DEVELOPMENT OF ION ENGINE SYSTEM FOR ETS-VI

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Abstract

Ion Engine System (IES) for Engineering Test Satellite VI (ETS-VI), which is to be launched in the summer of 1994, is under development successfully. IES will be used for the north-south station keeping of ETS-VI.

This IES for ETS-VI consists of six components, and has features such as 1) the application of high specific impulse xenon ion thrusters for north-south station keeping, 2) simultaneous operation of two thrusters on orbit, 3) full redundant system for high reliability.

After successful completion of qualification tests using prototype and proto-flight models, flight models of ion thrusters are fabricated and now under the final test.

On the other hand, to investigate the interference of neutralizing current, extended tests were performed using two ion thrusters and two neutralizer hollow cathodes. The results showed that the interference of neutralizing current on orbit can be solved by the control of propellant flow rate for the neutralizers.

Introduction

The development of Ion Engine System (IES) for Engineering Test Satellite VI (ETS-VI) has been carrying on by Mitsubishi Electric Corporation (MELCO) under the contract of National Space Development Agency of Japan (NASDA). [1]

ETS-VI is a three-axis controlled, geosynchronous satellite of 2 ton on orbit, and its mission lifetime is 10 years. Xenon ion thrusters of IES will be used for North-South Station Keeping (NSSK) of ETS-VI. [2,3] ETS-VI is to be launched in the summer of 1994 by H-II booster rocket.

After the successful results of qualification test using prototype and proto-flight models (component performance and interface matching in IES was verified), flight models (FM) of 4 thrusters (TRS) / mass flow controllers (MFC) and 3 power processing units (PPU) are now under fabrication. (1 of 4 PPUs is a proto-flight model,PFM). This paper describes the design concepts of ETS-VI IES and its components.

On the other hand, endurance tests using 4 engineering model (EM) thrusters and 2 PM thrusters are carrying on at Tsukuba Space Center of NASDA to verify the life time of ion thrusters. [4] In the endurance tests, interference of neutralizing current has been observed when two or more thrusters are operated simultaneously. [5] Extended tests were performed using two thrusters and two neutralizer hollow cathodes (NHCs), and the results are also described in this paper.

IES Design

Features of IES for ETS-VI

IES for ETS-VI has features listed below.

1) Application of high specific impulse xenon ion thrusters for NSSK.
2) Simultaneous operation of two ion thrusters.
3) Full redundant system for high reliability.
4) Compact design for easy access. (Two ion thrusters, mass flow controllers, and propellant management unit are integrated on one panel called IES Panel.)

Construction of IES

The construction of IES is showed in Fig. 1. As shown in Fig.1, IES is constructed of following six components.

1) One Thruster Control Unit (TCU)
   TCU controls the operation of PPUs and IVDEs in accordance with the desired sequence logic. Also, TCU has the command and telemetry interface with ETS-VI interface unit.

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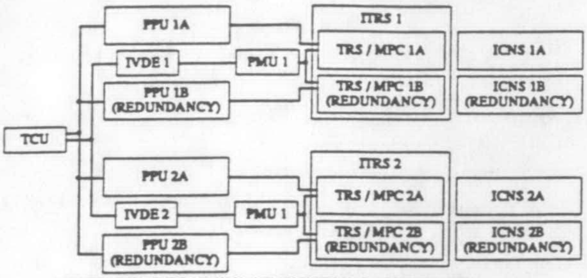

* NOTE : TCU / IVDE / PMU HAVE AN INTERNAL REDUNDANCY

Fig.1 IES SYSTEM BLOCK DIAGRAM

2) Four Power Processing Units (PPUs)
PPU supplies electrical power to ITRS under the control of TCU.

3) Two Ion Clusters (ITRSs)
One ITRS includes two Ion Thrusters (TRS') and two Mass Flow Controllers (MFCs). TRS generates thrust for NSSK under the supply of electrical power from PPU and xenon propellant from PMU via MFC. MFC controls mass flow rate of three routes to TRS independently.

4) Two Propellant Management Units (PMUs)
PMU stores pressurized xenon propellant, and supplies regulated xenon gas to ITRS.

5) Two Ion Engine Valve Drive Electronics (IVDEs)
IVDE supplies electrical power to actuate the latching valves in PMU under the control of TCU.

6) Four Ion Engine Contamination Shields (ICNS')
ICNS protects satellite surface from contamination by TRS.

IES Design Parameters

Main design parameters of IES are shown in Table 1 and detailed description is described below.

Table 1 Main Design Parameters of IES

Thrust Method	Kaufman-type Xenon Ion Thrusters
Operation Configuration	Simultaneous Operation of Two Thrusters
Thrust of Individual TRS	23.3 mN (Thrust Coefficient of 0.93 is assumed.)
Resultant Thrust	40.3 mN (Cant angle of 30 deg. is assumed.)
Specific Impulse	over 2516 sec
Power Comsumption	1570 W
Weight	< 98.7 kg
Propellant Weight	41 kg for 10 years operation
Total Operating Time	6500 Hrs
Total No. of Ignition	2920 cycles

1) Thrust / Specific Impulse

IES generates resultant thrust of 40.3 mN for NSSK. (Two TRS' are simultaneously operated, and each TRS is canted by 30 degrees. Thrust loss coefficient of 0.93 is assumed for TRS.) And effective specific impulse is over 2516 s. (2906 s for each TRS.)

2) Power Consumption / Heat Dissipation

Power consumption and heat dissipation in nominal operation (simultaneous operation at 23.3 mN thrust for each TRS) are 1489 W and 529 W respectively, and their breakdowns are as follows.

Component	Power Consumption	Heat Dissipation
TCU	8W	8W
PPU	1471W*	222W
ITRS	(1249W)	289W**
PMU	6W	6W
IVDE	4W	4W
TOTAL	1489W	529W

(*: Output for ITRS (1249W) is included.)
(**: Ionization loss is included.)

3) Mass

The dry mass of IES is under 98.7 kg, and propellant mass is estimated to 41 kg for 10 years mission.

Component	Mass*
TCU	7.7kg ×1
PPU	10.3kg ×4
ITRS	11.7kg ×2
PMU	10.2kg ×2
IVDE	1.2kg ×2
ICNS	0.3kg ×4
TOTAL	96.3kg

*: Based on the measured value of PFM/FM

4) Operation Time

IES will be operated four times a week, and one operation will be 3 hours, so the total operation time is estimated to 6000 hours and the number of firings is 3000 times for 10 years mission.

5) Operation Mode

IES has the following five operation modes.

a. Idling Mode (IDLG Mode)
In IDLG mode, low power is supplied to hollow cathode heaters (both Main Hollow Cathode : MHC and Neutralizer Hollow Cathode : NHC) for degassing.

b. Activation Mode (ACTV Mode)
In ACTV Mode, high power is supplied to hollow cathode heaters (both MHC and NHC) to activate them.

c. Neutralizer Mode (NEUT Mode)
In NEUT Mode, only the NHC keeper discharge is ignited and kept. This mode will be used for the experiment to control the spacecraft charging.

d. Discharge Mode (DISC Mode)
In DISC Mode, only the main discharge (including the MHC keeper discharge) is ignited and kept.

e. Beam Mode (BEAM Mode)
In BEAM Mode, IES generates thrust for NSSK maneuver.

Operation

On ETS-VI, two TRS' are installed on both east and west panels, and each one of those two TRS' will be operated simultaneously to produce the resultant thrust in the -Y (north) direction for NSSK maneuver during the required period at the center of the node point.

The control of each component in IES is performed by the software logic installed in TCU and the hardware logic installed in PPU.[1] (The major functions of PPU hardware logic are the high-speed control for the protection of the PPU circuits and TRS critical parts when so-called High Voltage Break Down in TRS' beam extraction system occurres.) The total control of IES is executed by the sequential commands to each component from TCU software logic.

For the practical NSSK maneuver by IES, BEAM Mode and PMU / IVDE Auto Mode are to be selected, and IES operates automatically. IES starts its operation when it receives " IES START " command from ground, and both PPU control algorithm and PMU / IVDE control algorithm are to be run. IES operation is to be terminated when it receives "SHUT OFF " command after turning off every power supplies of selected PPUs and closing every latching valves of selected PMUs. This " SHUT OFF " command is to be output by TCU when " ALARM " status signal is generated in whether PPU algorithm or PMU / IVDE algorithm , or by ground command. Fig. 2 shows the concepts of the command sequences from ground and control / operation of IES when BEAM Mode and PMU / IVDE Auto Mode are employed.

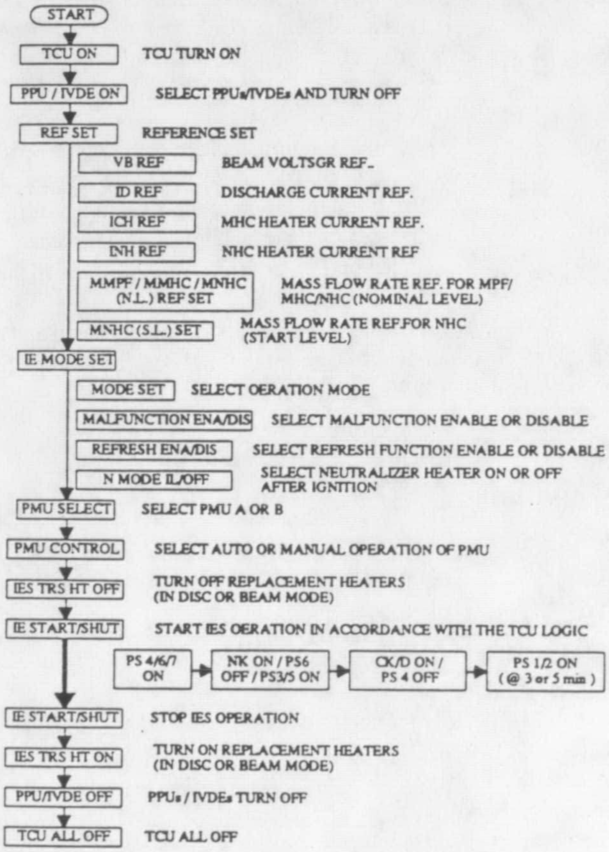

Fig. 2 Command Sequences of IES

IES Component Design

TCU

TCU has two one-chip CPU's and fully redundant electronics. It controls the operation of IES in accordance with the software logic installed in ROM of TCU and also manages telemetry / command data.

TCU software logic has the following two major algorithms.

1. PPU control algorithm
(Electrical Power Feed Algorithm for ITRS)
TCU controls on/off procedure and output levels of eight P/Ss in every PPU according to the operating status signals from PPU, such as 5 monitoring signals (Ink_m, Ick_m, Id_m, $HVBD_m$, $VBUS_m$). The start-up procedure of TRS is performed by these on/off and level control of P/Ss in PPU. Restart procedures for sudden discharge-out or HVBD is also included in algorithm.

2. PMU / IVDE control algorithm
(Xe Gas Feed Algorithm for ITRS)
Open / close controls of 8 latching valves in PMU are performed by this control logic in accordance with the open / close status signals and sub-tank pressure monitoring signals from PMU. The control of PMU / IVDE is performed by TCU automatically (in Auto Mode) or by the ground commands (in Manual Mode).

PPU

PPU supplies electrical power to ITRS by the following eight power supplies.

1. Beam Power Supply (PS 1, Vb/Ib)
Beam P/S is a constant voltage P/S (C-V P/S), and the voltage (Vb) is variable by command from 800 V to 1200 V.
2. Accelerator Power Supply (PS 2, Va/Ia)
Accelerator P/S is also a C-V P/S, and Va varies from 400 V to 600 V in accordance with the value of Vb.
3. Main Discharge Power Supply (PS 3, Vd/Id)
Main discharge P/S is a constant voltage - constant current P/S (C-V/C-C P/S). It works as C-V P/S before ignition, and as a C-C P/S after ignition. The voltage before ignition is 100 V, and the current after ignition is variable by command from 2.0 A to 4.0 A.
4. MHC Heater Power Supply (PS 4, Vch/Ich)
MHC heater P/S is a C-C P/S.
5. MHC Keeper Discharge Power Supply (PS 5, Vck/Ick)
MHC keeper discharge is a C-V/C-C P/S similar to P/S 3. The voltage before ignition is 150 V, and the current after ignition is 0.5 A constant.
6. NHC Heater Power Supply (PS 6, Vnh/Inh)
NHC heater P/S is a C-C P/S similar to P/S 4.
7. NHC Keeper Discharge Power Supply (PS 7, Vnk/Inh)
NHC keeper discharge P/S is a C-V/C-C P/S similar to PS 5.

8. MFC Power Supply (PS 8)
MFC P/S is a C-V P/S, and it supplies electrical power at constant voltage of ± 15 V.

PPU also outputs telemetry signals to TCU in order to monitor the performance of TRS. The telemetry signals are Vb/Ib, Ia, Vd/Id, Vck, Vch/Ich, Vnh and Vnk/Ink.

PPU includes protection circuits to prevent P/Ss and TRS from being damaged at high voltage breakdown (HVBD).

ITRS

ITRS consists of a clusterbracket, two TRS', two MFCs and other small parts including thermal control equipments. The clusterbracket is made of CFRP and Al-honeycomb panels, and it provides appropriate mechanical and thermal conditions for TRS' and MFCs. Also, it provides proper cant angles for TRS' (approximately 30 degrees). The photograph of ITRS is shown in Fig.3.

TRS of ITRS is a Kaufman-type electron-bombardment xenon ion thruster. Nominal thrust level (actual thrust) is 23.3 mN and it is adjustable within the range from 18.6 mN to 27.9 mN by changing the mass flow rate of MHC and MPF (Main Propellant Feed), discharge current, or beam voltage. The actual thrust T_{act} is calculated by following equation.

$$T_{act} = \alpha \times T_{ideal}$$
$$= \alpha_d \times \alpha_{Xe}^{++} \times T_{ideal}$$

where

α: Thrust correction Factor ($\alpha_d \times \alpha_{Xe}^{++}$)
T_{ideal} : Ideal thrust calculated by following equation

$$T_{ideal} = I_b \times (2mV_b / e)^{0.5}$$

α_d: Thrust correction factor by beam divergence angle
α_{Xe}^{++} : Thrust correction factor by doubly charged ions
I_b : Beam current (A)
V_b : Beam voltage (V)
m: Xe ion mass (kg)
e: Electric charge (Coulomb)

Thrust correction factor α is assumed as 0.93. The measurements of the beam divergence angle and the fraction of doubly charged ions showed that the correction factor α is greater than 0.97, and direct thrust measurement also showed the same result.[6] (Actual thrust was measured by thrust stand.) The photograph of TRS is shown in Fig.4.

MFC of ITRS has thermal flow sensors and thermal valves, and it independently controls the mass flow rate of three propellant feed lines to TRS (MHC/MPF/NHC). This controllability enables TRS to operate always at its best operating point.[7] The photograph of MFC is shown in Fig.5.

PMU

PMU consists of one main tank, one fill-drain valve and one subtank module (STM) which includes two subtanks, eight latching valves and three pressure transducers (one for high pressure and two for low pressure). Above parts are installed on IES panel prepared by ETS-VI system.

Xenon propellant is stored in main tank at 9.8 MPa (MEOP), and is depressurized to 0.25 MPa through STM by open-close procedure. When PMU Auto Mode is selected, TCU controls the open/close procedure in accordance with the selected TRS and PMU automatically. In that case, TCU controls the filling up process by monitoring the signals from pressure transducers. When PMU Manual Mode is selected, any latching valve can be opened or closed by the ground command. The photograph of PMU is shown in Fig.6.

IVDE

IVDE supplies electrical power to actuate latching valves in STM in accordance with the open/close signals from TCU.

ICNS

When ion thrusters are operated on spacecraft, some portions of thrusters are eroded by ion sputtering. It causes contamination to the spacecraft surface, and influences its thermal control.[8] Therefore, ICNS' are installed on IES panel in front of TRSs to prevent the contamination.

ICNS is made of aluminum alloys, and its surface is anodized black for thermal control. The photograph of ICNS is shown in Fig.7.

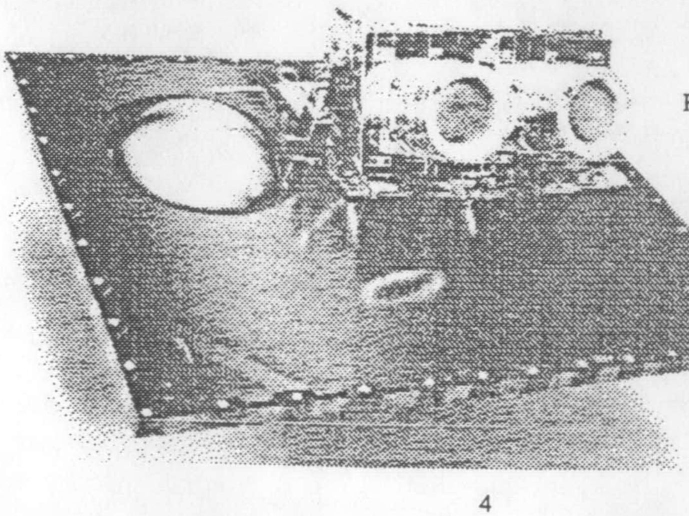

Fig.3 Photograph of ITRS
(on IES Panel)

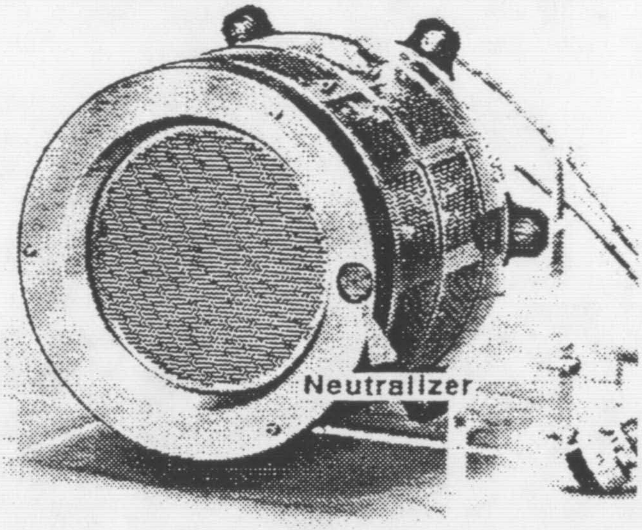

Fig.4 Photograph of TRS

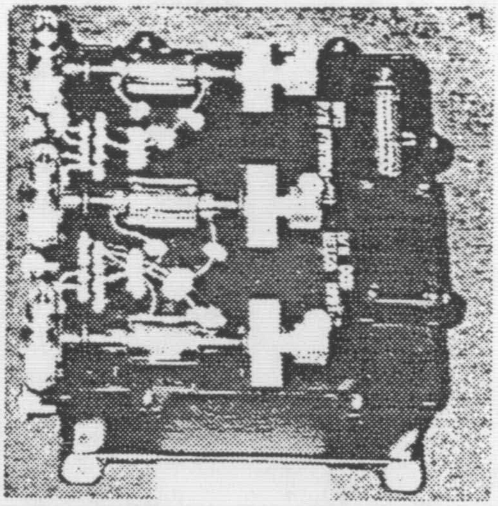

Fig.5 Photograph of MFC

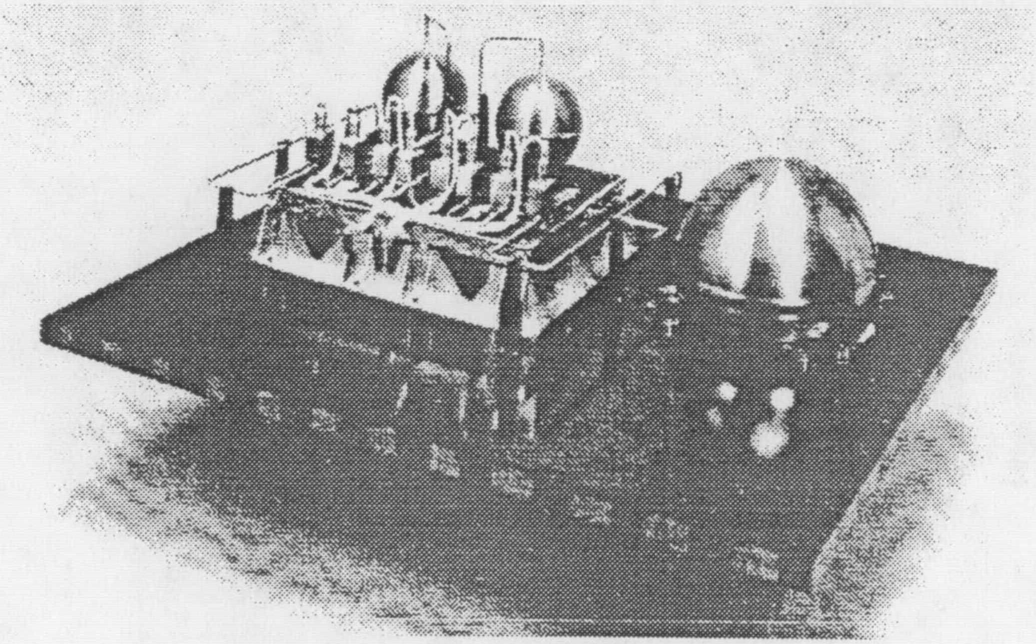

Fig.6 Photograph of PMU (on IES Panel)

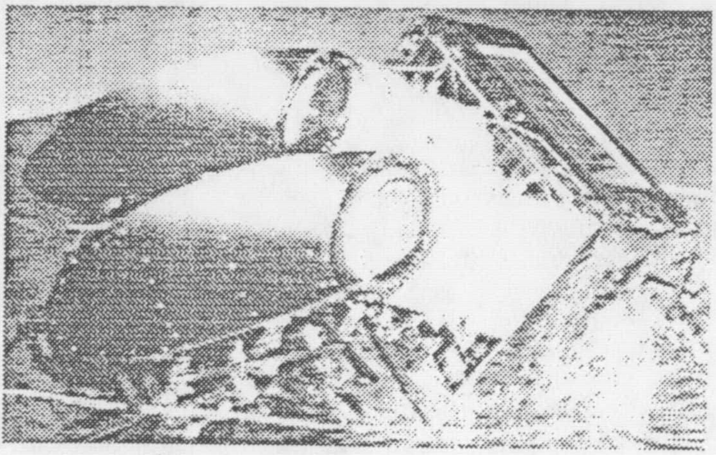

Fig.7 Photograph of ICNS (with ITRS)

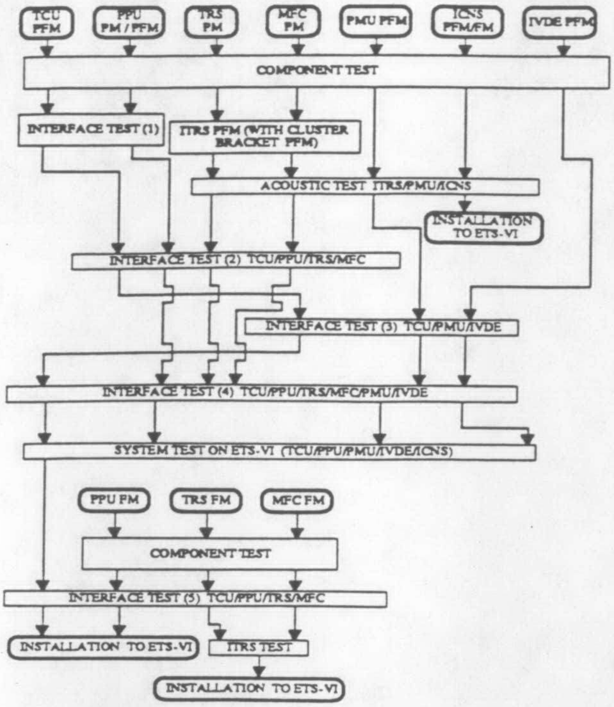

Fig.8 Test Flow for PM/PFM/FM

Components and Subsystem Tests

Both component-level and subsystem-level tests were conducted to directly confirm the design and fabrication to meet the requirement of ETS-VI. The environmental tests such as thermal vacuum, sinusoidal vibration, random vibration and acoustic tests were also performed. The tests flowchart for PM/PFM/FM are shown in Fig.8.

Neutralization Problem

Extended tests were performed to investigate the imbalance of neutralizing current in simultaneous operation of ion thrusters. The tests were divided in two cases, 1) NHC level, 2) TRS level. Test configurations and their results were as follows.

NHC Level Test Configuration and Results

NHC level test was performed in a small bell-jar (40 cm in diameter), attached to a cryo-pumping unit, whose pumping speed is 10000 L/s for nitrogen. The pressure in the chamber was 8.0×10^{-4} Pa in operation, and under 2.7×10^{-6} Pa before operation. The distance between hollow cathode and collector electrode was 25 mm, and that between two hollow cathodes was 100 mm (see Fig.9).

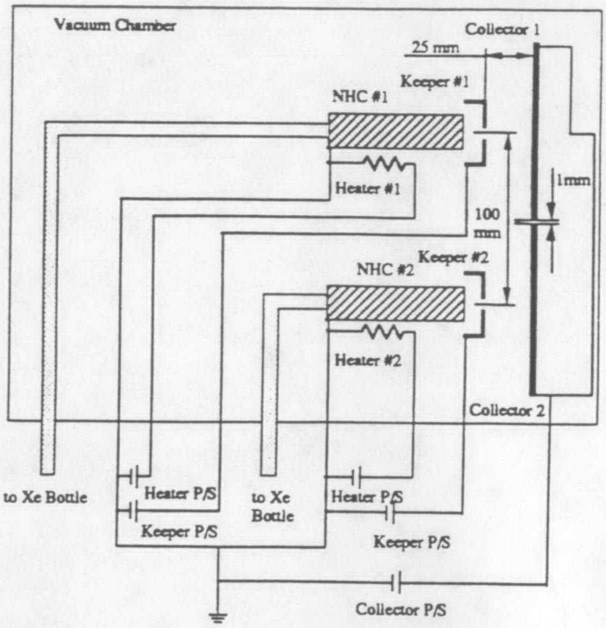

Fig.9 H/C Level Test Configuration

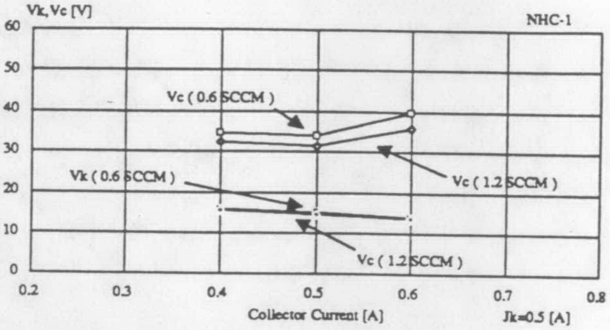

FIg. 10 (1/2) Discharge Characteristics of NHC-1

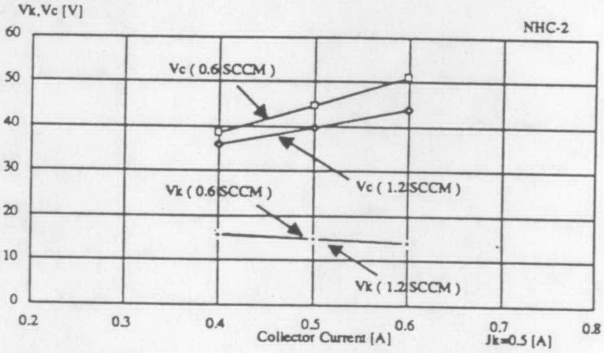

FIg. 10 (2/2) Discharge Characteristics of NHC-2

Before the evaluation of simultaneous operation of 2 NHCs, single operational characteristics of each NHC was measured and the results are shown in Fig. 10. (NHC keeper current was fixed at 0.5 A in all cases.) As shown in Fig.10, in single operation, collector voltage Vc for NHC-1 is lower than that for NHC-2, which means that NHC-1 has a better characteristics for electron emission.

In a simultaneous operation case, total collector current was fixed at 0.8/1.0/1.2 A, and mass flow rates for each NHC were changed from 0.5 to 1.0 SCCM. In each case, total collector current, collector current (Ic) from each NHC, collector voltage(Vc), and keeper voltage

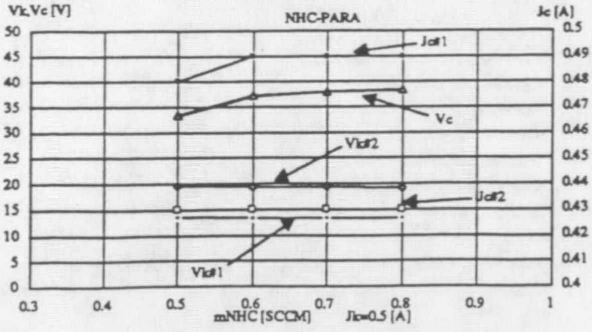

FIg. 11 Discharge Characteristics of Simultaneous Operation

(Vk) of each NHC were measured. (NHC keeper current was also fixed at 0.5 A in these tests.) The example of result obtained in these tests is shown in Fig.11.

The results of these tests showed that the difference of collector current from each NHC was about 50 ~ 80 mA, which is considerably small compared to the value estimated from single operation test results. (For example, in case of mass flow rate = 0.6 SCCM, and Vc = 36 V for each NHC, Ic is estimated 0.56 A for NHC-1 and 0.4 A for NHC-2 from Fig.10, and the difference is 160 mA. But the results of simultaneous operation test showed that the difference is only 80 mA.)

Also, the sensitivity of collector current imbalance to the mass flow rate is very small in simultaneous operation. As shown in Fig.11, the difference of collector current is almost constant, though mass flow rate of NHC-2 is increased from 0.5 to 0.8 SCCM.

TRS Level Test Configuration and Results

Neutralizing current balance was evaluated using 2 TRS' (PM TRS and EM TRS) in Ion Engine Test Facility at Tsukuba Space Center of NASDA.[9] Test configuration is shown in Fig.12. Similar to the NHC level test, NHC characteristics of each TRS in single operation was measured before a simultaneous operation, and the results are shown in Fig.13. From these results, NHC of TRS PM has a better characteristics for neutralization of ion beam.

The typical result of simultaneous operation is shown in Fig.14. The test was performed by following procedures.

1. Operate each thrusters at a chosen thrust level. In this test, thrust levels for each thrusters were selected as follows.
    1) 23.3mN for both thrusters (see Fig.14)
    2) 21.4mN for TRS EM and 27.9mN for TRS PM
    3) 27.9mN for TRS EM and 21.4mN for TRS PM

    (Beam current for 23.3mN thrust is 480mA,and 440mA for 21.4mN, 560mA for 27.9mN.)
2. Set mass flow rate of each NHC at 0.4 SCCM (case1), 0.5 SCCM (case2), 0.6 SCCM (case3) and 0.7 SCCM (case4).
3. After the measurement of operating parameters, the mass flow rate for NHC whose neutralizing current is less than the other at initial point is increased and repeat the measurement.
4. Continue above procedures until each neutralizing current reaches the same value.

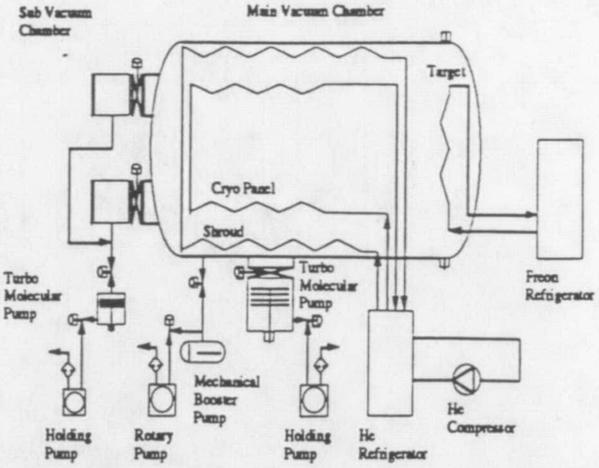

Fig.12 TRS Level Test Configuration

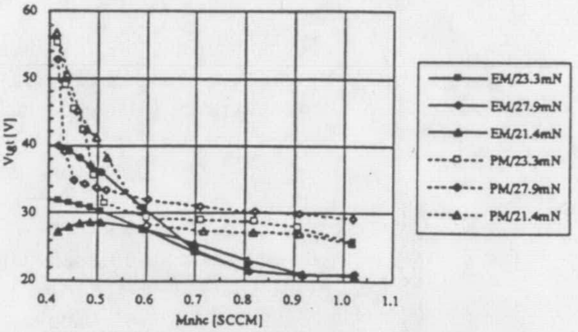

Fig.13(1/2) Discharge Characteristics of TRS

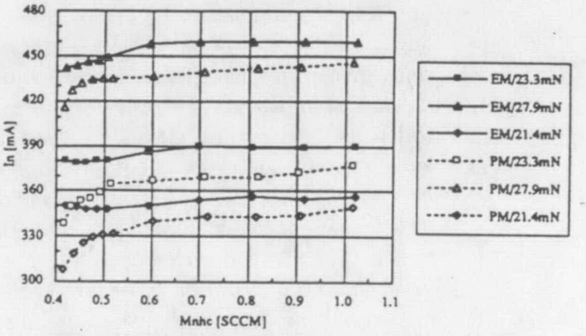

Fig.13(2/2) Discharge Characteristics of TRS

As shown in Fig.14, the tendency of neutralizing current in TRS level is quite different from NHC level test results. First, in most cases, neutralizing current from TRS PM, whose NHC is less efficient for neutralization, is larger than that from TRS EM. Second, the sensitivity of neutralizing current balance is very large, and it is easy to control each neutralizing current at a balanced level by changing the mass flow rates.

The mechanism which determines the distribution of neutralizing current is not clear at present, but we suppose that the distribution is determined under 2

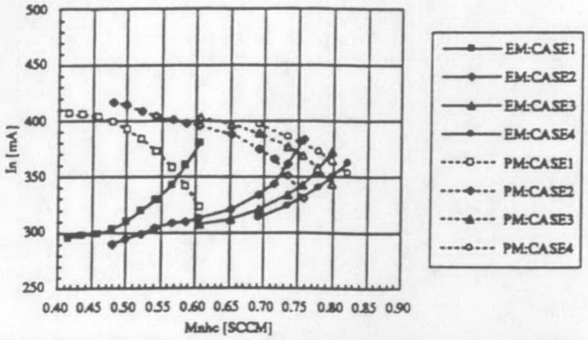

Fig.14 Typical Result of Simultaneous Operation of TRS

restrictions as follows.

1. To lower the target potential according to the V-I characteristics of each NHC. (Note that NHC of TRS PM has a negative V-I characteristics.)
2. To minimize the potential difference at neutralizing surface of each TRS. (Note that each ion beam has a same potential at the beam target.)

Discussion

Test results described above were investigated together with the test results obtained in IES test at MELCO Kamakura (TRS-level #2) and another NHC level test (NHC-level #2) in which collector potentials for each NHC were kept at different values. (In this test, resistors (about 10Ω) were inserted in each collector power line to produce the potential difference.)

The features of those 4 test results and configurations are shown schematically in Fig.15 and Table 2.

The imbalance of neutralizing current is caused by following two items ; 1. the emission ability of NHCs, 2. the electric field to extract electrons from NHC. And the differences of above four test configurations are 1. the distance between two neutralizers, 2. whether the electric field is induced by ion beam or collector, 3. the distance between two collectors or ion beams. With above considerations, the mechanism for test results are explained as follows.

In NHC-level tests, as the distance of NHC is very small, the keeper plasma can interfere with each other. This results in the small imbalance and the low sensitivity of the distribution to the mass flow rates. However, when the potential of two collectors are different, the distribution changes in accordance with the shape of electric field.

In the test of TRS-level #2, the distance between NHCs is intermediate, but still the interference can occur. This causes a difficulty to balance the neutralizing current by controlling the mass flow rates. On the other hand, when the electric field is induced by ion beams, the neutralization surface can vary its position. This causes the imbalance though two ion beams intersect near the thruster. In the test of TRS-level #1, the distance between NHCs is large, additionally chamber wall (which has a GND potential) exists between NHCs. Therefore, the interference of keeper plasma cannot occur, and each NHC show their characteristics. This enables easy balancing of neutralizing current by the control of mass flow rates. In this case, imbalance is caused by the ristriction that the target is unique.

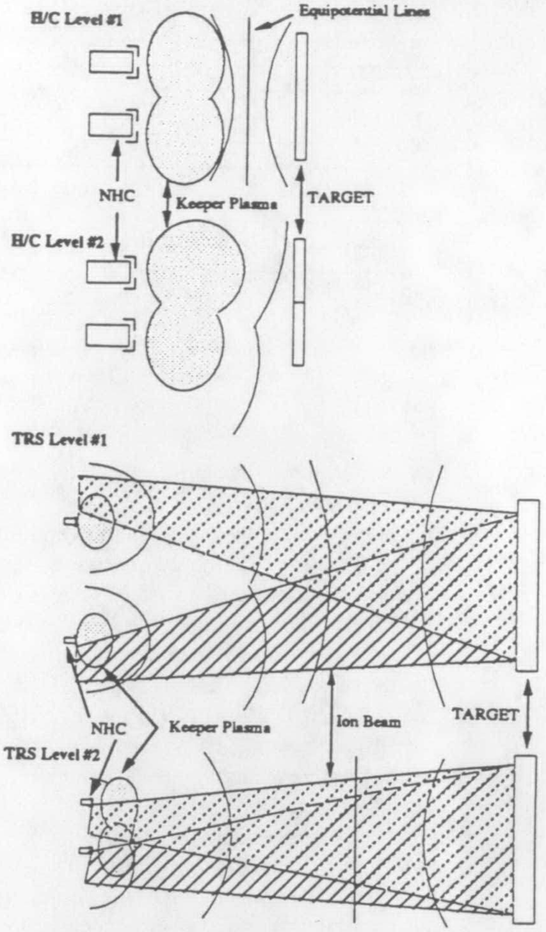

Fig.15 Characteristics of Test Configurations

Table2 Tendencies of Test Results

	H/C Level #1	H/C Level #2	TRS Level #1	TRS Level #2
Ion Beam	No	No	Yes	Yes
Distance between NHCs	Near	Near	Far	Medium
Target Potential	Equal	Different	Equal	Equal
Distance between NHC and Target	Near	Near	Far	Far
Imbalance	Not Observed	Large	Large	Large
Controllability	N/A	Possible but Difficult	Possible	Possible but Difficult

As for the on-orbit operation of ETS-VI IES, though two ion beams would not intersect each other, there is still a possibility that the interference will occur, because two NHCs (or TRS') have the same common potential. However, the imbalance will be smaller than the test results obtained in TRS level tests. Moreover, because two TRS' is installed on east and west panels of satellite, it will be easy to balance the neutralizing current by the control of mass flow rates.

However, if two or more ion thrusters will be installed closely like the case in SERT-II or EOTV (Electrically-propelled Orbit Transfer Vehicle), it will be necessary to consider this problem[10]. (One solution of this problem is to prepare a bias power supplies for neutralizers whose bias voltage is controlled in accordance to the neutralizing current distribution like SERT-II.)

Neutralizer Experiment for Spacecraft Charging

Neutralizer experiments for spacecraft charging using neutralizer of ion thrusters is planned by Tsukuba Space Center of NASDA .The potential of satellite is measured by Potential Monitor (POM) of Technical Data Acquisition Equipment (TEDA), and the changes of satellite potential induced by the operation of ion thrusters, especially neutralizers, will be evaluated. Details of the experiment is now under study, but valuable results are expected like that obtained in ATS-6 and SERT-II[10,11] .

Concluding Remarks

Development status of IES for ETS-VI is described, including its design concepts, features and operation. Test results of PFM/FM showed no serious obstacles for its launch in 1994.

The extended test results about the interference of neutralizing current are also described. The results show that there is a possibility of imbalance on orbit. However it will be solved by controlling the mass flow rates of each NHCs.

References

1. Shimada, S. et al., "Ion Engine System Development for ETS-VI", IEPC-91-145, AIDAA/AIAA/DGLR/JSASS 22nd International Electric Propulsion Conference, Oct. 1991, Italy
2. Poeschel, R. L., " Ion Propulsion for Communications Satellites , " IEPC Paper 84-43, JSASS / AIAA / DGLR 17th International Propulsion Conference, May 1984, Tokyo, JAPAN
3. Day, M. L. et al., " Intelsat VII Ion Propulsion Subsystem Implementation Study , " AIAA Paper 90-2267, AIAA / DGLR / JSASS 21st International Electric Propulsion Conference, July 1990, Orlando, USA
4. Shimada, S. et al., "Ion Thruster Endurance Test Using Development Model Thruster for ETS-VI. ", IEPC-93-169, AIAA/AIDAA/DGLR/JSASS 23rd International Electric Propulsion Conference, Sept. 1993, Seattle, USA
5. Shimada, S. et al., "Evaluation of Ion Thruster Beam Neutralization.", IEPC-91-025, AIDAA/AIAA/DGLR/JSASS 22nd International Electric Propulsion Conference, Oct. 1991, Italy
6. Shimada, S. et al., "Beam Characteristics Evaluation of ETS-VI Xenon Ion Thruster.", IEPC-93-236, AIAA/AIDAA/DGLR/JSASS 23rd International Electric Propulsion Conference, Sept. 1993, Seattle, USA
7. Shimada, S. et al., "Mass Flow Controller of Ion Engine System.", IEPC-91-109, AIDAA/AIAA/DGLR/JSASS 22nd International Electric Propulsion Conference, Oct. 1991, Italy
8. Shimada, S. et al., " Ion Thruster Contamination Evaluation, " AIAA Paper 89-2269, AIAA / ASME / SAE / ASEE 25th Joint Propulsion Conference, July 1989, Monterey, USA
9. Kajiwara, K. and Katada, M., " Test Facilities for the ETS-VI Ion Engine System, " AIAA Paper 90-2656, AIAA / DGLR / JSASS 21st International Electric Propulsion Conference, July 1990, Orlando, USA
10. Kerslake, W. R. et al., "Neutralization Tests on the SERT-II Spacecraft.", AIAA-79-2064, PRINCETON/AIAA/DGLR 14th International Electric Propulsion Conference, Oct. 1979, Princeton, USA
11. Olsen, R. C., "Operation of the ATS-6 Ion Engine and Plasma Bridge Neutralizer at Geosynchronous Altitude.", AIAA/DGLR 13th International Electric Propulsion Conference, Apr. 1978, San Diego, USA