ELECTRIC PROPULSION EXPERIMENT (EPEX) OF A REPETITIVELY PULSED MPD THRUSTER SYSTEM ONBOARD SPACE FLYER UNIT (SFU)

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ABSTRACT

A repetitively pulsed magnetoplasmadynamic (MPD) arcjet thruster was assembled as a propulsion system using liquid hydrazine propellant and was tested on-orbit. This space test is called Electric Propulsion Experiment (EPEX) onboard the Japanese unmanned reusable space-platform Space Flyer Unit (SFU) which was launched by H-II rocket in March 1995 and retrieved by the US Space Shuttle (STS-72) in January 1996. The EPEX successfully verified propulsive function of this MPD arcjet thruster system by repetitive firings over 40,000 shots during a few days of the allocated experiment period and confirmed the thruster performances in good agreement with those obtained in the ground testing. The post-flight inspection revealed no abnormal signature of arc discharges and successful disposal of residual hydrazine into space.

INTRODUCTION

The advantages of Magnetoplasmadynamic (MPD) arcjet space propulsion system are:

1) large thrust density, and being compatible to high power requirement,
2) simplicity of structure, principle, and operation,
3) absence of pre-heating,
4) low working voltage,
5) usage of propellants less influential to the Earth's environment,
6) wide selectiveness of propellant, hydrazine applicable to common use with Reaction Control System (RCS),
7) wide range of specific impulse.

According to these advantages, several space tests were already conducted,[1-2] however, the flight experiences as a propulsion system have been still unsatisfactory. For the ground test, a few endurance tests were tried targeting 10-million-pulse endurance as a main propulsion system with mission ΔV assuming a lunar orbiter or other interplanetary missions. As the precursor result, an epoch making 3-million-pulse endurance was successfully proved using a 1 kW class system and envisioned a real application to space missions. At that time in advent of the Space Flyer Unit (SFU: a Japanese Multipurpose Space Platform), the MPD arcjet thruster system was picked up as one of the experiment candidate in space. Although the SFU mission was imposed the NASA Safety Policy and very severe weight constraint on, the MPD arcjet thruster system employed hydrazine to share the propellant with RCS (Reaction Control System) in the future, a 1 kW class thruster head without scaling-down that would be the key technology of on/off cycle reliability of arcjet thrusters.

The operational principle is shown in Fig. 1. A pulsed high current arc discharge is initiated between a centered cathode and segmented coaxial anodes to ionize the hydrazine decomposed gas flowing through these electrodes. Each segmented anode connected to each pulse-forming-network was employed so as to distribute arc discharges azimuthally uniform. The electromagnetic thrust is generated by the coupling of the current flowing from the anode to the cathode and the self-induced magnetic field in the azimuthal direction. Besides this axial thrust, the compression force in the radially inward direction concentrates a high density high temperature plasma at the cathode tip to produce a nozzle-like expansion thrust.

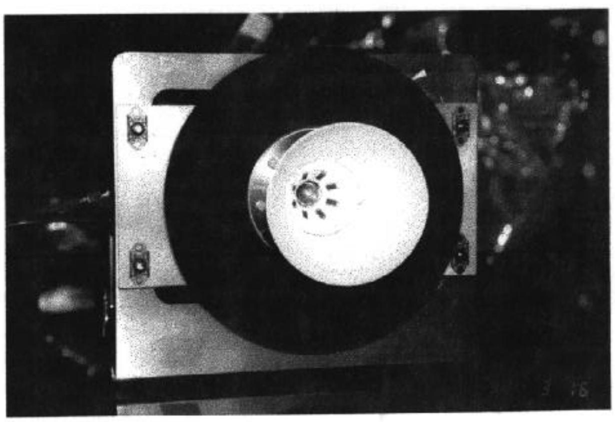


Fig. 1 The MPD arcjet thruster head used in the EPEX.

SPACE FLYER UNIT (SFU)

The EPEX (Electric Propulsion Experiment) was installed on a Japanese unmanned space-platform called

SFU (Space Flyer Unit). This versatile reusable space-platform was developed under the cooperation of the Institute of Space and Astronatuical Science (Ministry of Education, Science, Sports and Culture), the Institute for Unmanned Space Experiment Flyer (Ministry of International Trade and Industries), and National Space Development Agency (Science and Technology Agency of Japan). The SFU was launched on March 18, 1995 by a H-II rocket vehicle Test#3 from the Tanegashima Space Center and after about 9-month on-orbit activities it was retrieved by a US Space Shuttle "Endeavour" on January 13, 1996. The "Endeavour" landed at NASA Kennedy Space Center on January 20, 1996. The SFU has a deformed octagonal shaped cylinder consisting of Payload Unit boxes for experiments accommodation with the overall dimensions of about 4.6 m diameter and 3 m in height. The tip to tip length of the solar array deployed is 24 m and the weight is 4 ton. Figure 2 shows the view of SFU. Besides the EPEX, SFU installed 11 kinds of experiments such as an Exposed Facility model for the Space Station, an infra-red space telescope, furnaces of new material processing, and a Japanese red belly newt for space biology experiment, etc.

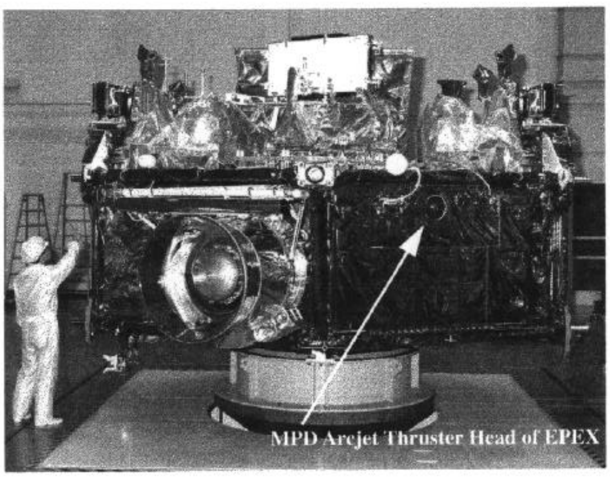


Fig. 2 Space Flyer Unit (SFU), a Japanese unmanned reusable multi-purpose space-platform accommodating 13 kinds of experiments including EPEX.

ELECTRIC PROPULSION EXPERIMENT (EPEX)

The EPEX (Electric Propulsion Experiment) using an MPD arcjet was installed on the SFU as one of the experiment candidates.[3-4] The EPEX objectives are:

1) to checkout the system compatibility to the space environment and/or the launch environment,

2) to verify the propulsive function with more than one thousand repetitive firings,

3) to dump residual hydrazine propellant for the safe retrieval of SFU by a manned space vehicle of the Space Shuttle.

If time-permitting and additional electrical resource is available in orbit, extra- success-level experiments were also planned so as to continue the firings or try several operational parameters other than the nominal.

The EPEX system comprises an MPD arcjet thruster head (HDS), a capacitor module (CAP), a coil module (CL), a charging control unit (CCU), a fast-acting valves (FAV) and trigger driver unit (FTDU), a valves and relays driver unit (VRDU), a propellant supply unit (PSS), a command and monitor unit (CMU), a terminal unit (TRU), and a dedicated experiment processor (DEP). These are installed inside Payload Unit box #2 (PLU-2) together with other electronic equipment of 2 Dimensional Array Deployment

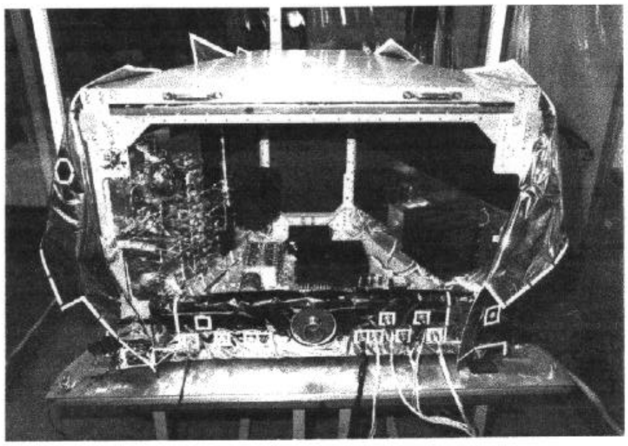


Fig. 3 Inside view of the Payload Box Unit-2 (PLU-2) co-integrated with EPEX devices and other experiments.

Table 1 Summary of EPEX specification.

MASS	**< 41 kg**	**Allocated**
POWER	**< 430 W**	**Allocated**
EXP. PERIOD	**46 rev.**	**Allocated**
PROPELLANT	**N2H4**	**< 130 g Loaded**
PFN CAPACITY	**2,240 μF**	**1/4 of full capacity**
PULSE WIDTH	**150 μs**	**1/4 of full width**
REPETITION	**0.5~1.8 Hz**	**Variable in 4 steps**
DISCHARGE CURRENT	**6 kA**	**Top value**
THRUST-TO-POWER	**> 20 mN/kW**	**Top value**
SPECIFIC IMPULSE	**> 1,000 sec**	**Top value**
COMMANDS	**9**	**Allocated**
DATA RATE	**< 625 bps**	**Allocated**
SAFETY COMPLIANCE	**NASA STS**	**NHB 1700.7B**

and High Voltage Solar Array experiments (2D/HV). Figure 3 shows the internal appearance of the PLU-2 with all the equipment installed. Table 1 summarizes the specification of the EPEX and the system block diagram is shown in Fig. 4. The details of EPEX components are described as follows.[5]

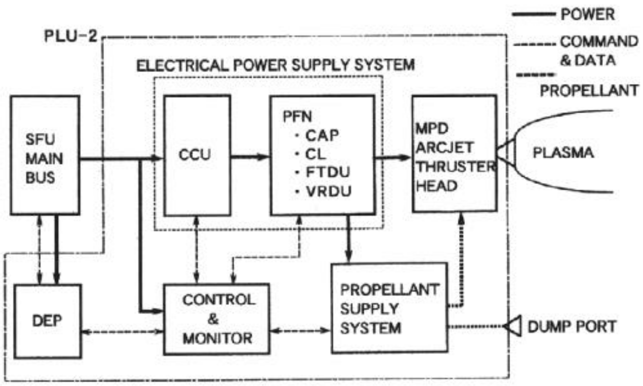


Fig. 4 EPEX system block diagram.

MPD Arcjet Thruster Head

An MPD arcjet thruster head has a coaxially configuration with a 10 mm diam. centered-cathode made of barium oxide impregnated porous tungsten and 8 segmented anodes made of molybdenum so that the self-induced magnetic field is produced between these electrodes. A nozzle made of layered boron nitride is attached downstream to enable aerodynamic thrust contribution. Two set of FAV's operation was synchronized with the arc discharge and required heat pipes to reject the heat emanation inside the FAV's.

Electrical Power Supply System

The CCU has a capability of transforming the SFU unregulated bus voltage (32 - 52 V dc) up to 350 V dc to charge up in 0.55 sec the CAP of the pulse forming network (PFN) (Fig. 5). The pulse forming network is configured by a CAP of 2,240 μF, consisting of 8 pair of 140 μF plastic film capacitors, and a CL of 2 μH with 8 bifilar winding power lines each of which is connected to the 8 segmented anodes and a cathode (Fig. 6). The trigger is applied by a 1 kV of 20 μsec pulse duration.

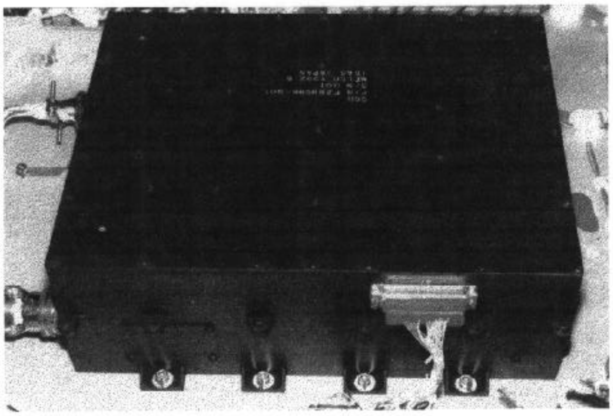
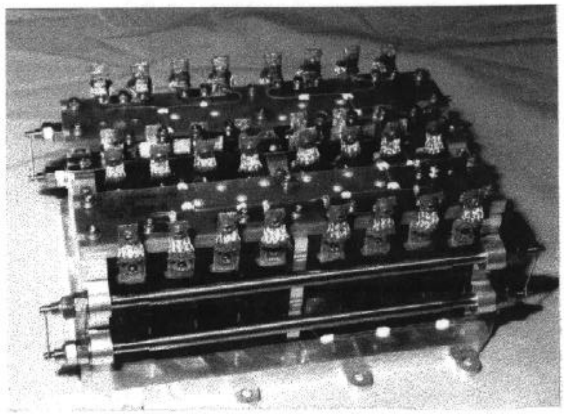


Fig. 5 Charging Control Unit (CCU).



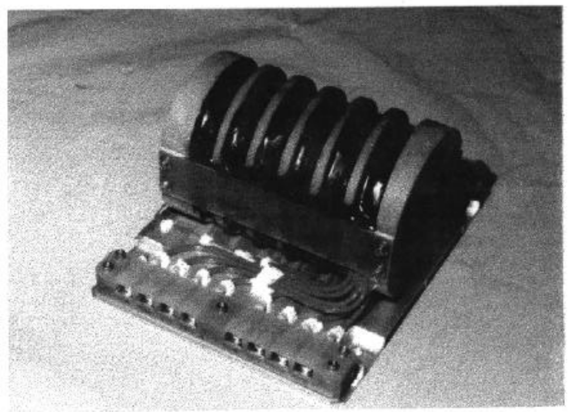


Fig. 6 Capacitor Module: CAP (upper) and Coil Module: CL (lower) of EPEX.

Propellant Supply System

The PSS comprises a primary tank (hydrazine propellant tank), a secondary tank, a gas-generator, filters, latching-valves, a propellant valve, a dump port and pipe lines. The primary tank of 16 cm diam. employed a surface-tension liner sustaining the 130 g of liquid hydrazine propellant with nitrogen pressurant gas. The liquid hydrazine in the primary tank is pressurized at 24 kgf/cm2 gauge (2.35 MPa absolute) and supplied to the gas-generator through a propellant valve to be decomposed into nitrogen and hydrogen gases. The decomposed gas is stored in the secondary tank and supplied to the HDS through 2 sets of FAV's.

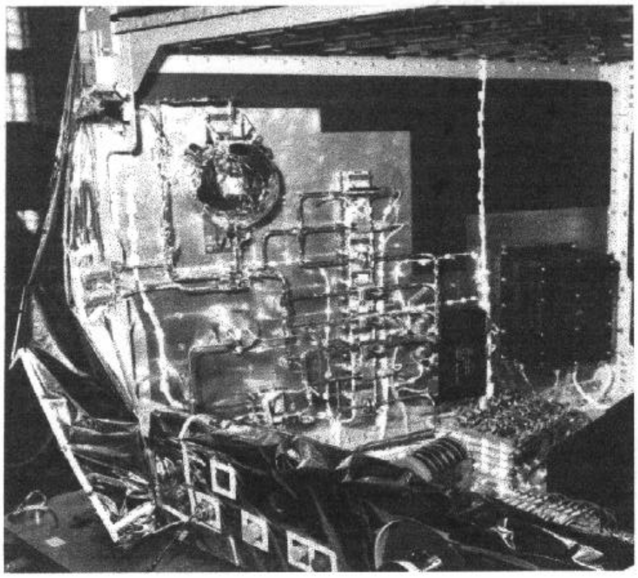


Fig. 7 Hydrazine Propellant Supply System of EPEX.

GROUND TESTS

Some of the ground test results are exhibited below to compare the on-orbit data.

Electrical Performance Test

A firing test was conducted inside a thermal-vacuum chamber to obtain waveforms of the discharge current of 150 μsec and the FAV's driving current providing nitrogen propellant in this case. Figure 8 shows these waveforms and Fig. 9 shows the plasma plume. The lower waveform indicates the current reverse due to low arc impedance, however, in the EPEX we employed diodes array circuit in the PFN to recharge the reversed current energy into the CAP. Also EMI (Electromagnetic Interference) tests were conducted to confirm no critical effects of MPD firings to the bus components of the SFU. The electric field noise exceeded the limits of RE-02 of MIL-STD461C Part3 but because the MPD firing is repetition of very short pulse and no bus or experiment components were susceptible to the MPD noise level, the RE-02 compatibility was safely wavered. Other conductive noise or susceptibility test showed no problem.

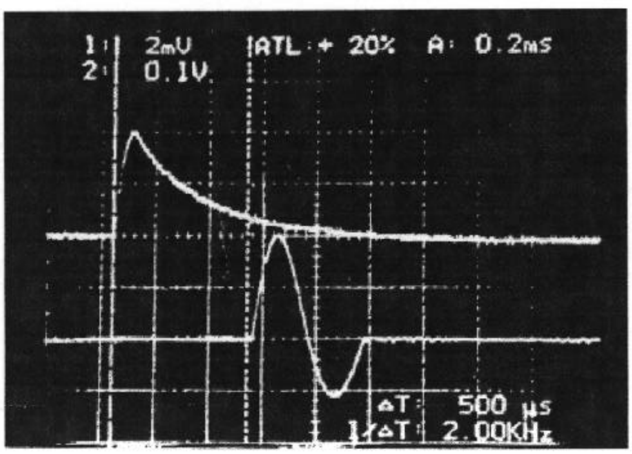


Fig. 8 FAV driving current (upper) and 6 kA arc discharge current waveform (lower); 500 μsec/div.

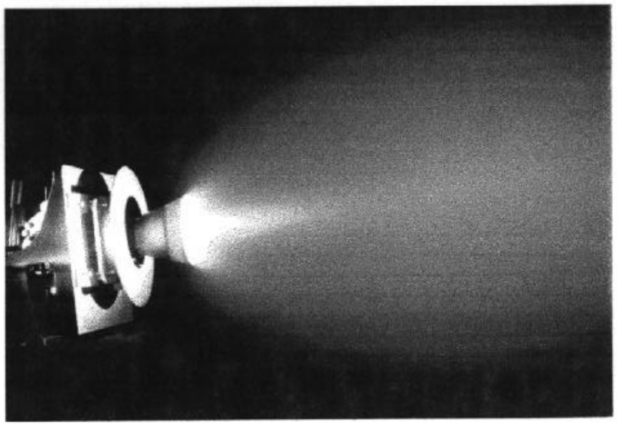


Fig. 9 MPD arcjet thruster plume inside a vacuum chamber.

Hydrazine Dump into Vacuum

The EPEX planned to dump the residual hydrazine propellant to assure the safety of manned Space Shuttle that should retrieve SFU into the cargo bay. The EPEX verified the vacuum dumping techniques of liquid hydrazine without any freezing or splashing by designing the dump port nozzle and its orifice. Water was used because of its triple point similar to liquid hydrazine for the ground tests and verified the dumping technique (Fig.10).

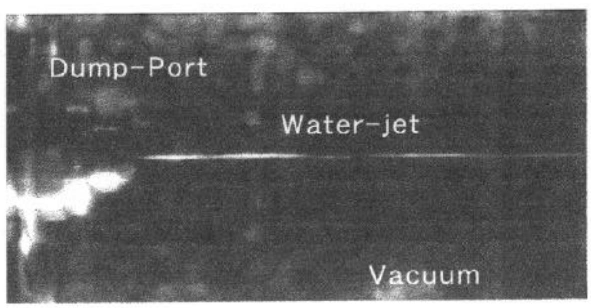


Fig. 10 Technological demonstration of water dump instead of liquid hydrazine into vacuum without splashing nor freezing.

Vibration Tests

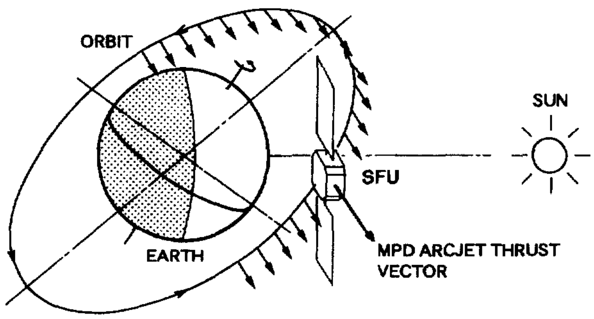
The vibration tests for verifying the EPEX structural strength against the mechanical environment of launch vehicle H-II and landing vehicle Space Shuttle were successfully conducted as PLU-2 qualification and acceptance levels.

Thermal Vacuum Test

The thermal vacuum test was conducted to verify the thermal interface to the PLU where the EPEX system was installed and to verify heater design, thermal insulation and/or radiation design. Especially the hydrazine system was strictly monitored to satisfy NASA safety requirement for the Space Shuttle.

ON-ORBIT EXPERIMENT RESULTS

An overview of flight operation is depicted in Fig. 11. The EPEX operation began with the system checkout on March 28, 1995 and after that the firing sequence was tested on May 29, 1995. On June 2, 1995, June 24, 1995, and July 17, 1995 the EPEX performed repetitive firings and dumped residual hydrazine propellant into space on July 20,



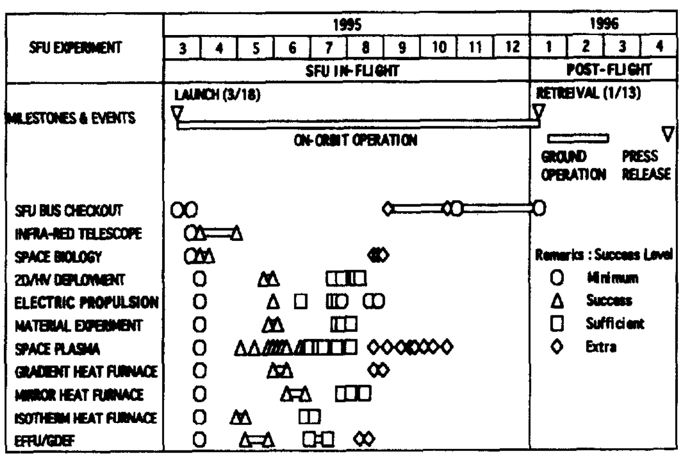


Fig. 11 EPEX firing onboard SFU during the sunshine period (upper) and overview of EPEX space test (lower).

1995. The hydrazine disposal was finished by about one-month vacuum drying of the PSS on August 22, 1995. The final telemetry of experiment success was confirmed on August 24.

Charge/Discharge of the Capacitor Bank

As one of the system checkout of EPEX, the charge/discharge capability was checked out followed by turning on the whole system including pressure and temperature monitors ability. Figure 12 shows charge / discharge waveform. It was striclty identical to the design

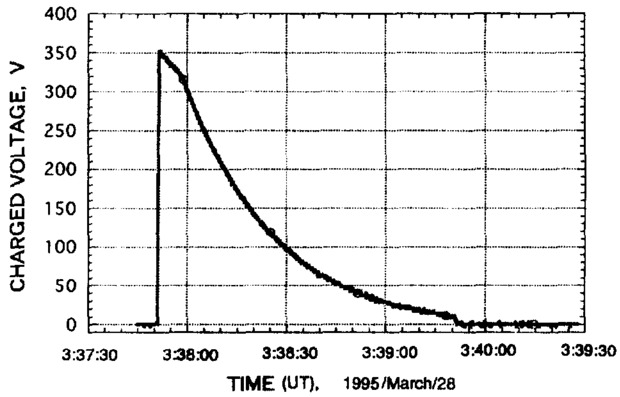


Fig. 12 Charge/discharge waveform of the capacitor module.

waveform of charging up to 350 V and decaying the charged voltage through dumping resistor. In this phase the plasma firing is inhibited to avoid inadvertent failure affecting the SFU bus or other experiment components. This was conducted to assure the CCU and PFN healthiness and the EPEX monitoring function. The EPEX employed a dumping resistor of PFN in order to eliminate residual electronic charge in the CAP. This was one of the NASA safety requirement.

Monitoring the Hydrazine System

The pressure and temperature trends of a primary hydrazine tank and a secondary tank were successfully monitored to verify their stabilization without any leakage on-orbit. The temperatures were maintained well between 40 ℃ and 20 ℃ during the rest and the firing (Fig. 13). Figure 14 shows the pressure decay of secondary tank that decreases the pressure of hydrazine decomposed gas according to the EPEX firing. In this figure a feed-back regulation process is successfully verified as the pressure started at 7 kgf/cm2 (0.69 MPa) decayed as progress of firings and was re-filled at 5.9 kgf/cm2 (0.58 MPa). From

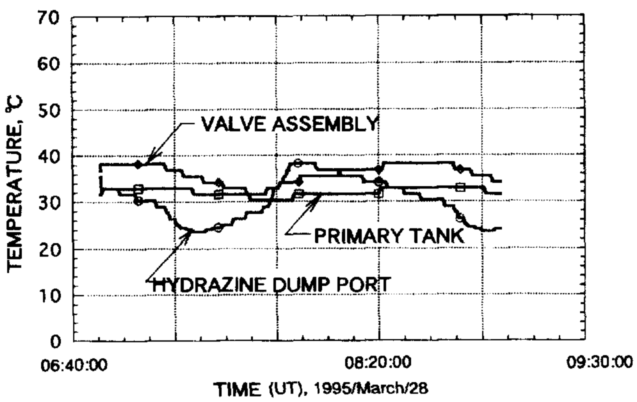


Fig. 13 Temperature monitor of hydrazine propellant supply system on-orbit.

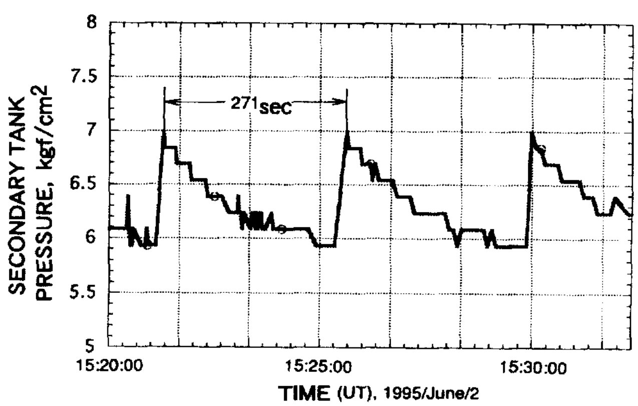


Fig. 14 History of the secondary-tank pressure decay during the firings and pressure recovery by the propellant feed control.

decreases the pressure of hydrazine decomposed gas according to the EPEX firing. In this figure a feed-back regulation process is successfully verified as the pressure started at 7 kgf/cm2 (0.69 MPa) decayed as progress of firings and was re-filled at 5.9 kgf/cm2 (0.58 MPa). From this decay rate, one can calculate the propellant consumption rate.

Plasma Firing On-Orbit

Figure 15 shows the discharge current and discharge voltage waveforms. The peak current of about 6 kA and the peak voltage of about 120 V showed good correspondence with the ground test data. The first half of the discharge voltage waveform corresponds to the charged voltage of 350 V in the CAP, and the latter corresponds to the discharge waveform through the PFN. The half-value width of the discharge waveform is about 150 μsec and also corresponds to the ground test data. Figure 16 shows the repetitive discharge voltage waveforms at a repetition rate of 1 Hz. Each voltage-drop implies the plasma firing at the charge voltage of 350 V and the discharge voltage of 120 V. The misfiring was less than 0.3 % of total firings and it was mainly observed at high repetition rate of 1.8 Hz.

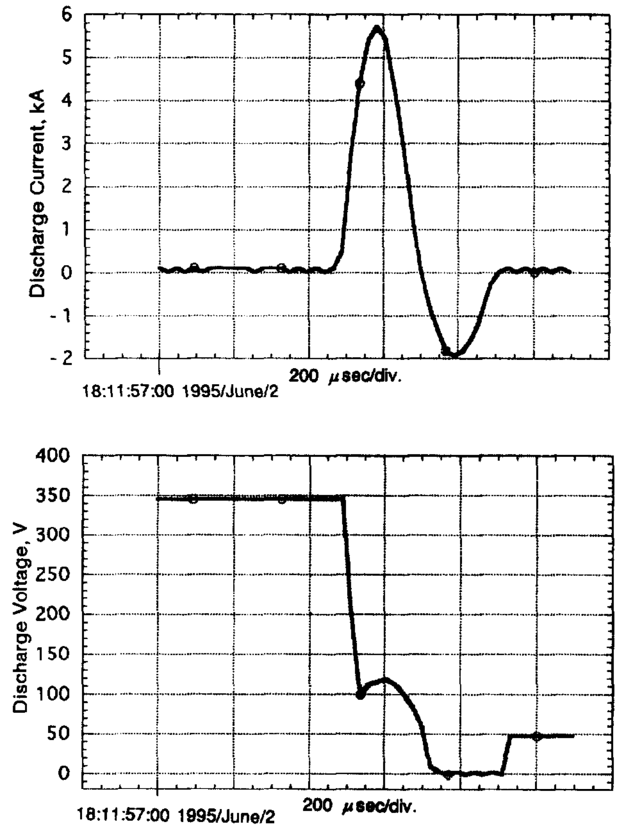


Fig. 15 Arc discharge current (upper) and voltage (lower) waveform on-orbit.

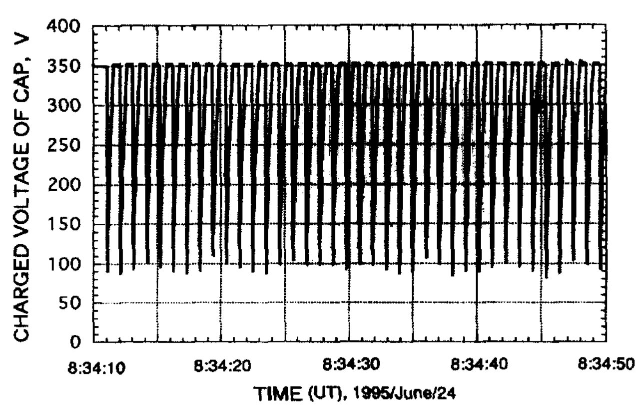


Fig. 16 History of the capacitor module (CAP) voltage during 1 Hz repetitive firings.

Thrust Measurement

Figure 17 shows the variation of the SFU attitude control expressed by the unit of N.m.sec before and after EPEX repetitive firings. Before EPEX firings the SFU attitude control indicated an increasing trend caused by natural disturbances such as gravity-gradient torque and atmospheric drag, but during the EPEX firings this trend turned out to be decreasing and the trend was restored after the EPEX firings.The difference can be concluded as the external disturbance generated by the EPEX plasma firings.

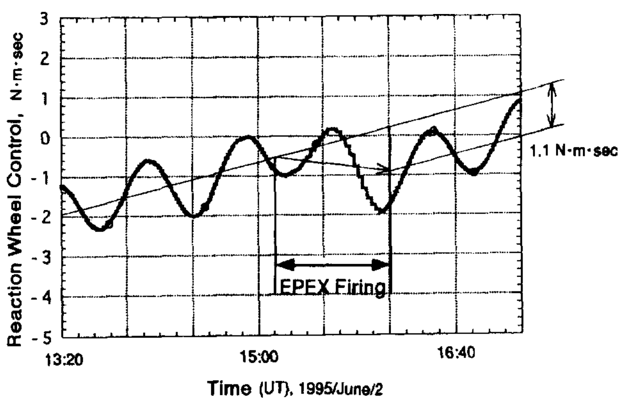


Fig. 17 EPEX-generated torque evaluated by the onboard momentum-wheel of SFU attitude control system.

In Fig. 18, the EPEX plasma firing and its generated torque around the SFU are exhibited. When the EPEX generates a torque around Y-axis of SFU, the momentum wheel of SFU detects it as an external disturbance to recover the sun-pointing attitude. From this control value of NGC (Navigation, Guidance and Control) system and a mechanical torque arm of the EPEX thrust vector, we can calculate the thrust impulse the EPEX generated on-orbit.

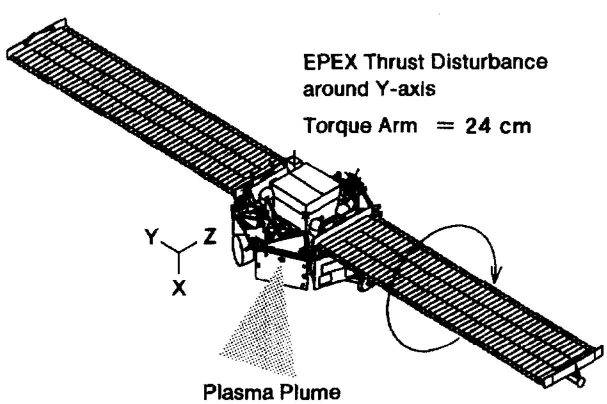


Fig. 18 EPEX thrust torque disturbance against the SFU attitude.

This measurement technique resulted in 3.6 mN.sec thrust impulse per shot and revealed good agreement with the ground test data. We can also calculate the propellant consumption rate from the pressure decay of secondary tank as shown in Fig. 14. The specific impulse was deduced from these data and it was proved to be 1,100 sec as the peak value which is correspondent with the ground test data. The total accumulated firings amounts to 43,395 pulses on-orbit during the assigned experimental period.

Interference of Plasma with Communication Link

On June 2, 1995 during the EPEX firings at the visible pass of Uchinoura-Station, we switched on an S-band communication antenna which is closest to the MPD arcjet thruster in a distance of 0.6 m. At that time the telemetry frame-synchronization was intermittently unlocked and apparently the communication was disturbed. The automated telemetry gain control at Uchinoura-Station observed 0.5 Hz well-regulated notches during the EPEX firings. This was analyzed that the plasma plume from the MPD arcjet thruster plume trespassed the S-band link at a distant of 7 m ahead of the SFU and the telemetry signal of PCM-PSK (Pulse Code Modulation - Phase Shift Keying) transmission was unintentionally modulated by the existence of plasma. To the contrary, this was also a good measure of plasma plume of the EPEX firing.

Residual Hydrazine Dump

The residual liquid hydrazine was successfully dumped into space on July 20, 1995. The pressure decay data of the primary tank (Fig . 19) was mandatory for the NASA Safety Review Board. Three redundant latching valves were kept open for vacuum drying of the PSS until August 22, 1995.

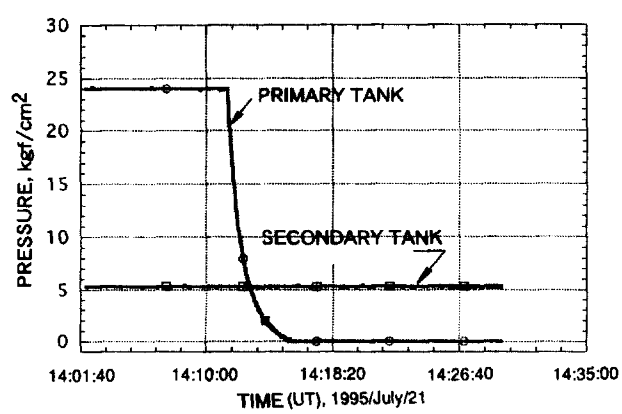


Fig. 19 Pressure decay of the primary tank associated with residual hydrazine and nitrogen gas-pressurant dump.