JPC-99-2857

Results of an On-going Long Duration Ground Test of the DS1 Flight Spare Engine

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Ground testing of the DS1 flight spare thruster (FT2) is presently being conducted. To date, the thruster has accumulated over 4500 hours of operation. Comparison of FT2 with the performance of the engineering model thruster 2 (EMT2) during the 8.2 khr test shows a transient, lasting for about 3000 hours, during which the discharge chamber efficiency decreases for both thrusters. The flow rates are 2% lower for FT2 than for EMT2 and the discharge chamber performance is 4.5% lower for FT2 during the transient. Sensitivity data obtained during the test show that the lower flow rate accounts for about half of the observed difference. After the initial transients decay, the performance of both thrusters is comparable with the exception of the electron backstreaming margin--which is 6 V lower for FT2.

Introduction

NASA's 30 cm diameter xenon ion thruster technology is being validated for use in planetary missions by the NASA Solar Electric Propulsion Technology Application Readiness (NSTAR) program. This program is designed to develop the industrial capability to produce flight engine, power processor, and propellant feed system hardware and demonstrate that the technology is mature enough for flight applications. One of the goals of the program is to provide flight managers with sufficient information on performance, reliability and spacecraft interactions to give them the confidence to use the technology.

The technology validation involves a number of ground tests designed to demonstrate engine performance over the required throttling range, characterizing the engine and plume interactions with the spacecraft, and understanding the dominant failure modes. The program includes 4 long duration ground based tests and in flight validation of the xenon ion thruster technology on the Deep Space 1 (DS1) spacecraft.

During the first test, 2000 hours [1] of operation were accumulated at the NSTAR full power point (2.3 kW thruster power). During this test several potential failure modes were identified and subsequently studied in shorter duration tests. Design changes, made as a result of this work, were then validated in a 1000 hour wear test at full power [2]. After validation of the design changes, four engineering model thrusters (EMTs) were built. The second engine, designated EMT2, was tested for 8200 hours in a long duration test (LDT) at the NSTAR full power point[3]. Subsequent to this test, two flight thrusters were fabricated by Hughes Electron Dynamics Division and short duration qualification testing was performed on them [4,5].

After qualification testing, one of the flight thrusters, designated FT1, was integrated onto the DS1 spacecraft. On October 24, 1998 the DS1 spacecraft was launched. Operation of FT1 began in November 1998; in May 1999 the second thrust segment required to perform a flyby of asteroid 1999KD was completed on schedule. A discussion of the operation and performance of FT1 on the DS1 spacecraft is given in Ref. [6].

For thermal and structural reasons, some modifications to the EMT design were incorporated in the flight thrusters[4]. Although these modifications were not expected to cause significant change in thruster performance from that observed during EMT testing, ground testing of the spare flight thruster, designated FT1, was initiated before the launch of DS1. Initial testing was done to determine if there were any significant problems with the flight thruster design prior to the launch of DS1. Ground testing of FT2 began on October 5, 1999 and 412 problem free hours of operation were accumulated before the DS1 launch. Life testing of FT2 has continued since the DS1 launch to identify potential problems before they occur on DS1 and to further study known thruster wear out modes. To date, most of the testing has been conducted at the NSTAR full power point; however, operation of the thruster at a lower power level (~1.5 kW thruster power) for an extended period is planned. This paper describes the results, for the first 4500 hours, of FT2 testing.

Thruster

The 30 cm diameter flight thrusters fabricated by Hughes Electron Dynamics Division (HEDD) have spun titanium discharge chamber has a conical upstream segment and a cylindrical downstream segment. The thruster magnetic circuit consists of three rings of rare-earth magnets. The back magnet ring is mounted behind the discharge chamber cathode. The middle ring is attached at the upstream end of the cylindrical section of the discharge chamber. The front magnet ring is attached near the ion optics system. The two-grid molybdenum ion optics is attached to the downstream end of the discharge chamber. The discharge chamber is enclosed in a perforated plasma screen designed to prevent beam-neutralizing electrons from reaching high voltage surfaces. A hollow cathode neutralizer assembly is attached to, but electrically isolated from, the discharge chamber. For this test, the thruster is mounted to a holding fixture with three equally spaced gimbal pads. On DS1 the thruster each gimbal pad is attached to the center of a titanium strap. The ends of the strap are attached to the gimbal ring.

The flight thrusters incorporate several minor design changes which are not included in the EMT2 design [4]. In the EMT2 design the discharge chamber is fabricated from spun aluminum and titanium parts while the flight design uses titanium for the entire discharge chamber. In addition, the gimbal brackets have been changed from stainless steel to titanium and some of the discharge chamber components have lightening holes in the flight design. Grit-blasted wire mesh which covers the upstream, conical portion of the discharge chamber for improved sputter containment in EMT2 has been extended to cover the downstream portion as well in the flight design. Many of the components in the flight thruster are being grit blasted to improve thermal radiation capability compared to EMT2. The flight design also uses slightly stronger magnets which have been thermally stabilized at a higher temperature than those used in EMT2. In EMT2 the main cathode keeper assembly is attached to the discharge chamber, while the flight design uses a brazed cathode-keeper assembly. These design changes were validated by analysis or short duration tests and were not expected to have a negative impact on engine performance or wear characteristics.

Vacuum Facility

The test is being conducted in a 3 m diameter by 10 m long vacuum chamber pumped by three 1.2 m diameter CVI cryopumps with a combined pumping speed of 45-50 kL/s on xenon. In addition, three xenon cyropumps [7] consisting of 0.7 m^2 pure aluminum panels mounted on Cryomech AL200 coldheads, each with a pumping speed of 18 kL/s, for a total pumping speed of 100 kL/s. This pumping system provides a base pressure of 1×10^{-5} Pa (1×10^{-7} Torr) and less than 5×10^{-4} Pa (4×10^{-6} Torr) at the full power flow rates. After the six pumps accumulate a total of about 10 kg of xenon, the pumping surfaces must be regenerated. This exposes the engine to an atmosphere composed primarily of xenon at a pressure of about 4000 Pa (30 Torr). The cathodes are purged during these exposures and are reconditioned after the subsequent pumpdown to high vacuum. After the pump regeneration, there is usually a temporary increase in neutralizer keeper voltage and in the magnitude of the coupling voltage.

To reduce the amount of facility material backsputtered onto the engine , the walls and rear of the chamber are lined with graphite panels. The backsputtered deposition rate is monitored with a quartz crystal microbalance located next to the engine in the plane of the grids. At full power the backsputter rate is 0.16 mg/cm^2 khr or 0.7 μm/khr.

The propellant feed system has two Unit Instruments mass flow meters in each of the main, cathode and neutralizer flow lines. All these meters are mounted on a temperature controlled plate inside a thermally insulated box. The downstream flow meter in each line is used to measure the flow rate to an accuracy of ±1 percent. The upstream flow meters are used as flow controllers. The output signal from each controller is used to actuate a solenoid valve which maintains the flow rate at the setpoint in each line. The three solenoid valves are mounted on a second temperature controlled plate which is placed in an evacuated box. The feed system lines from the evacuated box through the vacuum chamber walls to the thrust stand are all welded to eliminate air leaks into the low pressure part of the flow system. At the thrust stand resistoflex fittings are used to connect the feed lines to the thruster.

Laboratory power supplies have been used to run the thruster during this test. These supplies are the same ones used for the 1,000 hour test and for the last 5,200 hours of the 8,200 hour test. A computer data acquisition and control system is used to monitor facility and engine conditions as well as control the lab supplies. Engine electrical parameters are measured to within ±0.5 percent using precision shunts and voltage dividers. The system samples and stores data at ~5 second intervals. It is programmed to shut down the thruster if facility problems occur or out-of-tolerance conditions on certain engine parameters occur. This allows the system to be operated in unattended mode.

At present, work is being conducted to allow unattended operation of the thruster on the DS1 flight spare power processing unit (PPU). The PPU will be operated in a vacuum facility located adjacent to the thruster chamber. The PPU is mounted on a temperature controlled plate and was recently used to run the thruster during attended, short duration testing. Installation of interlocks that will shut down the thruster and PPU if facility problems are detected is nearing completion. During preparation of the PPU facility, the PPU has been used for grid clear testing to support the DS1 mission [8].

Diagnostics Equipment

Ion beam characteristics are measured using near and far field probes. Near field beam current density profiles are obtained with a Faraday probe. The probe is a 0.8 cm diameter molybdenum disk which is biased 20 V negative with respect to facility ground to repel electrons. The Faraday probe is mounted on a 0.65 m long arm which can be swung through the beam 4 cm downstream of the thruster.

A thrust vector probe [9] used to monitor the thrust vector is located 5.8 m downstream of the thruster. The probe consists of 16 horizontal and 16 vertical 9 mm diameter by 1.2 m long graphite rods configured in a square array. The rods are evenly spaced 7 cm apart. The rods are biased 20 V negative of facility ground to repel electrons. The current to each rod is the sum of the beam current density and charge exchange ion density integrated along the length of the rod. Therefore, the current to each rod represents the integral across the beam current density distribution at a given location. The currents to the vertical or horizontal rods can be fit with gaussian distributions. The intersection of the centriods of these distributions defines the locations of the thrust vector.

An ExB probe, mounted 6 m downstream of the thruster, is used to measure the double-to-single ion current ratio. The probe collimator allow ions emitted from a rectangular strip 1.8 cm wide in one direction and traversing the entire diameter of the thruster in the other direction to be sampled. The probe is mounted on a turn table. By adjusting the pointing of the probe the cross-section of the thruster from which ions are sampled can be varied. The probe was aligned with the thruster operating and was pointed in a direction which yielded the maximum single ion current.

Test Plan

As noted earlier, testing of FT2 is being conducted to study potential failure modes which might occur during ambitious solar system exploration missions. Many of these missions require throttling the thruster over a range of 0.5 to 2.3 kW, so it is desirable to conduct testing at throttled operating conditions. During a typical mission, the thruster power is throttled in small increments to use the maximum available solar power. However, to facilitate comparison of experimental data with thruster performance models, it is desirable to operate for relatively long periods of time at a given power level during ground testing. The thruster should be operated at a given power level for long enough to allow any transients to decay and to determine steady state wear rates and performance variations.

This plan for this test, designated the mission profile test (MPT), is an attempt to roughly follow the power profile of an outbound interplanetary mission. During the first portion of such missions the thruster operates at full power. As the spacecraft moves away from the sun, the available solar power decreases--forcing throttling to lower power levels. In many outbound missions more than one solar orbit is required and the trajectory swings back near enough to the sun to resume full power thruster operation. The present plan is to operate at full power until ~45 kg of xenon are processed (~4500 hours at full power) and then throttle to ~1.5 kW for the next 40 kg (~6,000 hours at 1.5 kW). Resumption of full power operation, to process an additional 40 kg of xenon by the end of calendar year 2000, is planned.

Test Results

Test results will be divided into discussion of the performance of the major thruster components. These are the ion optics system, the discharge chamber and the neutralizer. Approximately every 50 to 200 hours a set of measurements are made to determine the health of the thruster. Three measurements that help determine the health of the ion optics system are screen grid transparency, electron backstreaming and perveance. An indicator of discharge chamber performance is the single-to-double ion current ratio. Finally, a direct thrust measurement is made.

The ion optics is used to efficiently extract and accelerate the ions produced in the discharge chamber while keeping beam neutralizing electrons from backstreaming into the discharge chamber. Screen grid transparency to ions is a measure of how effectively the optics extracts ions. Electron backstreaming occurs when beam neutralizing electrons overcome the adverse potential applied to the accelerator grid and travel upstream into the discharge chamber. Measurements are made to determine the maximum accelerator grid voltage required to stop electron backstreaming. Accelerator grid erosion occurs when energetic ions impinging on the surface. Although some impingement due to charge exchange ions is unavoidable, care must be taken to avoid accelerating ions from the discharge chamber directly onto the accelerator grid surface during normal thruster operation. Direct ion impingement for a prolonged period can cause severe accelerator grid erosion because the ions are accelerated through the total voltage applied between the grids. Perveance measurements are made to determine the margin from direct ion impingement at normal operating conditions.

Screen grid transparency to ions is measured by biasing the screen grid 20 V negative with respect to cathode common. This keeps discharge chamber electrons from being collected on the screen grid. The screen grid transparency is defined as the ratio of the ion current extracted through the screen grid to the total ion current directed toward the screen grid. The total ion directed toward the grid is the sum of the current extracted through the grid and the current that impinges on the screen grid.

A plot comparing screen grid transparency for FT2, during the MPT, and EMT2, during the LDT, is shown in Fig. 1. A jump in the transparency data for the MPT is seen between the second and third data points taken at 57 and 124 hours, respectively. After the initial jump in screen grid transparency, the transparency measured at 1.96 kW on FT2 and at 2.3 kW during the LDT were comparable. When the power level was switched during the MPT the screen transparency was less than that of EMT2 up to about 2500 hours and after about 3000 hours the screen grid transparency has been slightly higher than during the LDT. The reason for these differences is not known; however, they may be due to small differences in grid spacing between the two tests.

Electron backstreaming limit is measured by decreasing the accelerator grid voltage until electrons can overcome the adverse potential at the center of the grids and stream back into the thruster. For the data presented here, the electron backstreaming limit is defined as the point at which the discharge loss decreases by 1%. Discharge loss is used as an indicator of electron backstreaming because the discharge loss is the ratio of the energy cost of producing beam ions to the extracted beam current. From the perspective of currents flowing through power supplies, a backstreaming electron is equivalent to an ion extracted through the optics system. Therefore, backstreaming electrons look like an increase in beam current and since the discharge supplies do not have to expend energy to produce the backstreaming current the discharge loss decreases when backstreaming occurs.

A comparison of electron backstreaming limit between the MPT and the LDT is shown in Fig. 2. The backstreaming limit is dependent on beam current; the magnitude of the accelerator grid voltage at which backstreaming occurs is lower at lower power levels due to lower beam current. Again an initial jump is observed in the MPT data. After that the electron backstreaming is lower at 1.96 kW during the MPT than at 2.3 kW during the LDT. When the power level was increased to 2.3 kW during the MPT the electron backstreaming limit margin was less by about 6 V than for the LDT. The electron backstreaming limit is affected by both the accelerator grid hole diameter and the grid spacing. The change before 124 hours could be accounted for qualitatively by a decrease in accelerator grid aperture size; however, since no mechanism for decreasing the aperture size is known, it is thought that the gap between the screen and accelerator grids changed. A decrease in the electric field between the grids would cause the electron backstreaming limit to increase, which is the observed direction of the initial transient. This suggests that the screen and accelerator grid spacing increased during the initial part of the test.

Perveance is measured by defocusing the ion beam until ions directly impinge on the accelerator grid. Defocusing is accomplished by reducing the screen grid voltage. When the beam becomes defocused enough ions to directly impinge on the accelerator grid. The perveance limit is defined as the screen grid voltage at which a 0.02 mA increase in accelerator grid current is caused by a 1 V decrease in screen grid potential.

A comparison of the perveance limit data for FT2 and EMT2 is shown in Fig. 3. Again the change in power levels at 448 hours is evident in the data. The perveance limit at 1.96 kW during the MPT was lower than that at 2.3 kW during the LDT. This is to be expected because the beam current is lower at 1.96 kW than at 2.3 kW and the beamlets must defocus more before they impinge on the accelerator grid. When the operating power was increased to the 2.3 kW level during the MPT, the perveance limit was higher than that observed during the LDT. However, by 2500 hours the perveance levels for both thrusters were comparable. Both have an initially steeper transient and then settle out to a nearly linear rate of decrease. This occurs because as the accelerator grid holes enlarge the beamlets must become more defocused to impinge on the accelerator grid. The transient prior to 124 hours is also noted in the perveance limit for the MPT; the first two data points are lower than subsequent measurements. Again this suggests that there was a change in the optics system. Because the perveance limit is a measure of the beamlet diameter, the holes would have to get smaller to account for the increase in the perveance limit between the second and third measurements. Since this is unlikely--ion impingement tends to erode material making the apertures larger--it is thought that the grid spacing must have changed. Grid gap measurements were made prior to the start of the test and will be made again at the end of the test, but no measurements will be made while the thruster is in the vacuum chamber; therefore, only qualitative discussion of changes in grid spacing can be made.

During the first 124 hours of the MPT, screen grid transparency, electron backstreaming limit and perveance limit measurements suggest the gap between the screen and accelerator grid increased. Subsequent changes in these measurements for the MPT can be accounted for by enlargement of the accelerator grid apertures or changes in nominal thruster operating power level.

There are slight variations in the ion optics performance measurements between the MPT and the LDT. The screen transparency was slightly lower for the first part of the MPT than for the LDT, but tends to be slightly higher for the MPT after about 3000 hours. Although the observed transparency differences are relatively small, they will have an effect on discharge chamber performance; more ions must be produced to provide the desired beam current if the transparency is smaller

The electron backstreaming limit is an important parameter because the accelerator grid must be kept more negative than the limit. Since the energy of the ions impinging on the accelerator grid depends on the magnitude of the grid voltage, it is desirable to minimize this magnitude. The data from the MPT show that the FT2 electron backstreaming limit will exceed the nominal accelerator grid voltage before EMT2 would have if the LDT had been continued. This will require increasing the magnitude of the accelerator grid voltage which increases the erosion rate of the accelerator grid--hastening grid failure. The thruster will fail when either the accelerator grid fails structurally or the voltage required to prevent backstreaming exceeds the capability of the PPU power supply. The accelerator grid voltage can be decreased to a minimum of -250 V with the DS1 PPU.

Although the perveance limit was higher during the first portion of the MPT than it was during the LDT, the limit for both tests coincide after about 3000 hours. The differences in perveance limit for the two thrusters do not have a significant impact on thruster performance because there is at least a 300 V margin at nominal operating conditions for both FT2 and EMT2. Perveance margin, which increases as accelerator grid apertures enlarge, actually improves as the thruster ages.

Production of ions which are subsequently extracted in the ion beam occurs in the discharge chamber. Since the energy required to produce ions in not converted into useful thrust it is desirable to minimize the energy cost of producing ions in the discharge chamber. Ions are produced by electron impact from energetic electrons supplied by the discharge chamber cathode. For efficient operation, the loss of primary energy electrons to the anode before they undergo an ionization collision should be minimized. This is accomplished through use of a magnetic circuit. Neutral propellant gas is injected into the discharge chamber where it is ionized before being extracted into the ion beam. The ion production rate is proportional to the neutral gas density in the discharge chamber and the primary electron density. Therefore, a decrease in propellant flow rate tends to increase the cost of producing beam ions while a stronger magnetic circuit tends to decrease the cost of producing ions.

It is desirable to have a low discharge voltage in order to minimize the rate at which ions sputter cathode potential surfaces. Discharge chamber ions can erode the screen grid which is held at cathode potential; if severe enough they can erode through the screen grid causing structural failure. In addition, the sputtered material can produce flakes of material when they deposit on discharge chamber surfaces; if these flakes break free from the surface, they can lodge between the grids, shorting them and causing thruster failure. Most of the erosion of discharge chamber surfaces is caused by doubly ionized propellant which has twice the kinetic energy of a single ion; since double ion production rates increase with increasing discharge voltage, it is desirable to minimize the discharge voltage. The discharge voltage required to provide the desired ion production rate is dependent on the effectiveness of the magnetic circuit and the propellant flow rate.

Shown in Figs. 4 and 5 are comparisons of the cathode and main flow rates, respectively. For the MPT the cathode flow rate is 2.5% than for the LDT and the main flow rate is 1.5% lower than the LDT. The initial plan was to run both tests at the same flow rate; however, a calibration error which was not discovered until 3780 hours resulted in the MPT flows being lower than the LDT. It is also noted that the main flow rate drifted an additional 1% lower between 2000 and 2350 hours. The flow meters were recalibrated at 2350 hours; however, the calibration error was dependent on the ambient temperature which was different for the calibration before the start of the test and the calibration at 2350 hours. The error introduced by the temperature difference coincided with the drift so the main flow rates remained low until the error was discovered. Since the lower flow rates increase the propellant utilization efficiency and did not appear to have a deleterious effect on the thruster, operation at the lower flow rates was continued.

Comparison of the discharge current and discharge voltage between FT2 and EMT2 is shown in Figs. 6 and 7, respectively. After changing to full power on the MPT, the discharge current was slightly higher than that for the LDT. During the LDT the initial 2100 hours were conducted using a breadboard PPU. The breadboard PPU discharge power supply was limited to 13.5 A; as the thruster wore the accelerator grid aperture size increased allowing more neutrals to escape which reduces the neutral density inside the discharge chamber. In order to produce the desired beam current a higher electron density was required. This required an increase in discharge current. The PPU failed at about the point where the discharge current limitations would have precluded extracting the desired beam current. It is evident that for FT2 the discharge current was greater than 14 A when the switch to full power occurred. The discharge current for FT2 continued to be greater than that for EMT2 up to about 3000 hours. At that point the discharge current for FT2 was slightly below that for EMT2.

The discharge voltage for FT2 and EMT2, shown in Fig. 7, are nearly the same up to about 2000 hours when the voltage for FT2 became slightly higher than that for EMT2. The decrease in flow rate between 2100 and 3780 hours appears to have affected the discharge voltage as it was increasing until the flow decreased. Once the flow decreased the discharge voltage decreased until the flow rate was increased after which it began to increase again.

A comparison of the discharge loss for EMT2 and FT2 is shown in Fig. 8. It is seen that the discharge for FT2 is higher by about 10 W/A than that for EMT2 during the initial 3800 hours of the test.

Sensitivity measurements of discharge voltage, discharge current and discharge loss to cathode and main flow rates were made. Based on the sensitivity data, about half the difference between the MPT and LDT is due to the lower flow rates during the MPT. The rest of the difference is probably due to the magnetic circuit design and the performance of the ion optics system.

The double-to-single ion current ratio is shown in Fig. 9 for the MPT and LDT. Initial pointing of the ExB probe during the MPT was done before the jump observed in the ion optics performance parameters before 124 hours. The probe was aligned so that the single ion current to the probe was maximized. The jump in the ion optics performance parameters caused a shift in the direction at which the ExB probe received the maximum single ion current and also resulted in less double ion collection. As a result the measured double ion ratio was low. The probe was operated with the initial pointing until 607 hours, when the probe was realigned to receive the maximum single ion current. With this pointing, the double-to-single ion ratio for the MPT was found to be comparable but slightly less than that of the LDT at full power. The difference is thought to be due to a slight difference in alignment of the probe between the two tests, but it is also noted that the probe used in the LDT accepted ions from a 3.1 cm wide strip across the thruster diameter while the probe used in the MPT accepts ions over a 1.8 cm wide strip across the thruster diameter. The difference in width of the acceptance area may also affect the observed double-to-single ratio if doubles are preferentially produced near the thruster centerline.

The neutralizer is used to provide beam neutralizing electrons to the beam. To keep the neutralizer from extinguishing during a recycle, a keeper electrode and a current regulated power supply is used to continuously draw some current. The neutralizer keeper voltage is affected by the keeper current and the neutralizer flow rate.

The neutralizer flow rate for the MPT and LDT are shown in Fig. 10. As seen the MPT flow rate is higher than the LDT flow rate at the beginning of the test. It is desirable to minimize the neutralizer flow rate because the propellant expended through the neutralizer is not accelerated to high velocity to produce thrust. The neutralizer flow is used to produce a low impedance plasma bridge between the neutralizer and the ion beam. If the flow is reduced too much, the impedance becomes large and the charge neutralizing electrons have difficulty reaching the beam. Typically, large voltage oscillations occur when this happens and these oscillations can damage the neutralizer. Although there was enough margin at the 3 sccm during the LDT, the flow system for DS1 was set up so that the discharge cathode and neutralizer flow rates were nearly matched. Therefore, the higher flow rate for the neutralizer is being used for the MPT.

The neutralizer keeper voltages for FT2 and EMT2 are shown in Fig. 11. As seen the keeper voltage for FT2 is generally lower, but within 1V, than that for EMT2. The spikes in the keeper voltage for both tests correspond to situations where the cathodes were conditioned after pump regeneration. The lower keeper voltage on FT2 is accounted for by the higher flow rate. Other than the differences caused by the flow rates the performance of the neutralizers for FT2 and EMT2 are comparable.

Shown in Fig. 12 is a comparison of the thrust calculated from electrical thruster parameters for FT2 and EMT2 and thrust measurements made during the MPT. The calculated thrust for both tests are the same after the power level was increased to 2.3 kW during the MPT. The thrust measurements agree within the uncertainty of ±2.5 %; however, in general the thrust measurements are systematically between 1 and 2% below the calculated thrust.

Conclusions

Over 4,500 hours of operation have been accumulated on the DS1 flight spare thruster during an ongoing test. The thruster is performing well and no problems which would preclude processing 125 kg of xenon with this thruster have been identified. Other than slightly poorer discharge chamber performance during the first 3000 hours of the MPT and 6 V less backstreaming margin, the flight spare thruster performance is comparable to that of EMT2 during the LDT.

Acknowledgments

The research described in this paper was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

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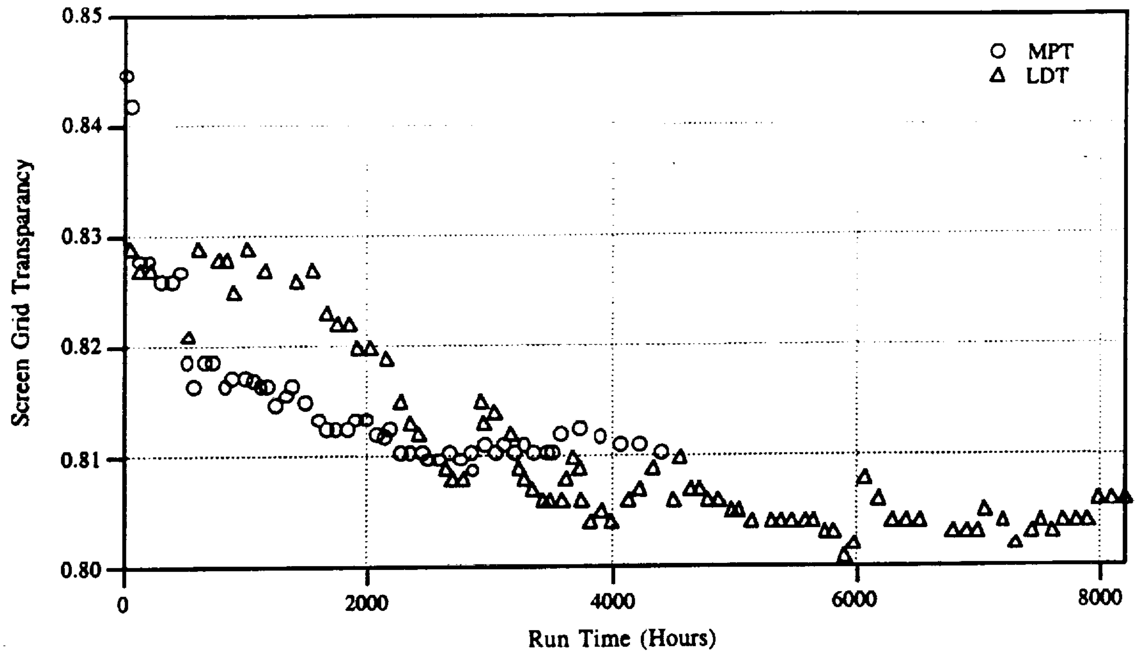

Fig. 1: Screen Grid Transparency Comparison for FT2 and EMT2

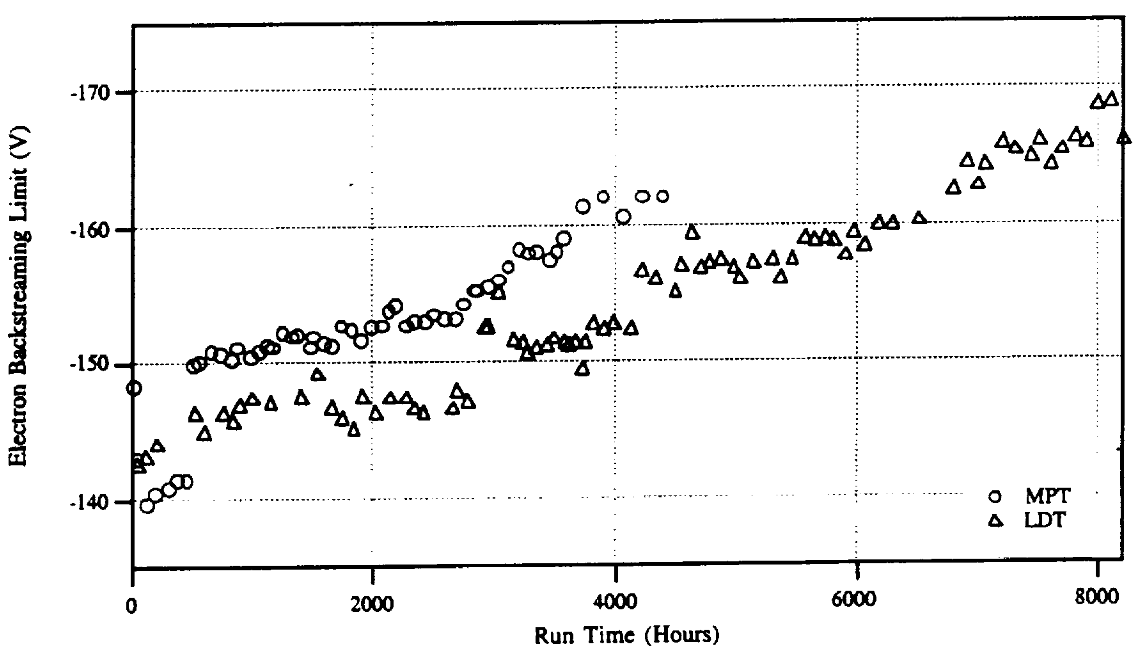

Fig. 2: Electron Backstreaming Limit Comparison for FT2 and EMT2

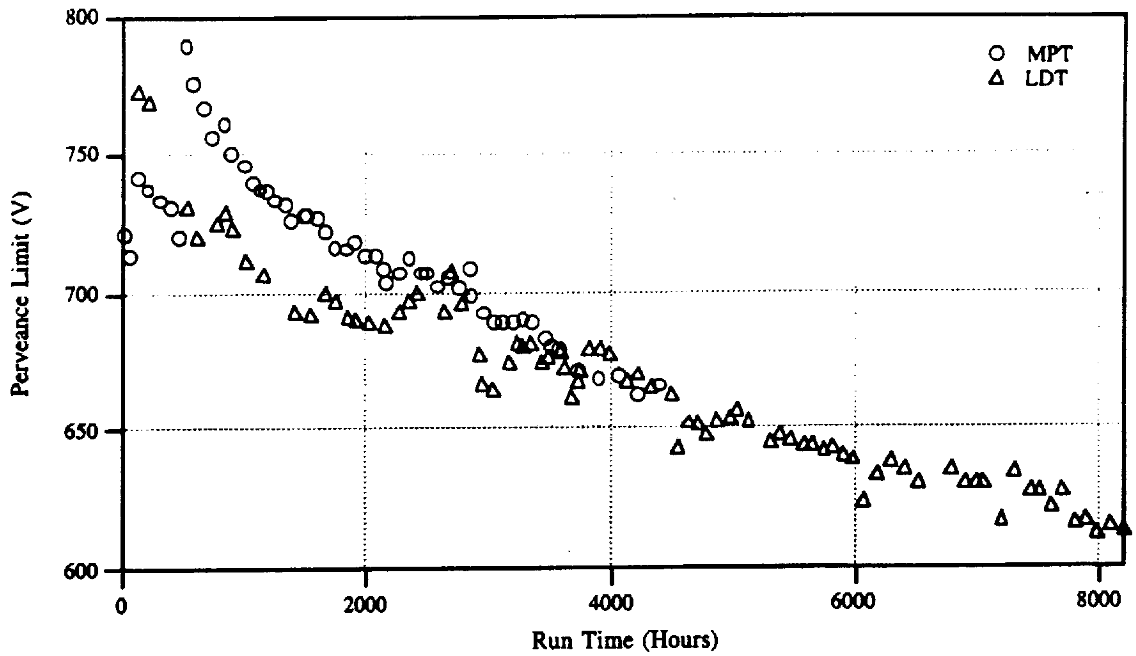

Fig. 3: Perveance Limit Comparison for FT2 and EMT2

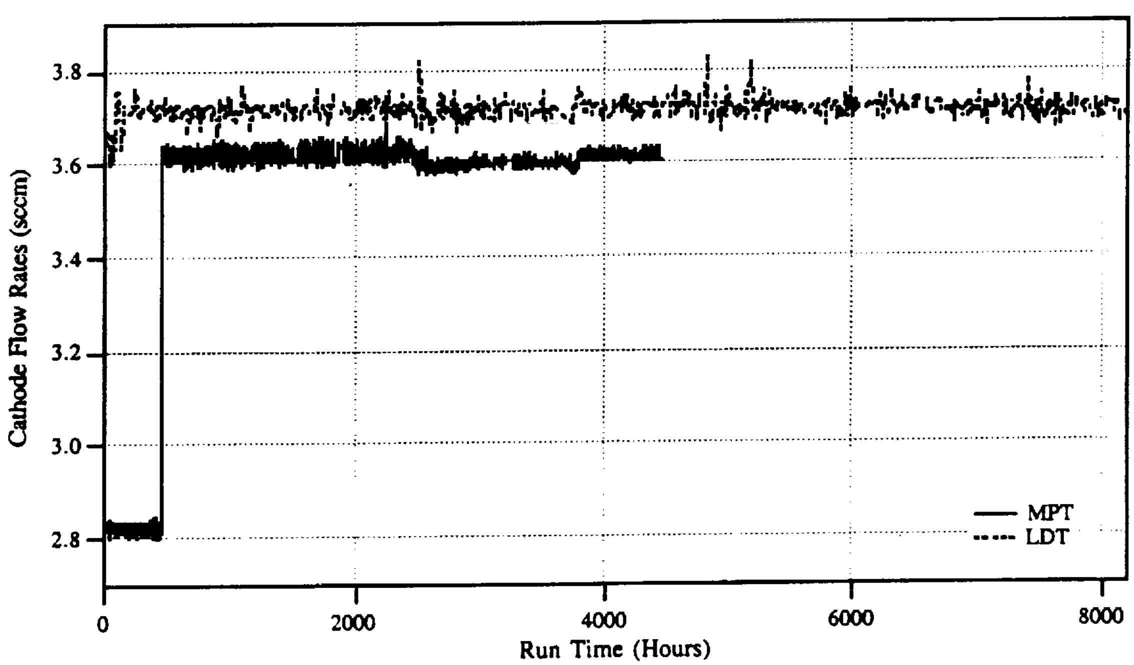

Fig. 4: Cathode Flow Rate Comparison for FT2 and EMT2

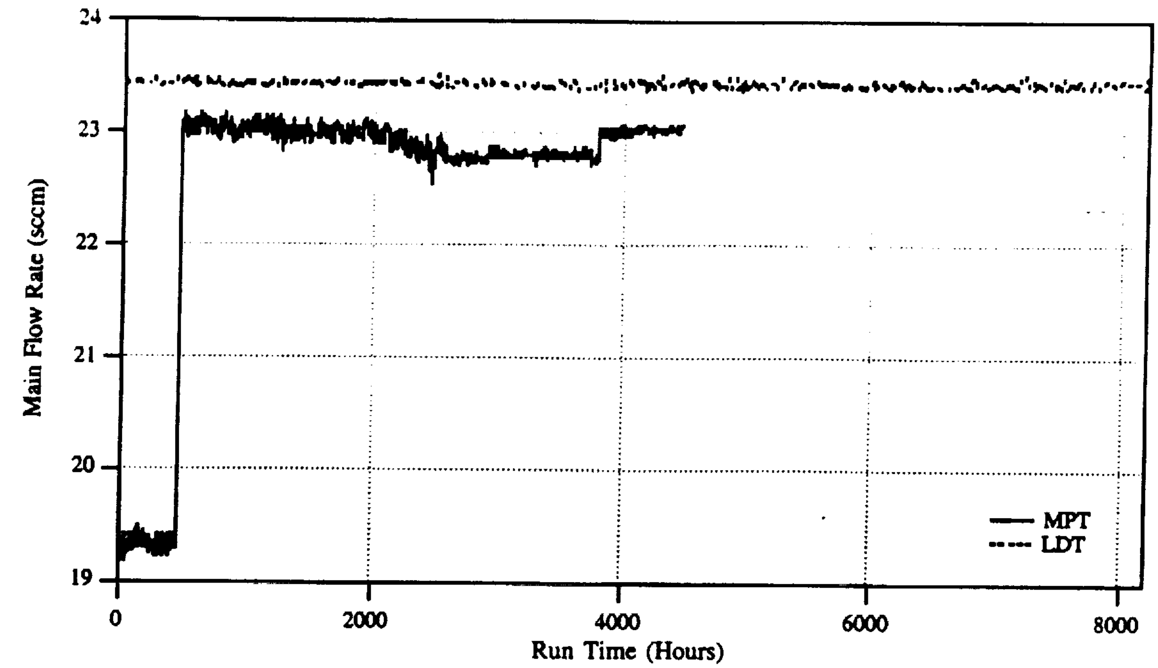

Fig. 5: Main Flow Rate Comparison for FT2 and EMT2

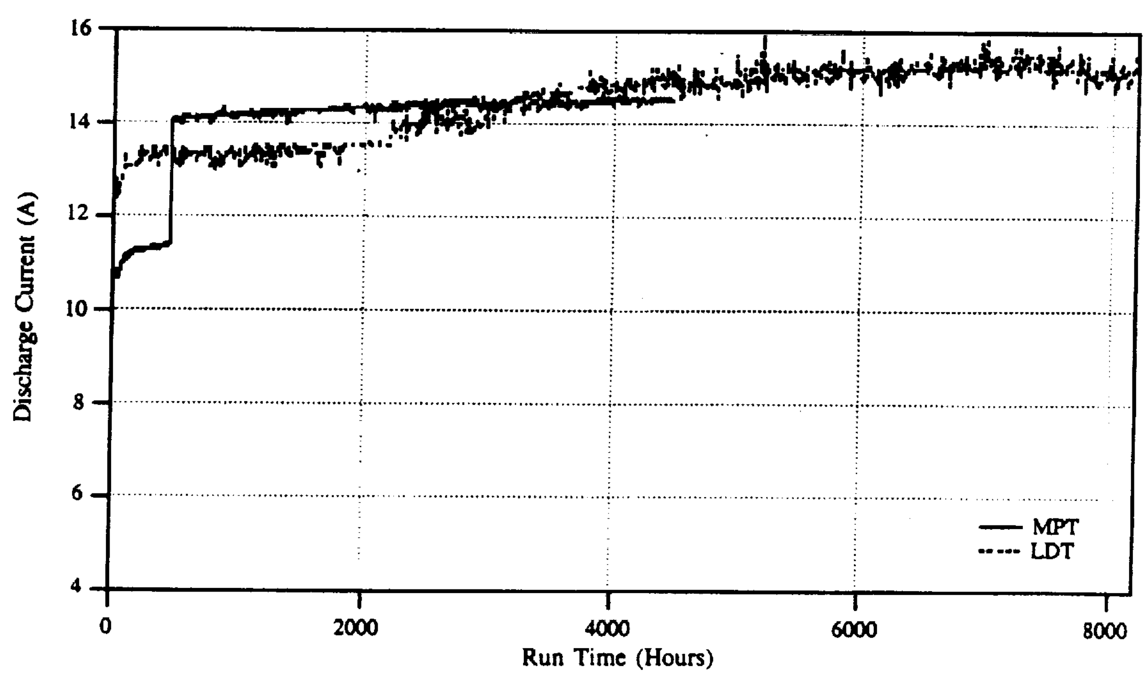

Fig. 6: Discharge Current Comparison for FT2 and EMT2

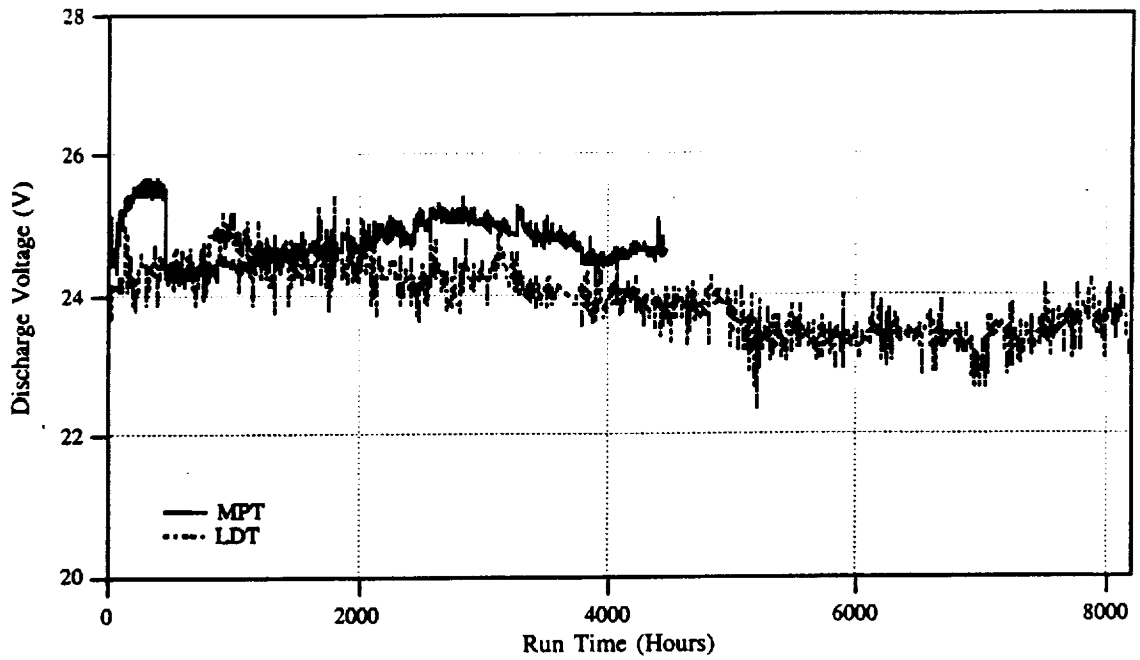

Fig. 7: Discharge Voltage Comparison for FT2 and EMT2

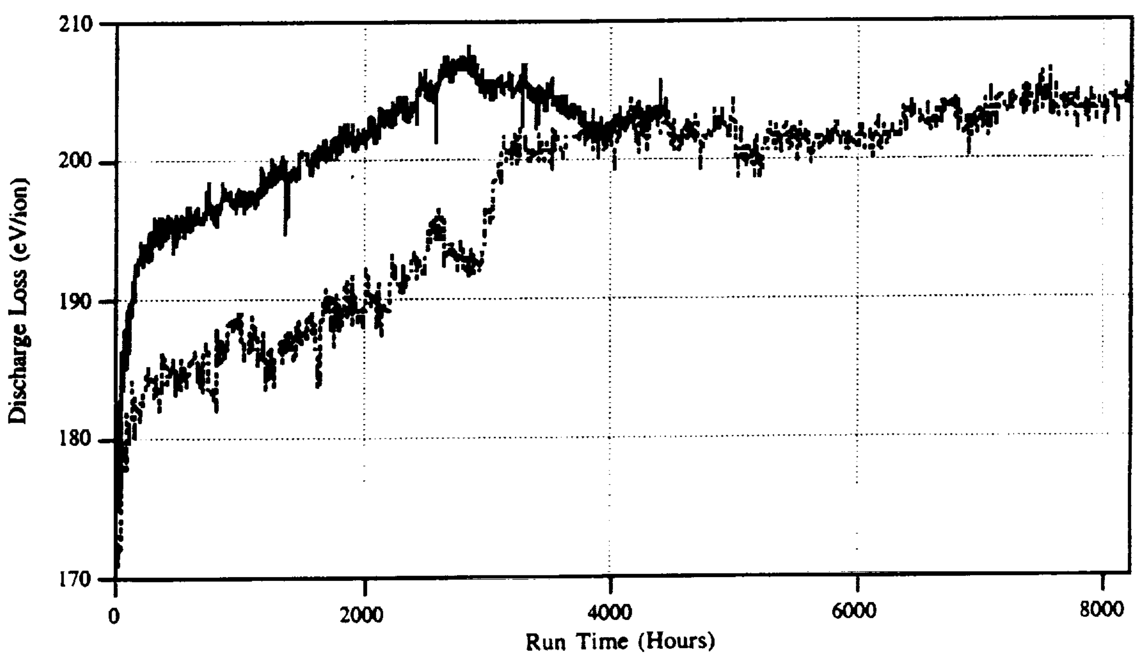

Fig. 8: Discharge Loss Comparison for FT2 and EMT2

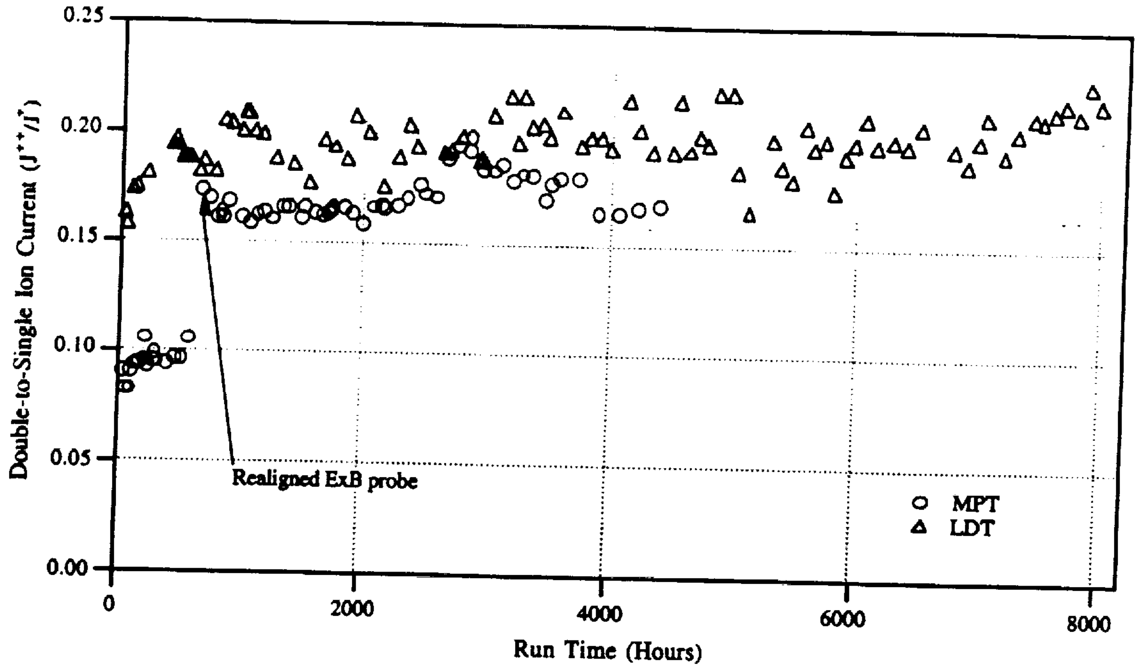

Fig. 9: Double Ion Ratio Comparison for FT2 and EMT2

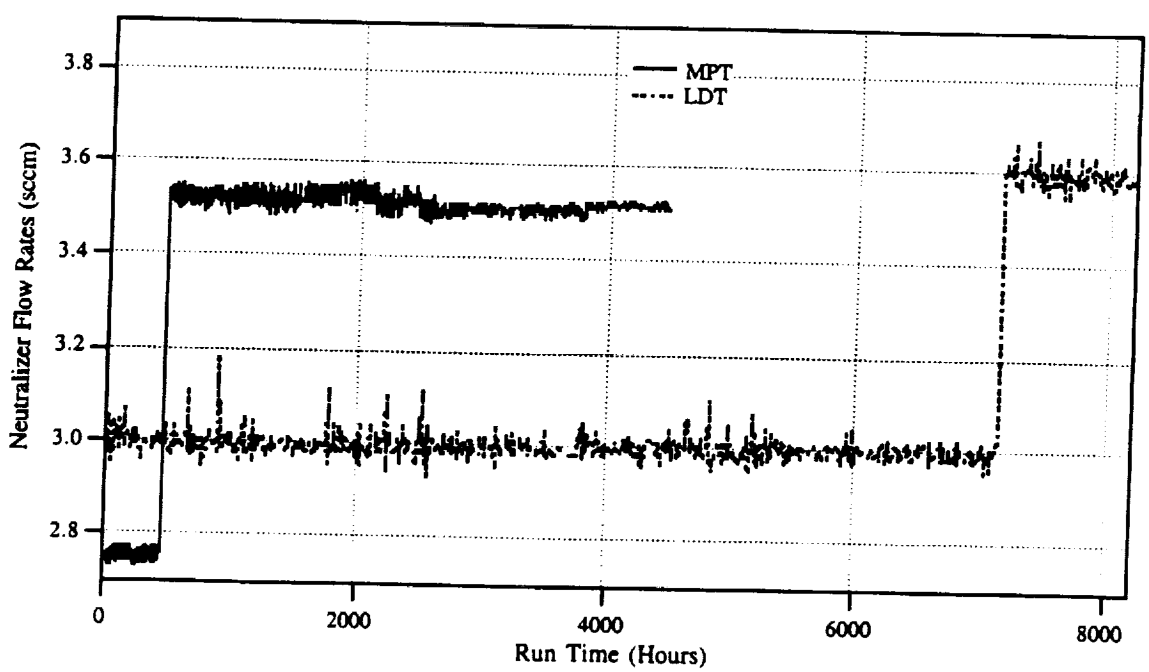

Fig. 10: Neutralizer Flow Comparison for FT2 and EMT2

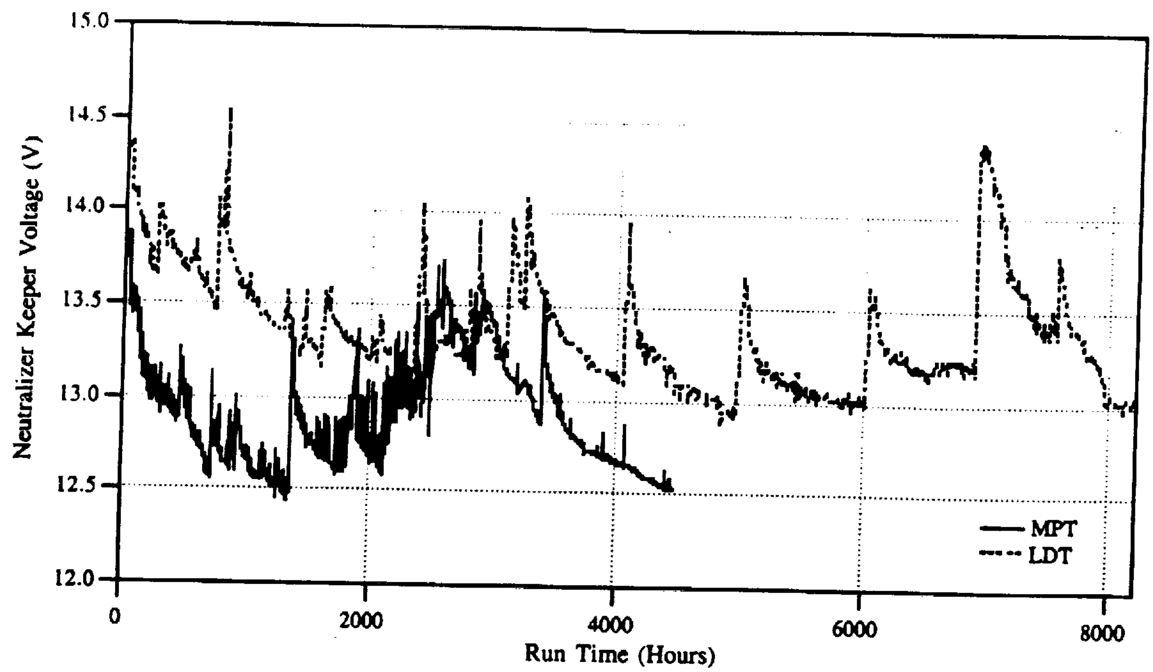

Fig. 11: Neutralizer Keeper Voltage Comparison for FT2 and EMT2

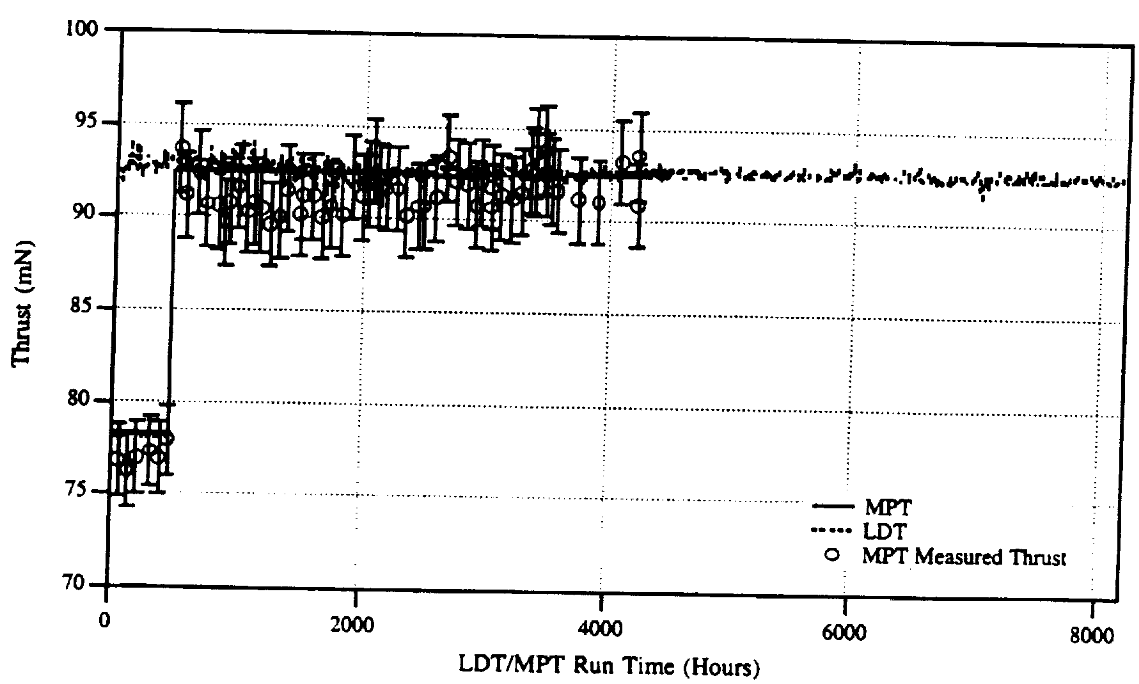

Fig. 12: Thrust Comparison for FT2 and EMT2