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STATUS OF THE EXTENDED LIFE TEST OF THE DEEP SPACE 1 FLIGHT SPARE ION ENGINE AFTER 30,352 HOURS OF OPERATION

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The extended life test (ELT) of the Deep Space 1 (DS1) spare flight ion thruster (FT2) was voluntarily terminated on June 26th 2003. The test was started in October of 1998, just prior to the launch of the DS1 spacecraft, with the primary purpose of determining the ultimate service life capability of the NASA 30-cm-ion thruster technology. During its 5-year run, the thruster operated for a total of 30,352 hours and processed 235 kg of Xenon propellant. The objectives of the test were to characterize known failure modes, identify unknown failure modes, and to measure performance degradation with thruster wear. Thruster performance data and operational characteristics, over the full DS1 throttle range, was collected and analyzed extensively during the course of the test. Significant observations include discharge cathode keeper erosion and heater power reduction, accelerator grid aperture and web erosion, deposition of material in the neutralizer orifice, and the resultant loss of neutralizer flow rate margin from plume mode (at low power). Other observations include degradation in electrical isolation between neutralizer keeper and neutralizer common, neutralizer common to ground, neutralizer keeper to ground, and cathode common to anode. The thruster continued to perform nominally and was running at 1 kW, prior to termination. The engine had not yet reached its end of life at the conclusion of the test, but the decision to terminate was made, as near term ion engine development programs would benefit from the subsequent destructive post-test analyses and inspection of the flight spare engine.

Introduction

The Deep Space One (DS1) mission was launched in October of 1998, on a mission to the Asteroid Braille and Comet Borelly. DS1 was a technology validation mission, flying a 30-cm-diameter Xenon Ion Engine as its primary propulsion system. The ion thruster successfully completed the mission in December of 2001, processing in excess of 73.4 kg of propellant and accumulating 16,265 hours of operation in space. Details on the DS1 ion thruster mission performance can be found in references [1-3]. The mission was a success, stimulating future NASA science missions utilizing solar electric propulsion to demand lifetimes and propellant throughput in excess of 20,000 hours and 200 kg. As a result, assessing the ultimate service life capability of the technology is vital, requiring extensive ground testing and data analysis.

Prior to the fabrication and testing of the flight unit engines, an extensive ground test program was initiated including several endurance tests performed on engineering model thrusters. The goals of the ground test program were to flight qualify the ion thruster technology by characterizing engine performance, understanding the interaction of the thruster plume with the spacecraft, and identifying dominant engine failure modes. The long duration tests were used to identify unexpected failure modes, and to characterize the parameters that drive potential failure and engine performance degradation. The program included a 2000-hr, 1000-hr, and 8000-hr test (LDT), all with engine operation at the full power point. Several potential failure mechanisms were identified as a result of these tests, and modifications were made to the flight engine design. Details on these previous endurance tests including failure mode analysis and suggested design modifications can be found in references [4-7].

Two flight unit thrusters were fabricated for the DS1 mission [8]. FT1 was mounted on the spacecraft, and FT2 was designated the flight spare engine. The flight spare ion thruster has been the subject of an extended life test (ELT) at the Jet Propulsion Laboratory since the fall of 1998. The thruster was started just prior to the launch of DS1, and was under vacuum, through the end of June 2003, when the test was voluntarily terminated. Thruster performance data has been collected and analyzed over the past 5 years, to determine and characterize potential failure modes, wear mechanisms, and performance degradation with thruster wear. The Extended Life Test (ELT), the subject of this paper, is to date the most successful endurance test of an ion thruster, with an excess of 30,000 hours of runtime and 235 kg of propellant throughput.

Test Plan

The initial objectives of the long duration test of FT2 were to demonstrate 150% (125 kg) of the DS1 mission through put capability, identify any unknown failure modes, characterize known failure modes, and determine how engine performance changes with operating time. The processing of 125kg of propellant was accomplished in December of 2000. As this level of throughput was accomplished with no signs of performance degradation or significant wear, the test was continued to demonstrate throughput capability in excess of 200 kg, a critical milestone for future NASA science missions utilizing ion propulsion.

Over the past 30,352 hours, FT2 was operated at four throttled conditions for approximately 5000 to 6000-hr intervals, to better understand wear and failure as a function of power level. Figure 1 is a comparison of the throughput of the LDT, DS1, and ELT engines. The hatched lines delineate the individual test segments that FT2 was operated at during the ELT. The thruster was operated for three test segments at 2.3 kW (TH15) for a total of 13,951 hours, a test segment at 1.5 kW (TH8) for 5509 hours, a test segment at 0.5 kW (TH0) for 5663 hours, and the final test segment at 1.1 kW (TH5) for 4646 hours. The emphasis has been on full power operation; in part to facilitate the processing of Xenon and with regards to accelerator grid erosion, it was believed to be the most stressful operating point for the engine.

Detailed performance measurements were taken every 100 to 200 hours, measuring thrust, double to single ion current content of the beam, the electron backstreaming and perveance limit, and screen grid transparency to ions. The test was fully automated and computer controlled, with thruster electrical parameters and facility data recorded every 5 seconds, and thrust vector data recorded every 300 seconds. Throttle tests, neutralizer characterizations, and sensitivity tests were performed every 2000 to 3000 hours. Throttling tests were performed to investigate engine performance and wear over the full throttle range. Sensitivity tests were performed to characterize discharge chamber sensitivity to small variations in engine operating conditions. Neutralizer characterizations were performed to measure flow rate margin from plume mode operation and to periodically characterize the neutralizer plume. Video and photographic data of the discharge and neutralizer cathode assemblies, and downstream face of the accelerator grid were taken every 1000 to 2000 hours, to monitor and quantify erosion processes of these critical engine components.

During normal operation, performance measurements are taken every 100 to 200 hours, including measurements of electron backstreaming limit, perveance, screen grid transparency to ions, doubly ionized beam content, and thrust. General electric parameters are recorded every 5 seconds, and location of the thrust vector every 300 seconds. In addition to normal operation, short duration throttling tests and sensitivity tests are conducted every 2000 to 3000 hours. During the throttling tests, six power points are investigated to measure the performance characteristics over the 0.5 to 2.3 kW throttling range as the thruster wears. In addition to the general performance measurements, at each throttle point, the beam current density profile is recorded, and a neutralizer characterization is performed, to determine flow rate margin from plume mode. Every 1000 to 2000 hours, video data is recorded, using a three-axis stage video camera system, inside the vacuum chamber. Video of the discharge cathode, downstream face of the

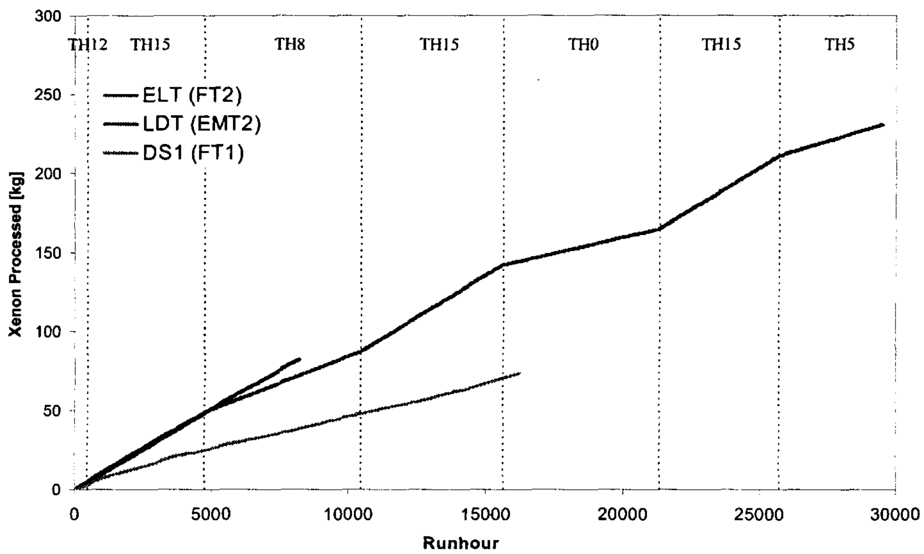


Fig. 1 Throughput comparison of the ELT (FT2), DS1 (FT1), and LDT (EMT2) Engines

NSTAR Throttle Level	Nominal Thruster Power	Beam Supply Voltage	Beam Current	Accelerator Grid Voltage	Neutralizer Keeper Current	Main Flow	Discharge Cathode Flow	Neutralizer Cathode Flow
	kW	V	A	V	A	sccm	sccm	sccm
TH 0	0.52	650	0.51	-150	2.0	5.98	2.47	2.40
TH 1	0.66	850	0.53	-150	2.0	5.82	2.47	2.40
TH 2	0.75	1100	0.52	-150	2.0	5.77	2.47	2.40
TH 3	0.91	1100	0.61	-150	2.0	6.85	2.47	2.40
TH 4	1.02	1100	0.71	-150	2.0	8.30	2.47	2.40
TH 5	1.12	1100	0.81	-150	2.0	9.82	2.47	2.40
TH 6	1.24	1100	0.91	-150	2.0	11.33	2.47	2.40
TH 7	1.34	1100	1.00	-150	2.0	12.90	2.47	2.40
TH 8	1.46	1100	1.10	-180	1.5	14.41	2.47	2.40
TH 9	1.58	1100	1.20	-180	1.5	15.98	2.47	2.40
TH10	1.72	1100	1.30	-180	1.5	17.22	2.56	2.49
TH11	1.85	1100	1.40	-180	1.5	18.51	2.72	2.65
TH12	1.96	1100	1.49	-180	1.5	19.86	2.89	2.81
TH13	2.08	1100	1.58	-180	1.5	20.95	3.06	2.98
TH14	2.20	1100	1.67	-180	1.5	22.19	3.35	3.26
TH15	2.33	1100	1.76	-180	1.5	23.43	3.70	3.60

accelerator grid, and neutralizer cathode is recorded, in addition to general inspection of the thruster exterior.

Thruster Design and Operation

The flight engines were fabricated by Boeing, formerly Hughes Electron Dynamics (HED). The FT2 thruster employs a spun titanium discharge chamber, with a three-ring cusp magnetic field design. A two-grid molybdenum ion optics assembly is attached to the downstream end of the discharge chamber. A hollow cathode in the discharge chamber serves as the electron source. The neutralizer hollow cathode, located external to the discharge chamber provides electrons to charge neutralize the ion beam. The discharge chamber is enclosed in a perforated plasma screen to prevent beam-neutralizing electrons from reaching high voltage surfaces [8].

The thruster is throttle-able to maximize use of available solar array power in space. The spacecraft thruster utilized a total of 50 throttle levels. For the extended life test, 16 throttle points were chosen, to facilitate testing. Table 1 is the throttle table for the ground test, where the designation TH is given for each operating point, with a power range of 0.5 kW (TH0) to 2.3 kW (TH15). The beam current and voltage are controlled to provide fixed levels of thrust and specific impulse. The main and cathode flow rates were chosen to maximize propellant utilization efficiency, whilst minimize discharge chamber erosion due to the production of double charge xenon ions. The neutralizer flow rate was set to minimize cold flow losses, whilst providing sufficient margin from plume mode operation.

The flight thrusters, incorporated several minor design changes not in the EMT2, engineering model design. The design modifications improved the efficiency, sputter containment, and radiative properties of the discharge chamber. 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. Details on these design changes can be found in references [9] and [10].

Test Facility

The test was conducted in a 3-m by 10-m-long vacuum chamber with a total xenon system pumping speed of 100 kL/s [12]. The vacuum system provides a base pressure of less than 1.3E-10 atm (1E-7 Torr) and 5.3x10-9 atm (4x10-6 Torr) at the full power flow rates. The pumping surfaces are regenerated after accumulation of approximately 10 kg Xenon, during which time; the engine is exposed to a mostly xenon background pressure of 1.3x10-3 atm (1 Torr). The Cathodes are purged with Xenon during the regenerations, and are conditioned with by applying prescribed heater currents, following the subsequent pump-down to high vacuum. The vacuum chamber was equipped with a residual gas analyzer (RGA) to monitor the presence and quantity of trace gases at high vacuum. The vacuum chamber was lined with graphite panels to reduce the amount of material that is back sputtered onto the engine and test diagnostics. A quartz crystal microbalance (QCM) was located next to the engine, and provided real time measurements of back sputtered material in the plane of the grids. The propellant feed system consisted of two mass flow meters for each of the cathode, neutralizer, and main lines. The downstream meters were used to measure the flow, and the upstream meters were used as flow controllers. Laboratory power supplies, with similar capabilities to the flight PPU, were used to run the thruster. The ground electrical design referenced facility ground, and the reference potential was neutralizer common, whereas in flight ground was spacecraft ground. A computer data acquisition system was used to monitor the engine and test facility. It recorded data at 5-second intervals, and was programmed to shut down the thruster in the event of a facility problem or out of tolerance engine parameter. Details of the flow system and electrical system can be found in references [9,10,13].

An extensive array of diagnostics was used to measure the ion beam plasma characteristics as well as general engine performance parameters. The near field beam current density was measured with a faraday probe mechanically swept across the diameter of the thruster beam. An ExB probe, located downstream of the beam, was used to measure the double-single ion current ratio. The probe was aligned with the beam on, in the location of maximum single ion current. A thrust vector probe, consisting of a series of current collecting graphite rods, located downstream of the thruster, provided current density measurements across the beam. A modified version of the GRC inverted pendulum thrust stand was used to make direct thrust measurements.[2] A retarding potential analyzer (RPA) was mounted downstream of the neutralizer, and above the engine. The RPA was used to characterize the neutralizer ion energy distribution. Two cameras mounted on a three-axis positioning system inside the tank, allow detailed photography and video recording of the discharge cathode, neutralizer, and downstream surface of the accelerator grid A laser profilometer was also mounted on the positioning system, for detailed measurements of accelerator grid webbing erosion. Specific details on the operation and design of the diagnostics can be found in references [4,6,0,10,11].

Test Results

Throttling Test Results

Results of the throttling tests indicate that thrust and engine efficiency degraded slightly over the engine's 30,000 hours of operation for throttle levels TH0 through 12, and more significantly for TH15 at the conclusion of the test. Engine thrust, specific impulse, and efficiency, as a function of power and runtime are shown in figures 2 through 4. The throttling test results indicate, for TH0 through TH12, a measured thrust and efficiency degradation of up to 5% from BOL values by the conclusion of the test, with variation increasing with throttle level. Full power (TH15) thrust degraded more severely from 29,000 to 30,000 hours, approximately 10% from the BOL value. The large variation at TH15 is the result of electron backstreaming, which could not be prevented within the constraints of the lab power supplies at the conclusion of the test. Variations in thrust and efficiency for TH0 through 12 can most likely be attributed to increasing double ion current and/or increased beam divergence as the thruster wore, as beam voltage and current were held at fixed values for each throttle point.

Figures 5 through 7 also indicate little variation in the

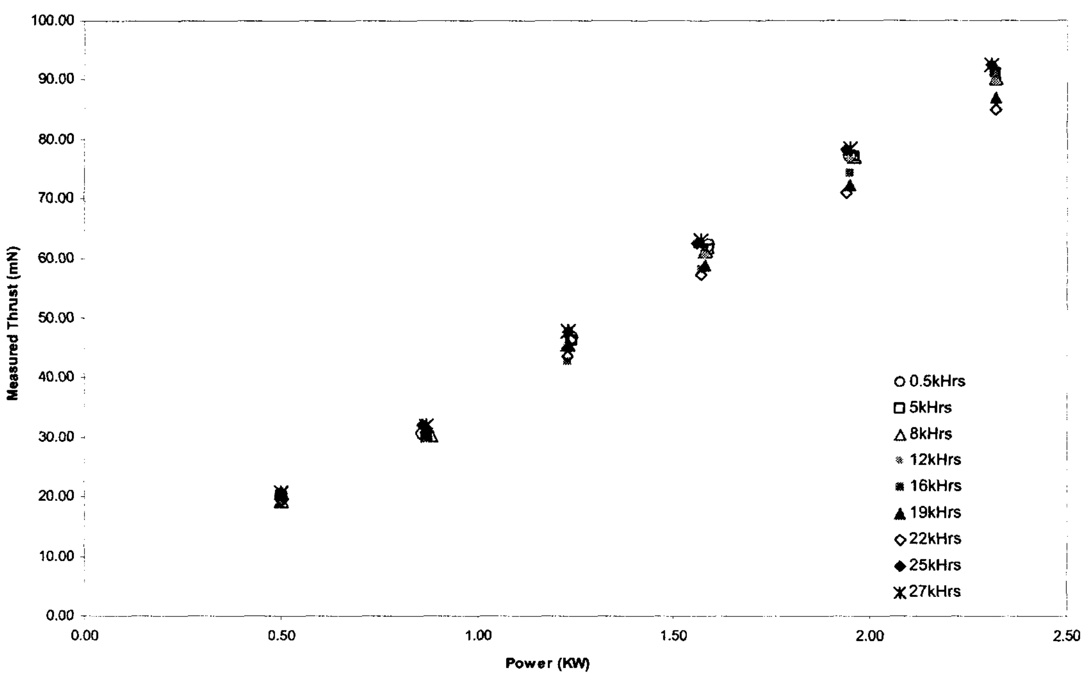


Fig. 2 FT2 Thrust vs power

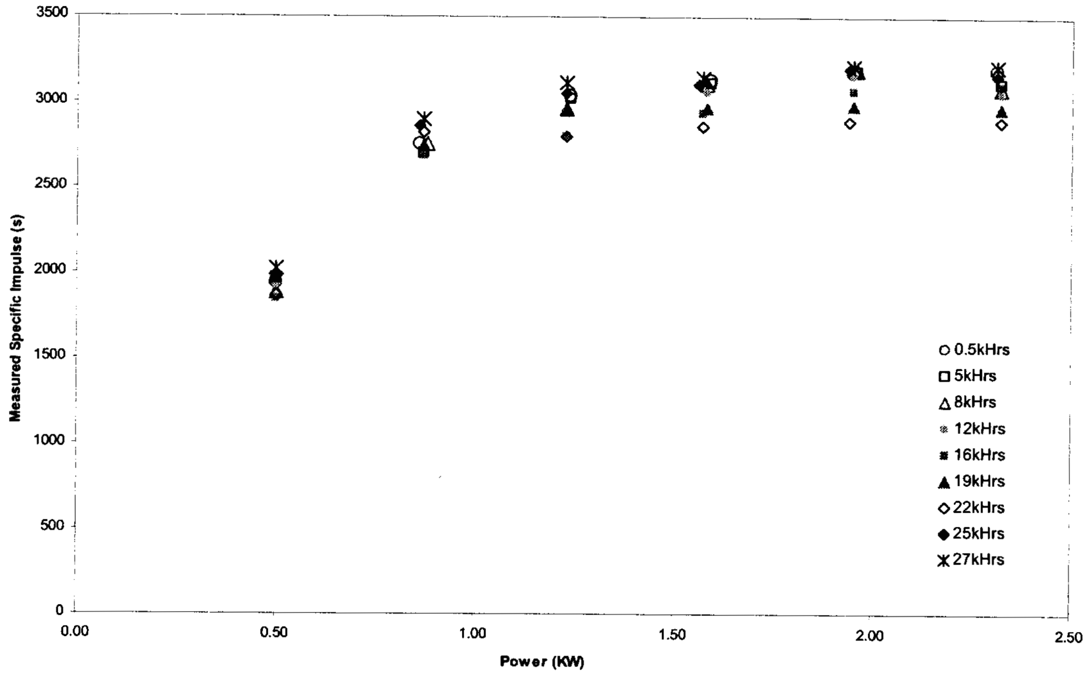


Fig.3 FT2 specific impulse vs power

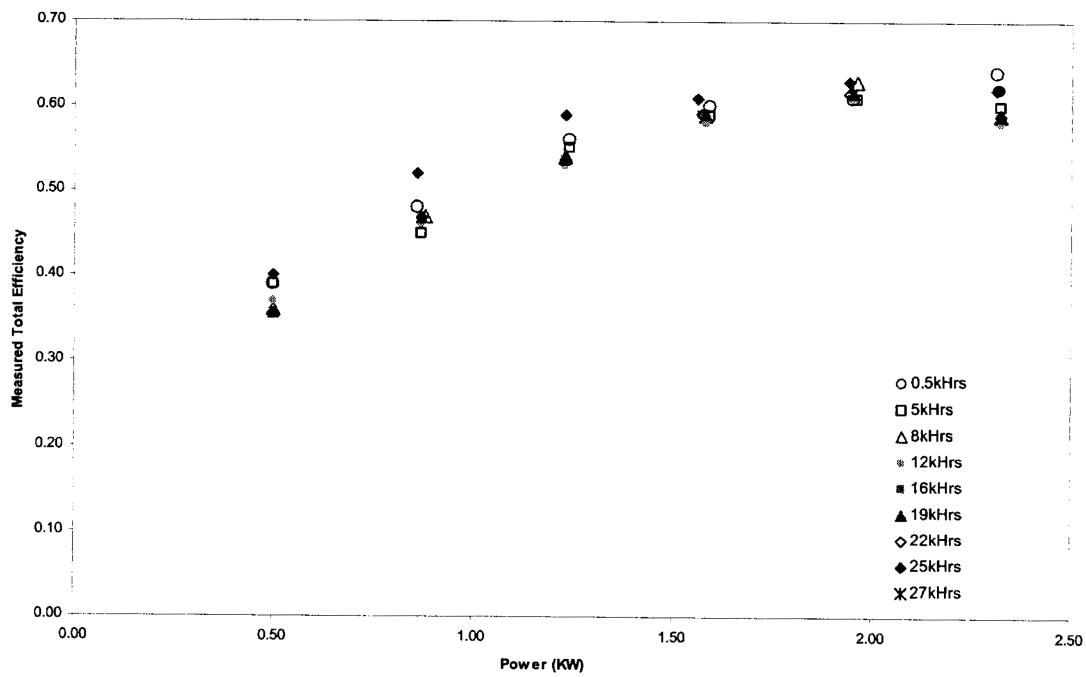


Fig. 4 FT2 total efficiency vs power

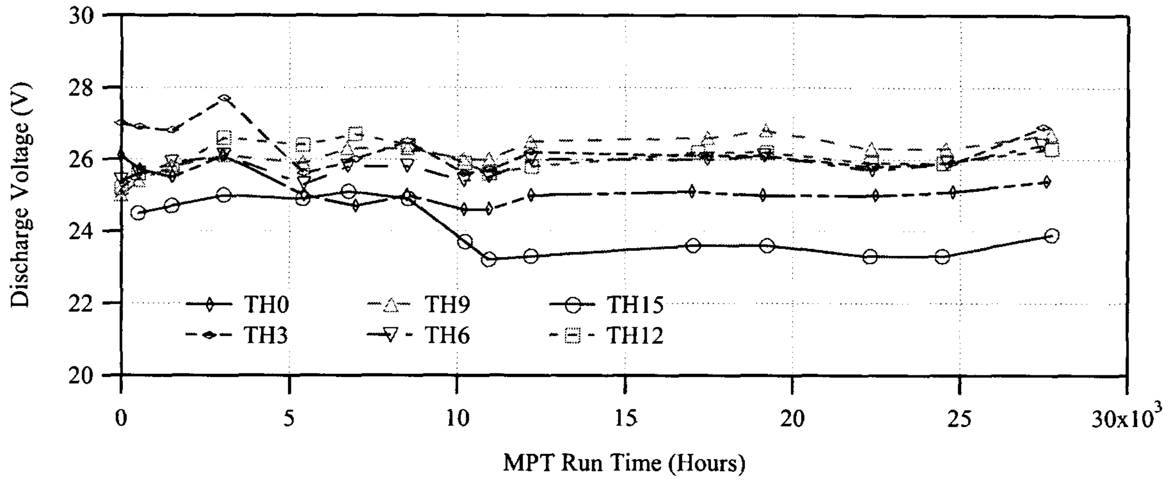


Fig. 5 FT2 Discharge voltage vs. runtime over full throttle range

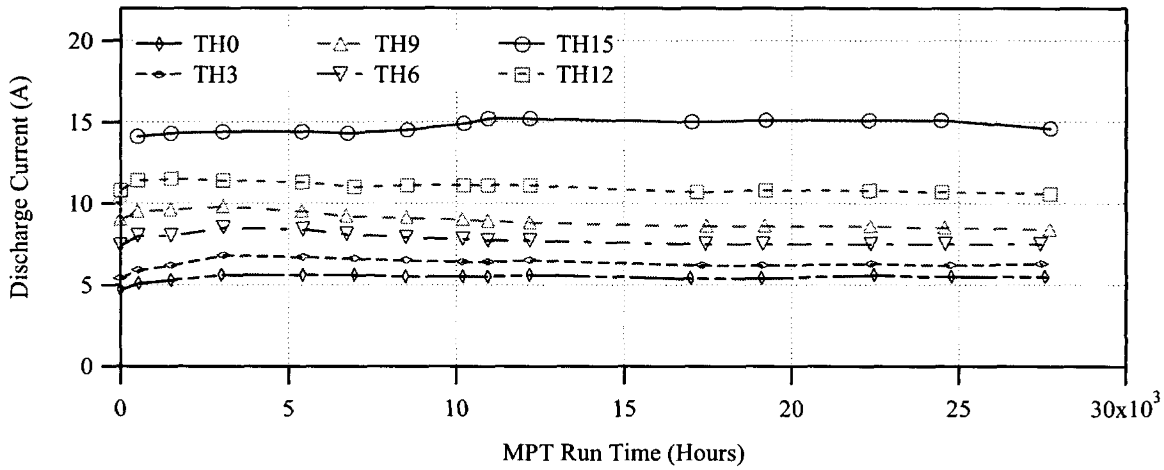


Fig. 6 FT2 Discharge current vs. runtime over full throttle range

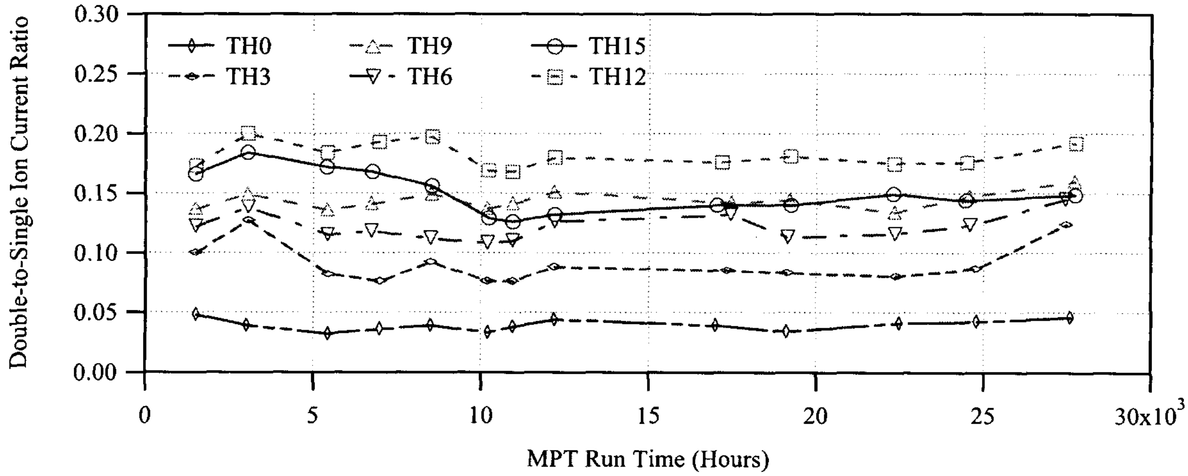


Fig. 7 FT2 Double to single ion current ratio vs. runtime over full throttle range

engine discharge chamber operation over its life, with discharge voltage and current, and double ion content remaining relatively stable for the duration. The apparent increase in double to single ion current ratio from 25,000 to 27,000 was the result of a flow calibration error, which was later corrected.

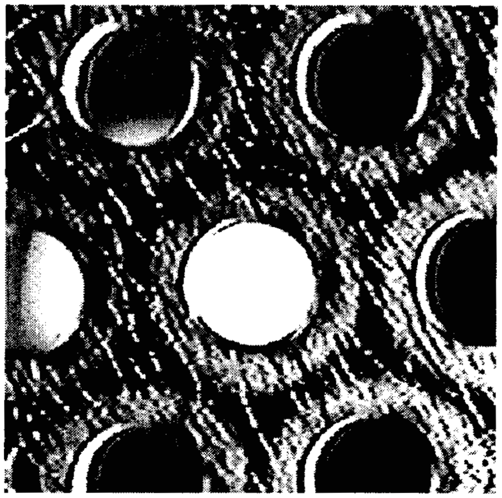
Another notable performance variation, measured during the throttling tests, was the change of neutralizer flow rate margin to prevent plume mode operation. Neutralizer characterizations were performed at each throttle point, during the throttling tests. The flow rate of Xenon to the neutralizer wais reduced in small increments to determine the flow rate at which the transition to plume mode occured. For the ground test, plume mode was defined as operation of the neutralizer where the AC keeper voltage exceeded 5 volts peak-peak, as measured on an oscilloscope. Operation in plume mode leads to the production of energetic ions, with sufficient energy to erode neutralizer surfaces, reducing the lifetime and performance of the neutralizer cathode. It was therefore desirable to know at which flow rate this transition occurred, to maintain sufficient margin over the full throttle range. As neutralizer cold flow loss were most significant at TH0, the TH0 point was operated with the smallest flow margin to improve engine efficiency. TH15 was operated with the largest margin from plume mode, as cold flow losses are less significant at the higher power levels. Over the first 5,000 hours, neutralizer margin decreased for TH0, 3, 9 and 12. From 5000 to 13,000 hours, the margin remained the same. From 13,000 to 15000 hours, the margin increased slightly, and remained the same through 19,000 hours. For TH 6 and 9, the flow rate margin remained constant. The most notable result of the neutralizer characterizations was the loss of flow rate margin from plume mode abetween 21,000 and 22,000 hours, following a 6,000-hour interval at the TH0 (0.5 kW) operating point. Subsequent operation at full power restored this margin, and this will be discussed in further detail in a later section. Overall the flow rate margin from plume mode decreased from beginning of life values, with the most significant reduction at the TH0 throttle point.

Accelerator Grid Erosion

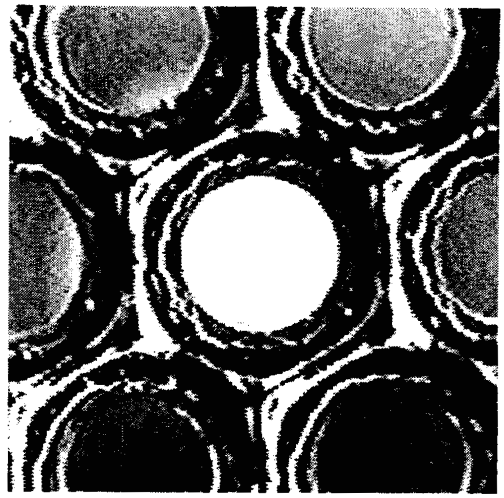
Video and images of the downstream face of the accelerator grid were taken at regular intervals over the course of the test. Prior to 23,770 hours, images of accelerator grid aperture and web erosion were taken at 4 different radial locations, using the camera-positioning system inside the vacuum chamber. At 23,770 hours, one axis of the positioning system failed, preventing use of the laser profilometer and detailed imaging of the downstream face of the accelerator grid, for the remainder of the test. Detailed images of accelerator grid erosion following this event were obtained with a high-powered telephoto lens camera focused through a tank port window. From the ELT image data and the previous endurance tests, it is known that accelerator grid erosion is characterized by enlargement of the grid apertures, and the formation of pits and grooves in the grid webbing surrounding each hole [4,15]. Shown in Fig. 8(a) are photographs of the center hole of the FT2 accelerator grid from 125 to 30352 hours. After only 4694 hours, the aperture enlargement was apparent, and the erosion of the grid webbing had begun to manifest itself into the characteristic pits and grooves pattern. Pits are located between every three adjacent apertures, and grooves between each two neighboring apertures. Also apparent in the images is the transition from a hexagonal grid webbing erosion pattern (9473 Hrs) to one that is circular (21306 hrs), as more material is eroded away. Figure 8(b) is an image taken at an angle to the grid plane, showing a larger section of the grid at 28,500 hours. The transition from hexagonal to circular webbing erosion can also be discerned in this image, suggesting that grid webbing erosion is most severe in the center of the grid, and minimal at the outer edge of the grid. The photo in figure 8(a) labeled 30,252 hours, is an image of the center accelerator grid region taken after the thruster was removed form the vacuum chamber. It can be seen that after 30,000 hours of operation the pits in the grid center region have eroded through the webbing, forming through pits. There also appears to be a hexagonal pattern etched into the aperture wall, suggesting that the aperture erosion had intersected the grooves in the grid webbing. Initial post-test inspection of the grids indicates that through pits and etching of the aperture walls is limited to the center of the grid, where the beam current density was maximum.

Figure 9 is a plot of aperture erosion at four different radial locations on the accelerator grid, for the first 21,306 hours of operation. Each vertical line marks the beginning of a new test segment. The data indicates that aperture erosion was most significant at TH15, and negligible at TH0. TH15 is associated with the highest beam current density and total accelerating voltage, and as a result the most significant erosion. Faraday probe profile in figures 10 and 11 indicate that the maximum current density is a factor of three greater for TH15 as compared to TH0. Results also indicate the most significant aperture erosion occurred in the center of the grid. The faraday beam profiles of figures 10 and 11 also indicate the beam profile is peaked, with maximum current density along the centerline of the thruster, leading to higher aperture erosion rates at the center of the grid, as well as more severe web erosion discussed previously. Aperture diameter measurements were not available from 21306 hours to 30,000 hours, due to a test equipment failure in the positioning system.

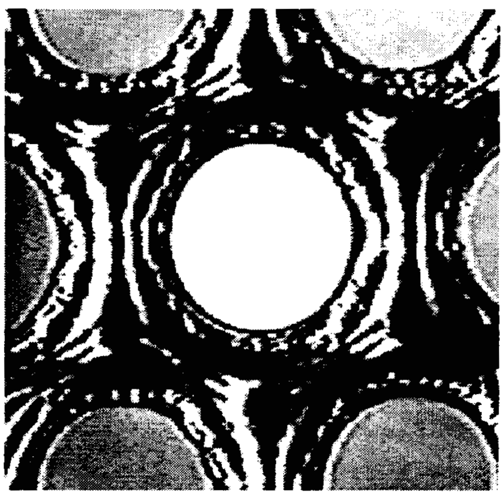
Charge exchange ions are likely responsible for the erosion on the downstream face of the accelerator grid and the observed barrel enlargement. Computational results



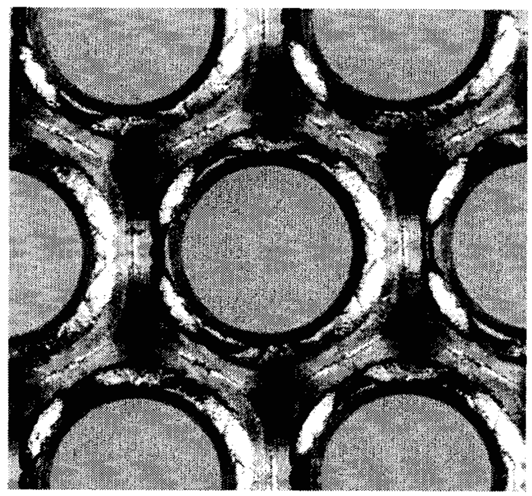
125 Hours



9473 Hours

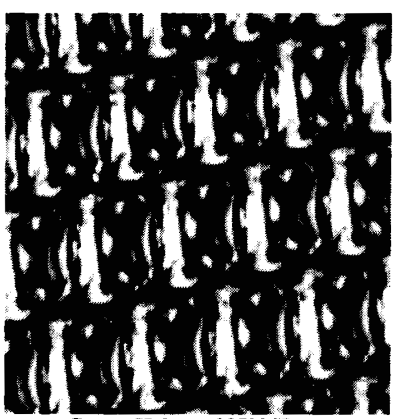


21306 Hours

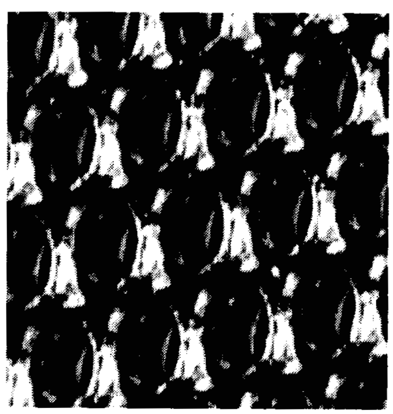


30352 Hours

Fig. 8(a) FT2 Accelerator Grid Erosion at the Center of Grid normal to the surface



Center Holes at 28500 Hours



Off Center Holes at 28500 Hours

Outer Edge Holes at 28500 Hours

Fig. 8(b) FT2 Accelerator Grid Erosion at 28500 hours across the grid at an angle to the surface

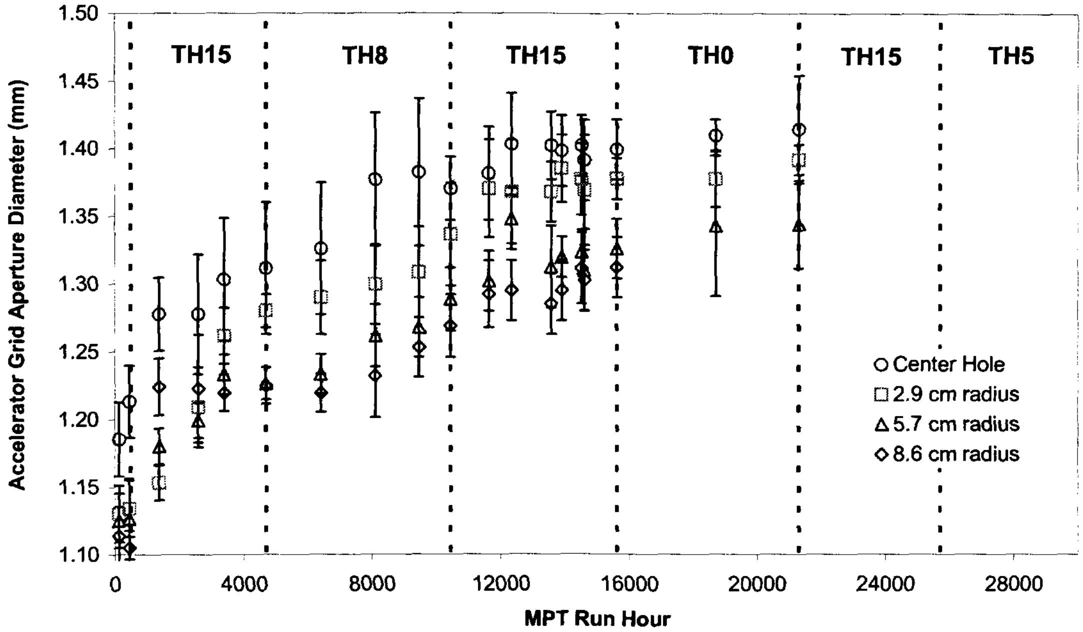


Fig. 9 FT2 Accelerator Grid Aperture diameter vs. runtime at 5 different radial locations

indicate the sites of charge exchange birth are both between the screen and accelerator grid apertures and downstream of the accelerator grid, leading to the accelerator aperture enlargement and pits and groove erosion, respectively. In addition, the higher neutral density during ground testing, may lead to a larger production of intra-grid charge exchange ions further aggravating aperture erosion [16,17].

Accelerator grid aperture enlargement and severe grid webbing erosion also manifest themselves in the ability of the optics system to focus the individual beamlets and prevent beam neutralizing electrons from entering the discharge chamber. Variations and rate trends in the electron backstreaming and perveance limits, which were monitored on a weekly basis, provide further insight into the accelerator grid erosion process. These will be discussed in more detail in a later section.

Discharge Cathode Keeper Erosion

Discharge cathode keeper erosion is a potential failure mode for ion thrusters, as demonstrated by the previous 8,200-hr test (LDT) of an engineering model thruster (EMT2) and the extended life test of FT2 [4,7]. After 30,000 hours of operation, the keeper on FT2 eroded to fully expose the cathode heater and cathode orifice plate. Keeper erosion was first observed during the TH8 test segment, following a short between cathode keeper to cathode common at 5850 hours. At that point the keeper began to erode at a significant rate. The intermittent short caused the cathode keeper voltage to drop from 3.5 V to ~0.4 V. At 8,873 hours the cathode keeper-cathode common short cleared apparently when the cathode keeper orifice eroded sufficiently. Cathode keeper erosion still continued, however, at the subsequent full power segments, and at a lower rate during TH5 operation. Keeper erosion did essentially stop however, during TH0 operation from 15,000 to 21,000 hours. Figure 14 is a plot of normalized cathode keeper inner diameter versus run time, and clearly indicates the onset and subsequent power level dependence of keeper erosion. It is important to note that this severe keeper erosion was not observed during the first full power test segment, from 500 to 4500 hours, or during the previous 8000-Hr endurance test of the engineering model thruster [4], which was operated exclusively at TH15. This suggests that either the TH8 operating conditions, the shorted condition, or both initiated the cathode keeper erosion observed during FT2 testing.

Figure 12 is a photographic comparison of the beginning of life condition of the cathode keeper to the most recent image taken after the thruster was removed from the chamber. All images except for 30,352 hours were taken using the internal tank video system, by focusing through the optics assembly. Surface pitting was initially apparent after 5000 hours of operation. By 10,000 hours, the keeper plate had eroded significantly exposing the cathode orifice plate. By 15,000 hours the keeper orifice plate had eroded to full expose the cathode orifice plate and heater. The image labeled 30,352 hours was

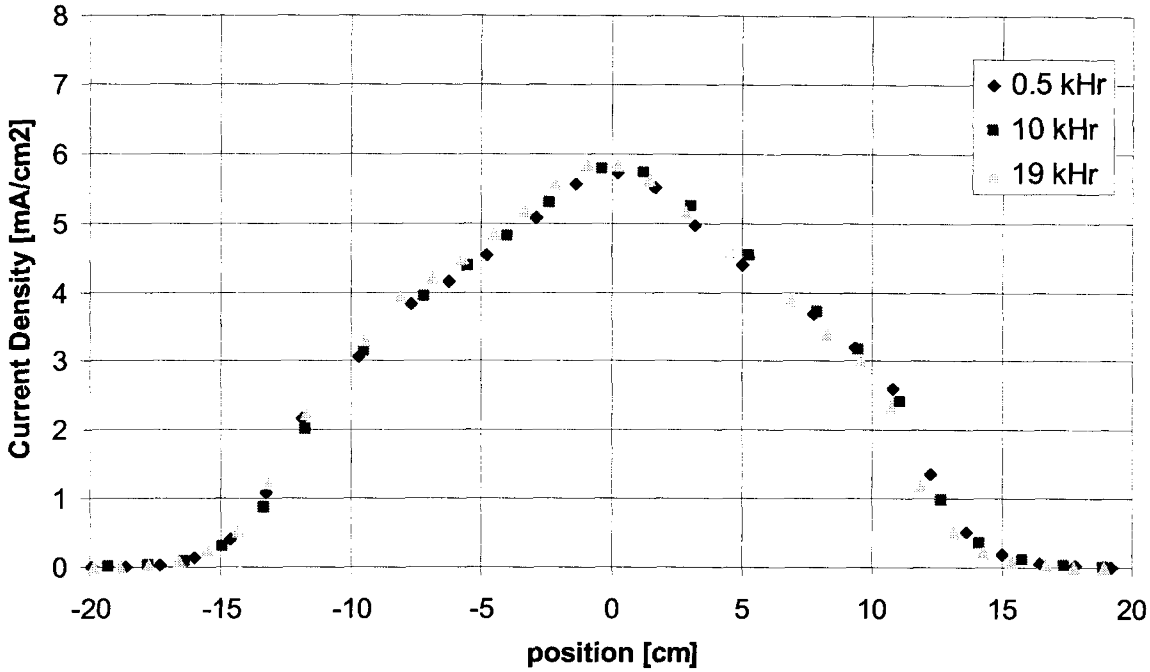
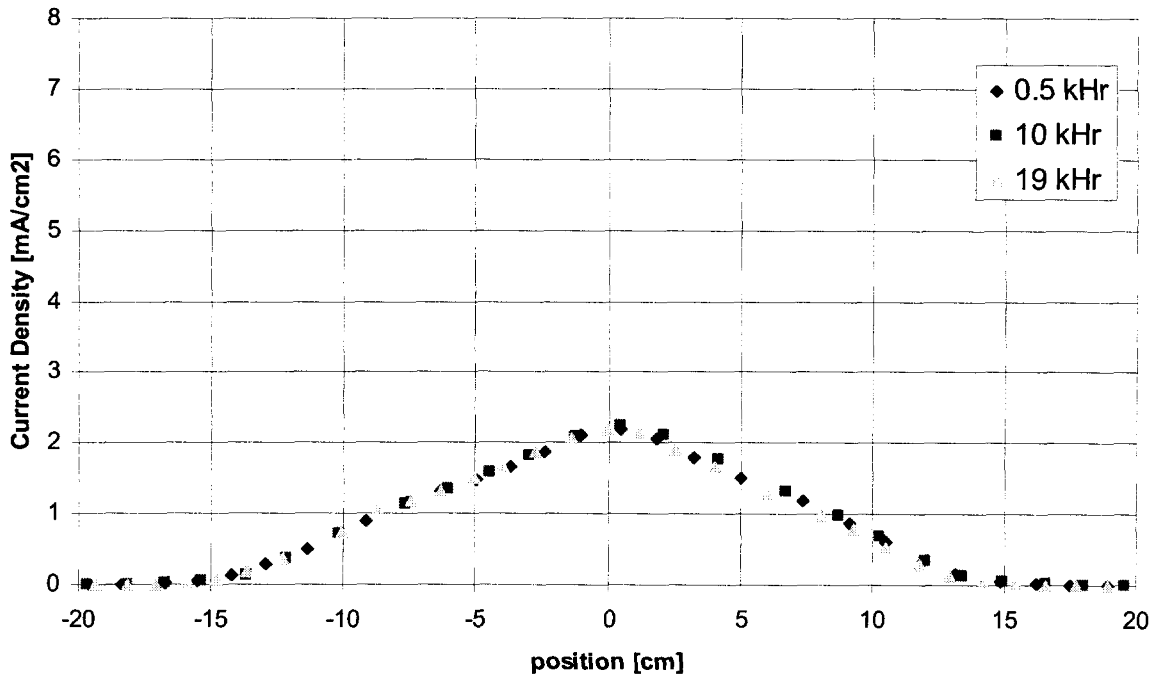
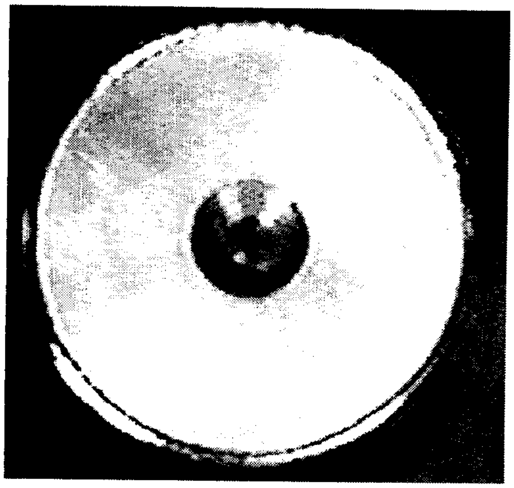
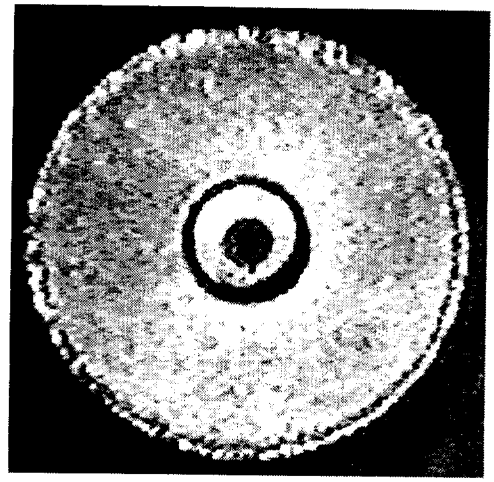
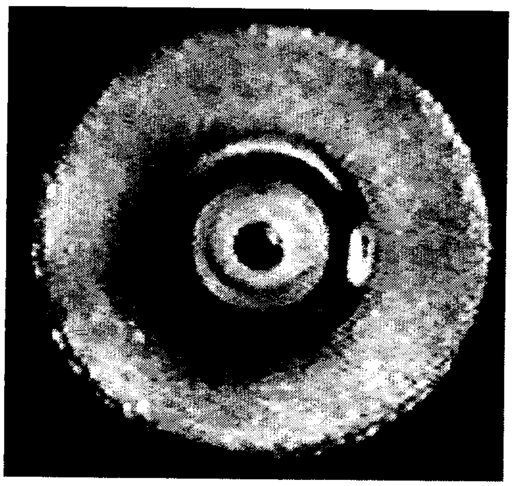


Fig. 10 FT2 Beam Current Density Profile at 2.3 kW (TH15)

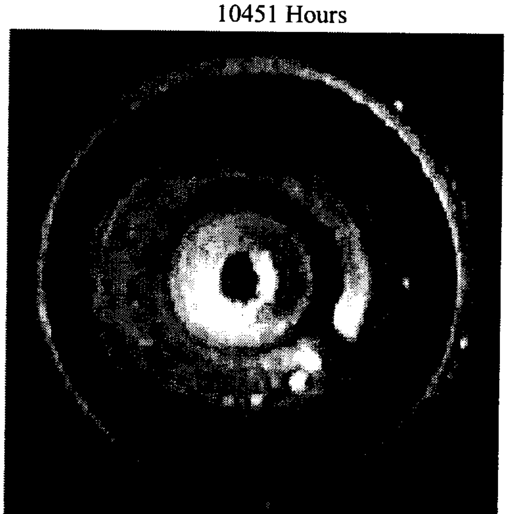



0 Hours


4693 Hours


10451 Hours


21306 Hours


28726 Hours

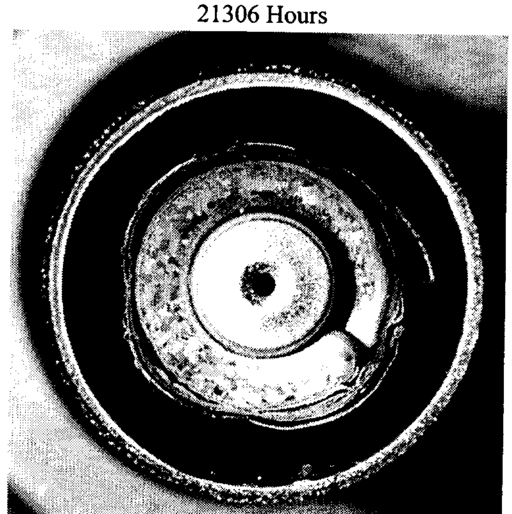

30352 Hours

Fig. 12 Discharge Cathode Keeper Erosion vs. runtime

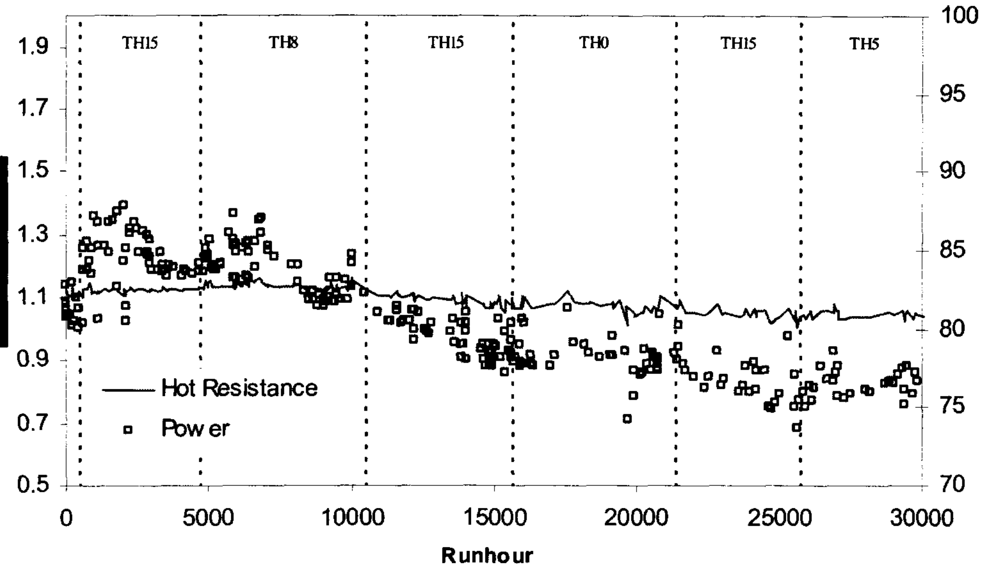


Fig. 13 FT2 Discharge Cathode heater performance

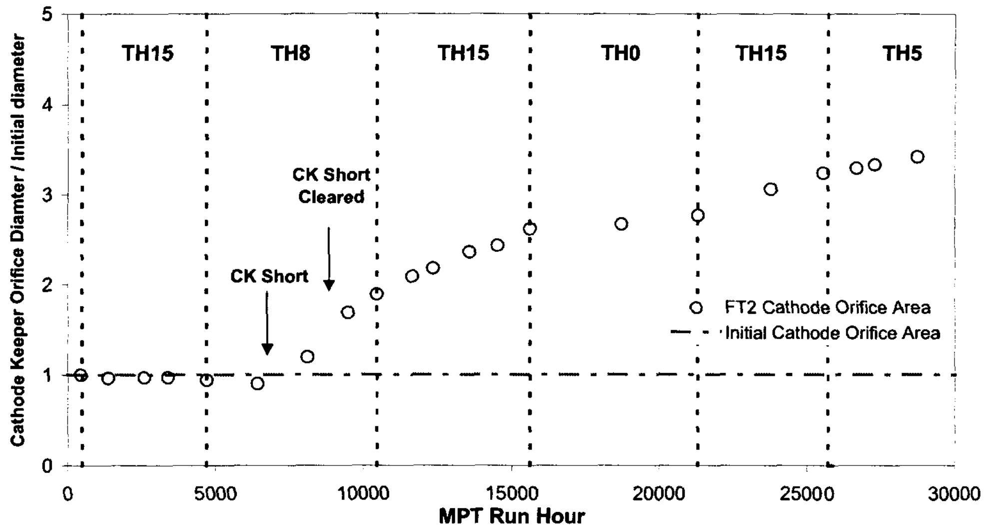


Fig. 14 Normalized Cathode Keeper Orifice diameter vs. run hour

taken after the thruster was removed from the chamber, with the grids removed. This most recent image indicates that the cathode heater and orifice plate were beginning to erode, as a result of their exposure to the discharge chamber plasma for the last 15,000 hours of operation. Although preliminary post test results indicate that surface erosion is apparent, it is important to note that cathode ignition was not compromised, and remained essentially unchanged from its beginning of life (BOL) performance, for the duration of the test.

Figure 13 is a plot of discharge cathode heater power and hot resistance versus runtime. The heater power began to decrease following the short between cathode common to keeper, mentioned previously. Cathode heater performance is critical to cathode life, as sufficient heater power is required to initiate electron emission of the cathode insert. Overall the heater power decreased ~12%, from the BOL value, and leveled off at a 75 W after at 25,000 hours of operation. A possible explanation for the heater power reduction is radiant heat lost to the environment as the keeper orifice enlarged. After 25,000 hours it is likely the keeper plate had eroded away entirely, resulting in no further change in open area from 25,000 to 30,000 hours As a result, steady state heater power was achieved.

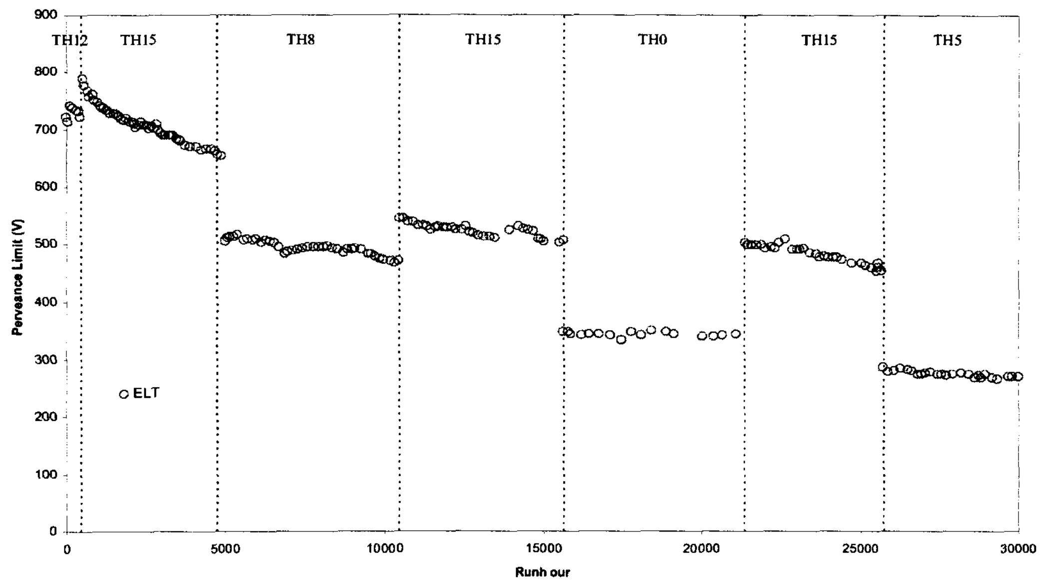


Fig. 15 FT2 Perveance Limit vs. run hour

The cause and throttle level dependence of cathode keeper erosion is not yet well understood One possible explanation for the onset of keeper erosion at the TH8 power point is the increase in production of multiply charged ions, due to a proportionately low cathode flow rate, as compared to TH0 and TH15. For a fixed space charge current limit from the cathode, lowering the flow will result in an increase in the charge of the ions. Multiply charged ions may have sufficient energy to sputter erode the keeper material, resulting in the erosion ongoing since 5850 hours. As the keeper orifice enlarged, neutral density in the orifice reduced, increasing the production of multiply charged ions, to maintain a fixed current level. This may explain why keeper erosion continued at the subsequent TH15 test segments, when none was observed during the first 5000 hours of operation at TH15. Alternatively it may have been the shorted condition that initiated keeper erosion. Results of experimental work discussed in reference [18], indicate that when the keeper is shorted to cathode common, the rate of keeper orifice plate erosion is increased as compared to non-shorted condition.

In spite of the severe keeper erosion and degradation in heater performance, the cathode did not experience any noticeable change in its ignition characteristics over its 30,452-hour life. Ignition voltage and ignition time did not vary at all after a total of 300 restarts of the discharge cathode. This suggests that sensitive cathode heater components, the cathode orifice, and the cathode insert were not compromised, in spite of the severe keeper place erosion, and subsequent exposure of the cathode to the discharge chamber plasma for in excess of 15,000 hours. The FT2 engine test has therefore set a new minimum lifetime for the hollow cathode technology, of 30,452 hours total runtime.

Ion Optics Performance

In addition to the visual measurements of the downstream face of the accelerator grid, wear of the ion optics system is characterized from perveance, electron backstreaming, and screen grid transparency measurements that were taken every 100 to 200 hours of operation. These measurements indicate the ability of the system to extract, focus, and accelerate ionized propellant, to produce thrust.

The perveance limit provides a measure of how defocused the beam can be before direct ion impingement on the accelerator grid occurs. Direct ion impingement, with ions energies equivalent to the total accelerating voltage, can lead to rapid accelerator grid wear and eventual structural failure. The perveance limit is also an indicator of changes to the intra-grid electric field, and possible disturbances in the neutralization plane. For the ground tests, the perveance limit was defined as the screen grid voltage where a 1 V reduction in screen voltage, results in a 0.2 mA increase in accelerator grid impingement current. Perveance data is shown in Fig. 15 versus run hour, where vertical lines delineate each test segment. The perveance limit decreases with accelerator grid aperture enlargement, as the beamlets must become increasingly defocused to impinge on the surface of the

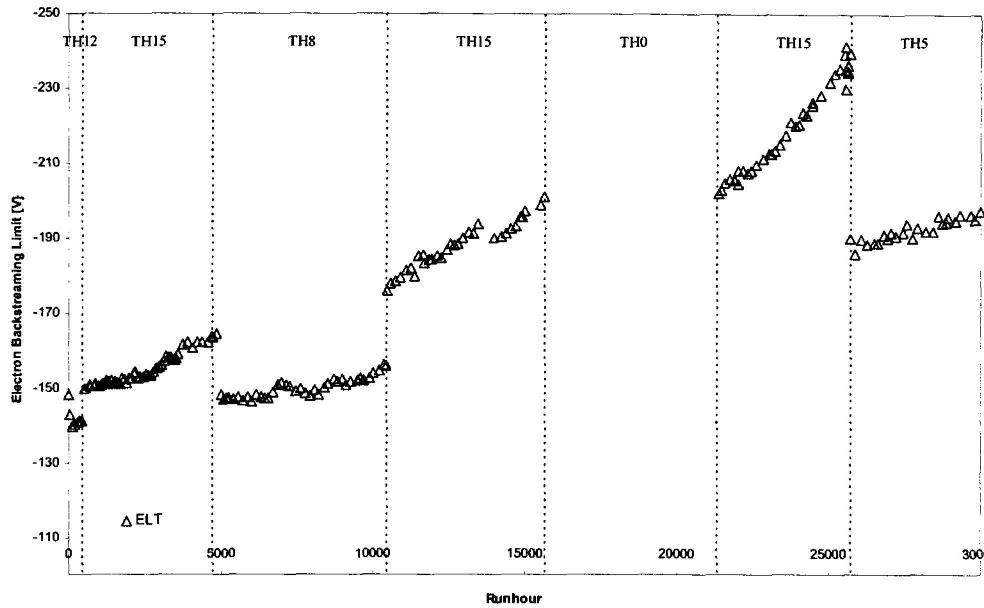


Fig. 16 FT2 Electron Backstreaming Limit vs. run hour

grid. As a result, the rate of perveance limit change was highest during full power operation. During the test, the rate of change was essentially linear, with the exception of the first 1000 hours, shifts at 13993 and 25548 hours, and during the last 2000 hours of the third TH15 segment. At the beginning of the test, it is likely that wear of aperture manufacturing cusps accounted for the rapid change in perveance limit, and subsequent leveling off period. The shifts in perveance limit are not fully understood, although each discontinuity followed an extended shutdown period, where the thruster was exposed to a 1 Torr background pressure for several days. It is possible that during this exposure, adsorption of oxygen and water vapor present in the chamber, may have reacted with carbon deposits on the grids, resulting in a change in the grid material thermal emissivity. An increase in the hot grid-gap, would lower the intra-grid electric field, and could account for the measured shift in the perveance. The non-linear increase during the last TH15 segment is not fully understood, although it is related in part to an increase in the rate of accelerator barrel erosion. At TH0 and TH5, the perveance limit increase was linear, and exhibited a much lower rate of change than TH8 and TH15. This supports the reduced accelerator grid barrel erosion observed at the lower power levels [9-11].

The electron backstreaming limit versus run hour is shown in Fig 16. Electron backstreaming occurs when the potential at the center of the accelerator grid apertures is not sufficiently negative to prevent beam-neutralizing electrons from streaming into the discharge chamber. Electrons backstreaming into the discharge chamber are indistinguishable from ions accelerated out of the thruster, to the beam power supply. Therefore at a fixed beam current, electron backstreaming results in a decrease in discharge current, reducing ionization, thereby significantly decreasing thruster performance. To prevent this, the accelerator grid is biased to a sufficiently negative voltage to prevent electrons from getting into to the discharge chamber. For the ELT, the backstreaming limit is determined by reducing the accelerator grid voltage until a 1% reduction in discharge loss occurs. Discharge loss is the ratio of the energy to produce beams ions to the extracted beam current. Results indicate the backstreaming limit is most negative at TH15, and least negative at TH0. As the thruster is throttled to higher power levels, the beam current and voltage are increased, along with the positive space charge. As a result the aperture potential increases, requiring a more negative accelerator grid voltage to prevent electron backstreaming. Similarly, as the accelerator grid holes enlarge, the applied voltage required to prevent backstreaming becomes more negative. Therefore, the rate of increase of the electron backstreaming limit is most significant at TH15, and negligible at TH0. The rate of increase of backstreaming limit was relatively linear for the first 23,000 hours of operation at each of the test segments, however, 2000 hours into the third TH15 segment, the backstreaming limit began to rise rapidly. Initially it was thought that the accelerator grid holes had begun to intersect the pits and grooves in the grid webbing, resulting in a change in the material erosion rate. However detailed photographic

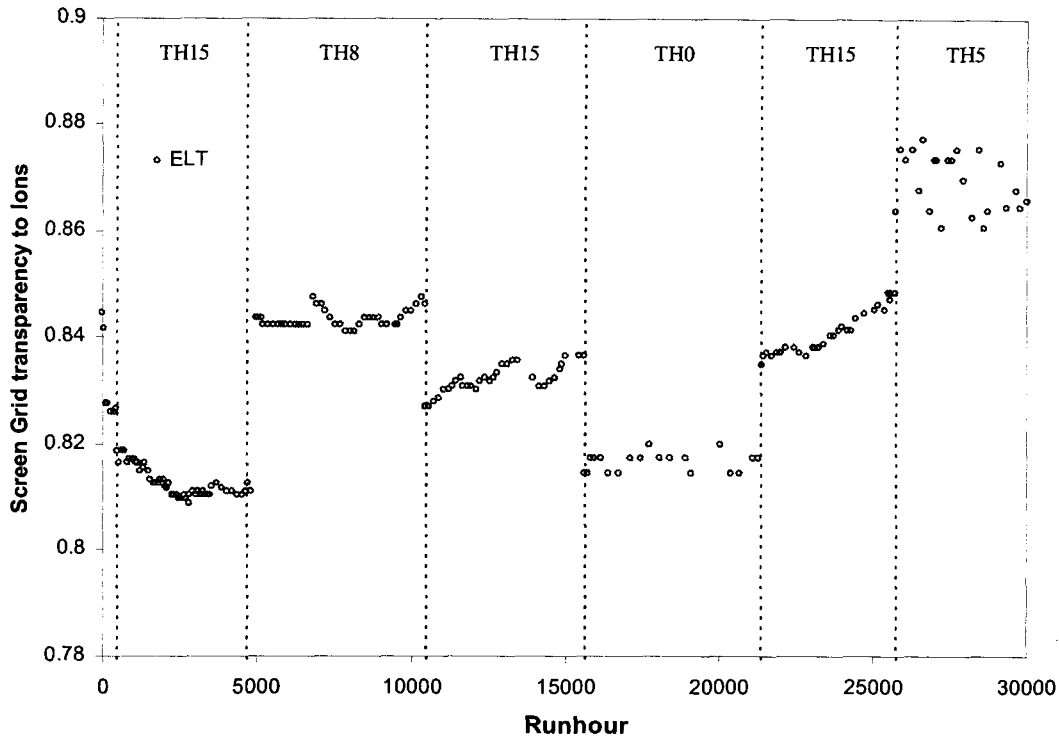


Fig. 17 FT2 Screen Grid Transparency vs. run hour

and telescopic inspection of the downstream face of the accelerator grid did not indicate that operation in this regime had occurred at this point. By the conclusion of the test the electron backstreaming limit at TH15 surpassed the upper range of the accelerator grid power supply, resulting in the reduced performance in the final throttling tests. Although the thruster was fully operational below TH15, the thruster electron backstreaming at the full power point could not be prevented after 29,000 hours of operation. This finding demonstrates that accelerator grid wear is the critical life limiting mechanism at full power operation.

Significant shifts in the electron backstreaming limit on the order of 5 to 10 V occurred at 13,993 hours and 25548 hours, respectively. As mentioned previously, these shifts may have been due to changes in the hot grid-gap, as a result of extended exposure to a 1 Torr background pressure. It is most probable that the shifts were a result of changes to the intra-grid electric field, as both the backstreaming and perveance data exhibit similar discontinuities. As with the perveance, the backstreaming limit change at TH5 was linear and minimal. This also suggests that aperture enlargement was minimal at 1kW [9-11].

Screen grid transparency to ions is a measure of how effectively ions are extracted from the discharge chamber. The measurement was made by biasing the screen grid negative of cathode potential to repel discharge chamber electrons. The total beam current and current to the screen grid was then measured, and the ratio of ion current extracted through the grid to the total current is defined as the transparency. Fig. 17 shows the transparency measured over the course of the test. The trend was an increase in screen grid transparency with thruster wear, likely due to the enlargement of screen grid apertures. This effect was most noticeable at the higher power levels, where it is expected screen grid wear is maximum. The variation in screen grid transparency during the final test segment, at TH5, was the result of a problem with the beam control loop of the beam power supply during measurement taking towards the end of the test.

The shifts mentioned previously in the electron backstreaming and perveance limits, were also apparent in the transparency data. Changes to the intra-grid electric field, directly affect the optics ability to focus ions. Similarly, as the electron backstreaming limit increased, the accelerator grid was biased more negatively to prevent backstreaming. This resulted in stronger intra-grid electric field, facilitating ion extraction, and therefore improved the screen grid's transparency to ions. Therefore the trend to increasing transparency with runtime is a result of screen grid aperture enlargement, as well as changes to the accelerator grid voltage [6].

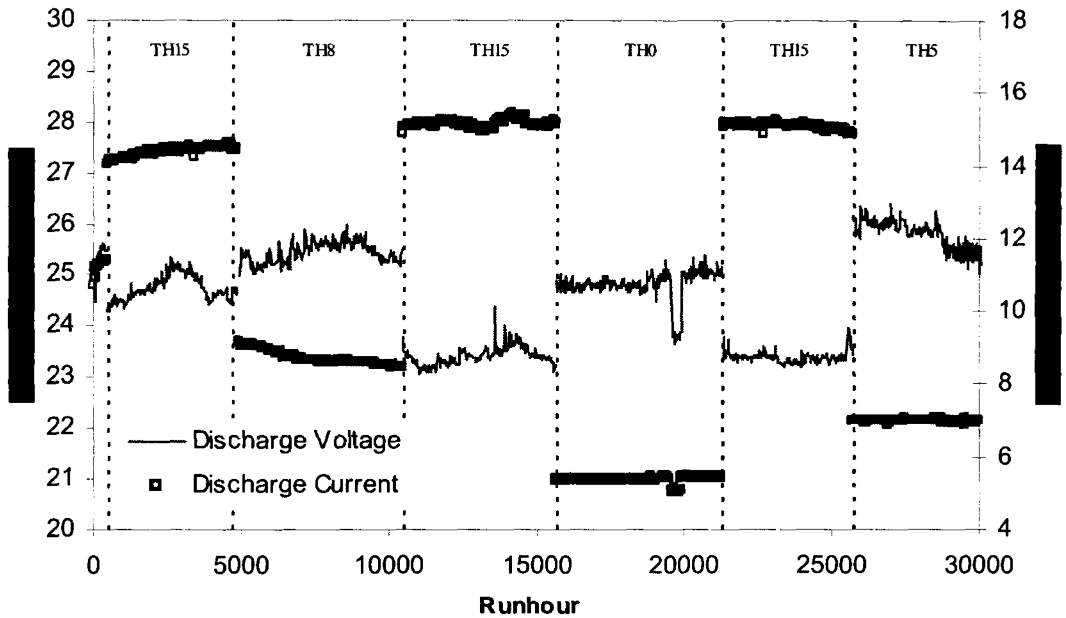


Fig. 18 FT2 Discharge Current and Voltage vs/ run hour

Discharge Chamber Performance

Discharge voltage, discharge current, and thruster efficiencies were monitored to track discharge chamber performance and wear as a function of runtime and power level. In addition, measurements of doubles and singles current were taken every 100 to 200 hours, to prevent operating in a regime that can lead to accelerated discharge chamber wear.

Figure 18 is a plot of discharge current and voltage versus runtime. There was a trend to increasing discharge current with run time during the full power segment, most noticeable over the first two TH15 segment. As the accelerator apertures enlarge, more neutral xenon is lost from the discharge chamber. As beam current is proportional to neutral density, the discharge current would have to increase to maintain the fixed beam current. This may be a factor in discharge current variations observed in FT2. The TH8 segment exhibited a net loss in discharge current after 5509 hours of operation. Although the cause is unknown, the period of discharge current decrease coincided with a short that developed between cathode keeper and cathode common, and a marked increase in the discharge voltage. Virtually no change in discharge current occurred over the 5663-hour TH0 segment. This may correspond to the absence of accelerator grid enlargement at this power level. The third TH15 segment was stable, until 24,000 hours, when the discharge current began to decrease. This is unusual as this test segment experienced a rapid change in electron backstreaming limit, characteristic of accelerator aperture enlargement. It was first thought the thruster was operating whilst electron backstreaming, resulting in the lowered discharge current. However, extensive electron backstreaming testing and thrust measurements did not reveal this to be the case. The decrease in discharge current was on the order of a tenth of an ampere, but the reduction does suggest improved ionization efficiency, in spite potentially increased neutral loss due to aperture enlargement. Operation at TH15 was terminated at this point, and the thruster was throttled to TH5 operation. Operation at TH5 also yielded a relatively constant discharge current until the conclusion of the test.

The nominal discharge voltage range for FT2 was between 23 and 27 Volts, and was highly sensitive to the main and cathode flow rate for each throttle point. Discharge voltage is a critical parameter, as high voltages can lead to increased production of multiply charged ions. FT2 was operated to maintain sufficiently low voltages to limit double ion production, whilst maintaining high propellant utilization efficiency. Figure 18 indicates that TH8 and TH5 segments had the highest discharge voltages, as compared to TH15. The TH0 segment indicates a significant drop in discharge voltage at 19,000 hours. This was the result of a flow calibration error, which was corrected at 19,500 hours, returning the discharge voltage to the nominal level. The third TH15 segment exhibited no change in discharge voltage as compared to the previous full power segments. The final

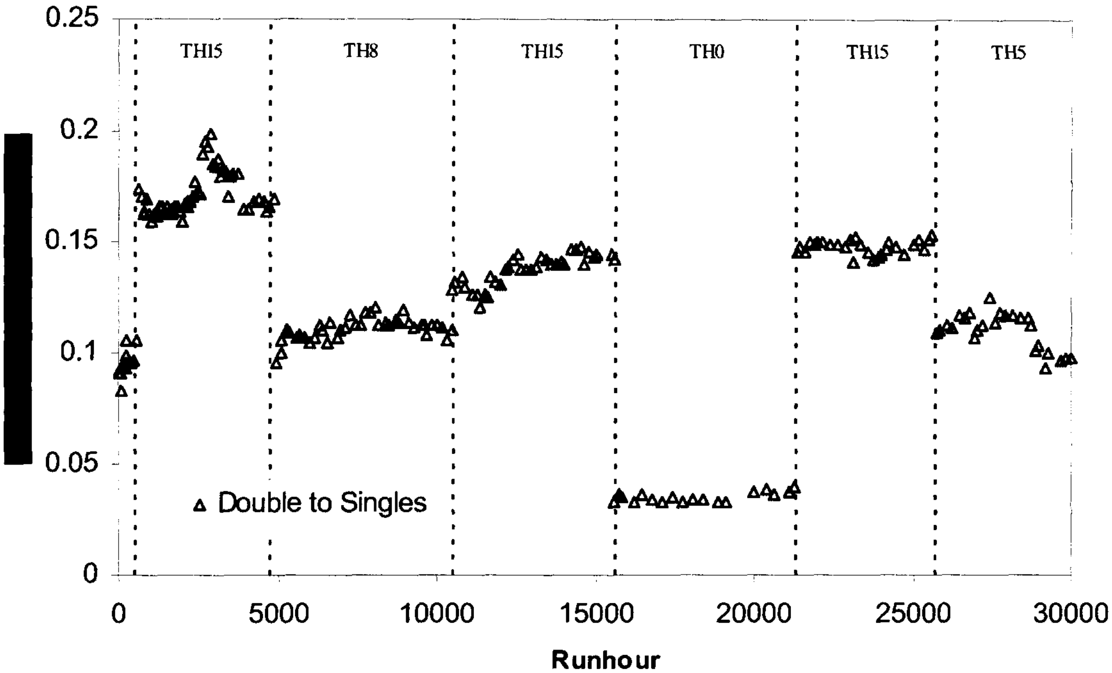


Fig. 19 FT2 Double to single ion current ratio

test segment at TH5 also exhibited a stable discharge voltage.

The double-to-single ion current ratio is an important parameter directly related thruster performance and wear. Doubly charged ions are more energetic and can sputter erode discharge chamber surfaces. Severe sputter erosion of the discharge chamber surfaces, cathode, and flake formation can lead to thruster failure. Additionally, it takes almost twice the energy to create a doubly charged Xenon ion, reducing power efficiency. Double ion current also reduces overall thrust, further impacting thruster performance. The double-to-single ion current ratio is shown in Fig. 19. During the first test segment, at TH15, the doubles ratio peaked at approximately 2500 hours, and then returned to the level at the beginning of the test segment. During TH8 operation, the double-to-single ion ratio exhibited an increase on the order of one percent. During the second TH15 test segment, the doubles ratio increased roughly two percent. During the TH0 test segment, the doubles ratio remained relatively constant. During the third TH15 test segment, the doubles ratio increased less than one percent, the smallest full power change. At TH5, the double ratio increased at a comparatively high rate, similar to that seen at the beginning of the first TH15 segment. A flow calibration error noticed half way through the TH5 segment, resulted in a shift towards a lower double content, although it continued to increase following the shift. This is an indicator of the sensitivity of discharge chamber operation to small changes in flow. A second shift towards the end of the final TH5 segment is not yet understood. Comparison of operation at the TH0, 5, 8, and 15 operating points, indicates a direct power level dependence on doubles to singles content of the beam.

Neutralizer Performance

The neutralizer cathode is the source of beam neutralizing electron current to prevent spacecraft charging. The neutralizer is a hollow cathode, with neutral xenon gas flowing though it, inside a cylindrical keeper electrode (anode). The keeper power supply maintains the neutralizer current at the fixed level specified in the throttle table. Results from the ELT indicate, the neutralizer keeper voltage was dependent on the flow rate of xenon through the cathode, the condition of the orifice, and the keeper current. The neutralizer flow rate was set to prevent plume mode operation, whilst minimizing cold flow losses, to improve thruster efficiency. Neutralizer keeper voltage and current AC characteristics were monitored continuously for the duration of the test on an oscilloscope, to prevent inadvertent operation in plume mode. The neutralizer keeper DC voltage and current are shown in Fig. 20. The spikes in the neutralizer keeper voltage seen repeatedly over the course of the test correspond to cathode conditioning events. Cathode conditioning is a process where cathode heater current was applied at various levels to burn off surface contaminants that may have deposited/adsorbed on the cathode surfaces during exposure to the higher tank pressure due to a cryopump regeneration or pressure spike. The spikes in the keeper voltage, following each conditioning, were likely due to changes to the insert chemistry as a result of the applied heater current, as opposed to the exposure to the higher tank pressure. With runtime, following a cathode

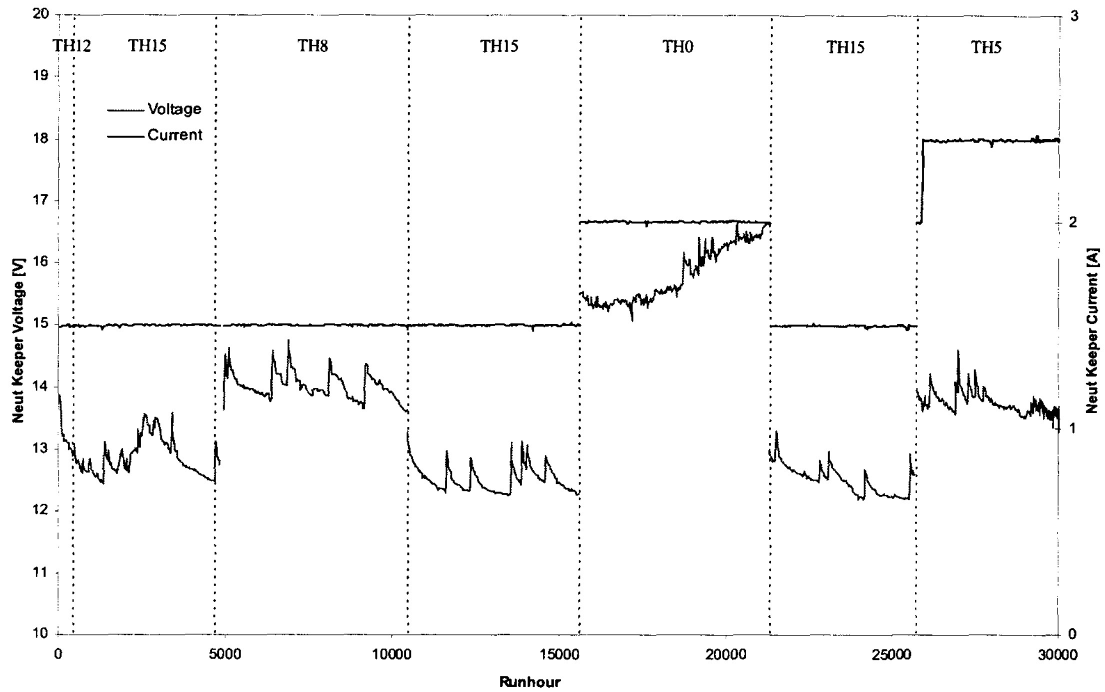


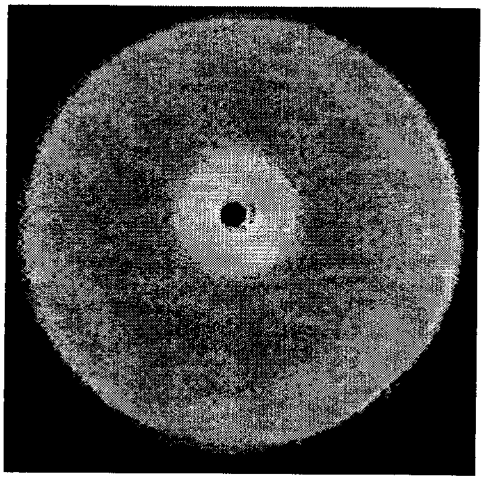
Fig. 20 FT2 Neutralizer Keeper current and voltage

conditioning, the keeper voltage tended to return to the pre-conditioning level, until the next cathode conditioning.

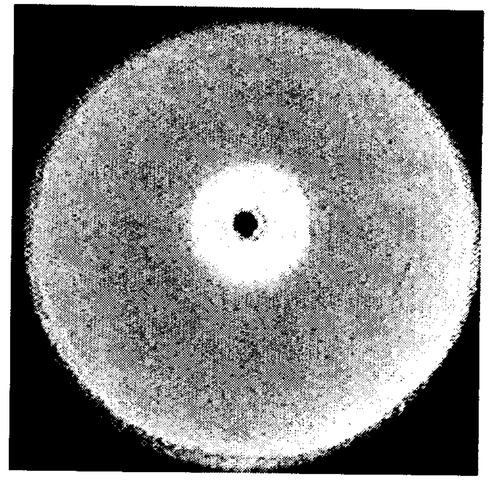
Neutralizer keeper performance characteristics were relatively stable during the TH15, TH8, and TH5 test segments. An interesting trend was observed, however, during operation at TH0. The keeper voltage began to steadily increase 2000 hours into the test segment. Internal tank photographic inspection revealed the formation of deposits within the orifice, significantly reducing its effective area. Figure 21 compares the condition of the orifice at BOL up to the end of TH0 operation. By the end of the TH0 segment, at 21,306 hours of operation, the measured area of the orifice was 40% of the initial size.

Nominal operation of the neutralizer is called spot mode, where the voltage oscillations of the keeper are significantly less than 5 V peak-to-peak. Plume mode occurs when the cathode sheath extends to the anode, resulting in large voltage oscillations, an increase in neutralizer keeper voltage, and the production of energetic ions. These ions may have sufficient energy to erode neutralizer surfaces, reducing the lifetime and performance of the neutralizer cathode. Operating with sufficient flow rate margin and keeper current can prevent plume mode operation, and as such, the flow rate margin was routinely checked. By the end of the TH0 (0.5 kW) segment, the flow rate margin fell to less than 0.1 sccm. It is believed that the deposits within the orifice are both responsible for the increase in DC and AC keeper voltage, and loss of flow rate margin. Following operation at the subsequent TH15 test segment, for 5000 hours, the TH0 keeper voltage characteristics and flow rate margin from plume mode returned to nominal levels. This suggests that operation at the higher power level removed the deposits, and that the deposition mechanism may be power level dependent, manifesting itself during low power operation.

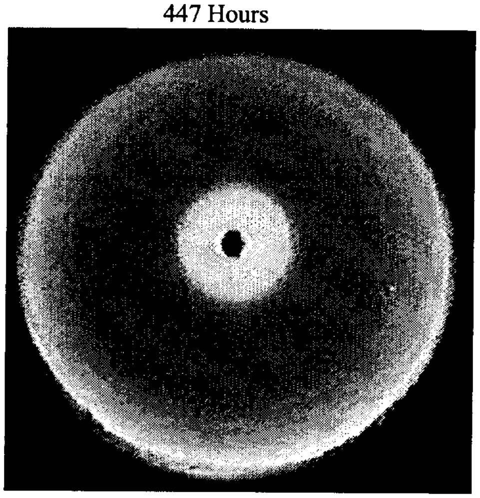
Additionally, a similar phenomenon was observed during the DS1 mission. The flight neutralizer exhibited signs of plume mode operation following extended operation at 0.54 kW. Several on orbit and ground tests were performed to characterize the effect of varying neutralizer flow and keeper current on energetic ion production from the neutralizer. They revealed that increasing flow or current reduced energetic ion production and increased margin from plume mode. Details on these tests can be found is references [1,19]. Based on these results and further ground testing, the neutralizer keeper current was increased for TH5 (1.1 kW) operation, to investigate its effect on neutralizer performance degradation at the lower power levels. FT2 was operated for 4646 hours at TH5, prior to termination, during which time the keeper AC and DC characteristics remained stable, and plume mode flow rate margin remained unchanged.



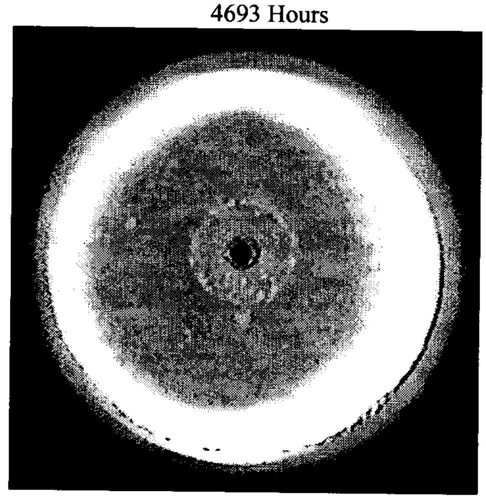
447 Hours



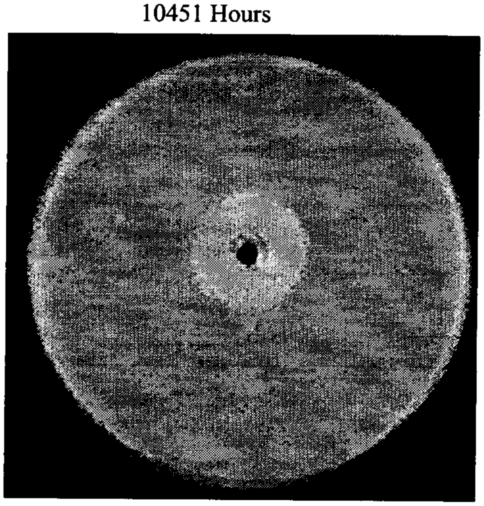
4693 Hours



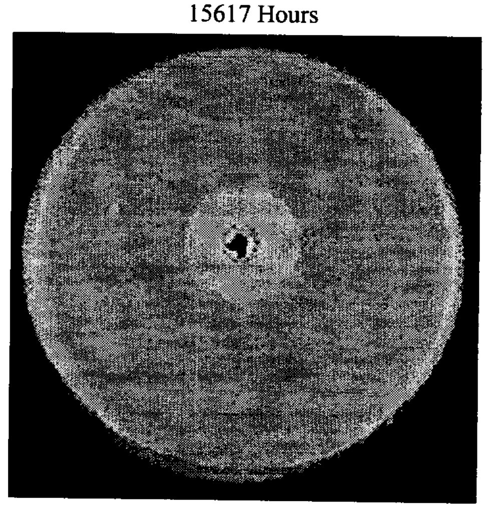
10451 Hours



15617 Hours



18706 Hours



21306 Hours

Fig. 21 FT2 Neutralizer Cathode Photos

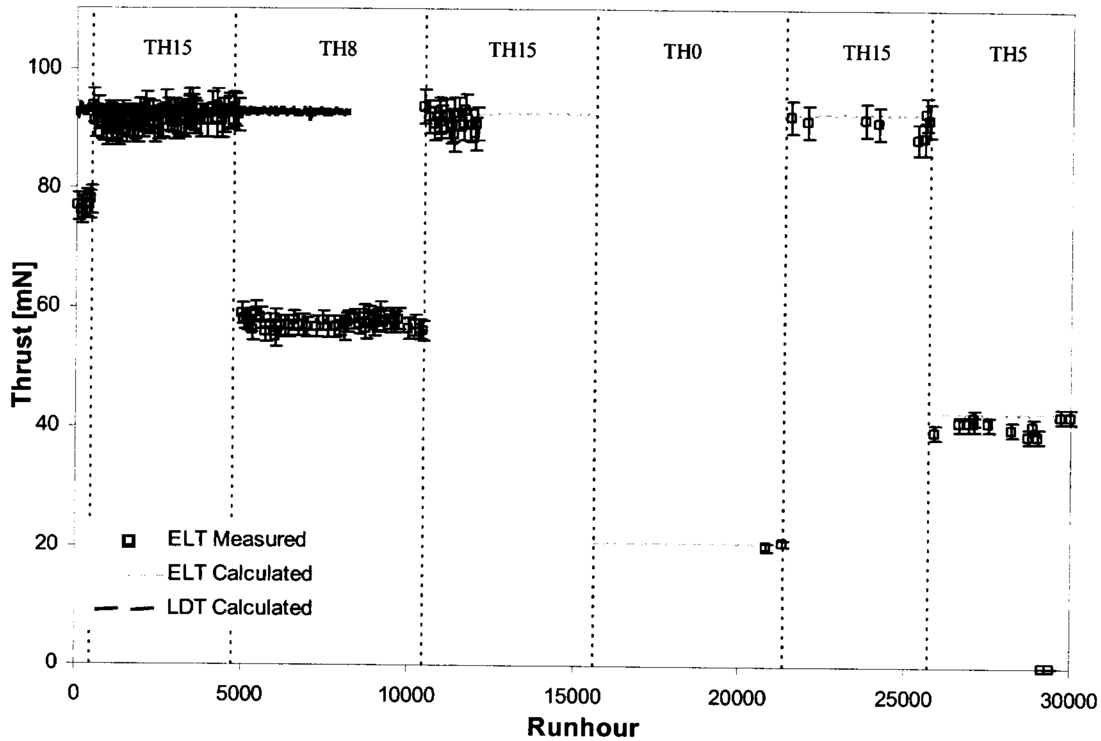


Fig. 22 FT2 Measured and calculated thrust

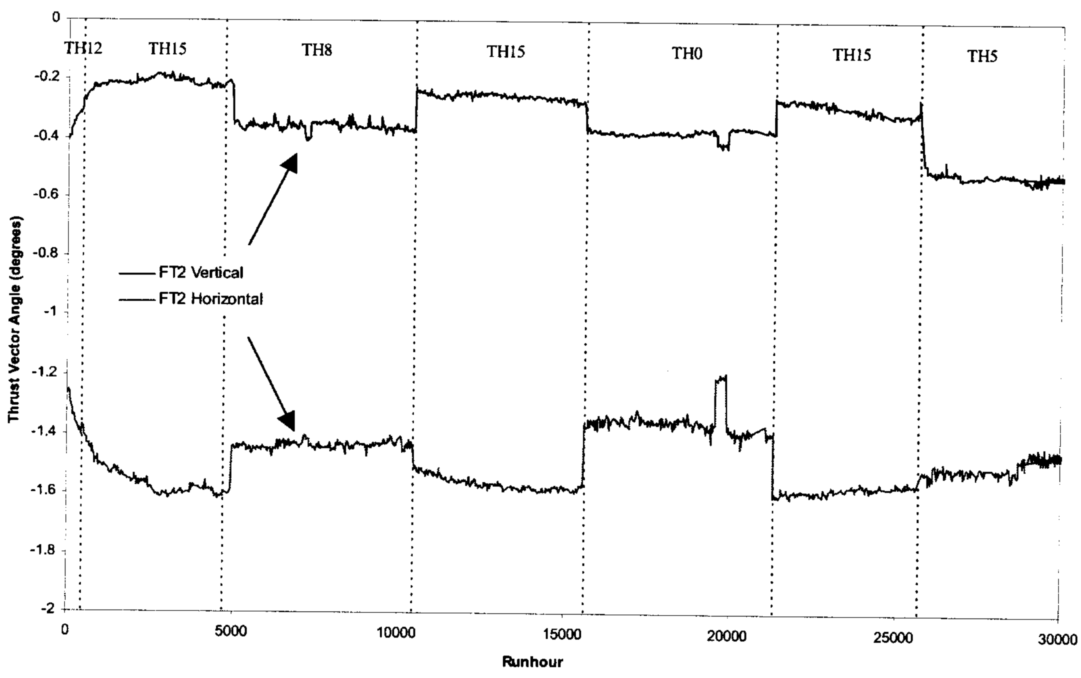


Fig. 23 FT2 Horizontal and Vertical Thruster Vector Angle

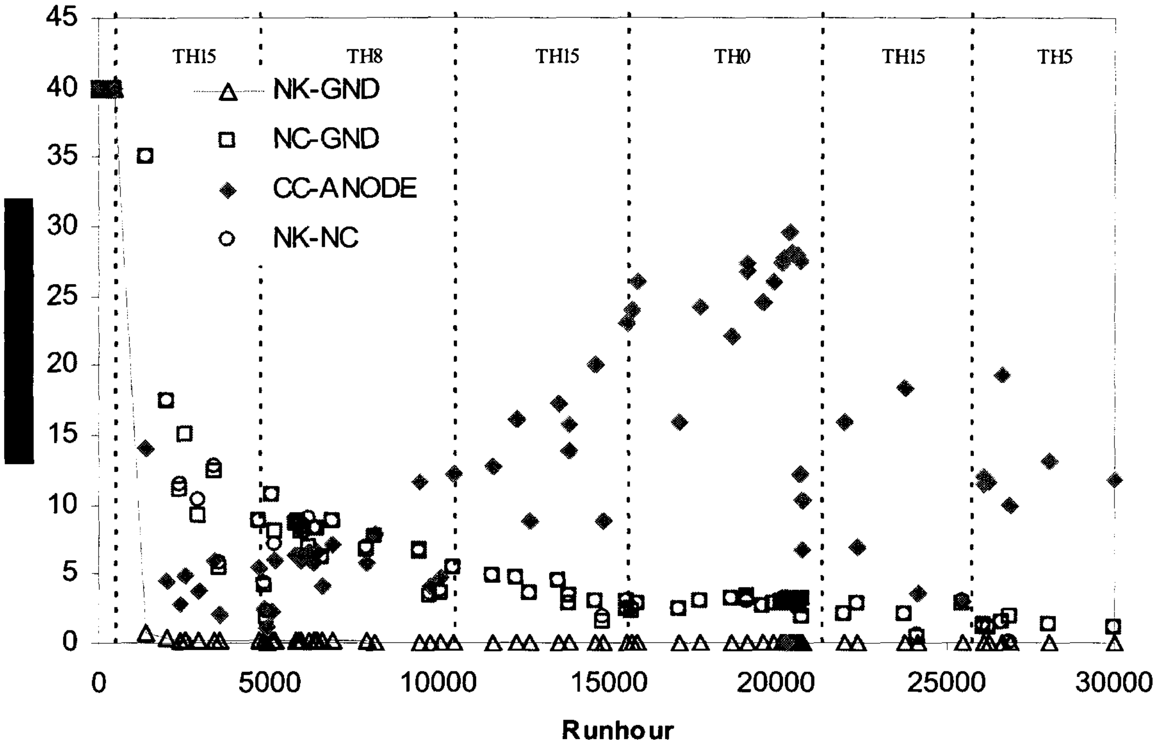


Fig. 24 FT2 Neutralizer and Cathode Electrical Isolation degradation

The deposition mechanism and composition of the orifice deposits are not known at this time. Analysis of the engineering model thruster's (EMT2) neutralizer, which operated at TH15 for 8000 hours, revealed thin deposits of tungsten around the keeper, and within the upstream and downstream ends of the orifice. It is important to note that the amount of deposition in the EMT2 orifice was minimal as compared to what was observed during the TH0 test segment of FT2. Post-test analysis of FT2's neutralizer will provide further insight into the composition of the deposits.

Thrust Magnitude and Direction

Figure 22 is a comparison of the thrust calculated from electrical thruster parameters and thrust measurements made during FT2 testing. Calculated thruster is based on the beam current, voltage, charge to mass ratio, and proportionality constant to account for double ion content. As the beam current and voltage were held constant for each throttle level, the actual thrust is held constant, to the first order. The BOL thrust at TH15 was 92.7 mN and 20.7 mN at TH0. Variations in actual thrust measured by the thrust stand to calculated thrust can then be attributed to increased beam divergence, a higher double ion content in the beam, or operating whilst electron backstreaming. The thrust did remain relatively constant over each test segment. The variation between measured and calculated thrust was less than 5%, with the exception of operation at the end of the third TH15 test segment, which was do to a mechanical error in the thrust stand. It is important to note that at the conclusion of the test, the engine could not be operated at TH15 at the nominal thrust level, because of unpreventable electron backstreaming. The engine was, however, fully operational from TH0 to TH12, with minimal performance degradation, after 30,352 hours runtime.

The thrust vector was also monitored during the test, as non-axial thrust must be accounted for, and corrected by mission operations. The horizontal and vertical thrust vector angle versus runtime is shown in figure 23. For the first 2000 hours of operation, the thrust vector experienced a variation of half a degree in the horizontal plane. Following this burn in period, the thruster experienced minimal variation, less than 0.2 degrees, in thrust vector location over each individual test segment. Test data does indicate, however, that the thrust vector became slightly more off axis, as the power level was increased and with thruster wear. The variations experienced by FT2, however, were well within the range of a typical spacecraft gimbal system. [20]

Electrical Isolation Degradation

Loss of electrical isolation between critical components is another generic failure mode for ion thrusters. At the start of FT2 testing, all impedances were above 1 GΩ. However, degradation in the electrical isolation for neutralizer and discharge cathode components was first observed only 447 hours into FT2 testing. Figure 24 is a plot of neutralizer keeper and neutralizer common to facility ground impedances. The impedance of both fell rapidly during the first 2000 hours of operation. The impedance for neutralizer keeper to ground dropped to from 10 GΩ to approximately 10 kΩ, by the conclusion of the test. The impedance loss for neutralizer common to ground appears to be power level dependent, and at EOT was 0.53 MΩ. Figure 24 also shows degradation of neutralizer keeper to neutralizer common and cathode common to anode impedance. The neutralizer keeper to common impedance fell most significantly during the first 2000 hours, and leveled off at approximately 0.6 MΩ by the conclusion of the test. This can lead to thruster failure if the discharge cannot be maintained due to high leakage current. The cathode common to anode impedance also fell rapidly during the first 2000 hours, reaching a minimum of 1 MΩ at 5000 hours. From 5000 hours on, the impedance varied widely between 3 and 30 MΩ, and was 5 MΩ at EOT. Degradation of cathode common-anode impedance can reduce discharge chamber performance, and if severe enough, can also lead to thruster failure [9-11].

Conclusions

Over 30,352 hours of operation and 235 kg of Xenon propellant were accumulated by the DS1 flight spare ion thruster, prior to its voluntary termination on June 26th 2003. At the conclusion of the test, the thruster continued to perform well with little measurable degradation in thrust, specific impulse, or thrust vector location for operation between 0.5 and 1.96 kW. Although the accelerator grid downstream wear was significant, preventing operation at the full power point, the engine was still fully operational at the mid to lower end of the throttle envelope. Significant discharge cathode keeper erosion continued through to the end of the test, fully exposing the cathode heater and orifice plate. In spite of this, the cathode and its heater were not compromised, as ignition and discharge characteristics remain unchanged and stable when compared to BOL. The neutralizer continued to perform well through the end of the final TH5 test segment, with no visible keeper erosion. Neutralizer operation at TH5 also remained in spot mode through the conclusion of the test. Degradation in electrical isolation continued for the cathode and neutralizer assemblies, but impedances remained sufficiently high to prevent major leakage paths or thruster failure.

The post-test analyses of the thruster have been initiated. Preliminary examinations of the ion optics, discharge chamber, and cathode assemblies indicate that none of the known failure modes would have caused near-term thruster failure. Detailed results of this analysis will be presented at a future date.

Acknowledgements

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