upstream of the injector and firing tests conducted subsequently until meeting the required thrust at the specified supply pressure. Then, mechanical environmental tests are conducted under acceleration conditions estimated from the vibration environment at launch. Afterwards, functional tests and leakage tests for each component are conducted to check for malfunctions in the thruster. Then, a health check is performed by a firing test, followed by more combustion tests within the assumed supply pressure range to confirm the performance characteristics in the assumed operating range (operation range confirmation tests). Finally, combustion tests at the actual operating cycle are conducted including a 1,000 second duration firing test.

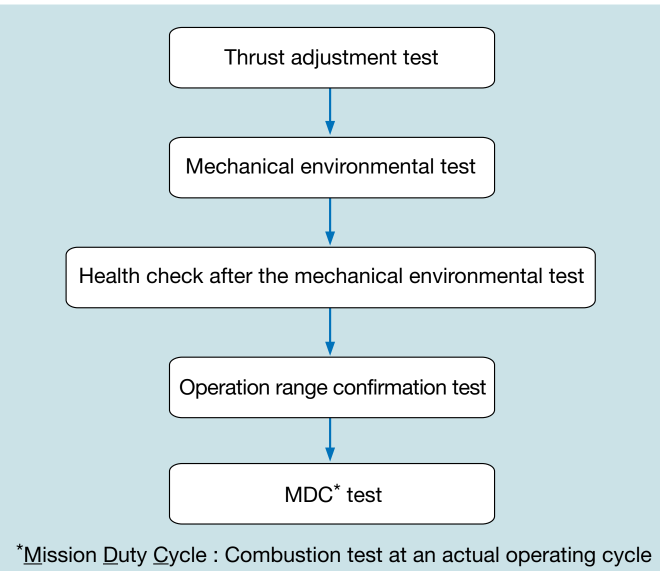


Fig. 7 Qualification test flowchart

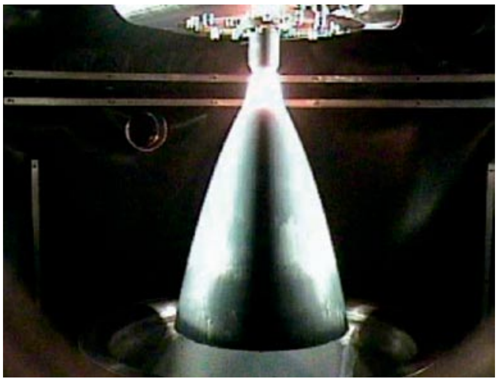


Fig. 8 500N ceramic thruster setup in the vacuum chamber during the thrust adjustment test

Table 2 Results of the thrust adjustment test

	Planned (required) value	Test result
Combustion pressure (MPa)	0.69	0.69
O/F	0.80±0.01	0.80
Thrust (N)	500±25	502
Specific impulse (s)	≧310	319

Presently, the thrust adjustment tests and the mechanical environmental tests are underway. The results are discussed below.

Thrust adjustment tests

The thrust adjustment tests were conducted, as shown in **Fig. 8**, using the combustion test facilities described above. The test results are given in **Table 2**. We confirmed that the mass flow rate ratio of the oxidizer and fuel (O/F), the thrust, and the specific impulse met the design requirements.

Mechanical environmental tests

Vibration tests were conducted by loading the thruster with the acceleration conditions estimated from the vibration environment at launch. The vibration conditions are listed in **Table 3**, and the setup is shown in **Fig. 9**. The results of random and sinusoidal vibration tests confirmed that no excessive stresses were observed and that the thruster was not damaged. The evaluated fracture probability (**Table 4**) was small enough to meet the required values. From the test results, we confirmed that the thruster for the PLANET-C explorer has sufficient strength to withstand the vibration environment at launch.

5. Future plans

We plan to continue the qualification tests for the PLANET-C thruster, which contains firing tests at the assumed actual operating pattern including the 1,000 second duration firing test. Afterwards, we plan to conduct combustion and mechanical environmental tests of a flight model (FM), which will be used for the actual flight. Since firing test results indicate that the measured combustion chamber temperature was sufficiently lower than the heat resistance temperature, we will work to improve the thruster performance further by increasing the combustion gas temperature.

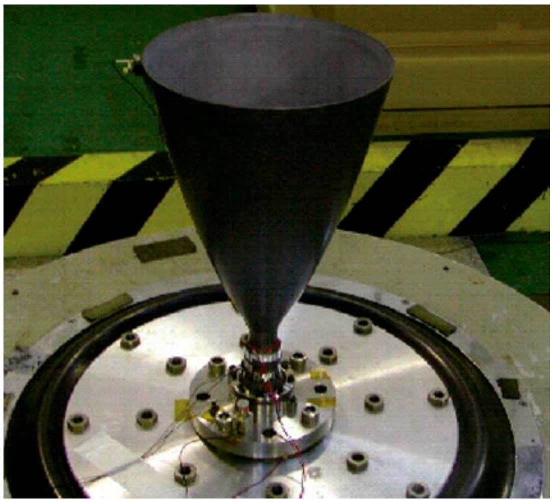


Fig. 9 Setup of the mechanical environmental test with the 500N ceramic thruster fixed on the vibrator

Table 3 Mechanical environmental test conditions

(a) Random vibration

	Horizontal direction		Vertical direction	
Loading time	80s		80s	
Vibration level	Frequency (Hz)	PSD (G^2/Hz)	Frequency (Hz)	PSD (G^2/Hz)
	20	0.004	20	0.0150
	40	0.020	30	0.0200
	160	0.020	40	10.0000
	250	0.400	55	10.0000
	370	0.400	60	0.0500
	430	2.000	90	0.0800
	520	2.000	1 000	0.0800
	730	0.080	2 000	0.0800
	1 900	0.080		
	2 000	0.050		
	22.8 Grms		17.0 Grms	

(b) Sinusoidal vibration

	Horizontal direction		Vertical direction	
Vibration method	2 oct/min 1 sweep up and down		2 oct/min 1 sweep up and down	
Vibration level	Frequency (Hz)	Acceleration (G)	Frequency (Hz)	Acceleration (G)
	5	0.55	20	0.55
	18	12.0	30	25.0
	100	12.0	40	25.0

PSD: Power Spectrum Density

Table 4 Evaluation of fracture probability

	Required values	Analysis	Test
Random	$\leqq 2.9\times10^{-5}$	4.0×10^{-11}	5.6×10^{-13}
Sinusoidal wave	$\leqq 2.9\times10^{-5}$	2.0×10^{-21}	5.1×10^{-16}

6. Conclusion

Qualification testing is currently underway to evaluate the capability of employing the 500N bipropellant thruster made of high strength and high toughness silicone nitride ceramics in the PLANET-C Venus explorer. From the test results, we are viewing the prospect that the ceramic thruster will be used in the PLANET-C Venus explorer.

In the future, we will continue the qualification testing. Then we plan to conduct acceptance tests (AT) to confirm that the FM (Flight Model) for the actual flight can meet the required specifications. We will also work to further improve the thruster performance.

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Tetsuya Matsuo

Katsushige Morishima

Ryohei Inoue

Yoshinori Nonaka