DEVELOPMENT STATUS OF A MICROWAVE ION ENGINE SYSTEM FOR THE MUSES-C MISSION

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Abstract

The Institute of Space and Astronautical Science (ISAS) has developed a cathode-less microwave discharge ion engine system applicable to the asteroid sample return mission "MUSES-C", which will depart from the Earth in 2002 and will come back to the Earth in 2006. An engineering model of the thruster was assembled into an endurance test system and was dedicated for its life verification since February 1997. The total operational time reached was 18,000 hours without any fatal problems attributed to the electrode-less microwave discharge and the carbon-carbon composite grid system was proved to be compatible to the requirement of long-term ion electrostatic acceleration.

Introduction

The electric propulsion with high specific impulse gives big advantages for the orbit maneuver in low gravity interplanetary space nevertheless the electric propulsion produces much lower thrust than the chemical propulsion. The Institute of Space and Astronautical Science (ISAS) in Japan has been preparing the sample return from an asteroid to the Earth mission, the "MUSES-C" of which launch is scheduled in 2002 and some specimens will be brought to the Earth in 2006 from a small celestial body. The primary objective of MUSES-C project is to demonstrate the following space engineering technologies that are thought to be essential to the future scientific sample returning missions: [1]

(1) ion engine system (IES) as a primary propulsion in the interplanetary space,
(2) an autonomous navigation and guidance via optical measurements,
(3) a sample collection mechanism and
(4) direct reentry and sample recovery from the interplanetary space.

The MUSES-C spacecraft shown in Fig. 1 will be launched by the ISAS launch vehicle M-V toward a near Earth asteroid either Nereus (4660) or 1989ML in 2002 and the flight period is about 4 years until returning the specimens to the Earth in 2006. In case of Nereus the launch will occur in January 2002 and in the 1989ML case the launch window

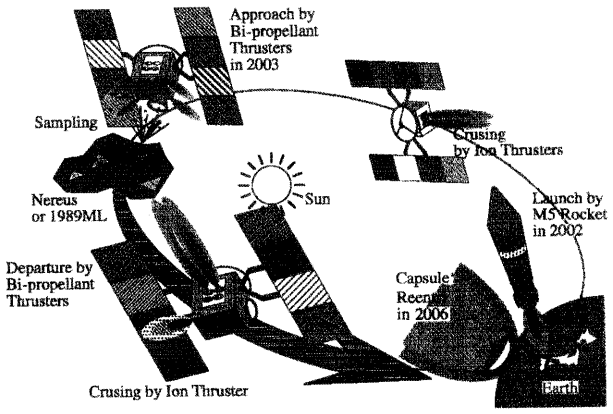

Fig. 1 MUSES-C mission sequence of events.

will slip about 6 months later. A pair of large solar-cell paddles are mounted on the spacecraft without driving mechanism will generate approximately 1.222 kW at 1.44 AU from the Sun and will supply nearly 1 kW for the electric propulsion. The funnel like sampling horn is installed on the bottom panel. When the spacecraft touches down the surface of the asteroid a projectile will be shot, and < crush its surface. Generated fragments are guided to the canister through the horn under the ultra-low gravity environment. The

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canister with the specimens of the asteroid is finally stowed in the reentry capsule, which will reenter the Earth's atmosphere directly from the interplanetary trajectory. In the heliocentric trajectories, toward the asteroid and back to the Earth of its return way, the ion engine system will propel the spacecraft. In general a round trip space mission requires very large propellant consumption for the conventional chemical propulsion to attain the ΔV of higher than 3.5 km/sec. The only electric propulsion systems let the spacecraft approach some of the asteroids and give a return way to the Earth. The alternative technique is the maneuver by the gravity assist, which is not applicable to the mission to/from asteroids or comets because of the small celestial body without large gravity field.

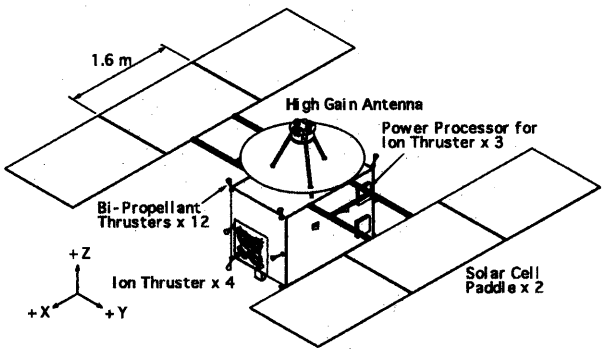


Fig. 2 Schematic view of MUSES-C spacecraft.

The MUSES-C spacecraft is designed using microwave discharge ion engine system developed by the Electric Propulsion Section in ISAS. The mass of the spacecraft is about 486 kg including chemical propellant and ion engine propellant of xenon gas. The ion engines are mounted perpendicular to the z-axis, along which the High Gain Antenna (HGA) aperture is oriented. The thrust direction of the ion engine is steered by rotating spacecraft attitude around the Sun direction. Four ion engines are installed on the plate gimbaled so that the thrust axis can track precisely the gravitational center of the spacecraft associated with mass drift due to propellant consumption. The round-trip mission is basically designed using 3 of the 4 ion engines, and thereby an extra thruster is installed on the spacecraft as a perfect stand-by redundancy. The following values are agreed with the mission planning group as the possible lowest performances to be used in the interplanetary orbit generation. A single unit of ion engine generates a thrust of 7.81 mN at the MOL, mean of life (arriving at the asteroid) and a specific impulse of 2,871 sec for the 391 W input power including power consumption of the propellant management system and the thruster control unit, etc. It can be throttled down the thrusting power to 80% of its full electrical power consumption.

The MUSES-C program requires a life time about 18,000 hours per a microwave discharge ion thruster. In order to verify the longevity, the engineering model (EM) is dedicated to an endurance test,[2] and the prototype model (PM) is under preparation for the next step. This paper reports the design of the ion engine system in the MUSES-C spacecraft and their results of the EM endurance test of cathode-less microwave discharge ion engine system.

Table 1 IES Specification at Mean of Life.

Thrusters	4 units including 1 stand-by redundancy
(3 units simultaneous operation maximum)	
System Thrust	7.81 – 23.42 mN
System Power	391 – 1,147 W
Specific Impulse	> 2,871 sec
Throttling	80 , 85, 90, 95, 100%
Xe mass flow	2.87 sccm / unit at 100%
Ion Production Cost	< 387 eV
Propellant Util. Eff.	> 84%
Lifetime	> 18,000 hours
Xe loading	< 73 kg
Dry weight	< 63.6 kg

Microwave Discharge Ion Engine System

The Electric Propulsion Section in ISAS developed a cathode-less microwave discharge ion engine system for the MUSES-C where the plasmas for an ion source and a neutralizer are generated by virtue of electron-cyclotron resonance (ECR) discharge.[3-4] The schematic diagram of the cathode-less microwave discharge ion engine system is illustrated in Fig. 3 and the actual in-house operation photography in Fig. 4. The ion source and the neutralizer are supplied microwave power by a single microwave generator and fed the propellant by a single gas flow controller using passive dividers. The discharge regions of the ion source and the neutralizer are simple chambers with permanent magnets and no electrodes as seen in Figs. 5 and 6. The microwave power is introduced into the ion source through a wave-guide, and to the neutralizer through a coaxial cable with an

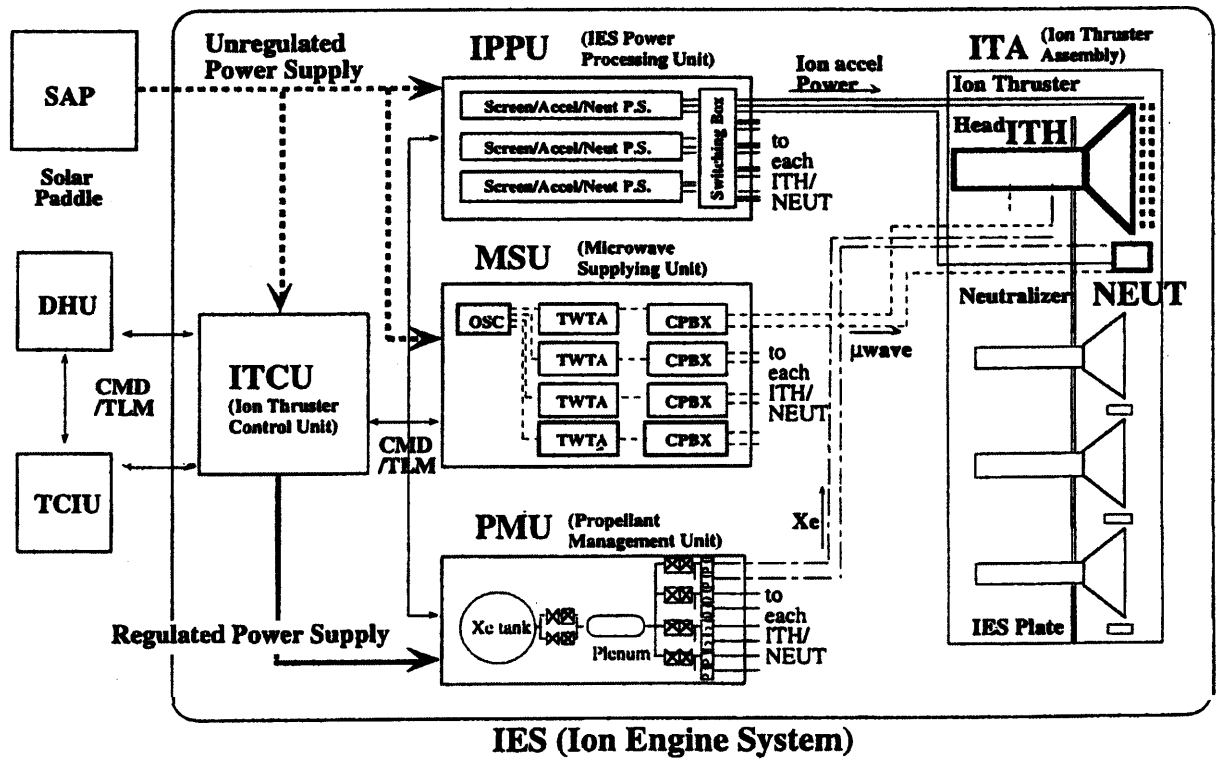


Fig. 3 IES system block diagram with bus interfaces.

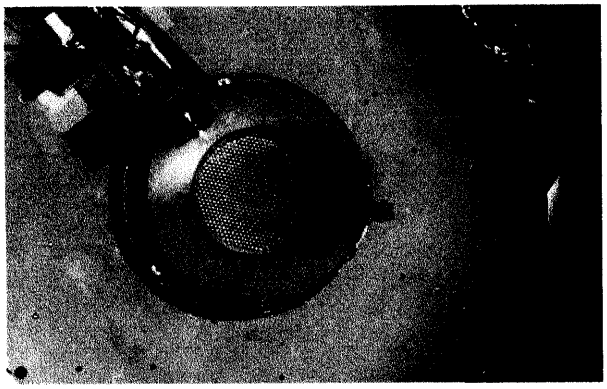


Fig. 4 In-house operation of the microwave discharge ion thruster (Engineering Model in the Endurance Test).

antenna. The alternating electric field of the microwave makes electrons accelerate continuously near an appropriate magnetic field produced by permanent magnets so that the propellant gas is ionized without any pre-heat sequences. The plasma generation both in the ion source and in the neutralizer is completely independent on the thermo-emissive electrons.[5-8] The ion source was designed as a dish-shaped axially-symmetric discharge chamber of 12 cm in diameter made of soft-iron as shown in Fig. 5. It had a pair of rings for the samarium-cobalt (Sm-Co) permanent magnets on its tapered internal surface. In the neutralizer the Sm-Co magnets and magnetic pole-pieces generate the magnetic field in the discharge chamber of the neutralizer. The generated plasma is exhausted through the orifice. The microwave ion engine is applicable to the MUSES-C mission because of long life in space operation and an easy maintenance / handling in the ground operation due to the elimination of troublesome hollow cathodes, which frequently reduce their lifetime due to atmospheric exposure and/or contaminant constituents in the propellant gas. And it is released from the material fatigue due to repetitively thermal shock because this ion engine system has no parts with high temperature like electrical-filaments. Another feature of this ion engine system is the employment of carbon-carbon composite material for the electrostatic 3-grid system in 10 cm effective diameter with 700 holes, which seems to be durable to the bombardment of xenon ions. The parameters of 3-grid system are summarized in Table 2. They are arranged at 0.5 mm grid-spacing. It is noted that the screen grid is directly attached to the ion source structural body without any potential gap.

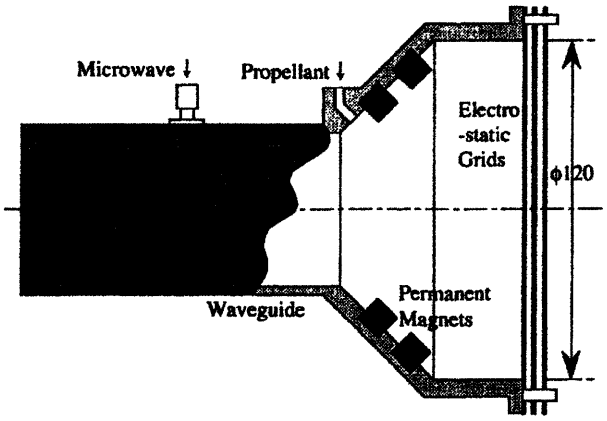


Fig. 5 Sectional view of the ion source.

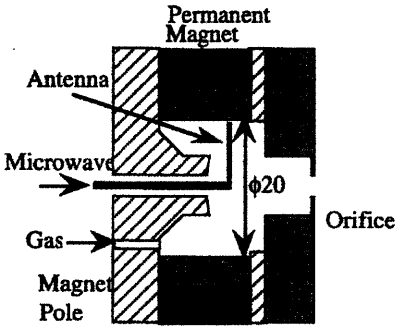


Fig. 6 Sectional view of the neutralizer.

Table 2 Parameters of 3-grid system of 10-cm effective diameter with 700 holes.

Grid	t, mm	Hole diam., mm,	Open Area
Screen	1	3.0	67%
Accel.	1	1.8	24%
Decel.	1	2.5	46%

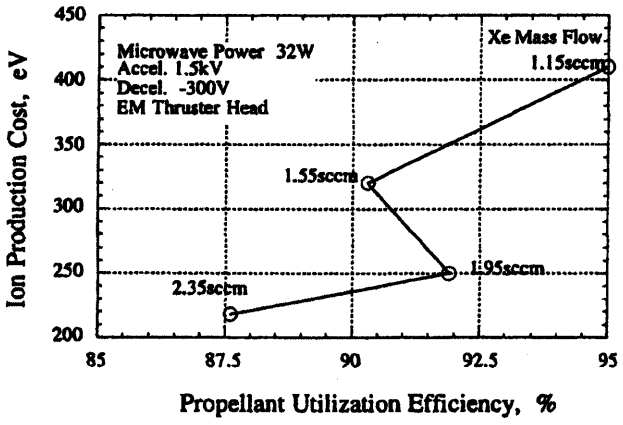


Fig. 7 Thrust performance of the engineering model (EM) for the MUSES-C.

The thrust performance of the EM was measured in June 1997 as shown in Fig. 7 and the power throttling was conducted by changing the xenon's mass flow rate.[9] Here the ion production cost was calculated by dividing the beam current by the microwave input power into the discharge chamber, and they don not include the effect of doubly charged ions and the beam divergence. Some appropriate margins should be subtracted for a mission design. As for the doubly charged Xe, the E x B probe measurement showed a Xe^{++} current ratio Xe^{+} was about 10% in the ion beam. It reduces a thrust force to 95% of the ideal one, in which all of ions are assumed to be singly ionized.

System Configuration in Flight Hardware

The Ion Engine System (IES) on MUSES-C has an ion thruster assembly (ITA) with 4 microwave power amplifiers (MPA) and 3 acceleration power supplies (IPPU) as seen in Fig. 3. An ITA includes 4 ion thrusters (ITR) consisting of a pair of ion thruster head (ITH) and neutralizer (NEUT). Four sets of ITRs are mounted on a plate, which can be gimbaled by a pointing mechanism so as to pass the combined thrust vector of 3 ITRs simultaneously operated through the center of gravity of the spacecraft. A single MPA is connected to each ITR and supplies C-band microwave power to both the ion source and the neutralizer at fixed division rate. Three IPPUs are connected to 4 ITRs via a high voltage relays box and 3 IPPUs can be operated simultaneously. The Propellant Management Unit (PMU) stores and feeds the xenon gas to 4 ITRs through flow restrictors. The Ion Thruster Control Unit (ITCU) and Data Handling Unit (DHU) manages IES operation. The most probable concern was the EMI by IES to the X-band onboard receiver. The space-born frequency domain which is assigned for the

Table 3 Nominal IES performances.

Throttling	100%	80%
Thrust per one ITR	8.22 mN	5.40 mN
Specific Impulse	3,022 s	3,084 s
Thrust-to-Power Ratio with 3 ITRs	20.6 mN/kW	17.5 mN/kW
Power Consumption		
With 1 ITR	401.6 W	308.1 W
2 ITRs	790.5 W	603.6 W
3 ITRs	1178.4 W	898.1 W

frequency domain which is assigned for the communication, however the noise level is expected to be much lower than the signal from the Earth over 3 AU distance. The overall performance IES in the nominal condition is summarized in Table 3.

Endurance Test for EM system

The MUSES-C project requires the life-time about 18,000 hours of the cathode-less microwave discharge ion thruster. In order to verify the lifetime, an engineering model (EM) was devoted to the endurance test, and the prototype model (PM) is also under preparation for serving. The EM endurance test was planned in order to achieve the following objectives:[10-11]

(1) to assess the endurance of the carbon-carbon composite grid system, especially the acceleration grid,
(2) to identify the failure modes of the ion thruster system, and
(3) to obtain preliminary data to determine the PM designs.

The EM endurance test was carried out inside a vacuum chamber of 2 m in diameter and 5 m long as seen in Fig. 8. Four cryogenic pumps in 800 mm diameter evacuate the vacuum chamber below 2×10^{-4} Pa ambient pressure during the thruster operation. The internal surface is covered with a titanium-made shroud panel and a beam damper refrigerated below -40 ℃ . The operation and data acquisition of the EM thruster and the vacuum facility are fully automated by a UNIX work station, which was linked into the internet so that the real-time operational information was observable in the homepage at the URL of http://www.ep.isas.ac.jp/open. The propellant feed system, the microwave power generators, the power supply units for ion acceleration, and the data acquisition system, are all integrated in a GPIB bus interface.[12]

Fig. 8 IES endurance test chamber.

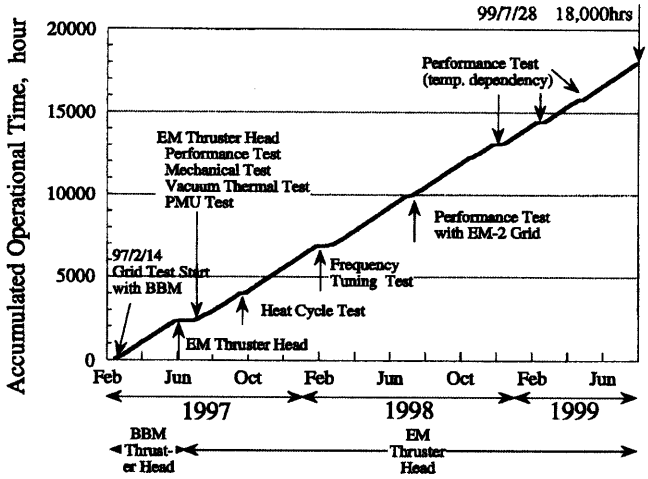


Fig. 9 Accumulated operational time of EM endurance test.

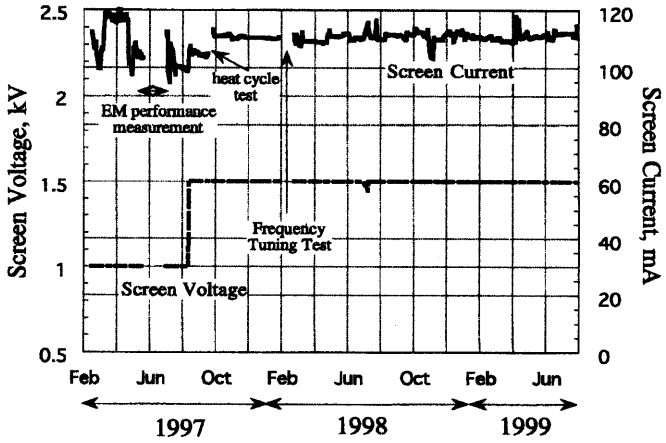


Fig. 10 Screen current / voltage history of EM endurance test.

The chronology of the endurance test and the screen current / voltage history are shown in Fig. 9 and Fig. 10, respectively. For the first 3,000 hours, the EM grid system was integrated with the laboratory model of the ion source structure and tested with relatively low screen voltage. In this period the microwave DC-block frequently caused electrical short, which was solved by improvement of the electrical isolation. The EM ion source with the EM grids was devoted to the endurance test from August 1997. The test was voluntarily interrupted at several times for performance tests, a thermal cycle test, a frequency tuning test, and visual inspection, etc. In the beginning of May 1999 the total accumulated operational time reached 16,000 hours without any fatal problems and continued. In the end of July 1999, the EM endurance test successfully accomplished the operational time of 18,000 hours that was our final goal of the EM endurance. It was of great interest to assess

the grids mass loss caused by the sputtering erosion processes. This is one of the most critical bottle-neck constraint to the thrusters lifetime. The MUSES-C ion engine system employed carbon-carbon composite grids instead of the conventional Molybdenum grids, expecting long-term durability. Periodically the inspection was carried out to evaluate the weight of each grid as seen in Fig. 11. Consequently, the acceleration grid showed sufficiently small erosion to meet the MUSES-C mission requirements. And the screen grid never caused weight loss because it has no potential gap to the plasma between the ion source.

The ion thruster operational conditions for this EM endurance test were summarized in Table 4.

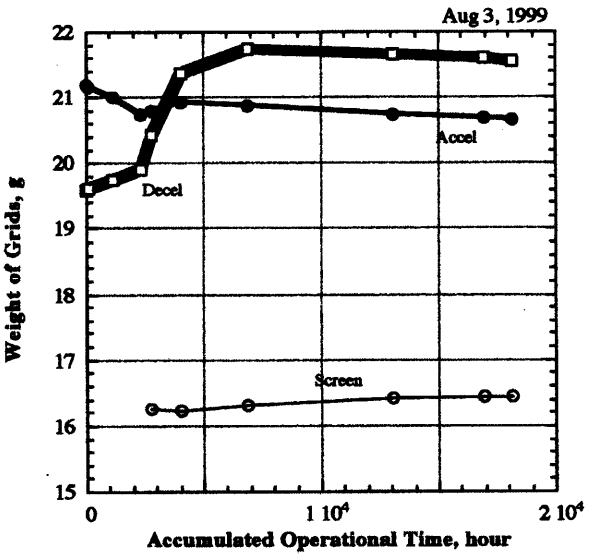
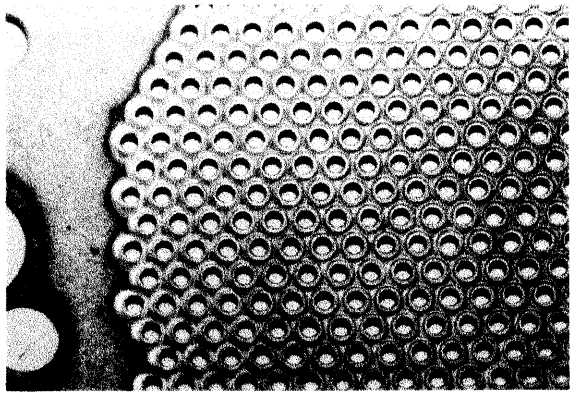


Fig. 11 Mass loss of the EM grids during the endurance test.

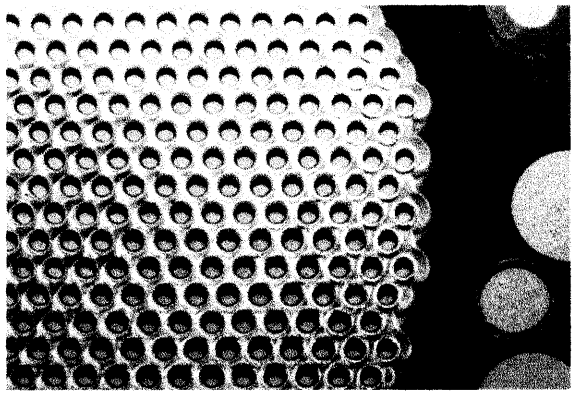
Table 4 EM-phase endurance test conditions.

Screen Voltage	1.0 / 1.5 kV
Accel. Voltage	- 300 V
Decel. Voltage	GND
Beam Current	> 100 mA
Accel. Current	~ 0.5 mA
Microwave Power	
Ion Source	< 35 W
Neutralizer	< 8 W
Xe Flow Rate	
Ion Source	1.15 - 2.35 sccm
Neutralizer	0.29 - 0.59 sccm
Vacuum Condition	$< 10^{-5}$ torr

The result of the grid weight measurement in Fig. 11 shows that only the acceleration grid eroded at a rate below 0.2 μg/hour, which is not a serious problem to threat the required lifetime of 18,000 hours. The large weight loss of the screen grid for the first 3 months was attributed to a crack made by a mishandling and was replaced in 3,000 hours. From that time, there were no noticeable weight change. In contrast, the deceleration grid increased its weight mainly due to the effect of titanium back sputtering. The Ti came from the beam damper which reflected and bent the high speed plasma beam and also generated sputtered Ti. Except the slight erosion of the acceleration grid no noticeable erosion or damage were found inside the discharge chamber. In Fig 13, the photographs of the both sides of the acceleration grid after 18,000 hours EM operation are exhibited and are found almost free from severe erosion.



a) Upstream side.



b) Downstream side.

Fig. 13 The acceleration grids after 18,000 hours EM endurance test.

Environment Tests

Thermal Vacuum Test

To demonstrate the thruster operation under thermal environment in space, temperature measurement of the EM components was conducted using digital thermometers and thermo-couples. For the temperature of the IES plate raging from 50 to 80 ℃, maximum temperatures were observed at the magnetic circuits of the ion source, at the grid assembly, and at athe neutralizer, but they were at most 110 ℃. These temperatures are below the limit of the maximum temperature (200 ℃), which is the acceptable temperature of Sm-Co magnets. Also no large temperature difference was found inside the thruster head. Based on the measurement, a thermal model was created and thermal design for the entire spacecraft is now being conducted and a thermal vacuum test is also planned in the PM phase.

Mechanical Test of Carbon-Carbon Composite Grid

The vibration tests of the C-C grid were performed to evaluate the mechanical strength under the launch environment of M-V launch vehicle. The shock test, sinusoidal vibration test, random vibration test, and static load test were conducted at the vibration level of MUSES-B's which was the recent reference of launch environment. The resonant frequency of each grid was found around 300 Hz, but the vibration level about 10 dB higher than the nominal level was successfully applied without any damage of grids. The whole assembly of an ion thrusters on the gimbal plate will be tested as the mechanical test model in the PM phase.

Preliminary EMC Test

Two preliminary narrow-band EMC tests were conducted. One follows the RE-02 of MIL-STD-461C and was conducted in an electromagnetic shield room where only a neutralizer was activated inside a glass chamber. The other test was conducted for the ion source inside a metallic vacuum chamber, however, it was not compatible to the MIL-STD-461C. The results seemed to be no problem. The major concern about electromagnetic interference was the ion engine frequency interaction with X-band telecommunication link of the spacecraft. To prevent possible interference, the microwave frequency of the ion engine is selected as 4.25 GHz of which second harmonic is sufficiently apart from the communication band of 8.4 GHz by 100 MHz.

Development Milestones

After the successful completion of EM thruster testing the grid longevity was confirmed, the possible failure modes were clarified and the precise design guidelines were acquired.[13-14] The PM tests started in this September. In the PM phase, 2 ITRs, electrical power supplies, mechanical / thermal models of the PMU and an ITCU, the ion thruster control unit, are to be fabricated and dedicated to the interface tests with other subsystems.[15] Also a PM phase endurance test using one of the PM thruster heads is planned. On the other hand, Xe loading in the launch site was an important technique and discussed. Finally we employed a new method of liquefaction loading of which detailed description is available elsewhere.[16] In the actual flight, a kind of electric propulsion diagnostic package is under discussion for the evaluation of contamination caused by long-term operation,[17] however, the installation of such package is very difficult at present due to weight penalty.

Acknowledgement

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