JOURNAL OF PROPULSION AND POWER
Vol. 16, No. 5, September–October 2000

On-Orbit Demonstration of a Pulsed Self-Field Magnetoplasmadynamic Thruster System

K. Toki,* Y. Shimizu,† and K. Kuriki‡
Institute of Space and Astronautical Science, Kanagawa 229-8510, Japan

A repetitively pulsed self-field magnetoplasmadynamic arcjet thruster was integrated into a propulsion system, which was tested on-orbit using liquid hydrazine propellant. This space test was designated as Electric Propulsion Experiment (EPEX) onboard Space Flyer Unit that was a Japanese unmanned reusable space platform launched by an H-II rocket in March 1995, and retrieved by a U.S. Space Shuttle in January 1996. The EPEX successfully verified the propulsive function of the pulsed magnetoplasmadynamic arcjet thruster system by repetitively firing over 40,000 shots during a few days of allocated experiment period, and confirmed that the on-orbit thrust performance was in good agreement with that obtained in the ground test. The residual hydrazine was successfully dumped into space according to NASA safety requirements. The postflight inspection exhibited no signature of abnormal arc discharge and no hydrazine concentration in the EPEX system.

Introduction

THE magnetoplasmadynamic (MPD) arcjet has been analyzed as an electric propulsion system for space application,[1–6] and its advantages include the following: 1) large thrust density at high power regime, 2) simple structure and operation, 3) absence of preheating, 4) low operating voltage, 5) wide range availability of specific impulse, and 6) usage of diverse propellants (noble gases, N_2H_4, NH_3, H_2, etc.).[7] These advantages have encouraged MPD arcjet studies for years in worldwide laboratories.[8–14] However, owing to the unsatisfactory thrust efficiency and lack of available power in space, flight systems have not been established. In Japan, a self-field repetitively pulsed application has been recognized as a stepping-stone toward future high-power steady-state MPD arcjets,[15,16] and hence, several space tests have already been attempted.[17,18] Using ground facilities, a few endurance tests have been conducted as a primary propulsion system by assuming a ΔV for a lunar orbiter or other planetary missions. Previous work included a 3-million-pulse life endurance, which successfully demonstrated a 1-kW class system of four-staged LC-ladder pulse-forming-network (PFN) with 600 μs discharge duration and envisioned real applications to space missions.[19–22] During the development of the Space Flyer Unit (SFU), a Japanese Multipurpose Space Platform, the MPD arcjet thruster system was selected as one of the experiment candidates, called Electric Propulsion Experiment (EPEX). The SFU mission had to conform to NASA Safety Policy, and furthermore, very severe weight constraints were imposed on the EPEX to reduce four-staged LC-ladder PFN to only single-staged PFN. Although the arc discharge duration was accordingly reduced to 150 μs, a quarter value of the 1-kW full system, the EPEX employed a 1-kW class thruster head and hydrazine propellant supply to share with the Reaction Control System for future applications. Therefore, the EPEX as a functional model of 1-kW full system included key technologies for on/off cycle reliability of DC arcjet thrusters as well as MPD arcjet thrusters.

Figure 1 shows the flight hardware of a repetitively pulsed self-field MPD arcjet thruster. A pulsed high-current arc discharge is initiated between a centered cathode and segmented coaxial anodes to ionize hydrazine decomposed gas supplied between these electrodes. Each segmented anode connected to each PFN was employed to distribute arc discharges azimuthally uniformly.[23] The electromagnetic thrust is generated by coupling the anode-to-cathode current flow 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-pressure plasma at the cathode tip to eventually produce a nozzle-like gasdynamic thrust.

SFU

The EPEX was installed on the Japanese unmanned SFU. This versatile reusable space platform was developed under the cooperation of the Institute of Space and Astronautical Science (Ministry of Education, Science, Sports and Culture), the Institute for Unmanned Space Experiment Flyer (Ministry of International Trade and Industries), and the National Space Development Agency (Science and Technology Agency of Japan). The SFU was launched on 18 March 1995 by an H-II rocket vehicle (Test #3) from the Tanegashima Space Center and after about 9 months of on-orbit activities, it was retrieved by the U.S. Space Shuttle *Endeavour* on 13 January 1996. The *Endeavour* landed at NASA Kennedy Space Center on 20 January 1996. Figure 2 shows a view of SFU on the ground with 13 kinds of experiments including the EPEX.

EPEX

The EPEX MPD arcjet thruster system was developed for one of the experiment candidates of the SFU.[24–26] The EPEX objectives were: 1) to check out the system compatibility to the space environment and the launch environment, 2) to verify the propulsive function with no less than a few thousand repetitive firings, and 3) to dump residual hydrazine propellant for the safe retrieval of SFU by a manned space transportation system of the Space Shuttle. If time permitted and additional electrical resources were available in orbit, extra-success-level experiments were also planned to simply continue firings or to try several operational parameters other than the predetermined conditions.

The EPEX system, shown in Fig. 3, comprises an MPD arcjet thruster head (HDS) with fast-acting valves (FAVs), a capacitor module (CAP), a coil module (CL), a charge control unit (CCU), FAVs and trigger driver unit (FTDU), a valves and relays driver unit (VRDU), a propellant supply system (PSS), a command and monitor unit (CMU), a terminal unit (TRU), and a dedicated experiment processor (DEP). These were installed inside Payload Unit box #2 (PLU-2) together with other electronic devices of 2-Dimensional Array Deployment and High Voltage Solar Array

Received 30 January 1998; revision received 2 July 1999; accepted for publication 20 August 1999.

*Associate Professor, Space Propulsion Division, 3-3-1 Yoshinodai, Sagamihara. Member AIAA.

†Research Engineer, Space Propulsion Division, 3-3-1 Yoshinodai, Sagamihara. Member AIAA.

‡Professor, Space Propulsion Division, 3-3-1 Yoshinodai, Sagamihara; currently Visiting Professor, Tokyo Metropolitan Institute of Technology. Fellow AIAA.

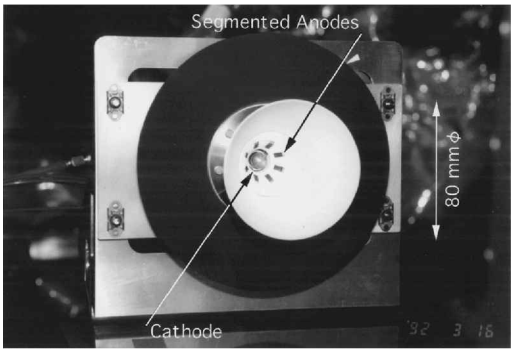


Fig. 1 MPD arcjet thruster head used in the EPEX.

Fig. 2 SFU, a Japanese unmanned reusable multipurpose space platform accommodating 13 kinds of experiments, including EPEX.

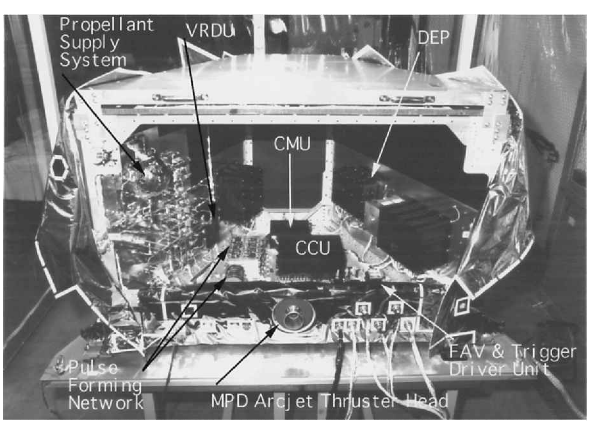


Fig. 3 Inside view of the Payload Box Unit-2 cointegrated with EPEX and other experimental devices.

experiments (2D/HV). Figure 3 exhibits the internal appearance of the PLU-2 with all the equipment installed, and Fig. 4 depicts the system block diagram. Tables 1 and 2 summarize the EPEX specification and weight breakdown, respectively. In Table 1, the peak value means the maximum instantaneous value during a 150 μs pulsed arc discharge, and it is almost equivalent to the actual thrust performance if a 1-kW full capacity PFN is employed. The details of EPEX components are described as follows.

MPD Arcjet Thruster Head

The MPD arcjet thruster head had a coaxial configuration with a 10-mm-diam centered cathode made of barium–oxide impregnated porous tungsten and eight segmented anodes made of molybdenum so that the self-induced magnetic field was produced between these electrodes. A nozzle made of layered boron nitride was attached downstream to enhance aerodynamic thrust generation. The gas puff from two sets of FAVs was synchronized with the arc discharge. Heat pipes were required to reject the heat generation of the FAVs.

Table 1 Summary of EPEX specification

Mass	<41 kg	Allocated
power	<430 W	Allocated
Exp. period	46 rev.	Allocated
Propellant	N_2H_4	<130 g loaded
PFN capacity	2,240 μF	$\frac{1}{4}$ of full capacity
Pulse width	150 μS	$\frac{1}{4}$ of full width
Repetition	0.5 ~ 1.8 Hz	Variable in 4 steps
Discharge current	6 kA	Peak value
Thrust-to-power	>20 mN/kW	Peak value
Specific impulse	>1000 sec	Peak value
Commands	9	Allocated
Data rate	<625 bps	Allocated
Safety compliance	NASA STS	NHB 1700.7B

Table 2 Weight breakdown of EPEX

MPD thruster head (HDS)	5.50 kg
Capacitor module (CAP)	4.74
Coil module (CM)	1.90
Charge control unit (CCU)	7.29
FAV and trigger driver unit (FTDU)	3.66
Valve and relay driver unit (VRDU)	1.01
Propellant supply system (PSS)	8.03
Control and monitor unit (CMU)	3.79
Wire harnesses and miscellaneous	2.51
Dedicated experimental processor (DEP)	4.70
Total	43.13

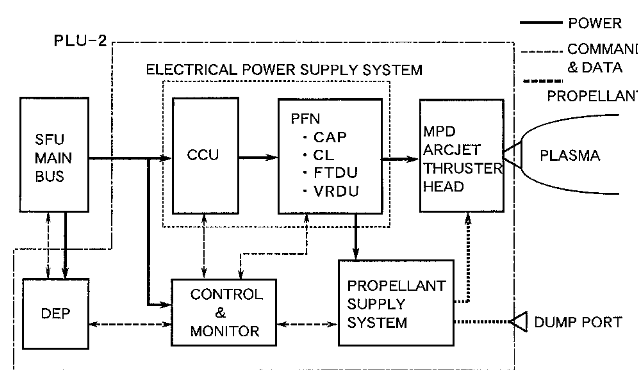


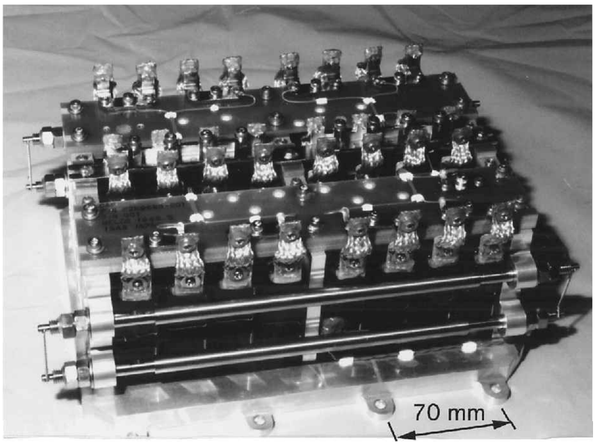
Fig. 4 EPEX system block diagram.

Electrical Power Supply System

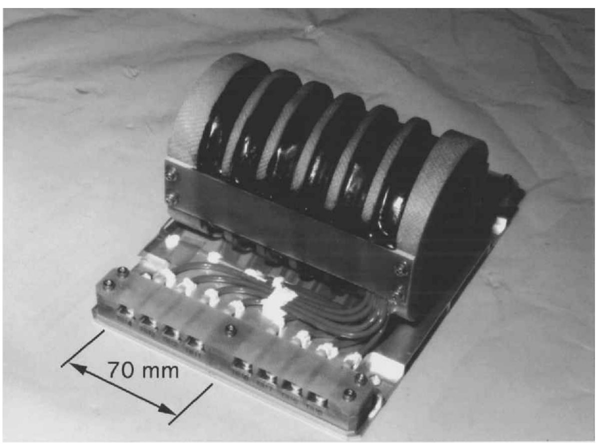
The CCU had a capability of transforming the SFU unregulated bus voltage (32–52 V dc) up to 350 V dc to charge up the capacitor bank of the PFN in 0.55 s. The power-conversion efficiency of CCU was very close to 90%. The PFN was configured using a CAP of 2240 μF, consisting of eight pairs of 140 μF plastic film capacitors, and a CL of 2 μH with eight bifilar-winding power lines, each of which is connected to the eight segmented anodes and also the cathode (Fig. 5). The PFN power-conversion efficiency was higher than 84%. About a 1-kV single pulse of 20 μs duration was used to trigger the discharge.

Propellant Supply System

The PSS comprised of a primary tank (hydrazine propellant tank), a secondary tank, a gas-generator, filters, latching-valves, a propellant valve, a dump port, and tubing. The 16-cm-diam primary tank employed a surface-tension liner and contained, in actual flight, only 130 g of liquid hydrazine propellant with nitrogen pressurant gas. The liquid hydrazine in the primary tank was pressurized to 24 kgf/cm^2 (2.35 MPa) and supplied to the gas generator through a propellant valve. The decomposed gas mixture of hydrogen and



a) Capacitor module



b) Coil module

Fig. 5 PFN of EPEX.

nitrogen was once stored in the secondary tank, and supplied to two sets of FAVs on the HDS. The secondary tank pressure was monitored by a pressure transducer, and was maintained between 5.9 kgf/cm^2 (0.58 MPa) and 7 kgf/cm^2 (0.69 MPa) during propellant consumption mode by a feedback control of the propellant valve.

Development Tests on the Ground

Some of the ground test results[27−29] are shown in the following section to compare with the on-orbit data.

Endurance Test and Thrust Measurement

In 1988, before developing an engineering model of the EPEX system, a 1-kW breadboard model was dedicated to a 3-million-shot endurance test. In this endurance test, a four-staged LC-ladder PFN processed the 1-kW input power at a repetition rate of 1.4 Hz. The arc discharge duration was over 600 μs and almost synchronized with the propellant gas pulse of 800 μs. The 3-million-shot endurance test (about 600 h) was successfully completed, and the thrust performance before and after the endurance test was proved to be unchanged.[19] Because of the stringent mass-saving modification of the SFU experiments, the four-staged LC-ladder PFN of the EPEX, however, was reduced in 1990 to only single-staged LC-ladder configuration of the engineering-model development phase. As a result, the arc discharge duration also was reduced to 150 μs, whereas the gas pulse duration could not be shortened due to FAVs' limitation of mechanical quickness.

For a proto-flight-model thruster head in 1992, thrust impulse was evaluated with a pendulum method where the thruster head was suspended by steel wires from a thrust stand inside a vacuum chamber, and the pendulum swing was calibrated by known impulses. Figure 6 shows the operational waveforms. Because of the

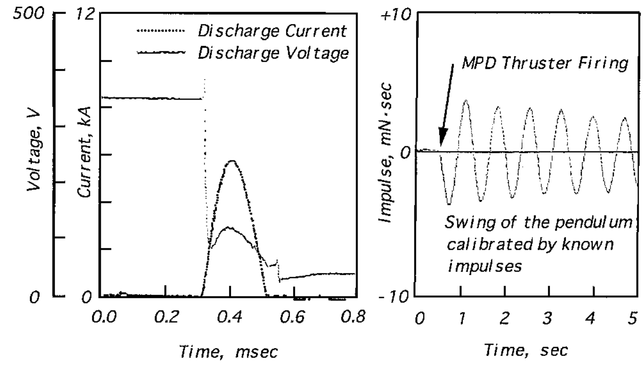


Fig. 6 Typical performance data of proto-flight-model of the thruster head (ground data).

cable losses via the vacuum chamber feed-through, the impedance matching is closer to critical damping than in the flight configuration. The typical measured impulse was 3.678 mN · s with ±5% error of shot-by-shot dispersion at a propellant mass consumption of 1.246 mg/shot with ±5% pressure gauge accuracy.

Electrical Performance Test and Hydrazine Dump into Vacuum

Some electrical performance tests were conducted such as CCU capability of charging the capacitor module, and demonstration of the firing sequence via the interface of the CMU with the EPEX electrical components using the HDS inside a small glass vacuum chamber. Finally, a firing test was performed using nitrogen as the propellant in a thermal-vacuum chamber to obtain health conditions for end-to-end electrical performance of the EPEX system. In addition, Electromagnetic Interference (EMI) tests were conducted to confirm that there were no critical effects of MPD firings on the bus or other experimental components of the SFU. The electric field noise exceeded the limits of RE-02 of MIL-STD461C Part 3 at lower frequencies from the kilohertz to megahertz range, but because the MPD firing was just a repetition of very short pulses and no bus or experimental components were susceptible to that noise level, the RE-02 compatibility was safely waived. Other conductive noise or susceptibility tests showed no problem.[27,28]

The EPEX was mandated to dump the residual hydrazine propellant to assure the safety of the manned Space Shuttle, which retrieved SFU into the cargo bay. The EPEX was obligated to verify the dumping capability of liquid hydrazine into the space vacuum, without any freezing or splashing, by providing a dump port nozzle and its orifice. Water was used in ground testing because of its triple point similarity to liquid hydrazine. The dumping technology into vacuum was successfully demonstrated.[28]

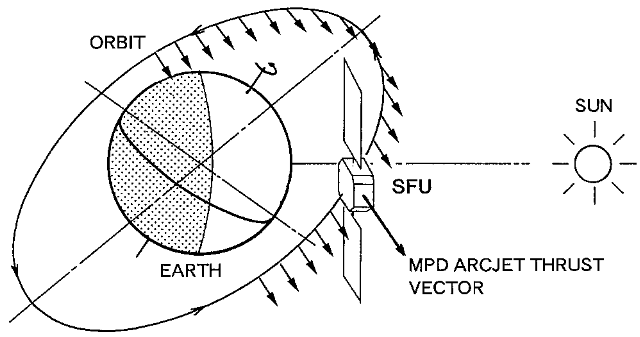
Environment Tests

Sinusoidal vibration tests for verifying EPEX structural strength against the mechanical environment of the H-II launch vehicle and the Space Shuttle landing vehicle were successfully applied at both PLU-2 qualification and acceptance levels.[27−29] A shock test was replaced by random vibration tests, and the static load test was exempted because of the light weight of the EPEX system.

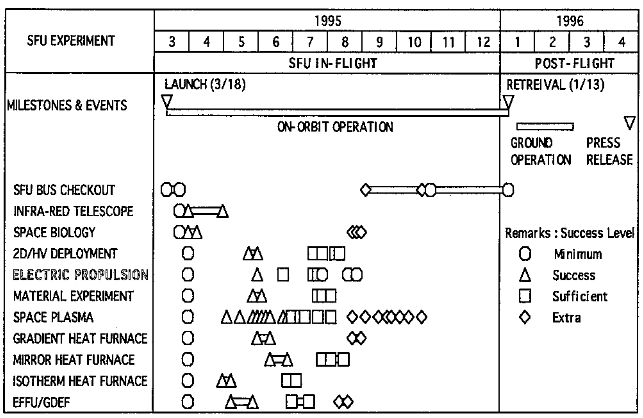
The thermal vacuum tests for both PLU-2 qualification and acceptance levels were also conducted to verify the thermal interface between the PLU-2 and the EPEX, and to verify heater sizing, thermal insulation, and/or radiation design.[27−29] Especially, the hydrazine system was strictly monitored in order to satisfy NASA safety requirements for the Space Shuttle. A firing test was performed in a thermal-vacuum chamber to confirm the end-to-end electrical performance of the EPEX system. A thermal cycle test was also undertaken to prove proper function of electrical components between −20 and 40 °C.

On-Orbit Experimental Results

The SFU baseline attitude of sun-pointing mode on-orbit during the EPEX experiment and an overview of the SFU flight operation



a) SFU attitude during sunshine period



b) Overview of EPEX activation during SFU flight

Fig. 7 EPEX flight operation.

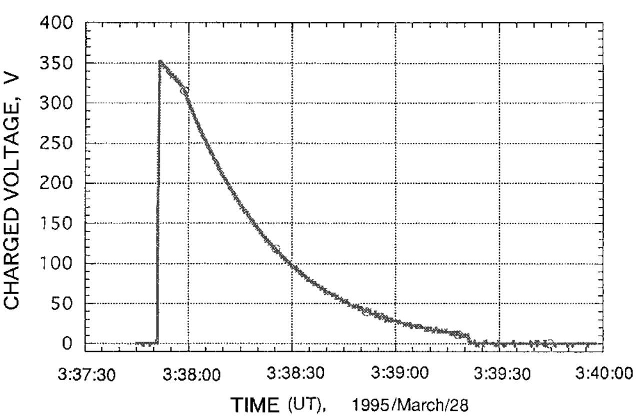


Fig. 8 Charge/discharge waveform of the capacitor bank (flight data).

are given in Figs. 7a and 7b. EPEX operation started with the system checkout on 28 March 1995 and was followed by the firing sequence tests on 29 May 1995. On 2 June 1995, 24 June 1995, and 17 July 1995, the EPEX performed repetitive firings and dumped residual hydrazine propellant into space on 20 July 1995. The hydrazine disposal was completed by approximately 1-month vacuum drying of the PSS on 22 August 1995. The final telemetry of experimental success was confirmed on 24 August.[30–32]

Charge/Discharge of the Capacitor Bank

As one of the system checkouts of EPEX, the charge/discharge capability was verified followed by turning on the whole system including pressure and temperature monitors. Figure 8 shows charge/discharge waveform of the CAP. It was exactly identical to the designed waveform of charging up to 350 V and decaying the charged voltage through dump resistors. In this phase, the plasma firing was inhibited to avoid inadvertent mishaps possibly affecting the SFU bus or other experiment systems. This was conducted to insure the CCU and PFN healthiness and the EPEX monitoring function. The EPEX employed dump resistors in order to prevent any residual electronic charge in the CAP. This was also a NASA safety requirement.

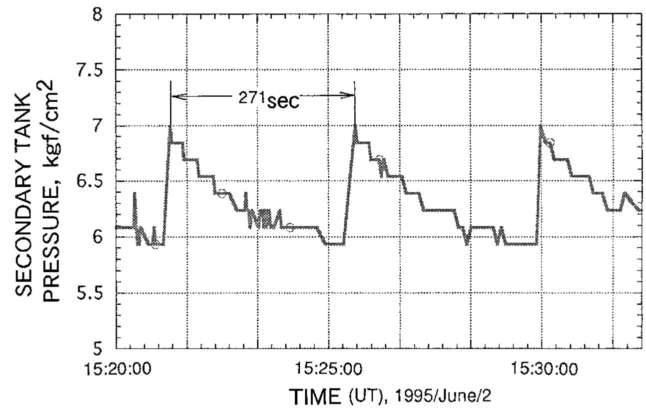


Fig. 9 History of the secondary-tank pressure decay during the firings and pressure recovery by the propellant feed control (flight data).

Monitoring the Hydrazine System

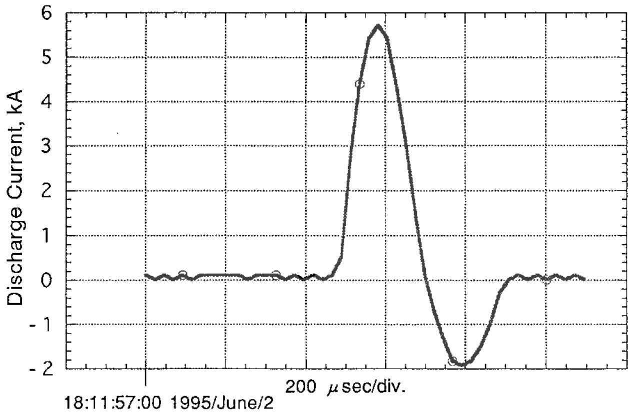
The pressure and temperature trends of the primary hydrazine tank and the secondary tank were successfully monitored to verify their stabilization without any leakage on-orbit. The temperatures were well maintained between 20 and 40°C during the firing and the stand-by periods. Figure 9 shows the pressure decay and recovery cycle of secondary tanks where the pressure of hydrazine decomposed gas decreases during the EPEX firing. In this figure, the regulation process by feedback control was successfully confirmed as a pressure function, starting at 7 kgf/cm^2 (0.69 MPa absolute), decaying during the firing, and the secondary tank was re-filled at 5.9 kgf/cm^2 (0.58 MPa absolute). From this decay rate, the propellant consumption rate was calculated as 1.19 mg/shot.

Plasma Firing On-Orbit

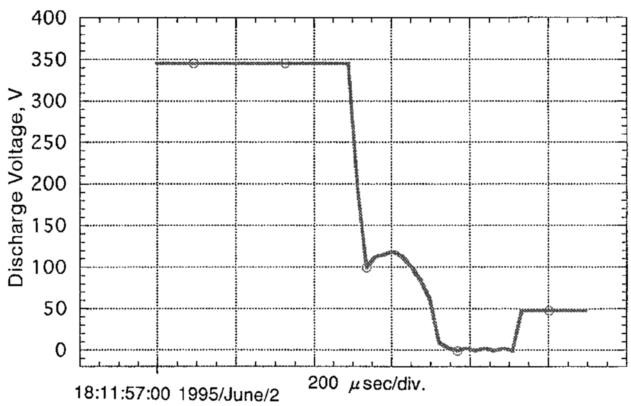
Figure 10 shows the discharge current and discharge voltage waveforms. The peak current of about 6 kA and the peak voltage of about 120 V showed good agreement with the ground test data. The first half waveform of the discharge voltage corresponds to the charged voltage of 350 V in the CAP, and the latter corresponds to the discharge waveform through the PFN. To reduce the specific mass of the capacitor bank, the discharge current was intentionally underdamped and reversed by high PFN impedance, (i.e., high voltage charge of low capacitance). Instead, in the EPEX flight, we employed a diodes array circuit in the PFN to recharge the reversed current energy into the CAP. The half-value width of the current waveform is about 150 μs, and also corresponds to the ground test data (In Fig. 6, the current was almost critical-damping and the reversed current was truncated by block-diodes). Figure 11 shows the repetitive discharge/charge voltage cycles at a repetition rate of 1 Hz. Each voltage drop implies the plasma firing from the charged voltage of 350 V and the discharge voltage of 120 V. The misfiring was less than 0.3% of total firings, and it mainly was observed at a high repetition rate of 1.8 Hz as was anticipated in the ground test. The total accumulated firing amounted to 43,395 pulses on-orbit during the allocated experimental period for the EPEX.

Comparison of Thrust Performance Estimation Between Space and Ground Tests

Figure 12 shows the variation of the SFU attitude control output expressed in units of N · m · s before and after the EPEX repetitive firings. Before the EPEX firings, the SFU attitude control indicated an increasing trend caused by natural disturbances such as gravity-gradient and atmospheric drag torques, but during the EPEX firings,



a) Discharge current



b) Discharge voltage

Fig. 10 Arc discharge waveforms on-orbit (flight data).

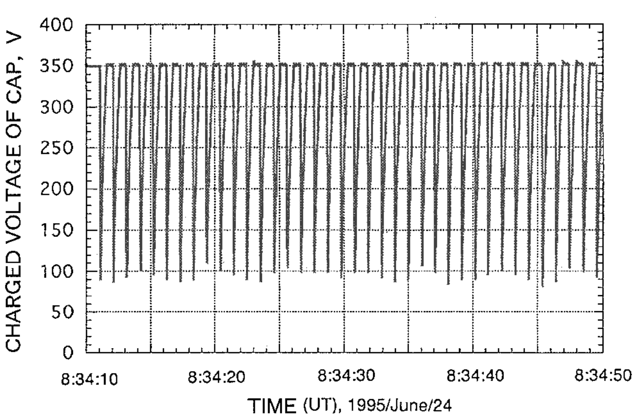


Fig. 11 Charge/discharge voltage history of the capacitor module during 1 Hz repetitive firings (flight data).

this trend was reversed. The difference is caused by the external disturbance generated by the EPEX firings. In Fig. 13, the EPEX plasma firing and its generated torque around the SFU are shown. When the EPEX generates a torque around the Y-axis of SFU, the momentum wheel of SFU detects it as external disturbances to recover the sun-pointing attitude. From this control value of the Navigation, Guidance and Control system, a mechanical torque arm of the EPEX thrust vector (the equivalent torque arm is 0.24 m with ±10% error due to ambiguity of the SFU gravitational center during flight) and the associated number of firings, we can evaluate the magnitude of an impulse bit during the EPEX firing. This measurement resulted in 3.6 ± 0.36 mN · s thrust impulse per firing, and was in good agreement with the ground test value of 3.678 mN · s. In the

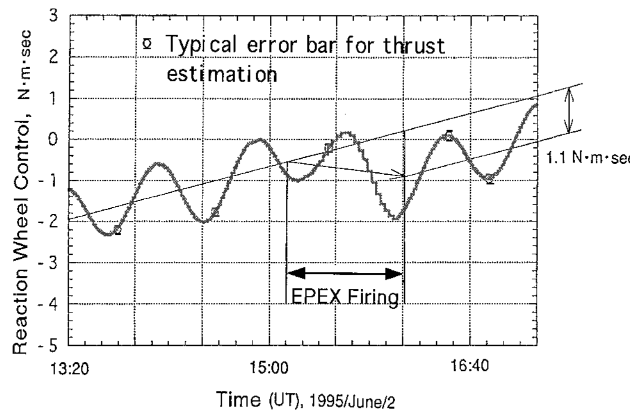


Fig. 12 EPEX-generated torque evaluated by the onboard momentum-wheel of SFU attitude control system (flight data).

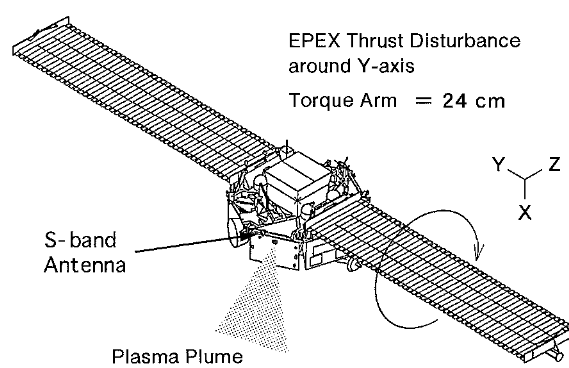


Fig. 13 EPEX thrust torque disturbance against the SFU attitude.

ground test, the propellant mass consumption was 1.246 mg/shot with ±5%. We were also able to calculate the on-orbit propellant consumption rate from the pressure decay of the secondary tank as already shown in Fig. 8, and it was 1.19 mg/shot with ±2% error of eight-bit pressure sensor accuracy. The value straightforwardly obtained as a division of measured impulse-bit over propellant mass consumption gives a specific impulse of no higher than 300 s. However, this is a meaningless figure, because the EPEX firing duration is only 150 μs at this time, whereas the gas pulse duration is almost 800 μs as half-value width. The peak value of specific impulse for the 150 μs EPEX firing (=the ideal value when a 1-kW system assumed with longer arc discharge duration) can roughly be evaluated from the following equation:

$$I_{sp} = \frac{I_{mes} - (1 - T_1/T_2)I_{cold}}{g(T_1/T_2)\Delta m}$$

where I_{sp}: specific impulse, I_{mes}: measured impulse bit, I_{cold}: impulse bit by cold gas pulse ($\Delta m \times 1.257$ mN · s), T_1: firing duration, T_2: gas pulse duration, Δm: propellant consumption as mass bit, g: gravitational acceleration.

This calculation shows the 1000 ± 120 s potential of the EPEX if a full 1-kW configuration of four-staged LC-ladder network (=longer than 600 μs arc discharge) is employed.

Presence of Plasma Plume

On 2 June 1995, during the EPEX firing at the visible pass of Uchinoura-Station, we switched on an S-band communication antenna (SFU has four S-band communication antennas on board), which was closest to the MPD arcjet thruster head at a distance of 0.6 m. At that time, the frame synchronization of telemetry was intermittently unlocked. The automated telemetry gain control at Uchinoura-Station observed 0.5 Hz well-regulated notches during the EPEX firings. This result indicated that the plasma plume from the MPD arcjet thruster head trespassed the S-band link at a distance

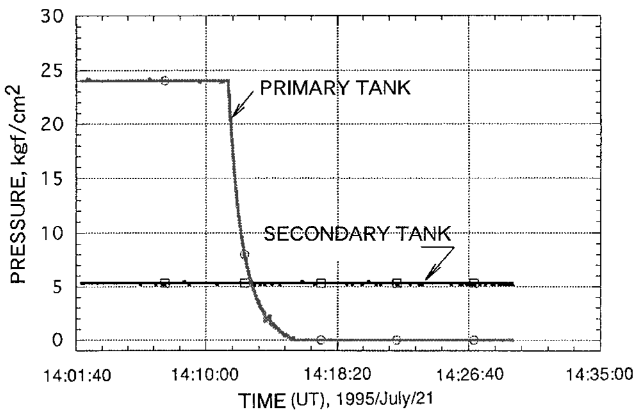


Fig. 14 Pressure decay of the primary tank associated with residual hydrazine and nitrogen gas-pressurant dump (flight data).

of several meters ahead of the SFU, and the telemetry signal of Pulse Code Modulation-Phase Shift Keying transmission was involuntarily modulated by the existence of plasma. This was also a good measure of plasma plume of the EPEX firing, although the identification of the plasma density was out of scope for the Uchinoura-Station activity.

Residual Hydrazine Dump

The residual liquid hydrazine dump of several tens of grams into space was successfully started on 20 July 1995 by opening three redundant latching valves (Fig. 14). The on-orbit verification of pressure decay and temperature profile during the hydrazine dump from the primary tank was so critical to the NASA Safety Review Board that the SFU would not be retrieved if the data acquisition failed or indicated any kind of anomalies. Three redundant latching valves were kept open about 1 month to expose the PSS to vacuum for drying until 22 August.

Postflight Inspection, Reflight Potential, and Future Prospects

After the retrieval of SFU, the EPEX system was completely checked out again on the ground by visual inspection and electrical performance tests. There were no signatures of abnormal arc discharges inside the PLU-2, and no hydrazine concentration was detected inside the PSS. Because no significant electrodes erosion was observed, and no malfunction of electrical circuit nor mechanical failures were observed, the EPEX system was recognized to have reflight potential if the hydrazine propellant was reloaded. As mentioned earlier, the EPEX system was merely a functional model for a 1-kW full system. However, the results imply successful operation on board the SFU. From the lifetime point of view, an EPEX breadboard model already finished a 3-million-shot endurance test successfully on the ground. Together with the functional demonstration of the EPEX in space, the MPD arcjet thruster system has become flight-proven as an electric propulsion system.

There are two potential future directions for the post-EPEX flights after the space test on board SFU. The initial goal of the EPEX was a full assembly of a 1-kW or higher system and hence, the follow-up flight was expected to be an orbit-raising/lowering demonstration combined with a 3-kW solar thermodynamic engine generator on a large test bed like the SFU. However, the kW-class system mass also becomes heavier due to a larger capacitor bank for longer pulse duration of arc discharge, resulting in a major penalty of quasi-steady MPD applications. The second direction of EPEX evolution in the future will be a repetitively pulsed application as, just like the operation in this report, with a higher specific impulse delivered by shorter duration of gas pulse. This may require a total improvement of the propellant feed system replacing the mechanical valves by other fast-acting techniques. In this case, lowerweight, robustness, and conciseness of the system will be the sales point for attitude control or station-keeping of satellites.

Conclusions

The following are the experimental achievements acquired from the EPEX:

1) The EPEX was verified to have a design compatibility to launch and space environments because the checkout of the system successfully demonstrated the healthiness of the EPEX control and monitor function. A very small mass flow rate of hydrazine propellant was successfully regulated through a gas generator with a simple automatic feedback control of the propellant valve.

2) The propulsive function of repetitive firings of MPD arcjet thruster was verified on-orbit. MPD arcjets had a few space flight experiences in the 1980s, but this is the first time hydrazine propellant was utilized and fired at a repetition rate of 0.5 Hz or higher. The total accumulated firings amounted to 43,395 pulses on-orbit with a very small misfiring rate of 0.3%. The thrust characteristics were measured on-orbit, and those results showed good agreement with the ground data.

3) The EPEX also verified the safe design of an MPD arcjet thruster system compatible with the manned space transportation system (i.e., the Space Shuttle), and its design policy was recognized as acceptable to the NASA Safety Review Board. The residual hydrazine dump and the propellant temperature and pressure maintenance without leakage, overheating, or freezing were the most critical features of the EPEX system. The residual electronic charge in the capacitor bank was also successfully eliminated in compliance with safety requirements.

Acknowledgments

The authors are deeply indebted to those who cooperated with the development, tests, integration, and flight operation of EPEX, especially to Ishikawajima-Harima Heavy Industries, Co., Ltd. and Mitsubishi Electric Corporation.

References

[1] Toki, K., Shimizu, Y., and Kuriki, K., "Application of MPD Thruster Systems to Interplanetary Missions," *Journal of Propulsion and Power*, Vol. 2, No. 6, 1986, pp. 508–512.

[2] Sovey, J. S., and Mantenieks, M. A., "Performance and Lifetime Assessment of Magnetoplasmadynamic Arc Thruster Technology," *Journal of Propulsion and Power*, Vol. 7, No. 1, 1993, pp. 71–83.

[3] Myers, R. M., Domonkos, M., and Giland, J. H., "Low Power Pulsed MPD Thruster System Analysis and Applications," *29th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit*, Monterey, CA, June 1993; also AIAA-93-2391.

[4] Choueiri, E. Y., Kelly, A. J., and Jahn, R. G., "Mass Savings Domain of Plasma Propulsion for LEO to GEO Transfer," *Journal of Spacecraft and Rockets*, Vol. 30, No. 6, 1993, pp. 749–754.

[5] Domonkos, M., Roderick, N., and Myers, R. M., "10 kW Class Pulsed MPD Thruster Design for SEOTV Applications," *30th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit*, Indianapolis, IN, June 1994; also AIAA-94-2993.

[6] Alexeev, Y. A., Kazeev, M. N., Kaminski, A. S., Kuznetsov, V. S., and Pavshuk, V. A., "2 Mwe NEP System with MPD Thruster," *Proceedings of the 24th International Electric Propulsion Conference*, IEPC-95-107, Vol. 1, Moscow, 1995, pp. 732–737.

[7] Uematus, K., Morimoto, S., and Kuriki, K., "MPD Thruster Performance with Various Propellants," *Journal of Spacecraft and Rockets*, Vol. 22, No. 4, 1985, pp. 412–416.

[8] Auweter-Kurtz, M., Kruelle, G., and Kurtz, H. L., "The Investigation of Applied-Field MPD Thrusters on the International Space Station," *Proceedings of the 25th International Electric Propulsion Conference*, IEPC-97-116, Cleveland, OH, 1997.

[9] Winter, M., Auweter-Kurtz, M., Boie, C., and Kurtz, H. L., "Investigation of the Plasma State of Steady State MPD-Thrusters by Emission Spectroscopy," *Proceedings of the 25th International Electric Propulsion Conference*, IEPC-97-113, Cleveland, OH, 1997.

[10] Tahara, H., Kagaya, Y., and Yoshikawa, T., "Performance and Acceleration Process of Quasisteady Magnetoplasmadynamic Arcjets with Applied Fields," *Journal of Propulsion and Power*, Vol. 13, No. 5, 1997, pp. 651–658.

[11] Paganucci, F., Rossetti, P., and Andrenucci, M., "Temperature Effects on Current Emission in an Artificially Heated MPD Cathode," *Proceedings of the 25th International Electric Propulsion Conference*, IEPC-97-119, Cleveland, OH, 1997.

[12] Choueiri, E. Y., "On the Thrust of Self-Field MPD Thrusters," *Proceedings of the 25th International Electric Propulsion Conference*, IEPC-97-121, Cleveland, OH, 1997.

[13]Tikhonov, V. B., Semenikhin, S. A., Brophy, J. R., and Polk, J. E., "Performance of 130 kW MPD Thruster with an External Magnetic Field and Li as a Propellant," *Proceedings of the 25th International Electric Propulsion Conference*, IEPC-97-117, Cleveland, OH, 1997.

[14]Goodfellow, K. D., and Polk, J. E., "Experimental Verification of a High-Current Cathode Thermal Model," *31th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit*, San Diego, CA, 1995; also AIAA-95-3062.

[15]Turchi, P. J., "Design of an MPD Arcjet for Operation at Gigawatt Power Levels," *Proceedings of the AIDAA/AIAA/DGLR/JSASS 22nd International Electric Propulsion Conference*, IEPC-91-058, Vol. 1, Viareggio, Italy, 1991.

[16]Myers, R. M., Parkes, J. E., and Mantenieks, M. A., "Multimegawatt MPD Thruster Design Considerations," *Ninth Symposium on Space Nuclear Power Systems*, Albuquerque, NM, Jan. 1992; also NASA TM 105405.

[17]Kuriki, K., Nakamaru, K., and Morimoto, S., "MPD Thruster Test on Engineering Test Satellite," *Electric Propulsion and Its Applications to Space Missions*, edited by C. Finke, Vol. 79, Progress in Astronautics and Aeronautics, AIAA, New York, 1981, pp. 605–615.

[18]Kuriki, K., Kawashima, N., Sasaki, S., Yanagisawa, M., and Obayashi, T., "Space Experiment with Particle Accelerators (SEPAC) Performed in Spacelab First," *18th International Electric Propulsion Conference*, Alexandria, VA, Sept. 1985; also AIAA-85-1996.

[19]Shimizu, Y., Toki, K., and Kuriki, K., "Development of an MPD Propulsion System," *Proceedings of the 20th International Electric Propulsion Conference*, IEPC 88-015, DGLR/AIAA/JSASS Garmisch-Partenkirchen, Germany, 1988, pp. 99–104.

[20]Suzuki, H., Uematsu, K., Ohtsuka, T., Shiina, K., Toki, K., and Shimizu, Y., "3 Millions-Shots Endurance Test of 1 kW-Class Arcjet Thruster," *20th International Electric Propulsion Conference*, IEPC-88-014, DGLR/AIAA/JSASS, Garmisch-Partenkirchen, Germany, 1988.

[21]Kunii, Y., Sumida, M., Moriai, T., Sasaki, H., Okamura, T., Harada, H., Ijichi, K., Shimizu, Y., and Toki, K., "Verification of Performance and Endurance of Capacitor Bank for the Eolectrical Propulsion Experiment (EPEX)," *Proceedings of the 20th International Electric Propulsion Conference*, IEPC-88-048, DGLR/AIAA/JSASS, Garmisch-Partenkirchen, Germany, 1988, pp. 292–299.

[22]Sumida, M., Kunii, Y., Moriai, T., Sasaki, H., Okamura, T., Yoshida, T., Ijichi, K., Shimizu, Y., and Toki, K., "Verification of Control Sequence and Argorithm for the Electric Propulsion Experiment (EPEX)," *Proceedings of the 20th International Electric Propulsion Conference*, IEPC-88-049, DGLR/AIAA/JSASS Garmisch-Partenkirchen, Germany, 1988, pp. 300–305.

[23]Nishida, E., Shimizu, Y., and Kuriki, K., "Improved Thrust Generation Mechanism for Electrothermal/Electromagnetic Arcjet," *Proceedings of the 20th International Electric Propulsion Conference*, IEPC-88-026, DGLR/AIAA/JSASS, Garmisch-Partenkirchen, Germany, 1988, pp. 163–168.

[24]Toki, K., Shimizu, Y., and Kuriki, K., "Electric Propulsion Experiment Onboard Space Flyer Unit," *21st International Electric Propulsion Conference*, Orlando, FL, July 1990; also AIAA-90-2557, AIAA/DGLR/JSASS.

[25]Shiina, K., Suzuki, H., Uematus, K., Ohtsuka, T., and Toki, K., "Development of MPD Thruster for a Space Test," *21st International Electric Propulsion Conference*, Orlando, FL, 1990; also AIAA-90-2558, AIAA/DGLR/JSASS.

[26]Okamura, T., Sakurai, J., Sasaki, H., Sumida, M., Kunii, Y., Ijichi, K., Shimizu, Y., and Toki, K., "Development of the Charge Control Unit for Electric Propulsion Experiment (EPEX)," AIAA-90-2626, AIAA/DGLR/JSASS, *21st International Electric Propulsion Conference*, Orlando, FL, July 1990.

[27]Shimizu, Y., Toki, K., Suzuki, H., Uematsu, K., Otsuka, T., Shiina, K., and Kunii, Y., "Development of MPD Arcjet System EM for SFU-1," *Proceedings of the 22nd International Electric Propulsion Conference*, IEPC-91-147, AIDAA/AIAA/DGLR/JSASS, Vol. II, Viareggio, Italy, 1991.

[28]Toki, K., Shimizu, Y., Kuriki, K., and Kuninaka, H., "An MPD Arcjet Thruster System for Electric Propulsion Experiment (EPEX) in Space," *30th AIAA/ASME/SAE/ASEE Joint Propulsion Conference*, Indianapolis, IN, June 1994; also AIAA-94-2989.

[29]Toki, K., Shimizu, Y., and Kuriki, K., "Ground Tests and Space Tests of a Magnetoplasmadynamic Arcjet Thruster System," *Journal of Space Technology and Science*, Vol. 13, No. 2, 1997, pp. 27–40.

[30]Suzuki, S., Sakaguchi, H., Miyata, M., Ohtsuka, T., Uematsu, K., Toki, K., Shimizu, Y., and Kuriki, K., "EPEX Flight Test Onboard SFU-1-Thruster, Propellant Supply System and Thermal Control System," *20th International Symposium on Space Technology and Science*, ISTS 96-a-3-14, Gifu, Japan, May 1996.

[31]Kunii, Y., Shimizu, Y., Toki, K., and Kuriki, K., "Results of Electric Propulsion Experiment (EPEX) Onboard SFU-Power Conversion and Control Subsystem," *20th International Symposium on Space Technology and Science*, ISTS 96-a-3-15, Gifu, Japan, May 1996.

[32]Toki, K., Shimizu, Y., and Kuriki, K., "Electric Propulsion Experiment (EPEX) of a Repetitively Pulsed MPD Thruster System Onboard Space Flyer Unit (SFU)," *Proceedings of the 25th International Electric Propulsion Conference*, IEPC-97- 120, Cleveland, OH, 1997.