DEVELOPMENT OF AN MPD PROPULSION SYSTEM

88-015

Y. Shimizu*, K. Toki**, and K. Kuriki+,
Institute of Space and Astronautical Science
Sagamihara-shi, Kanagawa 229, Japan

Abstract

A 1 kW MPD thruster system developed in ISAS recorded 3 x 10^6 accumulated firings which correspond to 25 days continuous operation demonstrating 34 mN/kW at an Isp of 600 sec. The critical components for system endurance, an MPD thruster head of segmented electrodes with improved thrust performance and a 574 J fail-proof capacitor bank were placed in a vacuum chamber to be operated in 1.4 Hz repetitively pulsed quasi-steady mode. The propellant was hydrazine simulative decomposed gas. A software for automatic control of firings and system diagnosis were also successfully verified without human manipulation for hold and restart. Since the system endurance was verified no less than 3 million shots, it was qualified as a breadboard model for EPEX (Electric Propulsion Experiment) onboard SFU (Space Flyer Unit) of which launch is scheduled in the early 1990s. The EPEX system is presently encouraged to reduce mass and power consumption matched with the SFU accomodation.

1. INTRODUCTION

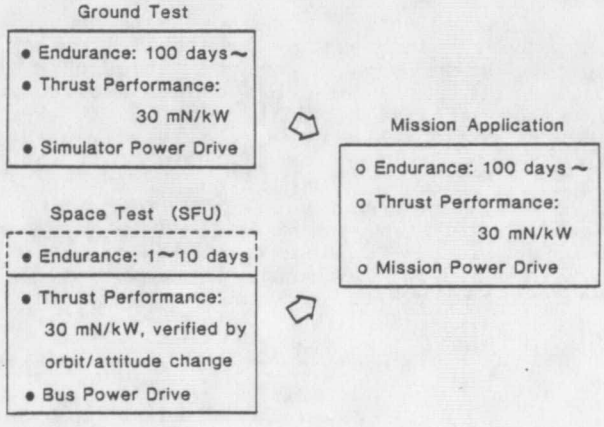
The MPD thruster system is characterized by simple configuration, high thrust density, variety of propellants, and being free of external magnetic field. A 1 kW MPD thruster system in ISAS will employ hydrazine propellant with consideration of commonality use to Reaction Control System (RCS) for many spacecrafts. Due to the lack of large power of hundreds kilowatts in space the MPD propulsion system should carry a capacitor bank for energy storage and intermittent discharge so as to reduce power consumption to the level of multi-hundreds watts available in near future Japanese space program. A great deal of efforts have been paid for years to develop a repetitively pulsed quasi-steady MPD thruster, however, its space test has been put off without getting an opportunity of sufficient power as a propulsion system.

A Japanese free flyer designated SFU (Space Flyer Unit) is scheduled to be launched by H-II rocket and retrieved by Space Shuttle in the early 1990s. The SFU, which is capable of involving EPEX (Electric Propulsion Experiment) of multi-hundreds watts, serves a testbed for advanced space technology and science. Although the available resource onboard SFU, time, mass, and electrical power are strongly limited, the EPEX will demonstrate at least the launch durability and propulsive function of the MPD thruster as a primary electric propulsion system.

In order to qualify an MPD thruster system as a space proven one, our development scenario is shown in Table 1. A ground test will be required for 100 days endurance with 30 mN/kW. On the other hand, the space test of EPEX verifies the launch durability, space survivalability with foreseeable endurance, and comparison of thrust performances obtained in space and those on the ground. These two ways verification will be necessary in advance of practical mission application, which includes orbit transfers in LEO, maintenance of long-term free flyers and space stations, and interplanetary exploration.[1]

A breadboard model of the MPD thruster system was fabricated and dedicated to an endurance test from December 1987 until March 1988. Since the previous endurance test resulted in 1x10^6 accumulated firings with human manipulation for hold and restart,[2] a software for self-diagnosis as well as automatic control of sequences were newly developed. Furthermore the system thrust performance assuming charge efficiency onboard SFU was evaluated before and after the endurance test.

Table 1 Development scenario of MPD thruster system.



2. EPEX ONBOARD SFU

2.1. Objectives of EPEX

The EPEX is one of the most promising opportunity to verify the propulsive function and space durability of the MPD thruster system (Fig. 1). The time resource of the SFU does not permit conducting an endurance test in space but would rather provide a chance to compare the laboratory performance data with those of space test. The space test offers a lot of unknown effects to the system such as infinite space, vacuum, zero-gravity, and extreme temperature cycles. The primary objective of the EPEX is to checkout the system

* Research Engineer, Member JSASS
** Associate Professor, Member JSASS/AIAA
+ Professor, Associate Fellow AIAA/ Director JSASS

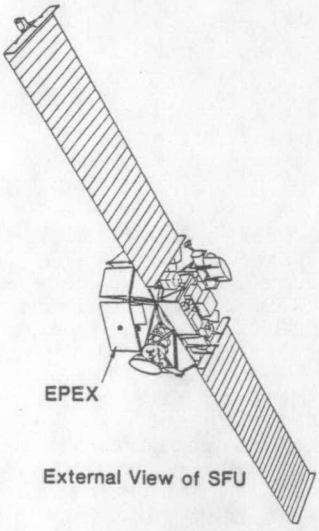


Fig. 1: EPEX onboard SFU.

survivalability against the space without losing its original performance confirmed on the ground. The orbital operation can include both engineering and scientific purposes below in the order of priority,

i) Functional checkout of the system,
ii) Thrust generation and evaluation,
iii) Environmental assessment for plasma exhaust.

2.2. EPEX System Design

2.2.1. Propellant Selection

Propellant selection criterion bases on not only the thruster performances but also the species prevalence of earth's atmosphere. One of the most preferable propellant from a viewpoint of storability in space is N_2H_4 (hydrazine) which has been extensively used in RCS gas-jet thrusters. Considering the impact of exhaust plume on the environment it will be expected that H, N, He, and O species are less influential to the upper atmosphere than rare earth species or heavy metals else. In that sense NH_3 (ammonia) is the second choice for MPD propellant because its convenient character of low freezing point at about -70° as well as quite similar thruster performances to hydrazine precludes careful temperature control. However, hydrazine provides more merits of commonality use of propellant tank between the MPD thruster and the RCS than its troublesome handling due to the toxicity.

2.2.2. System Definition

The EPEX system can be combined with various type of power sources such as solar array, batteries, solar thermodynamic generator, and even space nuclear power plant. In the first flight, the bus solar array of the SFU drives the system, and hence the power source is excluded from the EPEX system. A conceptual block diagram of the EPEX system is shown in Fig. 2. The MPD thruster system consists of 5 correlated major systems, MPD Head System, Electrical Power System, Propellant Supply System, Thermal Control System, and Control & Monitor System. The MPD Head System has one set of discharge head to generate thrust, and Fast Acting Valves (FAV's) for repetitive propellant gas feed.[3] The Capacitor Bank in the Electrical Power System can receive the power from Charging Control Unit (CCU) which can cope with low voltages (~55 V) generated by the bus solar array. The stored energy in the Capacitor Bank is transferred into the MPD Head System via the Pulse Forming Network (PFN) in a repetitive rectangular pulse.[4] The trigger for arc discharge and the FAV's for the MPD Head System are also driven by the Capacitor Bank. The liquid hydrazine propellant is stored in the Propellant Tank and fed through a gas-generator and pressure regulator into the secondary tank. In order to comply with NASA safety policy, the hydrazine Propellant Supply System has three independent shut valves with status monitors for avoiding unanticipated action during flight and ground operation. The waste heat from the MPD Head System is rejected into space by a high temperature radiative panel. A small amount of heat leakage from the MPD Head System and the waste heat from the Electrical Power System are rejected via heat pipes to the low temperature radiation structure. The Control & Monitor System is peculiar to the

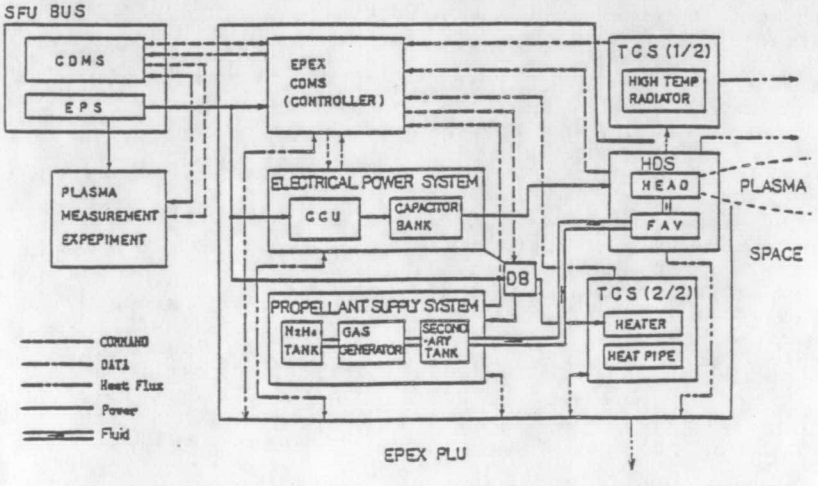


Fig. 2: Systems block diagram of EPEX.

MPD thruster system.[5] This generates internal commands monitoring the experimental data, and communicates with the bus CDMS (Command and Data Management System).

2.2.3. System Configuration

Since SFU has an octagonal structure including 8 payload-unit boxes (PLU's), it will be more convenient for the EPEX that the MPD thruster system occupies two of these PLU's for acceleration/deceleration direction. The SFU will assign one PLU box per one experiment in principle (Fig. 3) avoiding the thruster plume impingiment on the bus solar array. Major system of the EPEX, Capacitor Bank, is mounted on the main panel (beneith the ceiling) and side panels. The MPD Head System (one discharge head) is sustained by strucural support to align the thrust vector to the gravitational center of the SFU. The propellant Supply System is covered by thermal insulation blanket and attached to the side panels. The room space of PLU is utilized for CMS processors, wireharnesses, sensors for house keeping, and other SFU missions. Finally the PLU box is closed by an access panel with windows of discharge head, the hydrazine filling/drain valves, and test connectors. The thermal environment of PLU is controlled by thermal louvers with second surface mirror. The fundamental spceifications of EPEX are summarized in Table 2. The SFU will hopefully assign the mass resource of 50 kg, with electrical power of 770 W max in the daytime to the EPEX. These constraints impose on the EPEX one-half orbital operation in the daytime and repetitively pulsed firings of 330 μsec at 2.0 Hz for 23 mN averaged thrust. The delivered Isp may not exceed 600 sec. A higher Isp will be attainable, if more mass resource is available onboard the SFU. The hydrazine, space storable propellant, is selected for the EPEX. Fortunately, hydrazine decomposed gas exhibited excellent thrust power ratio for the MPD thruster.[1]

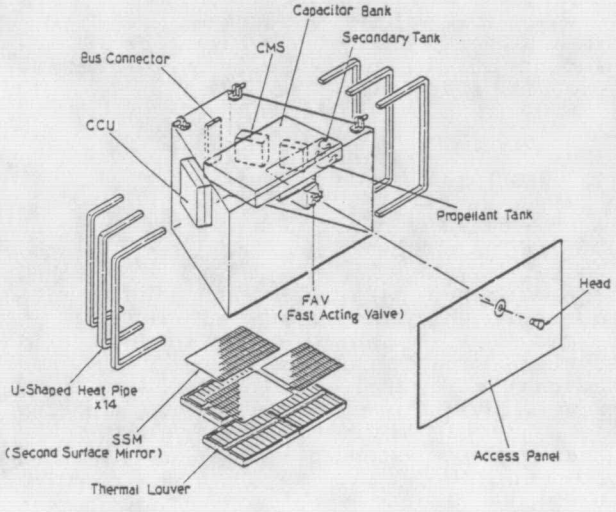


Fig. 3: Installation configuration of EPEX.

2.3. Orbital Operation in EPEX

Because the SFU is tentatively scheduled to be injected into a 482 km circular orbit with 28.5 deg inclination, it encounters air-drag of 10-30 mN (Fig. 4). The SFU provides 770 W to the EPEX only during the daytime. Due to the sun-oriented attitude with non-rotatable solar array of the SFU, the thrust vector of the MPD thruster is aligned parallel to the orbital velocity vector only at noon (Fig. 5). This attitude requirement is not most efficient for acceleration, however, the simple

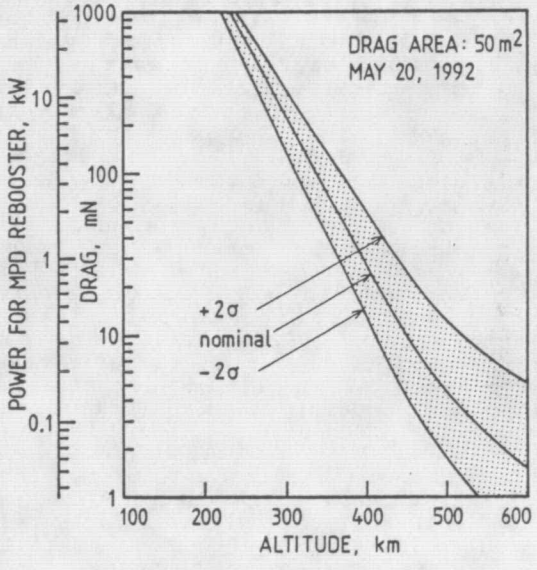


Fig. 4: Air-drag estimation of SFU.

Table 2 EPEX specifications.

	EPEX	'87 BBM
Mass	50 kg	78 kg [a]
Size, envelope	1.05x0.9x0.5 m	1.06x0.87x0.4 m
Power, bus	770 W	1,050 W
Pulse Width/Repetition	330 μsec/2 Hz	600 μsec/1.4 Hz
Command/Data Rate	9/640 bps	-
Propellant	Hydrazine	$N_2 + 2H_2$
Thrust	30 mN/kW	34 mN/kW
Specific Impulse	< 600 sec	600 sec

a) Capacitor Bank & Thruster Head

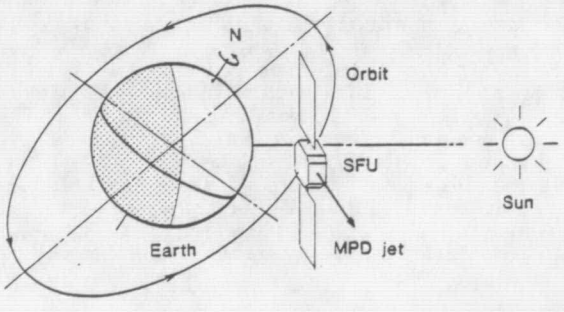


Fig. 5: Orbit and attitude of EPEX.

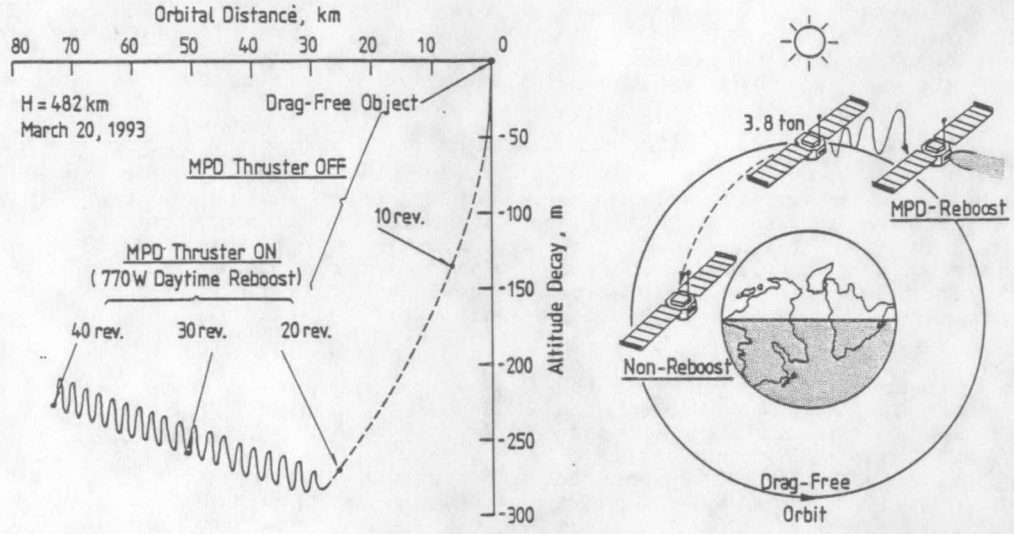


Fig. 6: Evaluation of thrust generation in EPEX.

requirement of attitude control facilitates the estimation of MPD thrust without disturbance of RCS or other attitude controls.

The functional checkout of the system includes a few stages of procedures. The first issue in the objectives is the activation of Control & Monitor System, then the temperatures, pressures, and status of critical components are checked out with proper action of valves and relays. Some basic sequences such as propellant gas feed, FAV's and trigger circuit operation, and PFN charging will be checked out with data acquisition. These are categorized into the minimum success of the mission. After that, the firing sequences starts for 4 successive firings to finish the preliminary checkout. A 770 W continuous operation is our primary objective in the EPEX, and hence the mission success criterion is defined by even one orbital revolution demonstrating the proper function of the MPD thruster system.

The second issue will be categorized into sufficient success in the EPEX. Since the available power level and its duration are limited as 770 W during the daytime, it is of secondary interest to demonstrate the altitude maintenance or orbit raising capability of the EPEX system. However, even in the restricted power, the thrust performance can be assessed in this experimental issue. Providing 770 W for the MPD thruster system during the daytime, the SFU can compensate its altitude decay to some extent as shown Fig. 6. An evaluation of altitude increase/decrease during thrusting and non-thrusting period gives the estimation of generated thrust. The value should be compared to the data obtained in the ground-based test. Since the measurement accuracy strongly depends on the magnitude of air-drag in the exosphere, the orbital reduction rate must be also measured during the non-thrusting period.

The third issue is categorized into extra success for the EPEX, because the environmental assessment of the spacecraft with and without MPD thruster operation is mainly examined. The measurements can be conducted by cooperative experiment with SFU Environment Monitor (SEM) and Space Plasma Diagnostic Package (SPDP) of plasma diagnostic group. Plasma measurements such as particles, waves, and luminosity will offer enviromnetal database of the plume/spacecraft interference during the MPD thruster operation. This will contribute to the assessment of future impact on LEO environment caused by a large amount of plasma exhaust from electric propulsion systems.

3. RESULTS OF SYSTEM ENDURANCE TEST

A breadboard model of the 1 kW MPD thruster system was fabricated (see Fig. 7) and tested in 1987. The system test corresponds to endurance assessment of on-off cycle operation in the vacuum environment on critical components such as MPD Head System, Capacitor Bank, and software for automatic control and monitor. The most remarkable feature of this test is adopting 18 segmented discharge electrodes of MPD Head with an extended nozzle and 18 Pulse Forming Networks separated for the segmented electrodes. Such a concept was already simulated in the laboratory test to demonstrate high thruster performances.[6,7]

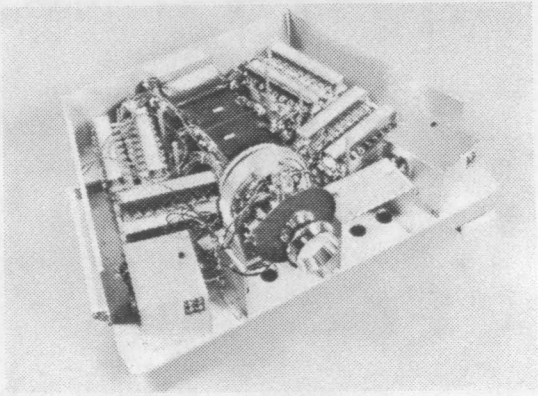


Fig. 7: Breadboard model of '87 system endurance test.

3.1. Test Objectives

i) To verify mechanical, thermal, and electrical endurance of the segmented configuration of the 1 kW MPD thruster system,

ii) To consolidate the database of flight/ground software design for autonomous control and monitor system,

iii) To evaluate the thruster system performance in terms of thrust power ratio (target: 30 mN/kW).

3.2. Test Condition

i) The MPD Head System and the Capacitor Bank are placed in the vacuum chamber with dimensions of 2 m diam. and 3 m length, which is kept less than 67 mPa (Fig. 8),

ii) The consumable system power is 1 kW (600 μsec x 1.4 Hz discharge) assuming the power conversion efficiency of the charger as 0.85 (Fig. 9),

iii) Propellant has simulative constituent of hydrazine decomposed gas (N_2+2H_2),

iv) The continuous operation can be voluntarily held for on-off cycle test, planned checkout, and for unanticipated failure of the facility.

3.3. Test Results

We started the system test December 1987 and successfully terminated in February 1988. The accumulated number of firings amounted to 3 million shots at 1.4 Hz which corresponds to 25 days continuous operation. As the operational history is outlined in Fig. 10, on every Saturday afternoon and Sunday, the system was completely powered-off. We had 3 times involuntary holds due to the failure of vacuum pump facility and 3 times voluntary holds for planned checkout. After the 3 million firings, the system was totally checked out, and we found no noticeable

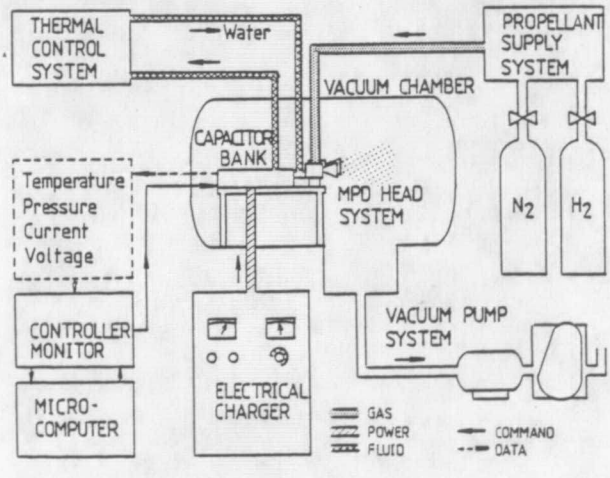


Fig. 8: Test conditions.

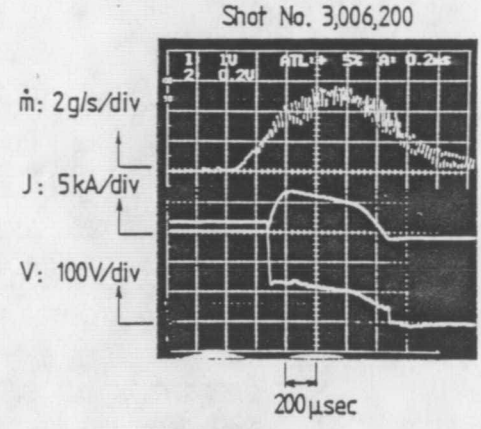


Fig. 9: Operation conditions (Waveforms).

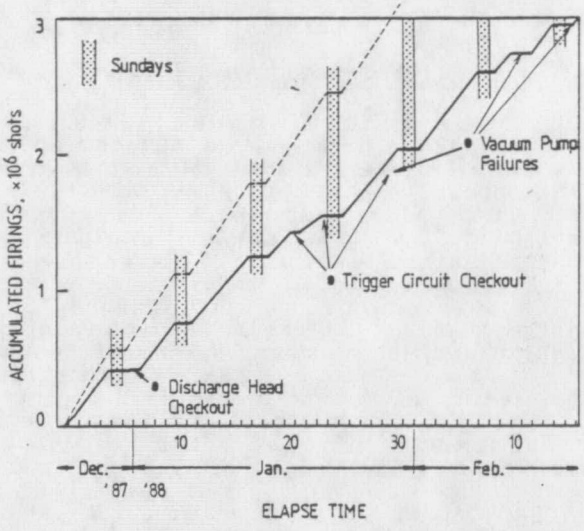


Fig. 10: Operational history of '87 system endurance test.

failures in the Capacitor Bank. The electrode erosion was in the tolerable order. The automatic control history and monitored data of the system were also obtained. The system thrust power ratio was kept during the test at 34 mN/kW which was higher than the expected value of 30 mN/kW (Fig. 11). The specific impulse indicates about 600 sec and several percents degradation was found after the system endurance test which might be caused by cathode erosion of the MPD Head System. The cathode erosion rate was estimated as 0.6 μg/C throughout the endurance test, which means that the cathode longevity will exceed 100 days continuous operation. In the additional test, alternate operation of two MPD discharge heads at 1.4 Hz, induced mechanical vibration measurement, and electrical ground test was successfully conduted. The plasma plume contamination inside the vacuum chamber are evaluated by degradation of reflection coefficient of stainless-steel pieces distributed inside the chamber. There found no optical damage due to MPD plume or sputtered material except the deposition of diffusion pump oil.

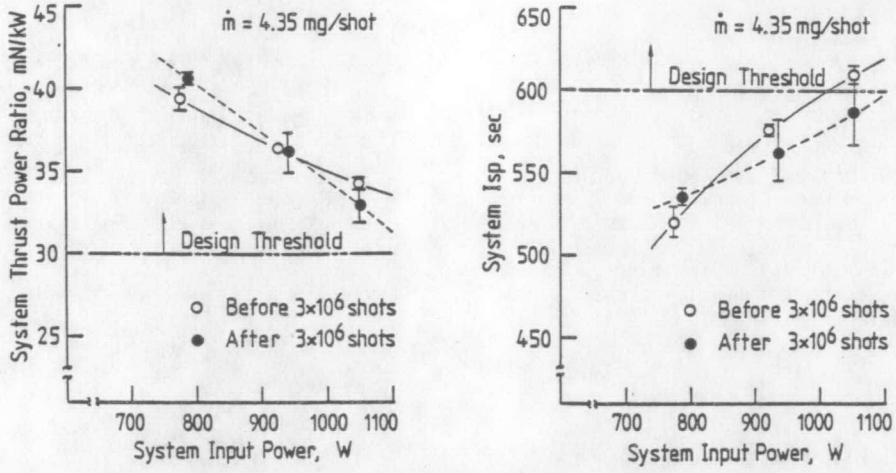


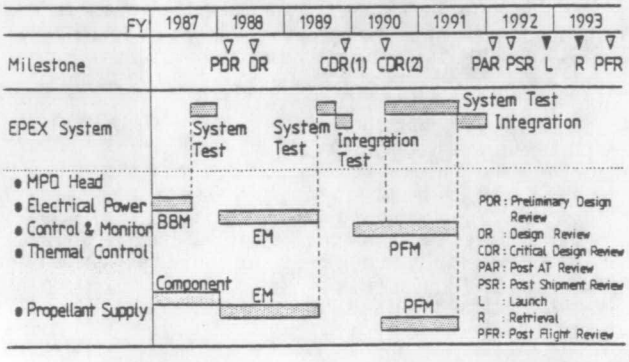
Fig. 11: System thrust performance of '87 endurance test.

4. DEVELOPMENT PROGRAM, FUTURE TASKS

On our tentative schedule of the development program of the MPD thruster system, the nearest space test will be the EPEX onboard the SFU in the early 1990s (Table 3). A remained problem is the mass saving of the whole system with safety consideration, electrical charger, and dedicated experimental processor. Based on the above results obtained in the '87 system test, it is required to develop a lightweight MPD thruster system of 50 kg (including 1 kg hydrazine) as the engineering model. The system is presently encouraged to reduce mass and power consumption matched with the SFU accomodation.

A few problems concerning the electromagnetic interference, and liquid hydrazine handling will also be solved in the course of development. Furthermore, a 100 days (10 million firings) endurance with refined thruster performance of 30 mN/kW at an Isp of 800 sec should be verified on the ground test at the beginning of the 1990s. These efforts will surely be reflected in the technological-readiness for the extensive application of MPD propulsion system to the interplanetary flight as well as near-earth targets.

Table 3 Development programmatics of MPD thruster system.



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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, Nov.-Dec. 1986, pp. 508~512.

2. Toki, K., Shimizu, Y., and Kuriki, K., "Development of Repetitively Pulsed Quasi-Steady MPD thruster", Proceeding of 15th ISTS, pp. 139~144, Tokyo, 1986.

3. Suzuki, H., Uematsu, K., Ohtsuka, T., Shiina, K., Toki, K., Shimizu, Y., "3 Million-Shots Endurance Test of 1kW Class Arcjet Thruster", IEPC 88-014, 1988.

4. Kunii, Y., Sumida, M., Moriai, T., Sasaki, H., Okamura, T., Harada, H., Ijichi, K., Shimizu, Y., Toki, K., "Verification of Performance and Endurance of Capacitor Bank for the Electric Propulsion Experiment (EPEX)", IEPC 88-048, 1988.

5. Kunii, Y., Sumida, M., Moriai, T., Okamura, T., Yoshida, T., Ijichi, K., Shimizu, Y., Toki, K., "Verification of Control Sequence and Algorithm for the Electric Propulsion Experiment (EPEX)", IEPC 88-049.

6. Kuriki, K., Shimizu, Y., and Nishida, E., "Anode Configuration for Electrothermal/Electromagnetic Arcjet", AIAA-87-1024, 1987.

7. Nishida, E., Shimizu, Y., and Kuriki, K., "Improved Thrust Generation Mechanism for Electrothermal/Electromagnetic Arcjet", IEPC 88-026, 1988.