Flight Readiness of the Microwave Ion Engine System for MUSES-C Mission

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Abstract

A microwave Ion Engine System (IES) has been developed in the Institute of Space and Astronautical Science (ISAS) to meet requirements for an asteroid sample return mission of MUSES-C (Mu Space Engineering Spacecraft) which will be launched by M-V expendable rocket vehicle this year. An 18,000 hour endurance test for an engineering model (EM) was finished in 1999, and second time endurance test is also successfully continued for a prototype model (PM) from 2000 until now. The flight models (FM) were already manufactured on the basis of prototype model thrust performances and integration specifications. Now they were integrated as sub-systems to check out their mutual interfaces as well as bus interfaces. This IES constitutes 4 ion thrusters on a radiation panel with a bi-axially movable gymbal mechanism, 4 microwave supplying units, 3 acceleration power processing units, and 1 propellant management unit. The MUSES-C mission requires the IES to generate thrust of about 24 mN for maximum power input of about 1 kW by 3 of the 4 ion thrusters simultaneous operation.

1. Introduction

In the Institute of Space and Astronautical Science (ISAS) we have been developing a microwave ECR (Electron Cyclotron Resonance) discharge type Ion Engine System (IES).[1,2] It will be launched by M-V vehicle in May 2003 as an asteroid sample return mission MUSES-C (Mu Space Engineering Spacecraft-C). In this mission the spacecraft, as shown in Fig. 1, will be propelled by this IES from the Earth escape until arrival at the asteroid through about 4 years corresponding to 90 % duty of the interplanetary flight. The target asteroid is 1998SF36 (not yet designated as of January 2003) and has been fixed. The major objectives of MUSES-C are:

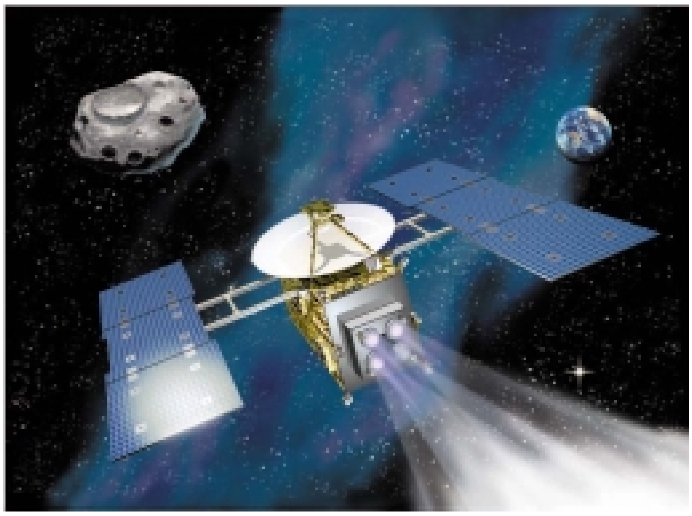

Fig. 1 MUSES-C will verify 4 engineering techniques essential to future interplanetary missions.

1) Application of electric propulsion to interplanetary mission,
2) Verification of autonomous optical navigation, guidance and control,
3) Establishing sampling technique,
4) Obtaining technique of reentry from interplanetary space.

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After the launch MUSES-C will take an oblique attitude toward the sun for the irradiation of +X and +Z direction for at least about 1 week. The IES baking will begin in order to conduct outgassing from high voltage devices and also grids. If the spacecraft will be launched in May 2003 into an Earth synchronous orbit to perform an Earth swing-by in May 2004 (Fig. 2), the spacecraft will arrive at the target in October 2005, will perform observations and sampling for longer than 2 months, depart from the target in December 2005 and finally come back to Earth in June 2007 to return the sample containing capsule. For more than 91 % period of the round-trip the IES is operated between 3 engines at 105 % throttling and 1 engine at 95 % throttling depending on the available solar cell power to accelerate the spacecraft. Just only for 2 or 3 months during transfer orbit, the spacecraft will coast with the IES deactivated while the spacecraft encounters the superior conjunction before the asteroid arrival. Other samples of transfer and return orbits are depicted elsewhere.[3] During the observation phase, the distance between the spacecraft and the sun is about 1 AU (Astronomical Unit) and the distance between the spacecraft and Earth is about 2 AU.

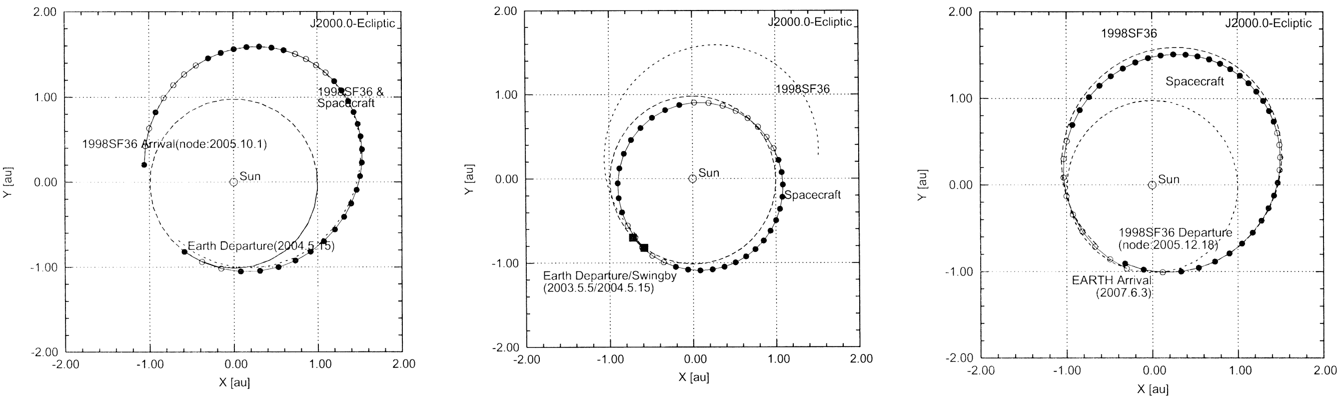


Fig. 2 A sample of MUSES-C orbit planning (● IES thrusting,, ○ IES coasting, Left : Launch to Earth swing-by, Middle: Departure to asteroid, Right: Return to Earth).

2. Ion Engine Propelled MUSES-C Spacecraft

The ion thruster is planned to use 61.9 kg Xe propellant and the MUSES-C spacecraft has a 73 kg capacity tank to be adaptive to the last minute target change after the design fixation. The IES will carry out a mission ΔV of about 3.7 km/s. There are 4 Ion Thrusters (ITR) consisting of Ion Thruster Head (ITH) with a Neutralizer (NEUT) each installed on the IES. At the maximum thrust level, 3 ITRs are simultaneously operated at 105 % power rating and at the lowest thrust level only 1 ITR is operated at 80 % throttled power. The endurance requirement in this mission is 16,000 hours per each ITR including a stand-by redundant ITR as one of the 4 ITRs. The MUSES-C spacecraft will employ a 3-axis stabilized attitude control, optical navigation / guidance and automated / autonomous flight operation. The wet weight with propellant is 521.45 kg and the dry weight is 381.45 kg. Figure 3 shows solar array paddle deployed in Y direction to generate 2,575 W at 1.0 AU. The IES is mounted on an IES plate which has a gymbal mechanism described later.

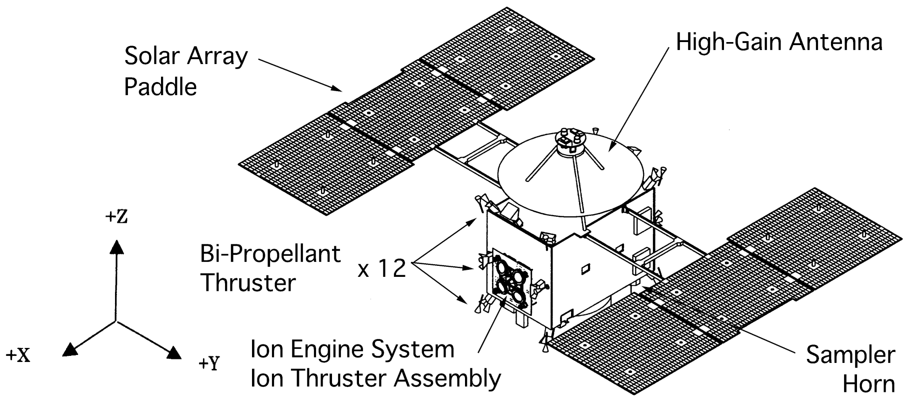


Fig. 3 MUSES-C Spacecraft.

2.1 Microwave Electron Cyclotron Resonance (ECR) Ion Engine

The microwave ECR ion engine generates plasma by introducing microwave into a discharge chamber with permanent magnet to take advantage of the electron cyclotron resonance.[4] As a remarkable feature of this design, a single microwave source is divided between a neutralizer having a small microwave antenna as well as ion source to develop plasma for ion acceleration with electron neutralization. This electrode configuration for plasma production greatly contributes to the thruster lifetime. The effective beam diameter is 10.5 cm (Fig. 4) and another remarkable feature of this thruster is 3-grid system of carbon-carbon composite material with 1 mm thickness (excluding accel. grid of 0.95 mm) . These grids have 855 holes perforated with each hole size of 3 mmϕ for screen, 1.8 mmϕ for accel. and 2.5 mmϕ for decel. and their porosity is 67%, 24% and 46%, respectively. These 3 grids are fastened to an aluminum support ring using ceramic studs with low thermal expansion coefficient. The typical grid separation is 0.32 mm for screen-accel. and 0.5 mm for accel.-decel. and they are verified no deterioration in their performance after temperature cycle test between -70-100 °C and thermal cycle test in the thermal vacuum between room temperature and 120 °C.

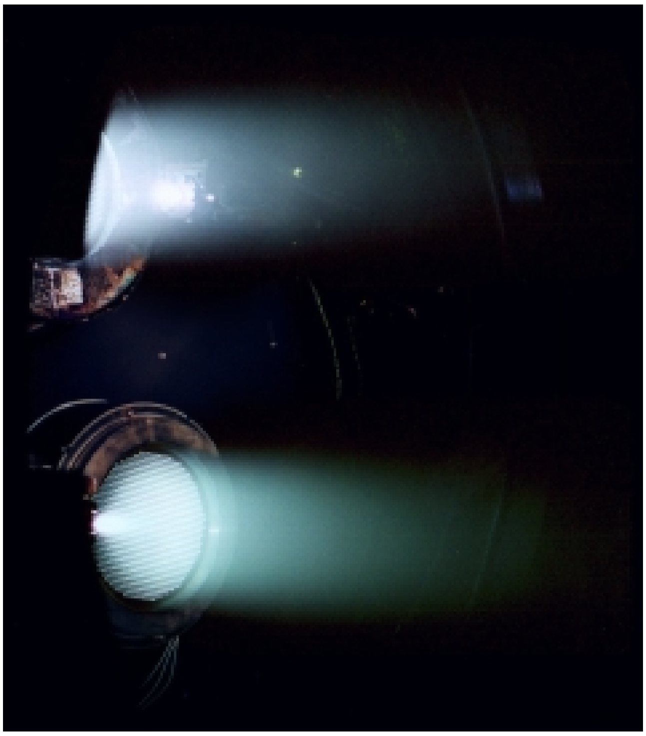


Fig. 4 Simultaneous operation of 2 microwave ECR ion engines inside a vacuum chamber.

2.2 Ion Thruster Assembly (ITA)

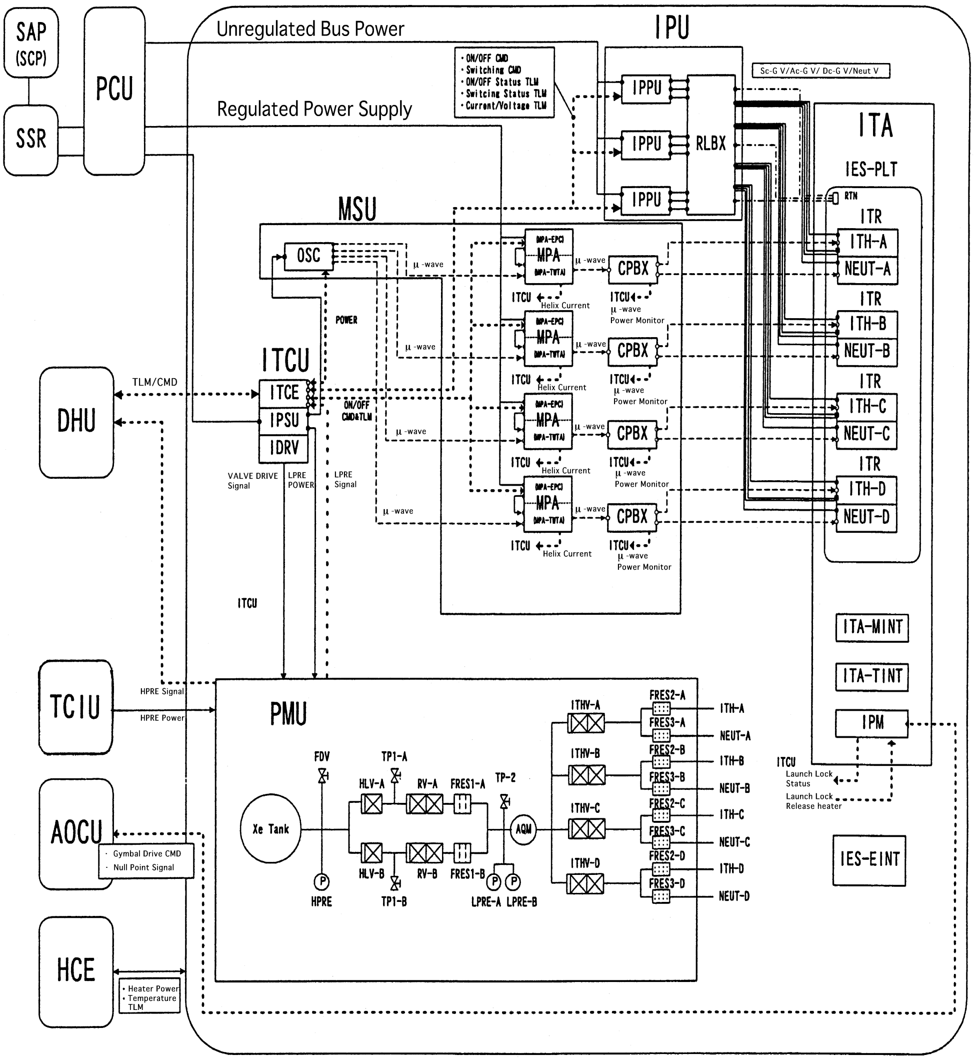
The 4 ITHs are installed on the gymbal plate (IES plate) with their neutralizer. This gymbal mechanism has a centered pivot with 2 axis rotatable with paraffine actuators in ± 5°. During the flight the IES thrust vector is controlled so as to point the spacecraft center of gravity by this gymbal mechanism. The IES is installed on the spacecraft in +X face so that the exhaust plume does not interfere with the solar array paddles which are deployed in Y direction. Each ITR has a cant angle from the +X mechanical axis to intersect the spacecraft center of gravity.

Table 1 Weight breakdown of IES components. (As of Jan. 2003).

Item	Quantity	kg
ITCU (IES Thruster Control Unit)	1	3.50
OSC (Oscillator)	1	0.27
MPA (Microwave Power Amplifier)	4	9.12
CPBX (Coupler Box)	4	1.59
IPPU (IES Power Processing Unit)	3	6.32
RLBX (Relay box)	1	0.77
PMU (Propellant Management Unit)	1	16.07
ITR (Ion Thruster)	4	20.73
IES-PLT (IES Plate)	1	↑
IPM (IES Pointing Mechanism)	1	↑
ITA-MINT (ITA Mechanical Interface)	1	↑
ITA-TINT (ITA Thermal Interface)	1	↑
ITA-EINT (ITA Electrical Interface)	1	↑
IES-EINT (IES Electrical Interface)	1	0.82
Total		59.19

2.3 Ion Engine System

As aforementioned, 4 ITHs including NEUTs are installed and correspondingly 4 microwave power source are also installed, however, the electrical power sources for acceleration are limited as 3 units for weight saving (Fig. 5). In this configuration the weight penalty of 1:1 installation of microwave power sources for each ITRs is inevitable but is excluded the switching loss by changing combination of the microwave power source unit with each ITR. The microwave oscillator is only one unit with a frequency of 4.25 GHz. The doubled frequency is still apart from the communication X-band at least 100 MHz. The IES dry weight is 59.19 kg ideal as summarized in Table 1. As for the Xe supply, so-called a mass flow controller of thermal conduction type was not employed due to weight limitation. In the MUSES-C, stored Xe in the primary tank is regulated at lower pressure for the secondary tank accumulation and then the orifice and the open/close propellant valve control the flow feed in sawtoothed profile. The initial primary tank pressure is 8 MPa and the secondary tank capacity is 3 litter with peak accumulation pressure of 0.06 MPa at maximum. Two orifices called flow-restrictor of Lee Co., Ltd. are necessary for 1 ITR and determine the flow rate of ITH as 2.35 sccm and 0.50 sccm for neutralizer at 100% rating operation.



AOCU : Attitude & Orbit Control Unit

DHU : Data Handling Unit

HCE : Heater Control Unit

IPU : IES Power Unit

ITA : Ion Thruster Assembly

ITCU : Ion Thruster Control Unit

MSU : Microwave Supply Unit

PCU : Power Control Unit

PMU : Propellant Management Unit

TCIU : Telemetry & Command Interface Unit

Fig. 5 IES system block diagram.

3. IES Operation

3.1 IES On-Orbit Operation

The IES operation is controlled by DHU (Data Handling Unit) and ITCU (IES Thruster Control Unit). The former generates timeline commands and macro commands to turn-on or -off the IES without any feedback while the latter generates sequence controls associated with full time monitoring for anomaly detection and corrective action. According to the flow chart in Fig. 6, for example, a DHU command train executes ITCU turn-on, operation parameter set-up and ITR ignition. After the build-up of one MPA (Microwave Power Amplifier), the DHU proceeds to another ITR ignition, while the ITCU will confirm the normal ignition or not. If the ITCU confirms the normal ignition and the break-point signal indicates disabled, the following steps of ion acceleration will begin to activate IPPU (IES Power Processing Unit). If the break-point signal indicates enabled, the sequence is hold at the ignition mode. To turn-off the IES or an individual ITR, the DHU issues a corresponding command to the ITCU so as to stop the ion acceleration or to extinguish the plasma. These stoppages can be selected for each ITR independently. In the event of ignition failure or acceleration failure, the ITCU implements the pre-determined procedures and issues a report packet. Upon receipt of this report packet, the DHU makes the IES reconfigure for backup so that the non-thrusting period with all the ITRs off is minimized. This automatic procedure is applicable to the first time anomaly but not valid for the second time anomaly during the first one. Temperature anomalies are monitored by HCE and if the temperature somewhere in the IES exceeds the upper limit, the DHU will issue a stop command to the ITCU. If the lower limit is touched, the heater will be powered up. These temperature limits are rewritable from the ground. If the total power consumption exceeds the upper limit of power supply capability of the spacecraft, UVC (Under Voltage Control) is met and the IPPU namely the IES ceases its operation. Usually the DHU issues a macro-command to decrease the screen voltage or to decrease the number of activated ITRs and then the power consumption is alleviated before reaching UVC stoppage. All these functions are autonomous without any commands from the ground station. The monitor data of the IES from the ITCU via the PIM (Peripheral Interface Module) are managed and stored as HK (House Keeping) data in the DR (Data Recorder). The DR is used for the notification of IES operation records to the orbit determination group and also used as a flight recorder for the anomaly information. There are two periodicity 128 s and 4 s partitions on the DR and the 4 s partition is always overwritten. Once an ITR anomaly takes place, a request command is generated to reconfigure the IES and the overwrite is inhibited and hence the information before and after the anomaly detection for several minutes is automatically stored in the DR. The request commands other than the reconfiguration of IES are the IES hold for unloading of the momentum wheel executed by AOCU (Attitude and Orbit Control Unit) and the lock-up prevention by decrease of power consumption.

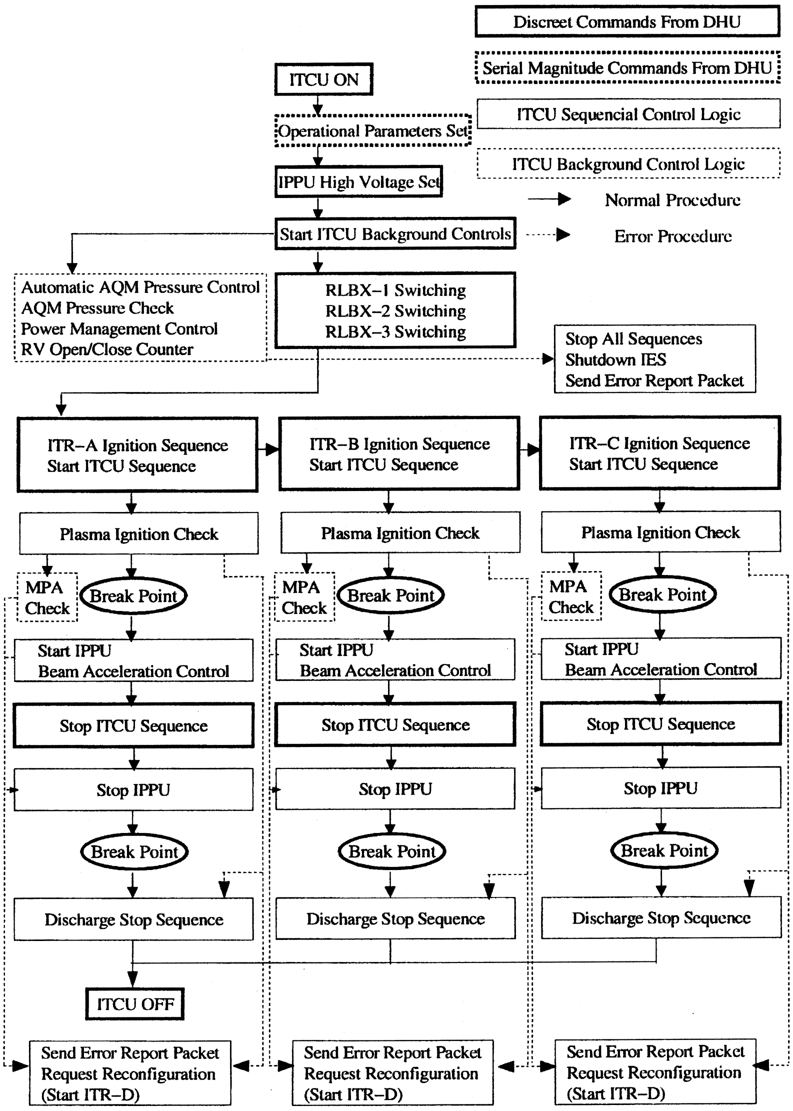


Fig. 6 IES operational command sequence and hardware logic.

3.2 Communication

In the MUSES-C mission we must take quite different navigation features into account from the missions so far, because the spacecraft is always accelerated by low continuous thrust during cruising. Basically the tracking operation is performed by UDSC (Usuda Deep Space Center) 64 mϕ X-band antenna and by KSC (Kagoshima Space Center) 34 mϕ X-band antenna as the backup. In the critical case, NASA/JPL DSN (Deep Space Network) support will be expected. These range and range-rate data will be used to determine the orbit

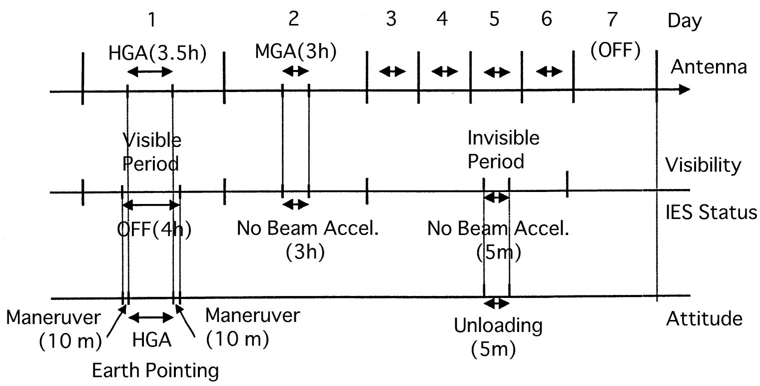


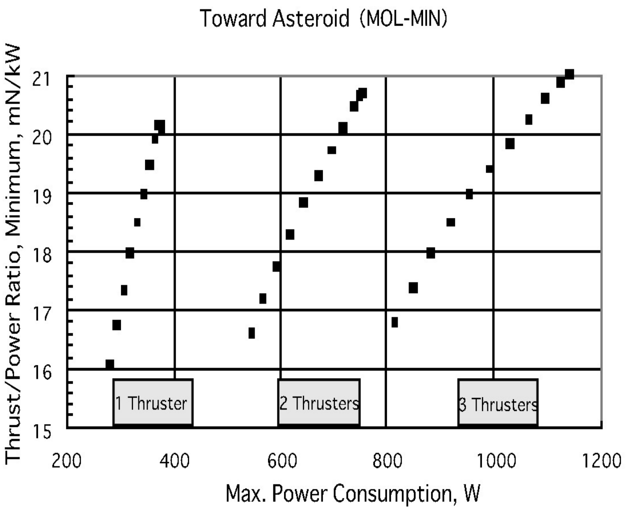
Fig. 7 Communication link.

and antenna forecasts for the ground station. The precision expected for the position and velocity are about 100 km and several tens of cm/s after 1 week data acquisition, respectively, if the electric propulsion thrusting has the accuracy within 1% and the high range-rate sensitivity. The communication links during the IES cruising constitutes 1 week routine period (Fig. 7). On the first day visible period of 4 hours in Japan the HGA (High Gain Antenna) is used with 4,096 bps data downlink and 1,000 bps command link, and the IES operation is completely hold because the spacecraft must orient the HGA to Earth. From the second day until the sixth day visible period in Japan is 3 hours per day for 512 bps downlink and ranging but no command link by using MGA (Medium Gain Antenna), and the IES does not accelerate the beam but maintains the ion source activated. The seventh day has no communication link. Other than the above periods during the IES operation, co-operations of the DSN is necessary to keep 15.625 bps commands uplink by LGA (Low Gain Antenna) and 8 bps data downlink by MGA .

4. Ion Engine System Performance

4.1 Thrust Performance

Figure 8 shows the thrust-to-power ratio and Isp characteristics required in FM (Flight Model) phase performance test. The propellant flow value is evaluated as the mean value, although the actual flow rate has a sawthoothed ripple about ± 5 % around the averaged value because of the feed system of a accumulator and open/close propellant valve assembly. The engine throttling is controlled by flow rate decrease, and hence the consumed electrical power, however, the thrust and the thrust-to-power ratio is almost proportional to the throttling %, the specific impulse is nearly constant except for the max power operation regime for each thruster numbers of simultaneous operation. The throttling levels range from 80 to 105 %. In the figure, BOL means “Beginning of Life”, MOL means “Mean of Life” corresponding to the time arrived at the asteroid, and EOL means “End of Life” corresponding to Earth returning. These represent the interface minimum values with orbit planning group, including each 2.5 % degradation from BOL and MOL.



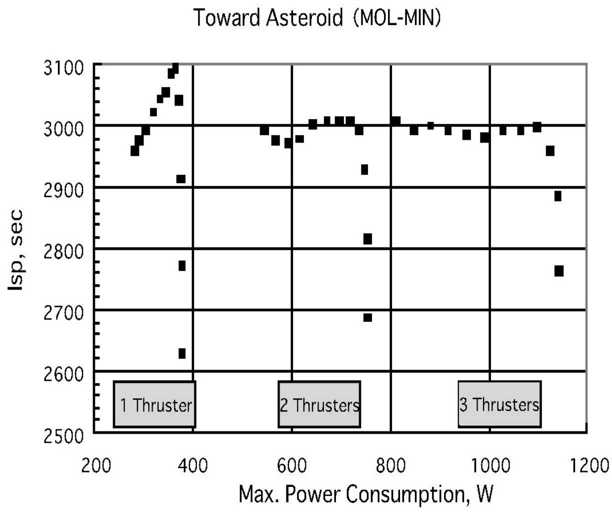


Fig. 8 Thrust performance required from the orbit planning (Left: Thrust/Power ratio, Right: Specific Impulse vs. power consumption for 1 – 3 thrusters simultaneous operation) at MOL.

4.2 Endurance

As for the endurance, we already finished 18,000 hours test from February 1997 until July 1999 using EM (Engineering Model) ITR to evaluate the endurance of an accel. grid.[5] As the result, the accel. grid erosion was proved to be very small and has no problem for the MUSES-C mission. The basic design of grid assembly was finalized so as to appropriately relieve the thermal strain of grids from low temperature (-50 °C) until high temperature (+120 °C) and revealed good thrust performance over the wide temperature changes. The PM phase (second time 18,000 hours) endurance test began from April 2000. In this time not only the accel. grid but also the whole ITR is dedicated to the 18,000 hours endurance test again. The testing conditions for PM endurance test, the minimum requirement of the screen current for the initial 9,000 hours and that for the 18,000 hours are different because they are the orbit interface minimum requirements to and from the asteroid. As the history exhibits, there have been no suspension of the endurance test except the momentary interruption of PM phase system test using PM ITR as the actual load and the thrust performance evaluation of temperature effects on the PM grids. The second time 18,000 hours was achieved last October (Fig. 9).

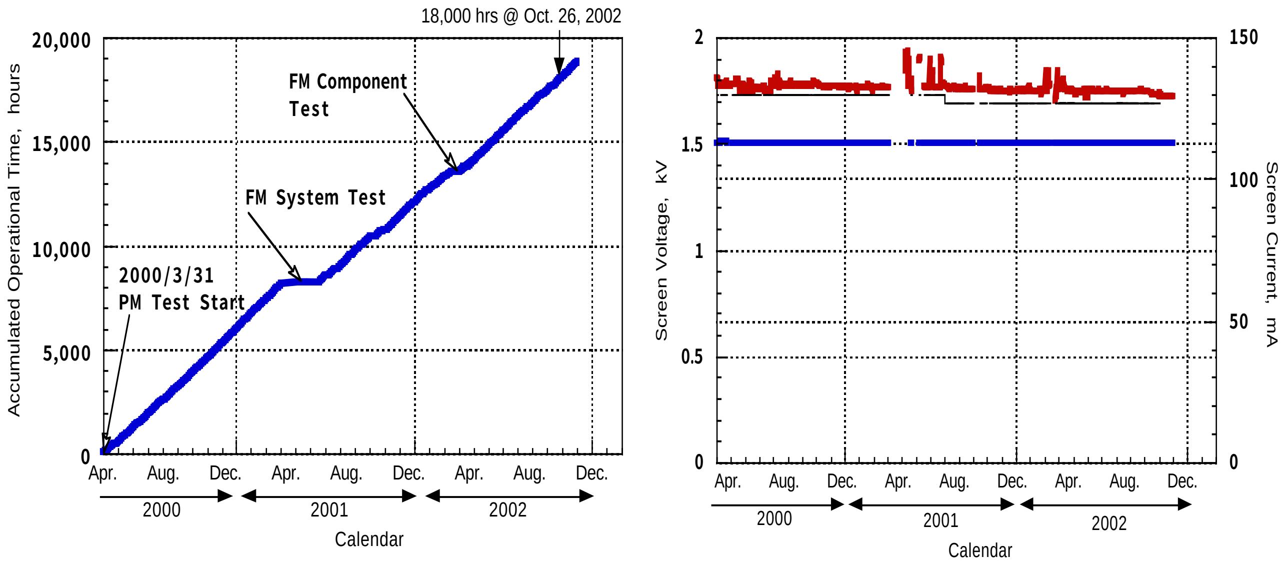


Fig. 9 PM-phase endurance test history (Left: Accumulated operation time vs. calendar, Right: Screen voltage & current vs. calendar).

5. MUSES-C System Integration Test

5.1 PM Integration & Tests

From December 1999 until June 2000, a PM phase system integration & tests are carried out. In this test the IES provided a mechanical test model (MTM) and a thermal test model (TTM) including one actual PM ITR with remaining dummies to be dedicated on the MUSES-C spacecraft structure to mechanical vibration, acoustic, shock and thermal vacuum environment tests. Resultantly the mechanical environment was confirmed for each installation location on the spacecraft and the actual PM ITR showed no problems at all. As for the TTM test, the thermal environments for the round-trip transfer to and from the asteroid and surface observation period are taken into consideration to apply the cases named “Transfer HOT” and “Transfer COLD” and the correlation between the thermal analysis and the test results are compared from the view points of component temperatures and heater sizing. The Xe tank temperature was well within the prediction but higher temperatures were observed in the flow orifices. For the correct flow control, it is determined that the downstream portion of the accumulator (secondary tank) should be voluntarily kept higher than 45 °C. In these PM phase system integration & tests, interfacing with bus DHU (Data Handling Unit) , the ITCU (Ion Thruster Control Unit) which is the IES control unit was tested to clarify the interface healthiness and mainly some precautions were found for the flight operation. Between these testing, FM (Flight Model) microwave amplifiers and PM IPPU (IES Power Processing Unit) are hooked up with PM ITRs to conduct plasma generation and acceleration. Some modifications were found to be necessary in the IPPU. Other tests were also conducted during this phase, such as the EMI (Electromagnetic Interference) tests with other subsystem components, the simulation tests of plasma plume interference with solar array paddle using a 1/10 miniature spacecraft model and the virtual test of spacecraft charging caused by just-in-case failure of the neutralizer. All these tests, however, revealed no fatal problems at all.[6,7]

From April until June of 2001, interface checkout of FMs were underway. In this test the sequences during actual flight were checked out to confirm the proper interface between the bus system and the subsystems including IES. In this test it was found that there was some possibility of noise interference of IES with the star tracker and the null-point detection failure of the gymbal mechanism, however, after the corrective actions they would be improved prior to FM integration & system tests.

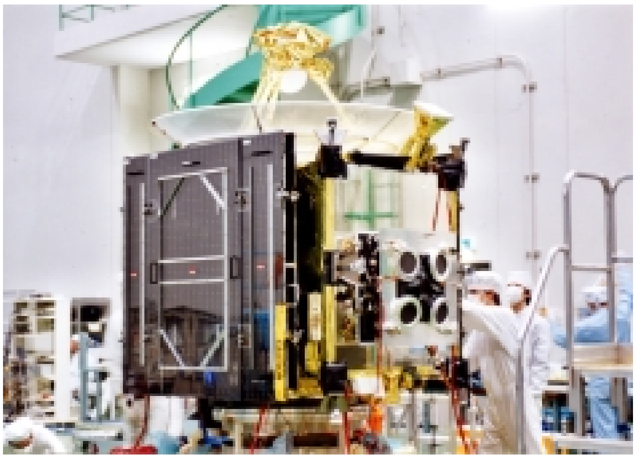


Fig. 10 MUSES-C spacecraft FM integration (as of June 2002).

5.2 FM Integration & Tests

The FM integration & system tests began from December 2001 and will be completed by March 2003 as shown in Fig. 10. The spacecraft integration is now underway including ITA (Ion Thruster Assembly) as shown in Fig. 11, and the electrical function tests are continued step-by-step. In last April, the RCS (Reaction Control System) and the PMU (Propellant Management Unit) for the IES were constructed into the spacecraft in the manufacturer works. As for the IES individual tests, the IPPUs (IES Power Processing Unit) were modified to achieve more stable operation for the actual FM ITR combination, and some electrical parts such as DC blocks which isolate the DC voltage from the microwave frequency voltage and microwave cables integrity were also modified and checked out. And the acceptance level tests (AT) for FMs were conducted such as mechanical vibration test, thermal vac. test, communication tests and simulative flight operation tests. Finally the end-to-end test of IES firing inside a thermal vacuum chamber where the whole systems integration are completed to be dedicated to the thermal vac. test prior to transportation to the launch site. Before implementing this rigorous test, we finished the verification of non-hazardous conditions to the fully integrated FM spacecraft. An ion engine (PM) beaming plasma from the simulative spacecraft was set and operated inside the thermal vac. chamber to evaluate the anticipated contamination and interference. Presently this end-to-end test has been approved to be feasible and is underway in plasma ignition for each of 4 ITHs, reconfiguration for 3 out of 4 selection, automatic flow rate control by PMU, and finally in plasma

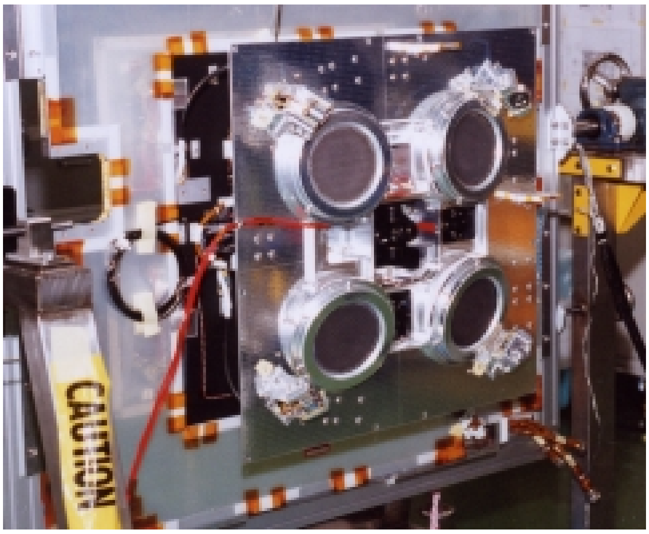


Fig. 11 FM ion thrusters mounted on a gymbal plate.

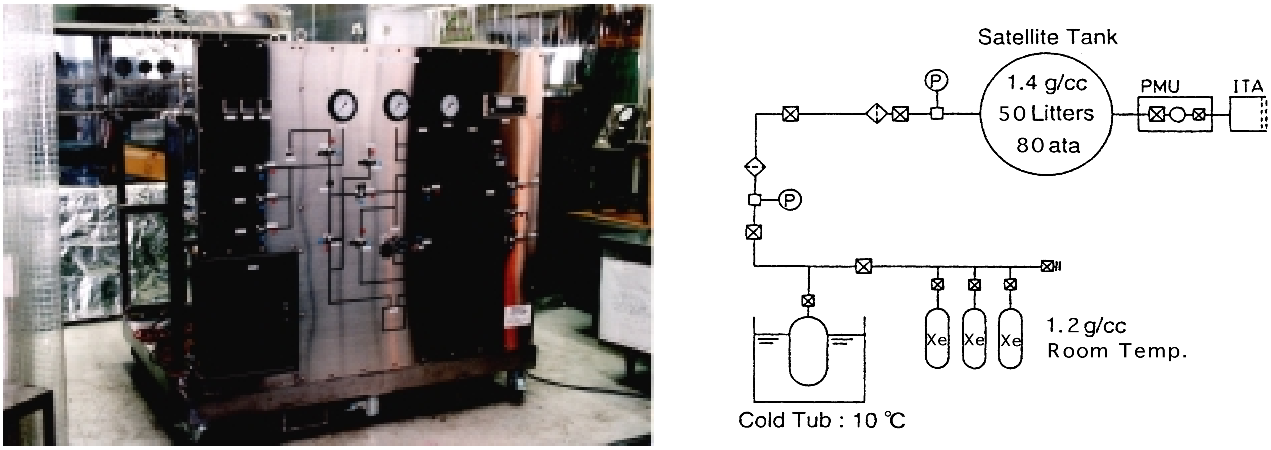


Fig. 12 Xe loading unit (Left) and schematic of liquefaction loading (Right).

beaming acceleration for 10 minutes or so per each thruster.

Besides these FM integration processes and testing, before entering the launch site we also verified a rehearsal of Xe loading by our newly developed liquefaction loading equipment (Fig. 12).[8] In this method the Xe cylinders of 1.2 g/cc density are prepared for press into the cold tub in liquid phase. The liquid Xe is transported into the flight tank of 51.4 litters by gradual heating of the cold tub. Then the cold tub is chilled down again to recycle the liquefaction process. This is repeated twice until the flight tank is filled by 1.4 g/cc Xe.

Acknowledgement

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