# RESEARCH AND DEVELOPMENT OF 150-mN XENON ION THRUSTERS

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Research and development activities on 150-mN xenon ion thrusters are described to define what achievements have been obtained so far and what matters are still open. After a couple of redesigning and trial fabrication to improve thruster performance, the first breadboard thruster achieved a very low ion production cost of 104 W/A, which was well blow the target of 140 W/A. On endurance, 1,000-h and 5,000-h thruster tests were conducted. Results suggested that the grid system would have a lifetime of about 25,000 h though it was a rough estimation. Results of a hollow cathode wear test suggested that it would be over 30,000 h before its orifice plate, one of the critical elements, is completely worn out. In the power conditioner development, high efficiencies of 88% and 87% were achieved on the beam and discharge power supplies, respectively. Main open matters are on thruster and cathode endurance, vibrations during launch, and power conditioner development.

## 1. Introduction

Japan has started using ion thrusters in space applications. Ion engine systems were launched for north-south station-keeping of ETS-6 and COMETS in 1994 and 1998, respectively. Unfortunately, both these ion engine systems could not be operated as planned because the satellites were not inserted into the geostationary orbit. Another plan is now being made to use ion engines on ETS-8, which is scheduled for launch in 2004. Though these thrusters are of direct current discharge type, a microwave discharge ion thruster is currently under development for MUSES-C [1].

The next target application for ion thrusters is primary propulsion with large thrust. In Japan, studies are being carried out into scientific space missions for which ion propulsion will be essential. One of these is an exploration mission of the polar regions of the Sun from a solar polar orbit. Although the study assumes Earth and Jupiter swing-bys to accelerate the spacecraft, it also indicates that using an ion propulsion system can significantly increase the payload. Another study is of a space-based X-ray telescope to observe the galaxy. They are planning to separate its mirror and sensor sections into a two-spacecraft cluster and to maintain the distance and orientation between them in an Earth orbit with no connecting structures. While one of the sections can fly along a Keplerian orbit, the other must keep thrusting continuously to maintain relative position. From a practical point of view, ion propulsion is very attractive by payload increase if it is applied to orbit transfer from LEO or GTO to GEO along with H-2A launch vehicles.

Although these missions are still in the study phase, research and development of appropriate ion propulsion systems must be started far in advance. The ion thrusters already developed or under development described above have thrust levels ranging approximately from 8 to 25 mN. These thrust levels are much less than the requirements for such missions.

Research and development was started with the aim of establishing basic technology of 150-mN class xenon ion thrusters for application to orbit transfer vehicles and to other missions requiring large velocity increments. In this paper, we will describe what has been achieved on the 150-mN thrusters, and also present on-going and further work which will be required to complete the research and development program.

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## 2. Research and Development Program of 150-mN Ion Thrusters

The research and development program of 150-mN-class thrusters was started in 1987 as a collaboration project of the National Aerospace Laboratory (NAL) and Toshiba Corporation and in cooperation with the National Space Development Agency of Japan. The objective of the program is to develop xenon ion thruster technologies for primary propulsion up to the phase which enables us to start engineering model development

The thrusters under development are of electron bombardment type, and have a thrust of 150 mN, specific impulse of 3,500 s. They use a ring-cusp magnetic field for the main discharge plasma confinement. The main specifications were determined by considering that the thrusters would be applied for orbit transfer vehicles launched by H-2 launch vehicle family. Target performance of the thrusters was set as an ion production cost less than 140 W/A at a discharge-chamber propellant utilization efficiency of 90%. The 3,500-s specific impulse corresponds to beam energy of 1 kV at 90% discharge-chamber propellant utilization efficiency. Lifetime requirement of the thruster was set as 30,000 h though it is tentative.

The specific impulse was optimized for orbit transfer missions using an H-2 Launch Vehicle. However, it can be raised easily to a certain extent by increasing the beam voltage, with increased isolation capability, in the case that the thrusters are applied for much larger $\Delta V$ missions. The thrust level was determined for rather practical reasons; the thruster diameter and xenon flow rate should have been compatible with the ion thruster test facility at NAL. Clustering the thrusters in a reasonable number can attain the thrust level required for the orbit transfer vehicles. If smaller levels of the thrust are required, they can be easily obtained by throttling. Even when much smaller thrusters are needed, development of such thrusters will be carried out without difficulties on the technological basis of this program.

The current research and development program covers main aspects required for developing ion thrusters; performance improvement, endurance improvement, compatibility with launch environment, and power conditioner development. Among these, tasks on performance improvement have been already completed, and the others are currently in progress.

## 3. Thruster Performance

### Performance Improvement

Thruster design, fabrication and testing were repeated to improve thruster performance and to achieve the target performance [2]. Three models (four thrusters) were fabricated; the first laboratory model mark-1 (LM-1-MK-1), the first laboratory model mark-2 (LM-1-MK-2), the second laboratory model (LM-2), and the first breadboard model (BBM-1). Figure 1 shows a sectional view of the BBM-1 thruster, the latest model for performance improvement. Table 1 shows the performance parameter targets and the achieved values. Figure 2 shows performance data obtained from the four thrusters, indicating how the performance improvement progressed. Descriptions of these thrusters are given below.

### LM-1-MK-1 Thruster

First, the LM-1-MK-1 thruster was designed for preliminary operation. It has a two-grid ion accelerating system of 30-cm diameter. The grids were made of stainless steel and formed convex. Twelve circumferential plate springs were used to support each of the grids so as to absorb thermal expansion of the grids. Five magnet rings were installed in the discharge chamber to form the cusped magnetic field; three were on the sidewall and two on the endwall. Test results of the LM-1-MK-1 showed an ion production cost of 139 W/A at a propellant utilization efficiency of 90%.

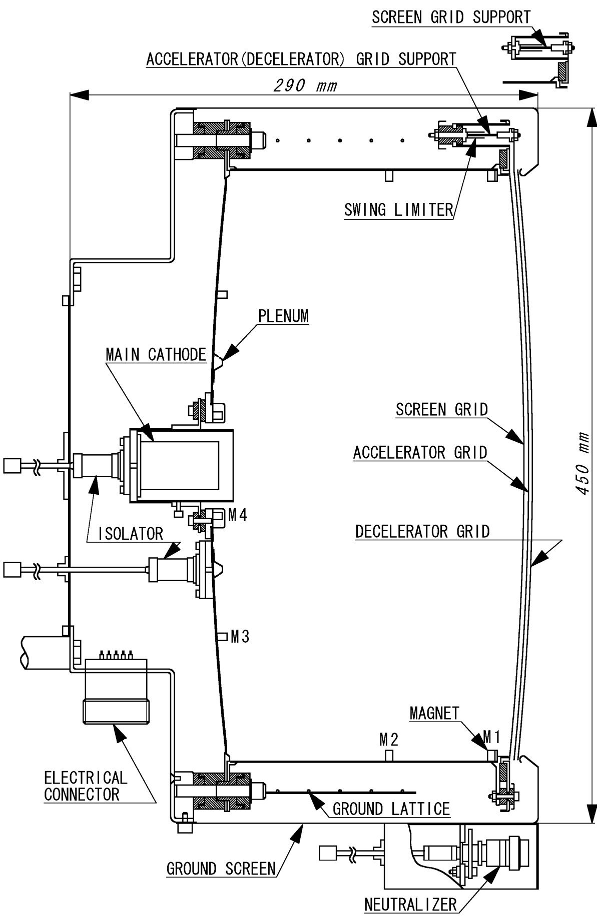



Fig. 1 Sectional view of the BBM-1 thruster.

The highest magnet temperature was $283^{o}$C, while the target is lower than 200 $^{o}$C to prevent magnet degradation. Of the five magnet rings, the inner magnet ring on the endwall reached the highest temperature. As a result of the evaluation, we found that improvements were necessary to achieve more stable operation and to reduce the magnet temperatures.

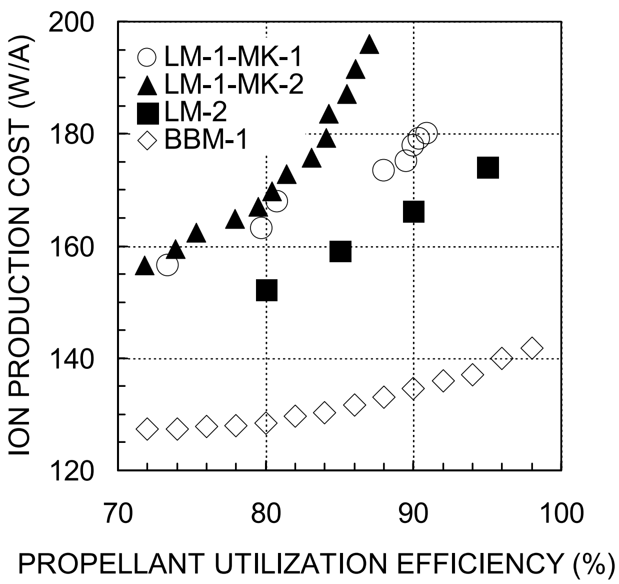
Table 1  Performance parameter targets and the achieved values.

| Parameter | Targeted | Achieved |
|---|---|---|
| Thrust,* mN | 150 | 150 |
| Specific Impulse,*† s | 3500 | 3518 |
| Total Electric Power, kW | < 3.4 | 3.29 |
| Xenon Flow Rate, mAeq. | | |
| Discharge Chamber | 3200 | 3200 |
| Neutralizer | < 70 | 70 |
| Total | < 3270 | 3270 |
| Propellant Utilization,† % | 90 | 90.0 |
| Ion Production Cost,‡ W/A | < 140 | 104 |
| Startup Time, min | < 10 | 13 |
| Beam Voltage,§ V | 1030 | 1030 |
| Beam Current, A | 2.88 | 2.88 |
| Accel. Grid Voltage, V | <500 | 300 |
| Accel. Grid Current, mA | < 29 | 12.7 |
| Decel. Grid Voltage, V | 0 | 0 |
| Decel. Grid Current, mA | < 29 | 7.0 |
| Discharge Voltage, V | < 30 | 30.0 |
| Discharge Current, A | < 16.4 | 12.9 |
| Neut. Keeper Voltage, V | < 20 | 22.8 |
| Neut. Keeper Current, A | < 1.2 | 1.0 |

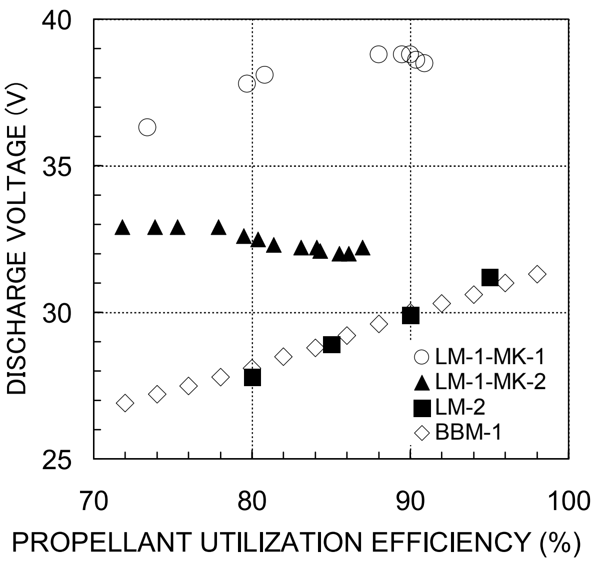
ot corrected for beam divergence and double ions.
† Neutralizer flow rate not included.

**LM-1-MK-2 Thruster**

Next, the LM-1-MK-2 thruster was designed mainly to achieve stable thruster operation and to lower the magnet temperature. Improvements over the LM-1-MK-1 thruster were made mainly in the ion accelerating grids. Like its predecessor, the LM-1-MK-2 has a two-grid ion accelerating system with plate springs in the grid supports, but unlike the LM-1-MK-1 the grids were made of molybdenum and dished inwards. Molybdenum was used to obtain greater grid stability against thermal expansion. Test results showed that the ion production cost was not improved from the LM-1-MK-1 thruster because the main improvements were made for stable operation. It was difficult to operate this thruster at a propellant utilization efficiency of 90%, mainly due to the large open area fraction of the accelerator grid. However, the discharge voltage was lowered significantly. As we expected, the thruster proved to have stable operation capability. The highest magnet temperature was reduced to $254^{o}$C. Problems remaining with this thruster were to achieve still lower magnet temperatures and to improve thruster performance.




a) Ion production cost.




b) Discharge voltage.

Fig. 2  Performance data obtained from the four thrusters.

**LM-2 Thruster**

On the basis of the results obtained with the first laboratory model, the second laboratory model (LM-2) was designed to allow long continuous operation as well as to obtain higher performance [3]. To achieve these objectives, the design of the grid supports and discharge chamber configuration were changed, and the thermal radiation capability was increased to further lower the magnet temperatures. Axial springs made from piano wires were used as the grid supports instead of the circumferential spring grid supports of the previous designs. Axial grid supports gave more flexibility in grid assembly which allowed fine adjustment of the grid system. Three magnet rings were installed in the discharge chamber; two on the sidewall and one on the endwall. This thruster attained an ion production cost of 138 W/A at a propellant utilization efficiency of 90% and a maximum magnet temperature of 240°C.

**BBM-1 Thruster**

On the basis of the results with the laboratory model thrusters, the first breadboard model (BBM-1) thruster was fabricated and tested [4]. While the previous model LM-2 thruster had given almost satisfactory thruster performance, the BBM-1 thruster was designed to improve reliability and endurance as well as performance. In particular, improvements were made to the ion accelerating system and discharge chamber. The thrusting capability was increased to 180 mN, though the nominal thrust requirement was still 150 mN. To achieve this, the ion accelerating grid diameter was increased to 35 cm. A three-grid ion accelerating system was used with the aim of achieving longer thruster life, and the grid fabrication process was improved. The previous grids were made from a single plate using photochemical etching, and inaccuracy in the grid hole diameter and position was a serious problem when thick plates were used. To overcome this, press-welding was introduced. In this fabrication method, thin molybdenum plates were photochemically etched, which gave an accurate grid configuration, and the etched plates were then stacked and press-welded to obtain the required grid thickness. The discharge chamber configuration of the BBM-1 thruster was almost the same as that of the LM-2 thruster. However, the number of the discharge chamber magnet rings was increased to four; two on the sidewall and two on the endwall.

This thruster achieved most of the initial targets for performance parameters. We estimate that its performance is very close to the upper limit. We obtained an ion production cost of 104 W/A at a propellant utilization efficiency of 90%. Total electrical power consumption was 3.29 kW, and the total xenon flow rate was 3.27 Aeq. The discharge voltage was as low as 30 V. This performance corresponds to an electrical power efficiency of 88% and a power-to-thrust ratio of 21.8 W/mN. Stable thruster operation was attained at an accelerator grid voltage of 300 V, while 700 V had been necessary to operate the LM-1 and LM-2 thrusters. This is preferable because lower accelerator grid voltages are necessary for greater accelerator grid life. The highest magnet temperature reached was 172°C, and it was well below the limit of 200°C required to assure long life of the magnets. The achieved ion production cost had some margin from the target value, and this could be allotted performance degradation that would be caused by redesigning the thruster for endurance improvement.

## 4. Thruster Endurance

**1000-Hour Thruster Test**

It is well known that endurance for very long operation time is essential to ion thrusters. Ion thrusters have small thrusts, and are still required to produce large velocity increments. Thus, the second phase, succeeding the first phase of performance improvement, should deal with thruster endurance. As the first task on it, the BBM-1 thruster was tested for 1,000 h [5]. The objectives were to validate new designs introduced to improve thruster endurance, and to reveal further weak points. The new designs were adopted in the ion accelerating system, thruster cooling and sputtered material capturing. Thermal shielding was installed between the main cathode and the discharge chamber to lower the magnet temperature. The inner surface of the discharge chamber sidewall was dimpled and molybdenum-coated, and the inner surface of the endwall was covered with mash screen. These were to firmly capture and trap the material sputtered from various parts in the thruster.

The thruster operation was conducted as continuously as possible, but had to be interrupted 24 times in total. Most of them were caused by facility-related problems, and none by thruster fatal failure. In the test, the thruster was operated stably for 1,000 h. Metal flakes were found negligible in the discharge chamber after the 1,000-h operation. The highest magnet temperature was 172°C, and well below the upper limit of

200°C, suggesting no degradation in the discharge chamber magnets. No peeling was found on the grid surfaces though one of the concerns about the press-welded grids had been peeling of the constituting sheets. These indicated that the new designs worked successfully.

The grid masses were measured four times. The averaged change rates in the grid masses were +2.47 mg/h (gain) for the screen grid, -6.12 mg/h (loss) for the accelerator grid and –4.86 mg/h (loss) for the decelerator grid. The lifetime of the accelerator grid was roughly estimated from these data, and it suggested that the lifetime target of 30,000 h would not be attained. Two countermeasures were devised for the next model thruster to elongate the lifetime. One is lowering the accelerator grid voltage. While this test was conducted with 300 V, the estimated preferable value was about 250 V or less. The other was making the accelerator grid thicker for supplying a more volume of the grid material that may be sputtered.

**5000-Hour Thruster Test**

To validate the countermeasures above and to evaluate the endurance capability, the second breadboard model (BBM-2) thruster was designed and fabricated, and an endurance test of the thruster was conducted aiming at 5,000-h operation [6, 7]. The objectives were to evaluate the grid lifetime and to find out further weak points in the thruster endurance. The BBM-2 thruster was identical with the BBM-1 thruster except for the ion accelerating system and main cathode. The accelerator grid thickness was increased from 0.6 mm in the BBM-1 to 0.8 mm in the BBM-2, and the screen grid thickness from 0.4 mm to 0.6 mm. The main cathode used in the previous 1,000-h test was also used for the first half of the test. At the middle of the test, however, the cathode was replaced to a new one, which was used for the second half of the test. The new cathode had been designed so as to improve shielding of its insulated parts against metal vapor contaminant and to keep its required resistance for much longer time. The insert was not replaced but the same one was used throughout the whole period of the test.

In the endurance test, the total operation time reached 4,994 h. This test was also intended to be continuous but interrupted 80 times in total. More than half of them were intentional or due to facility-related problems. Variations in the ion production cost are shown in Fig. 3. It was almost constant at about 120 W/A in the first half. Though it was increased to about 130 W/A in the second half, it was still within the target. Grid mass measurements were conducted also in this test. The averaged change rates in the grid masses were +0.22 mg/h (gain) for the screen grid and -6.50 mg/h (loss) for the accelerator grid. From this mass loss rate, the lifetime of the accelerator grid was estimated at about 25,000 h. The mass change rate of the decelerator grid was –0.925 mg/h (loss). The decelerator grid suffered exceptionally large erosion for the first 17% of the test time while the grid gap to the accelerator grid was set larger than the nominal value to avoid too frequent arcing. The mass change rate does not contain the mass loss in this period.

Inspections after the test revealed several problems in the thruster. The orifice plate of the main cathode had an eroded region around the center of the downstream surface. The cathode support cylinder was eroded at its downstream edge. A crack was found on the magnet cover for the magnet ring M4 (the nearest ring to the cathode). Though the temperature of the magnet ring M4 exceeded 200°C near the end of the test period, it was guessed that a direct current influx to the magnet caused the temperature rise.

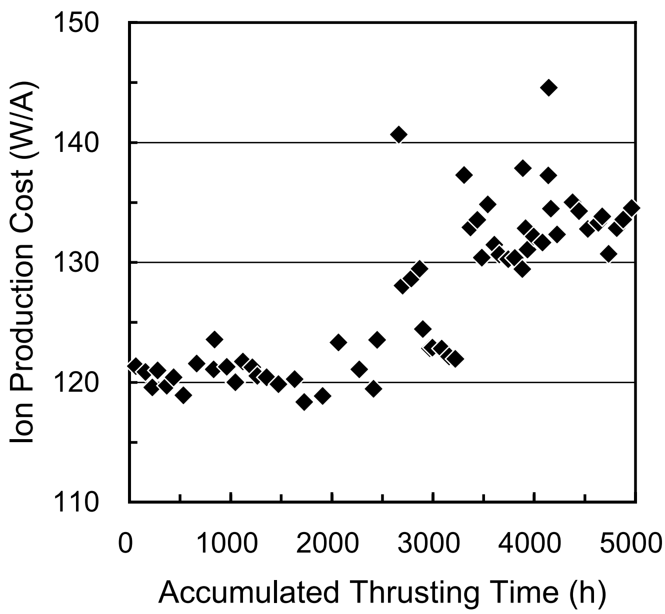



Fig. 3 Variations in the ion production cost in the 5,000-h endurance test.

**Hollow Cathode Wear Test**

A wear test of a main hollow cathode was conducted to investigate the wear process of its orifice plate [8]. The cathode had the same design as the one used in the previous thruster endurance test. The wear test had two more specific objectives. One is to supplement the operation time of the main hollow cathode in the endurance test. The total operation time of the same cathode in that 5,000-h test was 2,485 h because the main cathode, except its insert, was replaced in the middle of the test. The other is to examine how the wearing of the orifice plate

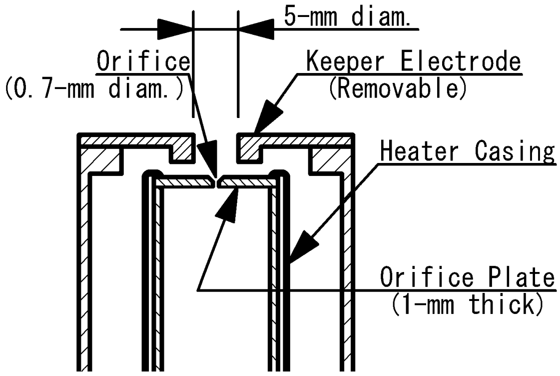



Fig. 4 Cross sectional view of the cathode top.

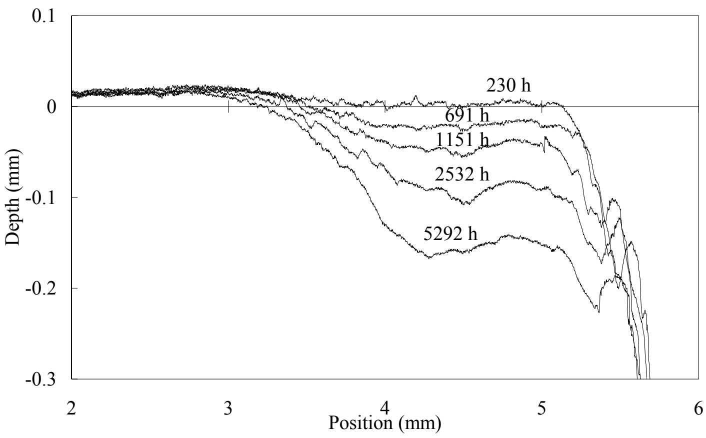



Fig. 5 Eroded depth profiles on the orifice plate downstream surface.

proceeds with operation time. Therefore, the test was segmented, and the wear rate was measured after each of segmented runs. The cathode was operated in the diode mode without being installed in the thruster, and the total operation time reached 5,292 h, with 23 segments of approximately 230 h each.

With this procedure, eroded depth profiles on the orifice plate downstream surface were obtained. Figures 4 and 5 show a cross sectional view of the cathode top and the eroded depth profiles, respectively. From these data, the wear rate of the orifice plate surface was obtained as a function of the accumulated operation time. This showed that the wear rate was approximately 0.08 μm/h before the wear depth reached 0.1 mm, and was less than 0.03 μm/h after that. It was estimated from these wear rate data that it will take more than 30,000 h before the 1-mm thick orifice plate is completely worn out.

In the thruster endurance test, the wear rate was smaller than in this diode mode test. It took 2,500 h before the orifice plate was worn out by 0.1 mm while it took a half of that in this diode mode test. This suggests that it will take much longer time than 30,000 h before the orifice plate in the thruster is completely worn out.

## 5. Propulsion System

### System Configuration

A conceptual study of an ion propulsion system was conducted to define the system equipped with the 150-mN ion thrusters under development [9]. An orbit transfer mission form LEO to GEO was assumed for flight demonstration of the system. The functional block diagram of the propulsion system is shown in Fig. 6.

Estimates of the mass and electric power of each component are summarized in Table 2. The mass of the propulsion system was estimated at 362 kg. It is the sum of the system dry mass of 198 kg and the xenon of 164 kg for a 10,000-h thruster operation. The system includes a back-up thruster. Electric power of about 3.9 kW is required for operating the thruster at the nominal thrust of 150 mN. For 60% throttling, that is 90 mN thrusting, the required power is reduced to 2.8 kW.

### Power Conditioner

The power conditioner is one of the critical components in the propulsion system. Preliminary designing and fabrication of the power conditioner were started to obtain its technological prospect and proper estimates for its efficiency. So far, all of the thruster operations were conducted using power supplies for ground operation tests, which have no great importance in their power efficiencies. The power conditioner contains seven power supplies to operate the thruster. The most powerful is the beam power supply, which has a nominal voltage of 1 kV and current of 2.88 A. The second is the discharge power supply, which has a nominal voltage of 30 V and current of 16.3 A. The objective is to confirm the feasibility for high efficiency.

A beam power supply of this class with a single DC/DC converter would bring too much concentration of mass and heat. To mitigate it, the beam power supply in this power conditioner was made up of four DC/DC converters, and the output voltages were added to obtain the required beam voltage. With this design, the electric power and loss carried with each converter was lowered almost to the same level as in the flight

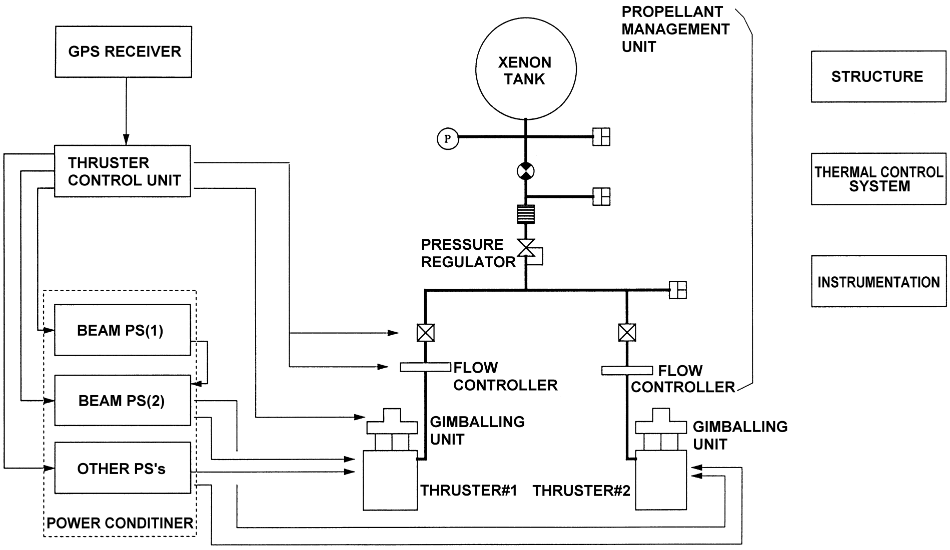



Fig. 6 Functional block diagram of the propulsion system.

power conditioners existing in Japan. Four types of DC/DC converter were compared, and the best one selected was the voltage-raising converter type which has a voltage-lowering push-pull inverter and a full-wave rectifying circuit. To decrease its size and mass, an FET was used for the main switching element, and the switching frequency could be raised up to 100 kHz. A DC/DC converter of push-pull converter type was used for the discharge power supply. The other power supplies were fabricated with the same circuit design as in those for the COMETS ion engine system. These power supplies were tested with resistance dummy loads. The beam power supply gave an efficiency of 88.4% at the nominal output of 1 kV and 2.88 A, and 90.2% at 1 kV and the maximum current of 3.2 A. The discharge power supply gave an efficiency of 87.3%. These results were satisfactory in terms of efficiency.

Table 2 Component mass and electric power of the ion propulsion system.

| Component | Number | Mass (kg) | Electric power (W) | | |
|---|---|---|---|---|---|
| | | | Sunshine | | Shade |
| | | | 150 mN | 90 mN | 0 mN |
| Ion Thrusters | 2 | 26 | 3360 | 2300 | 0 |
| Power Conditioner | 1 set | 30 | 370 | 265 | 20 |
| Control Unit | 1 | 10 | 25 | 25 | 25 |
| Propellant Management Unit | 1 set | 30 | 10 | 10 | 2 |
| Gimballing Units | 2 | 16 | 5 | 5 | 0 |
| Structure | 1 set | 40 | - | - | - |
| Thermal Control System | 1 set | 20 | 50 | 50 | 50 |
| Instrumentation | 1 set | 20 | - | - | - |
| GPS Receiver | 1 set | 6 | 36 | 36 | 36 |
| Propellant | - | 164 | - | - | - |
| Total | | 362 | 3856 | 2791 | 133 |

## 6. On-Going and Further Work

Until this phase of the development, the thruster operation tests were conducted mainly at the nominal operating conditions. In the next step, however, it is important to obtain the throttling capability and performance mapping for a wide range of operating conditions. This will serve for designing missions where the power levels may be changed with time for a wide range, as in some interplanetary missions.

In the previous endurance test, some of the thruster parts suffered sever erosion, but countermeasures were taken for them. The magnet cover on M4 had a crack, and the downstream edge of the cathode cylinder was severely eroded. These parts were covered with carbon though the original material was molybdenum. To improve the endurance further, two tasks have been started. One is fabricating the accelerator and decelerator grids with titanium. With the same masses, the grids can be made thicker, and grid lifetime can be elongated along with their thickness. The other is changing the material of the hollow cathode orifice plate to another one with lower sputtering yield. A hollow cathode wear test in the full mode is planed because the wear rate in the diode mode was higher than that in the thruster-installed test.

Because the grids are installed to the thruster body using flexible supports, vibrations during the launch may be a problem. Though preliminary and simplified, a vibration analysis of the grid system has been started and a vibration test is planed.

One of other issues on the power conditioner is compatibility with the thruster. A power conditioner test with real loads, or an operation test combined with the thruster, is scheduled as a next step on the power conditioner development.

## 7. Summary

After a couple of redesigning and fabrication to improve thruster performance, the first breadboard thruster achieved a very low ion production cost of 104 W/A, which was well blow the target of 140 W/A. On endurance, results of the 5,000-h thruster test suggested that the grid system would have a lifetime of about 25,000 h though it was a rough estimation. Results of the hollow cathode wear test suggested that it would be over 30,000 h before its orifice plate is completely worn out. In the power conditioner development, high efficiencies of 88% and 87% were achieved on the beam and discharge power supplies, respectively. Activities on the open matters related to thruster and cathode endurance, vibrations during the launch, and the power conditioner are going on, or will be started in the near future.

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