Evaluation of 25-cm XIPS© Thruster Life for Deep Space Mission Applications

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Abstract: The 25-cm Xenon Ion Propulsion System (XIPS©) thruster has been used for station keeping on Boeing 702 class satellites for nearly 10 years now, and 68 of these thrusters are operating in orbit on 17 spacecraft at this time. The 25-cm life-test thruster also successfully completed a 16,250 hour life test with 14,134 On-Off cycles distributed over two power levels with a total throughput of about 170 kg. This life performance satisfies Boeing's station keeping application requirements with adequate margin. However, prime-propulsion applications for deep space missions typically require significantly longer thruster operating times and higher throughput levels. A joint program at Jet Propulsion Laboratory (JPL) and L-3 Communications, Inc. has undertaken an evaluation of the life of the thruster for these applications. The primary wear locations in the ion thruster are the discharge and neutralizer cathodes and the high voltage grids. A 25-cm flight discharge cathode assembly successfully completed a 16,000 hour wear test at JPL at three different current levels and the data used to benchmark JPL's cathode life code predictions. The performance of a 25cm neutralizer cathode was investigated to determine the mechanisms responsible for the observed erosion in the thruster life test, and a wear test of a modified version of this cathode is underway to aid in demonstrating the desired life. Extensive modeling of the XIPS thruster grid wear has been performed using an upgraded version of JPL's CEX-2D code to determine the throughput capabilities of the thruster based on grid life. The CEX code has been benchmarked against the NSTAR LDT and ELT life tests and the observed accel-grid erosion in the 25-cm XIPS life test. The code predicts that the XIPS grid life significantly exceeds the NSTAR thruster grid life because of a higher accel voltage capability of the XIPS power supply, the third grid in the ion optics assembly which eliminates "pits-and-grooves" erosion of the downstream accel grid, and a flatter beam profile compared to NSTAR that reduces the peak current density on axis at a given power level. Evaluations of the grid life indicate that the XIPS thruster will process over 200 kg of xenon propellant with 50% margin, and even higher throughputs are possible for mission trajectories that have a large fraction of the thrusting time at low power levels.

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I. Introduction

Solar Electric Propulsion (SEP) is an enabling technology for many high Δ-v deep space missions and station-keeping applications on long-life communications satellites. This is well illustrated by the DAWN mission where NASA NSTAR ion thrusters provide all of the post-launch Δ-v, except for a Mars Gravity assist, related to heliocentric transfer to the asteroids Vesta and Ceres, in addition to orbit capture, orbit transfer, de-orbit maneuvering around these asteroids and the capability of attitude control and reaction-wheel unloading during flight[1]. Station keeping performance has also been demonstrated on commercial satellites by several companies[2-4], and literally hundreds of electric thrusters are in orbit providing these functions. Several studies have shown that U.S. commercial electric propulsion (EP) systems have advantageous performance in terms of power capability, throttle range, and efficiency compared to the systems NASA and ESA are flying to date, and the commercial systems also have the potential to significantly reduce the cost and schedule-risk of the Ion Propulsion System (IPS) for deep space missions[5,6]. The fleet of geosynchronous communication satellites that use SEP increases every year and is now over 40 satellites and over 150 thrusters, which demonstrates a significant measure of technical maturity and flight heritage for these commercial IPS that can be applied toward NASA applications. The European Space Agency (ESA) has already implemented the commercially-produced PPS-1350 Hall thruster in its successful SMART-1 lunar mission[7], demonstrating the viability of commercial station keeping EP hardware to perform in primary-propulsion, deep space applications.

The concern with utilizing commercial electric propulsion thrusters for deep space missions is seldom the performance of the thrusters, but is nearly always related to the life of the thruster. This is because the Δ-v requirements for challenging deep space missions of interest is usually much higher than that required for a 15 to 18–year life satellite station keeping applications, and so the thrusters are usually required to provide significantly more total impulse that requires longer life. Another item to be considered concerns environmental differences between deep space and earth-orbiting satellites. A methodology for qualifying commercial electric propulsion systems for deep space missions was recently published by Randolph[8]. A program to implement these processes for delta-qualifying XIPS® ion thrusters[9,10] for NASA deep space missions is nearing completion at JPL[11]. This program includes modeling of the thruster grid life[12] and cathode wear[13], performing environmental delta-qualification tests on a 25-cm EM thruster over vibe and temperature profiles required for deep space applications[11], and benchmark testing[9,14] of the thruster and cathodes to validate the models and demonstrate the life of the thruster components. The discharge cathode assembly wear test has successfully completed[15] 16,000 hours at three discharge current levels to benchmark the cathode wear codes. Modeling of the XIPS grids has demonstrated the benefits of the 3rd decel grid in essentially eliminating pits-and-grooves erosion on the downstream face[12], and improved models[16] of electron backstreaming provide good agreement with life test data. These models are being used to assess the XIPS thruster life for candidate deep space mission profiles. The results of the grid life modeling and benchmark wear testing of the XIPS cathode for deep space applications are discussed in detail below.

II. 25-cm XIPS Performance

The development[17] and performance[2,3,9] of the 25-cm XIPS thruster have been previously reported. The 25-cm thruster and Power-Processing Unit (PPU) are manufactured by L-3 Communications, Electron Technologies Inc. (ETI). Photographs of the 25-cm thruster and PPU are shown in Fig. 1. There are now 17 of the Boeing 702 communications satellites in orbit with four XIPS thrusters and two PPUs on each satellite (a total of sixty-eight 25-cm thrusters and thirty-four PPUs operating in orbit to date). A comprehensive description of the XIPS thruster production and manufacturing process was provided by Chien[10]. The fact that the XIPS thruster and PPU are manufactured continuously by a commercial vendor at rates of up to four thrusters and two PPUs per month provides a strong indication of the robustness of the source supplier with respect to engine/power supply component availability and reproducibility for NASA applications. In addition, long

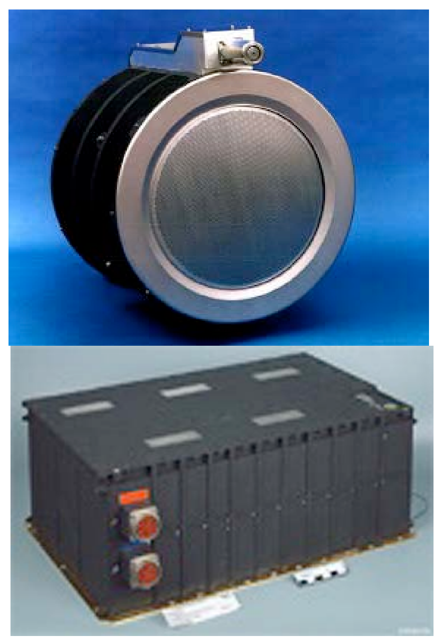

Figure 1. Photograph of the 25-cm XIPS thruster and flight Power Processing Unit (PPU).

range, multi-year procurement orders from non-NASA customers also help ensure the future availability of these same components with some reasonable assurances of cost-reproducibility. In communications satellite applications where the EP system is used for orbit raising and station keeping, the performance of the 25-cm XIPS thruster is summarized[18] in Table 1. The XIPS thruster normally operates in this case at two different power levels, with a thrust of 80 or 165 mN, an Isp between 3400 and 3600 s, and a total efficiency of over 67%. In all spacecraft applications, the total system efficiency, thrust and Isp of the EP system versus the input power level to the Power Processing Unit (PPU) are the important parameters, and so the PPU efficiency (also listed in the table) must be taken into account in the performance specifications.

Table 1. 25-cm XIPS thruster and PPU parameters in communication satellite applications[21].

	Low Power Station Keeping	High Power Orbit Raising
Active grid diameter (cm)	25	25
Thruster Input Power (kW)	2.0	4.3
Average ISP (seconds)	3420	3550
Thrust (mN)	80	165
Total Thruster Efficiency (%)	67.0	68.8
Mass Utilization Efficiency (%)	80.0	82.5
Electrical Efficiency (%)	87.1	87.5
Beam Voltage (V)	1215	1215
Beam Current (A)	1.43	3.01
Mass (kg)	13.7	13.7
PPU Efficiency (%)	91	93
PPU Mass (kg)	21.3	21.3

For deep space applications where throttling of the engine power is required, the XIPS ion thruster performance from 0.4 to 5 kW input power levels has been reported[9]. The total thruster efficiency versus input power to the PPU from this work is shown in Figure 3. Even though the NSTAR and XIPS thrusters have a similar electrical design and common development heritage, the XIPS based IPS has demonstrated over twice the throttling range as NSTAR and slightly higher efficiency over this range. This information, along with the thrust and Isp variation with PPU input power, is used for mission planning and performance analysis. Curve fits to the data for thrust, Isp and efficiency versus input power used in the present JPL mission studies[5] were previously published[11]. The XIPS thruster has significant performance and cost advantages over the NSTAR thruster.

The methodology for qualifying commercial electric propulsion systems for deep space missions, published by Randolph[8], and a NASA Standard for Life Qualification for thrusters[19], are being used to delta-qualify the XIPS ion thrusters for deep space applications. There are several topics that are being addressed. These are:

- Environmental
  - Dynamic
  - Thermal
- Mission Assurance
- Life
- Material analysis and certification
- Reliability
- Electromagnetic Compatibility

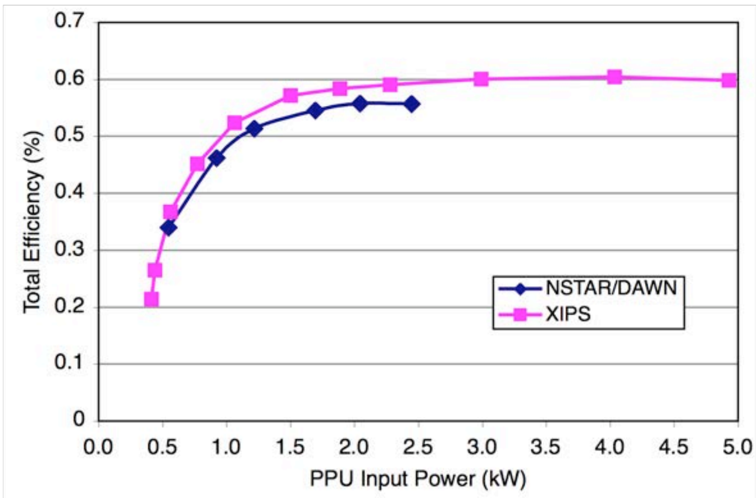

Figure 2. Total efficiency of the 25-cm XIPS thruster and PPU and the NSTAR thruster and PPU as used on DAWN versus PPU input power.

The specifications and status of the environmental, mission assurance, materials and compatibility aspects were discussed in a previous publication[11]. Execution of these tasks is still on going, and expected to be completed shortly. The major concern addressed by this paper is the life of the thruster in deep space applications where throttling of the thruster system and extremely high total impulse performance is required.

III. Life

The life of ion thrusters is of concern for deep space missions due to the high throughput and long operation time typically required of most missions[5]. The concerns for thruster life are centered on the potential wear-out failure mechanisms in the engine and the related wear-out mechanisms that lead to failure. Since ion thrusters have been in development for about 50 years and have accumulated over 100,000 hours of life testing to date, the failure mechanisms for this type of engine are very well known. A historical survey of the identified failure mechanisms and life tests has been produced by Brophy, et al.[20]. The credible failure mechanisms that still exist for ion thrusters, i.e. the ones that have not been designed out of the thruster or eliminated by manufacturing process modifications, and their causes were previously described[11,20] and are listed briefly again below and grouped in terms of the three main components of an ion thruster: the cathodes, the ion optics and the discharge chamber. The status of the evaluation of the XIPS cathodes will be summarized first, and then the thruster throughput as limited by ion optics (grid) erosion will be described.

Hollow Cathodes

1. Heater Failure
2. Thermionic Emitter Failure
3. Electrode Erosion
4. Shorts or Electrical Breakdown
5. Cathode Orifice Plugging

Ion Optics

1. Electron Backstreaming due to grid erosion
2. Grid Shorting
3. Grid Damage or Structural Failure
4. Electrical Breakdown

Discharge Chamber

1. Magnet degradation due to time at temperature
2. Insulation Failure from sputter deposition

Like all ion thrusters, the XIPS ion thrusters, are potentially susceptible to these failure mechanisms. However, the 25-cm XIPS thruster is a second-generation design based on the initial work of producing, qualifying and flying the 13-cm XIPS thrusters in the 1990's. Extensive design upgrades, process improvements and the manufacturing and testing of over 90 of the 25-cm thrusters to date have resulted in the elimination of some of these failure modes and mitigation of many others[11]. The XIPS thrusters have also undergone several life tests, the results of which are summarized in Table 2. A comprehensive description of the results from the 25-cm thruster life test and the post-test-analysis will be presented at this conference by Tighe[21].

Table 2. Life test durations and cycles[21] of the XIPS 13-cm and 25-cm ion thrusters.

Thruster	Power Level	Operation Hours	Cycles
13 cm (Q1)	0.5 kW	16,146	3,275
13 cm (Q2)	0.5 kW	21,058	3,369
25 cm	4.2 kW 2.0 kW	2,880 13,370	324 13,810

A. Hollow Cathodes

A significant amount of work has been on-going at JPL for the past three years to delta-qualify the XIPS discharge and neutralizer cathodes for deep space missions. This work is summarized here and described in detail in the referenced papers. The XIPS discharge and neutralizer hollow cathodes, shown in Fig. 3, are essentially identical to those used in the NSTAR engine with changes only in the heater and orifice sizes and some of the refractory materials used in the construction. The XIPS heater has been fully qualified[22] and tested for a large number of

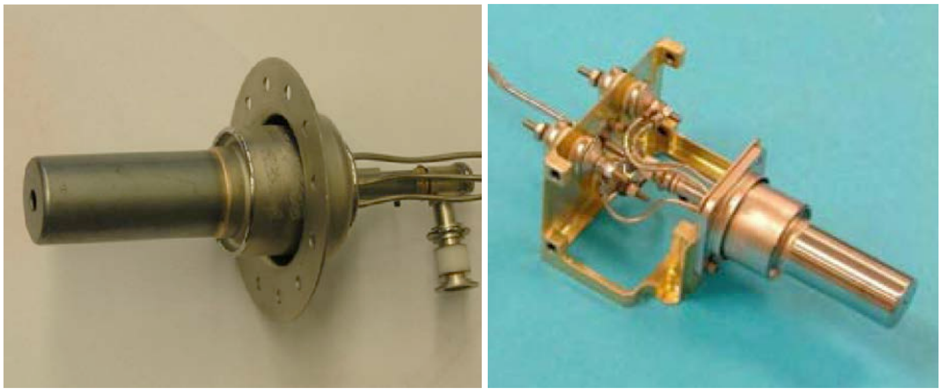

Figure 3. XIPS discharge (left) and neutralizer (right) cathodes.

thermal cycles and extended on-time durations. By reducing or eliminating keeper wear (described below) to provide protection of the heater sheath, heater failure is an unlikely problem for the XIPS thrusters.

Potential failure mechanisms related to the thermionic emitter depletion and poisoning have been extensively investigated at JPL[23-26]. The rate at which barium evaporates and the insert is depleted[27] in the XIPS discharge hollow cathode, assuming the worse case situation where the barium does not recycle to the surface, is shown in Figure 4 as a function of the cathode discharge current. The cathode operation time and total thruster throughput are extremely long for this cathode, and typically exceed mission requirements by a factor of over 5. In reality, barium is recycled in the insert region[24], which greatly extends the life of this cathode against this failure mechanism. Barium depletion is not anticipated to be an issue for the thruster life in deep space applications. Insert poisoning, tungstate formation and insert surface modifications are potential failure mechanisms related to impurities in the feed gas. Extensive investigations of these effects[25,26] have been performed. It has been found that providing the specified purity of xenon to the cathodes eliminates insert poisoning problems.

Erosion of the cathode orifice and keeper electrode of the discharge and neutralizer hollow cathodes has also been extensively investigated at JPL. The neutralizer cathode orifice erosion observed in the NSTAR ELT test[28] and the 13-cm XIPS life tests has been explained by a comprehensive model published by Mikellides[29]. The neutralizer orifice wear stops after a short time because the larger orifice reduces the neutral density and collisionality, which reduces the plasma potential and bombarding ion energy to negligible levels. Erosion of the discharge cathode orifice is typically small[13] because the ion flux is significantly lower than in a neutralizer cathode and the ion energy is low. This is not considered a failure mechanism for the NSTAR or XIPS cathodes based on the negligible orifice erosion observed in the various life tests of these engines. Keeper erosion, however, is potentially an issue for any ion thruster. Keeper wear on both XIPS discharge and neutralizer cathodes was observed in the thruster life test[21] at L-3 Communications and in the discharge cathode wear tests[14,15] at JPL. This is not an issue for the discharge cathode in that the wear did not impact the life test or thruster performance. The discharge cathode wear test found that keeper wear occurred only in the high power mode[14], and the wear test was run for 5600 hours in this mode to determine the extent of the wear. Once again, the keeper wear did not affect the cathode life, and caused only small changes in the discharge loss measured in the experiments. Since most applications will not

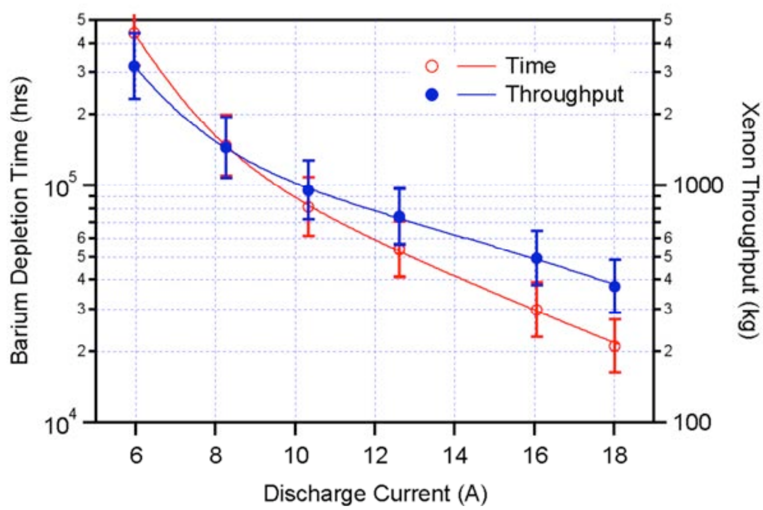

Figure 4. Barium depletion time calculated for the XIPS discharge hollow cathode as a function of discharge current level showing extensive cathode life.

use the thruster for this long in the high power mode, keeper wear is not expected to be an issue for deep space applications. Additional work aimed at minimizing the keeper wear using alternative materials is underway[15].

B. Ion Optics

The XIPS grids and ion optics assembly are designed and fabricated to eliminate many of the failure modes listed in the previous section. First, XIPS uses a three-grid geometry that incorporates a third "decel" grid into the assembly. This grid physically shields the negatively biased accel grid from charge-exchange-produced ion bombardment from the beam that causes the characteristics "pits and grooves" erosion of the accel grid in two-grid designs. The decel grid is biased near the neutralizer cathode-common potential, which is within 50 V of the spacecraft potential. This reduces the back-flowing ion energy impinging on the decel grid to the order of tens of volts, compared to hundreds of volts if allowed to bombard the accel grid. The low backstreaming ion energy reduces ion sputtering of the downstream face of the grids to negligible levels[18]. Figure 5 shows the downstream pits-and-grooves erosion rates calculated by Wirz[12] using the JPL CEX-3D code for the 3-grid XIPS system and the 2-grid NSTAR system both operating at the 2.3 kW TH15 throttle point. The 3rd grid in the XIPS system reduces the downstream accel-grid face erosion to negligible levels. Wirz stated[12] in the paper: "These results show that the decel grid effectively shields the downstream face of the accel grid from erosion except for a small amount of erosion just around the periphery of the accel grid aperture." Figure 5 shows that this even small hole-edge erosion is less than that found in the 2-grid case, which support's Wirz's conclusion that the 3rd grid does not redirect any of the ions backflowing from the beam into the accel grid walls and provides good protection of the accel grid. Examination of the downstream surface of the decel grid at the conclusion of the 16,000 hour XIPS thruster life test[21] showed a hexagonal pits-and-grooves patterns on the surface but insignificant change in the grid thickness, which supports the predictions of the code on the benefits of the 3rd grid.

To mitigate other potential ion optics failure mechanisms, the XIPS grids are manufactured to produce a stable radius of curvature over the life of the grids (ion thruster grids are domed to survive launch vibration and annealed to provide stable gaps during thermal expansion). The grids are also mounted on flex-structures[17] that permit radial expansion due to heating of the grids during operation without causing the grid gap to change. The manufacturing techniques and mounting structure of the grids improves the grid gap stability over time and temperature. Rogue hole formation and electrical shorting has been observed during development of the XIPS thrusters due to delamination of sputter-deposited materials on the grids. In general, this failure mechanism occurs near the end of the life when a significant amount of grid material has been eroded and deposited on a facing grid to create sufficiently thick layers that will delaminate from the surface. This failure mechanism has been mitigated by a modification of the surface processing of the grids to enhance adhesion of the sputter-deposited material. The success of this technique was demonstrated by the successful completion of over 21,000 hours by the second 13-cm life test[10], and by the successful operation of the NSTAR thruster (which was manufactured by the same vendor and used the same process) for over 30,000 hours in the Extended Life Test[28]. The XIPS thrusters avoid grid shorting failure mechanisms in the same manner as in the NSTAR thruster. The discharge chamber wall is manufactured to retain sputter-deposited material using the same textured surface-material as in NSTAR. The PPU has a grid-clearing circuit that provides high current pulses to

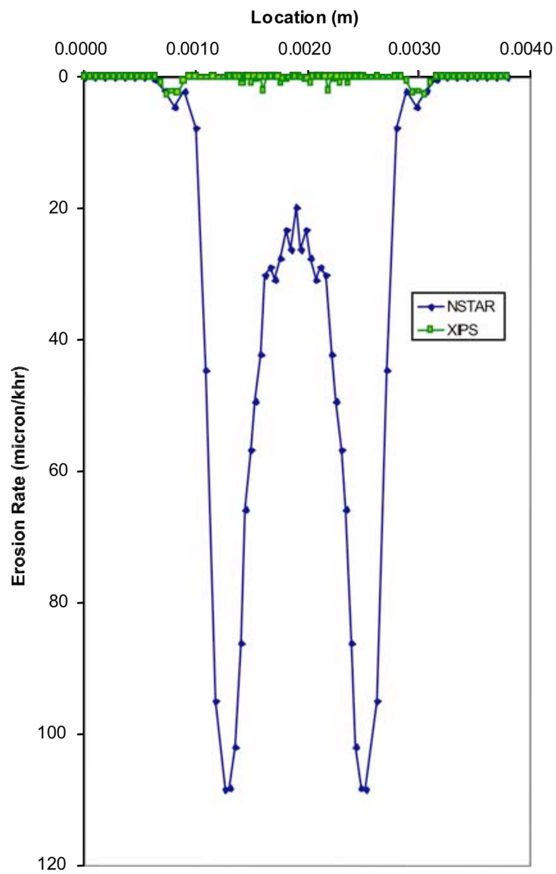

Figure 5. Calculated Pits and Groves erosion rates[12] showing the XIPS 3rd grid effectiveness compared to the 2-grid NSTAR erosion rate.

melt and open flakes or whiskers from launch debris or spalled material between the grids. However, the PPU is also designed to limit the energy deposited in the grids to avoid damaging the surfaces. The insulators are all shadow-shielded to avoid material deposition and electrical leakage. The high reliability reported[10] for the 25-cm XIPS thrusters on orbit illustrate the reliable and robust ion optics design and manufacturing techniques. A more detailed discussion of these potential failure mechanisms and the techniques used in the XIPS thrusters to mitigate them can be found in the references[10,11].

Finally, the life of the ion optics and the throughput capability of ion thrusters is primarily determined by electron backstreaming limitations due to accel grid barrel erosion and enlargement, and ion sputtering of the screen and accel grids that leads to structural failure. Since this is what ultimately determines the XIPS thruster life, it will be discussed in detail in the next section.

C. Grid Life and Throughput

Detailed modeling of electron backstreaming (EBS) and the total throughput capabilities of the XIPS thruster at different power levels have been made using the CEX-2D ion optics code[30], which has been modified to provide time dependent erosion results[31] and improved EBS determination[16]. The modifications to the CEX code permit detailed comparisons with the time evolution of the accel grid aperture diameter and the screen grid thickness, and produce excellent agreement with the results from the NSTAR benchmark testing[16]. In addition, the code results are benchmarked (below) against the XIPS life tests results[11, 21], which then provides more accurate life predictions for the thruster life. The operational history of the 25-cm XIPS thruster life test is shown in Figure 6. The thruster was operated at two throttle levels corresponding to the orbit insertion and station keeping levels required by Boeing for their 702 satellite. After about 2000 hours at the high power mode, the accel grid voltage was reduced from the starting nominal value of -300 V to -375 V to stop the occurrence of an increasing rate of recycles. The increasing recycle rate was found to be associated with the intermittent onset of electron backstreaming. The -375 V setting used is the next value that the PPU is capable of providing. The PPU can also provide -450V, but this was not required at any time during the life test. After 2880 hours, the thruster was then throttled down to 2 kW to life test the nominal station keeping mode for the Boeing 702 satellite, and the accel grid voltage was returned to the nominal -300 V. After about 14,000 hours in the low power mode, the accel grid bias was again increased to -375 V by the PPU through the end of the test.

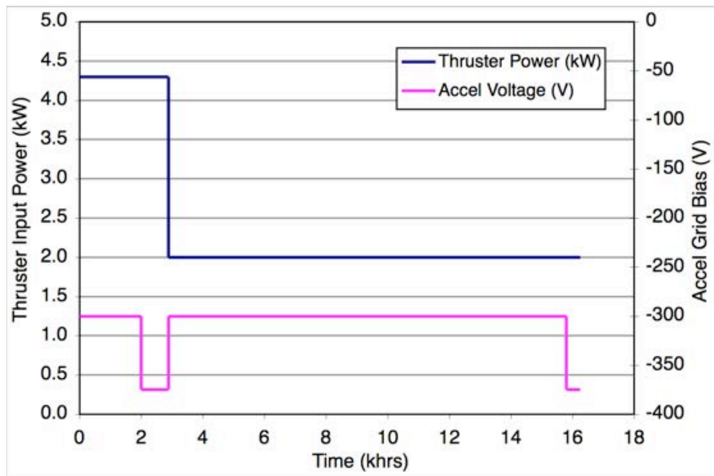

Figure 6. Thruster input power level and accel grid bias voltage during the 25-cm XIPS thruster life test.

1. Benchmarking Against the Life Test Data

The CEX code requires a complete description of the electrode geometry of the grids, the applied voltages, the plasma parameters in the upstream discharge chamber region and in the downstream beam-plasma, and the neutral gas densities throughout the system. The geometry of the grid electrodes, illustrated in Figure 7 for the input to the code, and the operating voltages and currents, were provided by the manufacturer L-3 Communications ETI. The plasma density, neutral density, and electron temperature in the discharge chamber were calculated by the 0D Analytical Discharge

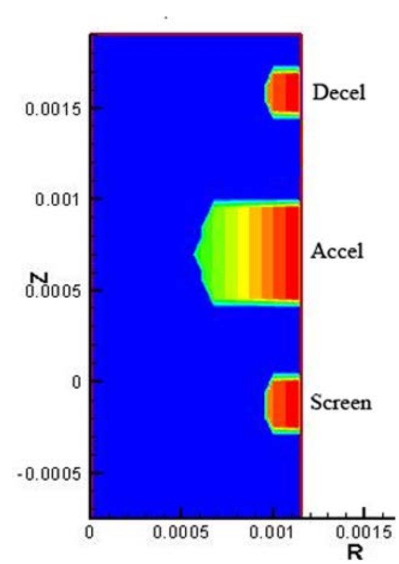

Figure 7. Initial conditions of the XIPS grids input into the CEX-2D code.

Model of Goebel, et al[32], and the downstream plasma parameters were estimated from NSTAR data. A sensitivity analysis showed that the downstream beam-plasma electron temperature and potential in the range of 1 to 3 eV and 5 to 20 V, respectively, did not change the EBS value significantly. Therefore, a beam electron temperature of 2 eV and beam plasma potentials of 10 eV were selected for these calculations. The hot grid gaps are not well known and have not been directly measured on the XIPS engine, but the values selected were chosen to match the perveance and EBS data measured from the life test. Finally, the CEX code is used to calculate the erosion rate and EBS in the center aperture where the erosion is the highest due to the peaked plasma profile in the discharge chamber. The WGW analytical electron backstreaming model[33] was used to relate the peak electron backstreaming value in the center beamlet to the average value integrated over the 25-cm diameter grid. It was found that for the 0.62 flatness parameter measured for the 25 cm XIPS thruster, the peak on-axis electron backstreaming current is about 16% of the ion current for the case of the average electron backstreaming current over the grid equal to 1% of the total beam current.

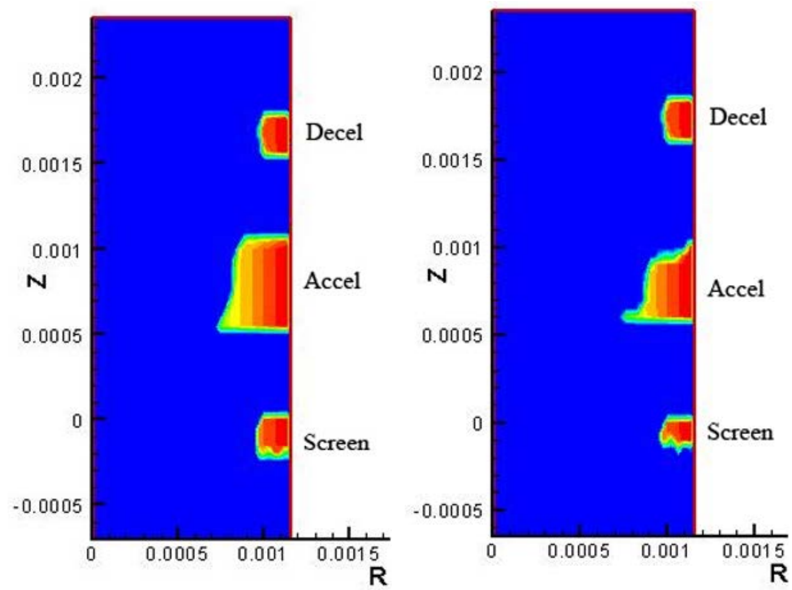

Figure 8. Eroded grids at 2.8 khrs (left) at the end of the high power mode operation and 16.8 khrs (right) at the end of the low power mode operation.

The grid shapes predicted by the code at the end of the high and lower power life test phases are shown in Figure 8. These plots show only the erosion and not the redeposition of the sputtered material. The cusp on the accel grid inner diameter was eroded completely away in the high power phase, and the accel grid was then chamfered on the downstream side of the aperture. during the low power phase. The minimum screen and accel grid aperture inside diameters were not significantly changed in the low power phase, but the thickness of the screen grid was found to decreased over the test. The decel grid inside diameter also increased over the duration of the test.

The calculated magnitude of the accel grid voltage at which electron backstreaming occurred from the CEX-2D code, and the value measured periodically during the life test, are shown in Figure 9. The red squares are the values of the EBS voltage from test used to benchmark the code. It was typically found that a 20 V margin was required to stop EBS onset in test, and that EBS produced spurious recycling. A more negative accel bias was necessary to run reliably once this voltage level was reached. The EBS predictions by the code in the high power mode are very good. After 2880 hours in the high power mode, the thruster was run in the 2 kW low power mode with -300 V accel grid bias. However, the periodic

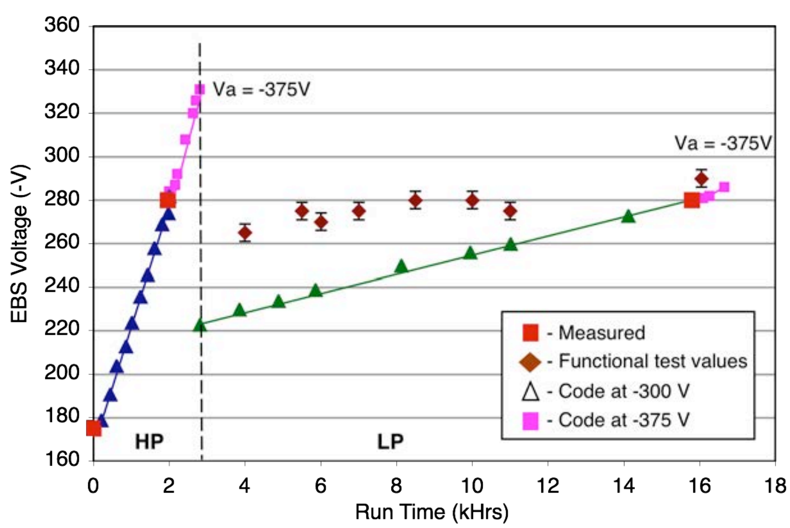

Figure 9. Measured and calculated electron backstreaming voltage during the 25-cm XIPS thruster life test.

sampling of the accel grid bias at which EBS onset was detected during the life test did not match the code prediction until the thruster had accumulated about 14,000 hours. The reason for this is not completely determined. The physics is clear in that the decreased space charge in the beamlet produced by reducing the current in half significantly reduces the required bias to stop backstreaming, but the test setup required more bias than predicted to avoid excessive recycling. In addition, the EBS test-measurements don't reflect the accel grid wear accumulated from 2880 hrs to 15,000 hrs. Since measured EBS voltage was nearly constant during this mode, and the recycling was intermittent, it is possible that noise and measurement uncertainty in the test setup are responsible for at least some of this discrepancy. The code does provide good predictions for when the grid bias voltage is insufficient to stop EBS, and so is useful for estimating the grid life from this mechanism.

The CEX code also was able to predict the minimum accel aperture diameter well over the duration of the test. Figure 10 shows the predicted minimum accel grid hole diameter and the measurements of the grid-hole minimum diameter during the test by an optical camera. The agreement is very good and consistent with the observation made in the NSTAR ELT[28] that later in life, as the accel hole diameter increases, the charge exchange ions tend to be swept downstream by the modified potential structure and either strike the accel grid past the mid line (causing chamfering of the aperture barrel seen in Figure 8) or miss the grid entirely. Post test measurement of the accel grid aperture shape in the ELT[28] and in the XIPS life test[21] are consistent with this prediction.

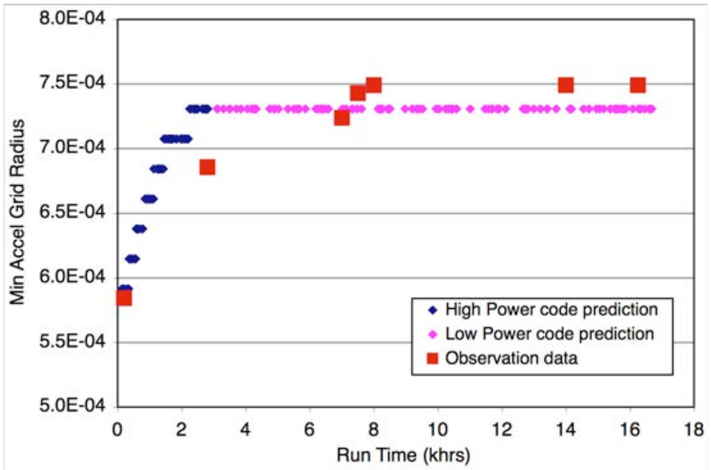

Figure 10. Predicted and observed minimum accel grid hole diameter during the 25-cm XIPS thruster life test.

Finally, the real-time erosion feature of the CEX-2D code calculates the screen grid thickness as a function of operating time of the thruster. Figure 11 shows the calculated mean screen grid thickness at the point of maximum erosion at the grid center line over the duration of the life test and the final measurement of the grid thickness. The grid webbing does not wear uniformly in thickness, which is shown in both Fig. 8 code predictions and the photographs of the post-test grid cross section[21]. The upstream edges of the aperture tend to chamfer, so an average value was taken for representation in the graph to show the erosion trend. In these figure, the more rapid erosion of the screen grid after 2000 hours in the high power mode and after 16,000 hours in the low power mode is associated with the higher negative bias applied to the accel grid during these periods that produced a higher chamfer rate of the aperture edges (and hence a decrease in the mean thickness).

This calculation and the final thickness data does not account for the deposition of material on the downstream face of the screen grid from the accel grid sputtering, which means that the actual net grid thickness is larger than shown here. Nevertheless, the prediction of the amount of screen material eroded by the end of the test and the code prediction are in good agreement. The relatively large amount of erosion of the screen grid during the low power mode of this test appears to be due to the selection of the discharge voltage at which the test was performed. While the nominal discharge voltage in the low power mode is about 25 V, the life test was run at 27 V as a worse case specification for the allowable value. Reducing the discharge voltage to the nominal level,

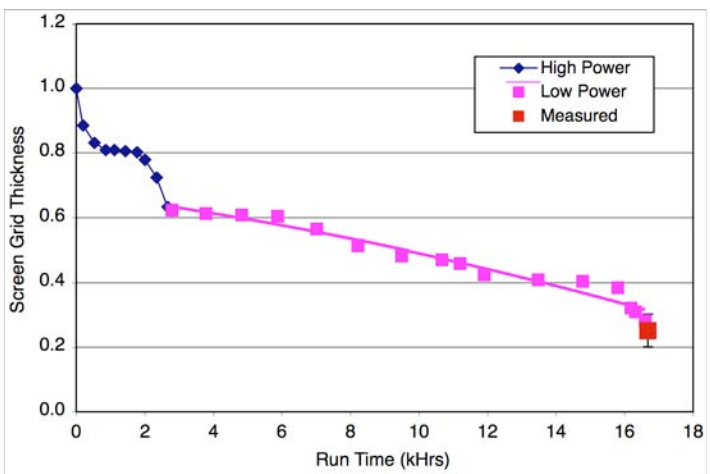

Figure 11. Mean screen grid thickness calculated during the 25-cm XIPS thruster life test and the measured end point.

which decreases the energy of the ions hitting the grid and reduces the double ion content in the plasma, nearly doubles the life of the grid and is sufficient for many deep space missions. If needed, even longer screen grid life is possible by operating at a discharge voltage approaching 24 V, but at the expense of some thruster performance.

2. Thruster Throughput Predictions

The CEX code has been previously benchmarked against the NSTAR LDT and ELT life tests by Brophy[34] in support of the DAWN mission thruster throughput rating. Since it has now also been benchmarked against the XIPS life test in the section above, it is possible to use it for predicting the throughput of the XIPS thruster under different operational scenarios.

The life of the XIPS thruster for the case of electron backstreaming limiting the life is shown in Figure 12 for the thruster operating solely at each of its two nominal operating modes. If operated at the 4.3 kW input thruster power, with the accel grid voltage increased more negatively (-300 to -375 to -450 V) once the EBS limit has been reached for each voltage, the CEX code predicts that the thruster will operate for 7270 hours and process 134 kg of xenon. Taking the standard 50% life margin[19,20], the thruster should be rated at full power for about 87 kg. In the low power mode at 2 kW of input power, the thruster will hit the EBS limit at 37000 hours after processing 340 kg of xenon. Again taking 50% margin, the thruster should be rated at its 2 kW low power point at 227 kg of xenon throughput.

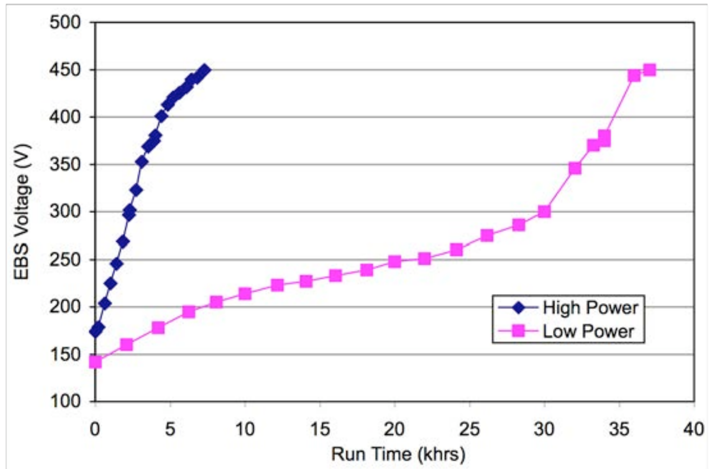

Figure 12. Magnitude of the voltage at which electron backstreaming occurs as a function of time for each of the XIPS high power and low power cases.

There ratings should be compared to the NSTAR engine. In the ELT, the NSTAR engine processed 144.8 kg of xenon at the maximum power level (2.3 kW to the engine) and a total of 235.3 kg of xenon over all the throttle levels tested. After processing 211 kg of xenon, the thruster could no longer be operated at the highest power level due to EBS at the maximum accel grid bias available from the PPU (-250 V), but was still fully functional at the 2 kW TH12 throttle level. If operated solely at the NSTAR TH15 power level of 2.3 kW, the CEX code indicates that the XIPS thruster would hit the EBS limit at about 290 kg, significantly in excess of the 144.8 kg at full power and 211 kg total achieved by NSTAR.

There are three reasons for this improved life over NSTAR:

1. The XIPS PPU is capable of providing significantly higher negative bias voltages to the accel grid (up to -450 V compared to -250 for NSTAR). While the ion sputtering rate of the accel grid increases with the negative bias, the ability to operate with more negative grid bias reduces the onset of EBS and significantly increases the throughput capability.
2. The XIPS discharge chamber produces a much flatter plasma density profile than NSTAR. This is shown in Figure 13, where a direct comparison of a measured NSTAR profile measured 2.5 cm from the grids at the 2.3 kW TH15 power level is made with a XIPS engine

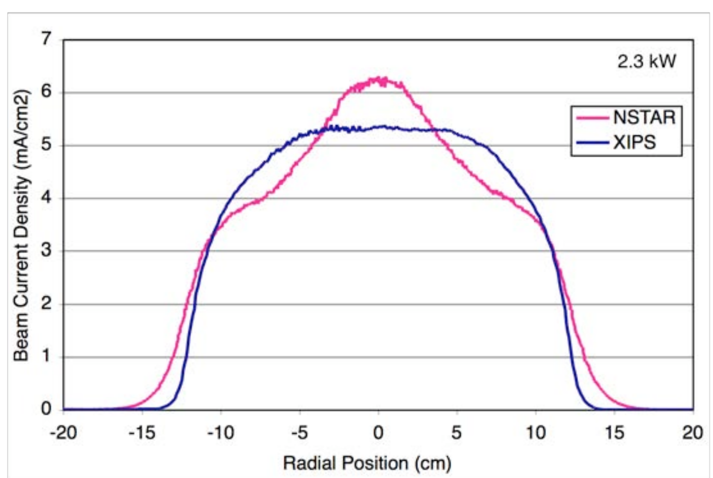

Figure 13. Comparison of the beam profiles of XIPS and NSTAR at the 2.3 kW thruster input power point.

profile at the same location and also running at 2.3 kW of input power. Both the grid erosion rates and the electron backstreaming occur at or near the peak beam current density. A flatter profile reduces these effects on axis and better utilizes the available grid area. As an added benefit, the perveance limit is higher with flatter beam profiles, which improves the capabilities and margin of the thruster.

3. The third grid used in the ion optics assembly on XIPS eliminates another potential failure mechanism of the grids associated with pit-and-grooves erosion of the downstream accel grid surface. A consequence of excessive pits-and-grooves erosion is structural failure of the grid, which can also contribute to screen-to-accel grid-gap changes that enhance EBS. The use of a third grid to eliminate this possibility increases the ultimate life of the engine against these failure mechanisms.

The EBS limited throughputs predicted by the CEX-2D code for the XIPS and NSTAR engines as a function the PPU input power are shown in Figure 14. The XIPS engine has higher predicted throughput capability than the NSTAR engine due to the three reasons described above. The throughput increases at lower power in both these engines because the thruster is operating at lower perveance (much lower than the maximum perveance used at the highest power levels) and the subsequent potential structure in the grid region tend to sweep the charge exchange ions out of the grids and into the beam region. The lower beam current at low power reduces the EBS onset and the lower ion bombardment of the accel grid reduces the erosion, which together increases the throughput capability of each thruster. The actual useful throughput rating for the thruster in any mission application must include a 50% margin on this EBS limited throughput, and so the values in the figure must be divided by a factor of 1.5 for use in mission planning.

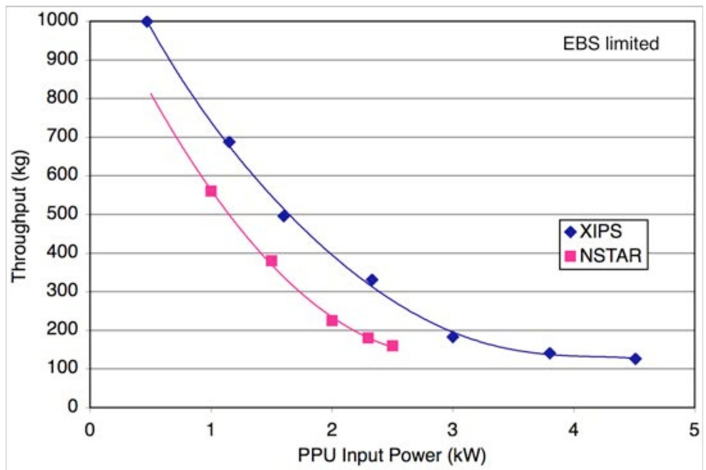

Figure 14. Maximum engine throughput for XIPS and NSTAR, limited by electron backstreaming, as a function of PPU in put power.

As an example of the use of this information in mission planning, Fig. 15 shows the available solar array power and the power available to the thrusters for the DAWN mission trajectory as a function of time in the mission from the start of operations. In the trajectory analysis, only one engine is used at a time with a maximum power to the PPU of 2.5 kW, and a total throughput for the mission of about 385 kg is required. The fraction of the useful engine life from the CEX code results in Fig. 15 that is expended during the mission, assuming two engines are used to provide the entire delta-v and that a 50% margin is used for the engine life against the electron backstreaming limit, is also shown. The graph shows that both NSTAR and XIPS can process the 192 kg per thruster required to perform this mission without exceeding the total engine life specification. The XIPS thruster provides greater margin, and actually has sufficient life to process as much as 240 kg for this trajectory without exceeding the life-margin limit. Other trajectories can also utilize the larger throttle range of the XIPS engine, and example missions have shown

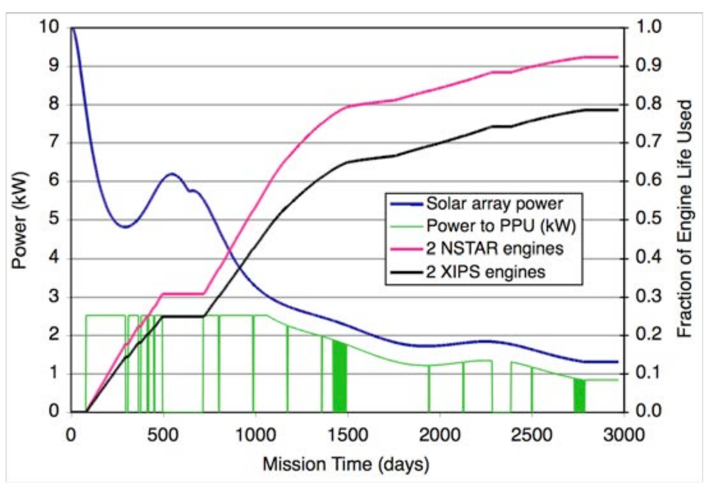

Figure 15. Maximum engine throughput for XIPS and NSTAR, limited by electron backstreaming, as a function of PPU input power.

throughput capabilities of the XIPS engine between 200 to 300 kg depending on the trajectory and power requirements on the engine. For both the XIPS and NSTAR, deep space trajectories that require significant operation time at reduced power levels enable higher throughputs per engine to be used because of the reduced grid wear caused by lower power operation.

IV. Conclusion

The XIPS 25-cm ion thruster is a viable candidate for use in NASA deep space missions. The thruster and PPU have extensive flight heritage on communication satellites and significant performance advantages over the NSTAR thruster presently operating on the NASA DAWN mission. The thruster has completed an extended life test at L-3 Communications ETI and satisfies the throughput requirements with margin for satellite station keeping and orbit insertion. An evaluation of the performance and life of the thruster for deep space missions shows that the thruster is capable of a large throttle range, high power operation, and can process 200 to 300 kg of xenon propellant with margin, depending on the mission trajectory, for deep space mission applications.

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