Keeper Wear Mechanisms in the XIPS© 25-cm Neutralizer Cathode Assembly

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Abstract: The 25-cm Xenon Ion Propulsion System (XIPS©) thruster has been life tested for over 16,000 hours for communication satellite station keeping applications. The neutralizer cathode assembly (NCA) was observed to experience a significant amount of erosion by the end of the life test. While the NCA competed the test successfully and the life exceeds the requirement for the Boeing 702 satellite orbit-raising and station-keeping mission, erosion of the NCA keeper is a concern for longer duration NASA missions. The performance of a 25-cm neutralizer cathode has been investigated in the JPL cathode test facilities to determine the mechanisms responsible for the observed erosion in the thruster life test. Experiments with fast scanning emissive probes showed that the thruster life test started in the 4.5 kW high power mode with the neutralizer cathode operating normally in the quiescent "spot mode" where low erosion rates are observed. After 2880 hours of operation in the high power mode, the thruster operation was changed to the 2 kW low power station-keeping mode and continued in that mode for remaining 13,370 hours of the test. The emissive probe measurements indicate that the neutralizer cathode started out in the low power mode with significant plasma oscillations in the near cathode region. This behavior is indicative of "plume-mode" operation, which produces energetic ions and is well correlated to high keeper and cathode electrode erosion rates. A reduction in the neutralizer cathode orifice diameter was effective in re-establishing the spot-mode operation and eliminating the oscillations responsible for energetic ion production. Additional wear reduction can be achieved using alternative materials with lower sputtering yields. A wear test is now underway of a modified version of this neutralizer cathode that incorporates the smaller orifice diameter and a replacement of the standard molybdenum keeper material by tantalum. The wear test, combined with JPL's validated neutralizer cathode life models, is intended to show that the erosion rate of the present keeper and of the smaller cathode-plate orifice is insignificant thereby demonstrating sufficient neutralizer life for deep space missions.

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I. Introduction

In the 30,532 hour extended life test (ELT)[1] of the NSTAR flight-spare thruster[2] from the DS1 mission, the primary wear out mechanism was identified as accel grid barrel erosion due to charge exchange ion sputtering[3], which ultimately limited the power level that the thruster could be run at near the end of the test due to the on set of electron backstreaming. The next significant wear issue was identified as erosion of the discharge cathode keeper electrode that enclosed the cathode assembly. During the 30,532 hours of operation, the keeper orifice plate was completely eroded away prior to the end of the test. Although this did not cause failure of the cathode or engine, it exposed the end of the cathode tube and heater assembly, which permitted erosion of the cathode orifice plate and heater to occur. This erosion would have eventually led to failure of the cathode assembly had the test been continued.

Keeper electrode erosion rates have been measured or inferred in various experiments[4,5] and in ion thruster life tests[3-7] for years, and have been found to be much higher than anticipated based on the ion energy being limited to values near the discharge voltage. These results have been attributed to higher-energy ions bombarding and sputtering the cathode electrodes, although the origin of the high-energy ions was not known at that time. Measurements of the ion energy from hollow cathode discharges did confirm that ions with energies significantly in excess of the discharge voltage are produced[8-12]. The source and characteristics of these high-energy ions has been a subject of much research and debate. In previously work reported[13,14], very large plasma potential oscillations in the near-cathode plume of hollow cathode discharges were detected by fast scanning emissive probes. The presence of these oscillations was correlated to the production of energetic ions in the neighborhood of the cathode exit, which likely caused the keeper erosion observed in ion thrusters under certain conditions. The source of these plasma potential oscillations is likely turbulent ion acoustic waves generated in the hollow cathode discharge plasma and ionization instabilities in the near-cathode plume region. Very large oscillations produced at low flows and/or high discharge currents for a given orifice size eventually transitioned into the classically observed "plume mode" characterized by high frequency oscillations coupled onto the keeper and discharge power supply voltages[15].

A program to delta-qualify the XIPS® ion thruster[16,17] for NASA deep space missions is presently underway at JPL. Part of this program includes and evaluation of the neutralizer cathode performance and life. Researchers at L–3 Communications Electron Technologies Inc. (ETI) recently completed a 16,250 hour life test of the XIPS thruster that included a flight neutralizer cathode assembly. The neutralizer cathode assembly (NCA) was observed at the end of the life test to have experienced a significant amount of erosion. While the NCA competed the test successfully and the life exceeds the requirement for the Boeing 702 satellite orbit-raising and station-keeping mission, erosion of the NCA electrodes is a concern for longer duration NASA missions.

The performance of a 25-cm neutralizer cathode has been investigated in the JPL cathode test facilities to determine the mechanisms responsible for the observed erosion in the thruster life test. The experiments suggest that the cathode started in Low Power (2 kW) phase of the life test in the transition to "plume-mode"[3], which produces energetic ions and is well correlated to high keeper and cathode orifice wear rates. Modifications to the NCA cathode orifice diameter and the use of alternative electrode materials with lower sputtering yields are projected to provide the life required for the JPL deep space missions. A wear test is now underway of a modified version of this neutralizer cathode to benchmark our cathode life model and demonstrate the desired reduced erosion rates. The performance results showing the wear mechanisms for this cathode and status of the wear test of the modified XIPS NCA will be discussed.

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

II. 25-cm XIPS Ion Thruster

The development[18] and performance[17,19,20] of the 25-cm XIPS thruster has been previously reported. The 25-cm thruster and Power-Processing Unit (PPU) are manufactured by L-3 Communications, Electron Technologies Inc. (ETI) in Torrance

California. Photographs of the 25-cm thruster and PPU are shown in Figure 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[16]. The performance of the 25-cm XIPS thruster is summarized[16,20] in Table 1 for communications satellite applications where the electric propulsion system is used for orbit raising and station keeping. 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%. The life test history for the 13cm and 25 cm XIPS thrusters is summarized in Table 2.

Table 1. 25-cm XIPS thruster performance in communication satellite applications[16].

	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 Efficiency (%)	67	68.8
Mass Utilization Efficiency (%)	80	82.5
Electrical Efficiency (%)	87.1	87.5
Beam Voltage (V)	1215	1215
Beam Current (A)	1.45	3.05

Table 2. Life test durations and cycles[16] 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	2,880	324
25 cm	2.0 kW	13,370	13,810

As indicated in Table 2, the 25-cm thruster was life-tested in the L-3 Communications ETI facilities for 2880 hours in the 4.3 kW high power mode and for 13,370 hours in the 2 kW low power mode. A description of this life test and the comprehensive analysis of the thruster performance and wear will be presented at this conference by Tighe, et.al[21]. A schematic of the neutralizer cathode assembly used in the 25 cm life test is shown[21] in Figure 2. The hollow cathode is a brazed, flight assembly with the cathode tip and keeper end-plate made of molybdenum-rhenium material. The XIPS NCA is similar in design to that used in the NSTAR ion thruster, but uses a larger cathode orifice diameter than that used in NSTAR in order to accommodate the higher currents required in the high power mode than those required by NSTAR. A photograph of a flight XIPS NCA is shown in Figure 3 mounted in the test facility at JPL.

III. NCA Cathode Wear

The 25-cm XIPS neutralizer cathode was observed at the end of the life test to have experienced significant wear of the cathode keeper and cathode orifice plate. Figure 4 shows photographs of the NCA keeper electrode at the end of the test. The keeper orifice plate inside diameter increased by over a factor of two and the plate was thinned by erosion to a knife-edge. In addition, material deposits were observed on the upstream face of the

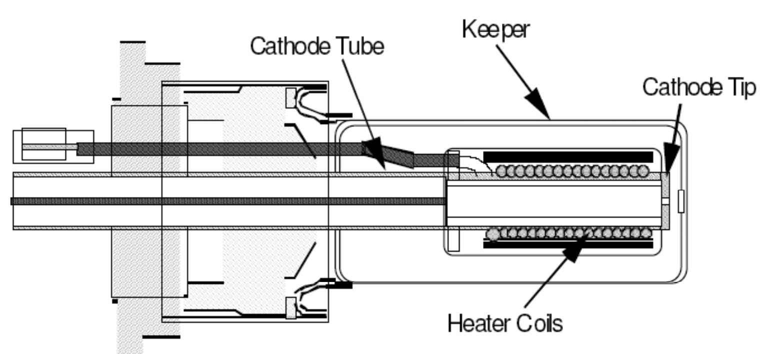

Figure 2. Schematic of the XIPS neutralizer cathode assembly showing the cathode orifice (tip) and surrounding keeper electrode.

keeper electrode, as seen in Fig. 4. This deposit appeared as flaky material that extended inwards from the eroded keeper edge toward the original inner diameter of the keeper orifice[21], but was extremely brittle and was lost during inspection of the thruster and cathode at the end of the test. While flaking of the deposited material into the cathode-to-keeper gap could cause keeper electrode shorts, none were detected in the life test data. However, any shorts like this would be rapidly removed by the keeper power supply, which effectively clears the short by passing the regulated 1-A keeper current through the thin flake material and vaporizing some or all of it.

The deposits on the upstream face of the keeper electrode likely came from the neutralizer keeper orifice plate, which also experienced significant erosion.

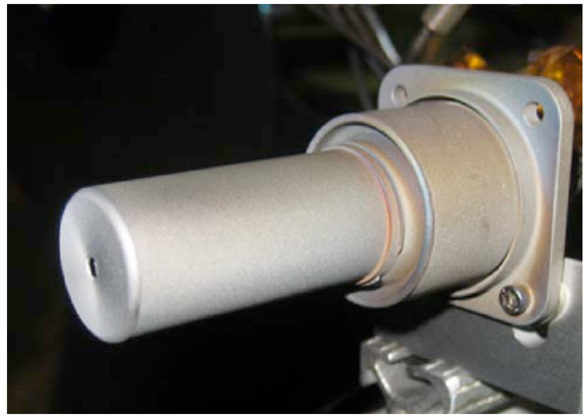

Figure 3. Photograph of a XIPS NCA cathode mounted in the cathode test facility at JPL.

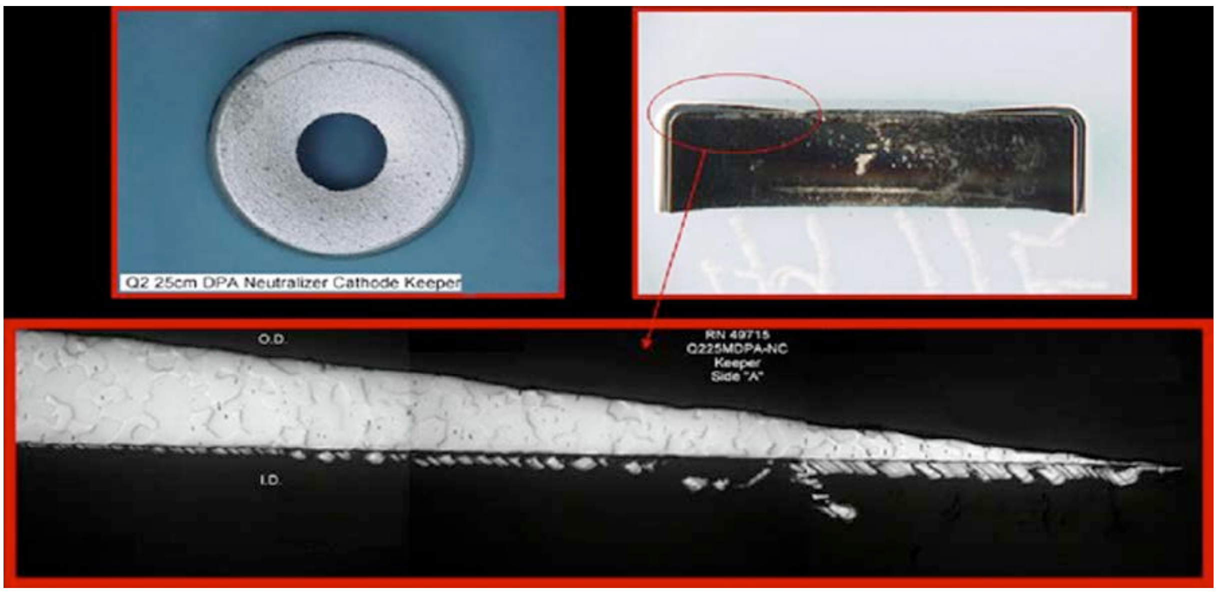

Figure 4. XIPS NCA keeper photographs at the conclusion of the life test showing the enlarged orifice diameter and surface erosion of the keeper electrode.

Figure 5 shows a photograph a cross section of the orifice plate after the test[21]. The orifice originally was a straight cylinder (no chamfer). While the original inside diameter was maintained on the upstream portion of the electrode, a large hemispherical erosion pattern is seen on the downstream face. This material certainly was sputtered by the plasma generated in the cathode orifice and keeper regions, and the fraction of the sputtered material that did not exit through the keeper orifice deposited on the upstream face of the keeper.

This erosion of the XIPS NCA electrodes was not expected due to the lack of any neutralizer erosion observed in the two 13-cm thruster life tests, and due to the essentially pristine appearance of the NSTAR ELT neutralizer cathode at the end of its 30,000-hour life test. In addition, visual inspection of the NCA made when the

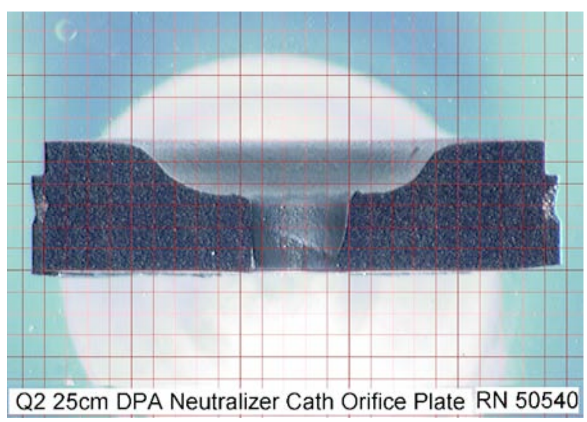

Figure 5. XIPS NCA orifice plate at the conclusion of the life test showing significant erosion of the downstream face.

chamber was opened between the high power and low power test campaigns detected no significant erosion or changes to the NCA keeper and orifice plate. Therefore, a mechanism for the observed erosion needed to be identified.

IV. NCA Cathode Investigation

A 25-cm XIPS NCA was provided to JPL to investigate the source of this cathode erosion and evaluate steps that can be taken to provide the life required for deep space missions. The JPL cathode test facility[22] was reconfigured to test neutralizer cathodes. The ion thruster discharge chamber was removed and the cathode electrically insulated from the grounded chamber walls. The discharge chamber was set at anode potential of a discharge power supply, which simulates the electron collection by an extended interaction region between the cathode plume and the ion beam from the thruster. The keeper supply was referenced to cathode potential, which is biased negatively with respect to the chamber by the discharge supply. High-frequency voltage probes and current probes were used on each lead into the vacuum system (cathode and keeper), and a separate voltage sense line was installed to the keeper electrode in the vacuum system to detect the potential of that electrode close to the cathode. Figure 6 shows a photograph of the test set up with the cathode and probes. The probes are described in detail in the references[13,14]. The cylindrical scanning probe is used for axial density profiles and the scanning emissive probe is used for radial plasma potential measurements. The emissive probe is configured for very high frequency response at high impedance, and can detect plasma potential oscillations well in excess of 1 MHz.

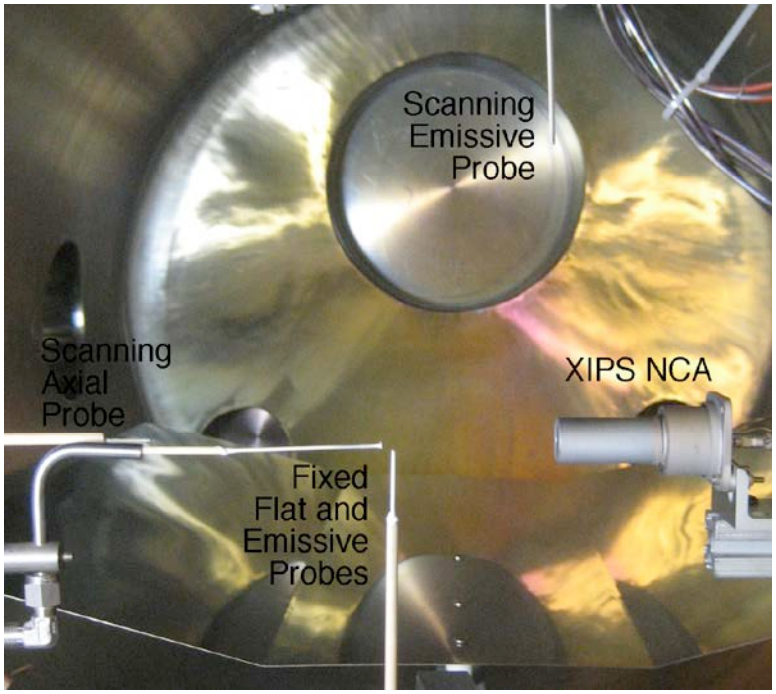

Figure 6. Experimental layout in the test chamber showing the XIPS NCA and the array of probes to measure the time dependent plasma parameters in the cathode plume.

In the high power mode, the neutralizer cathode provides 3 A of electron current to neutralize the ion beam and 1 A of current to the keeper. The plasma potential measured by the radial probe inserted into the edge of the plasma ball just downstream of the keeper, and the AC keeper voltage, are shown in Figure 7. The keeper voltage oscillation level is less than 0.25 Vpp, and the plasma potential is nominally about 20 V with small (<10V) occasional spikes of short time duration. This behavior is consistent with the quiescent "spot mode" operation in which the oscillations in the keeper voltages and the plasma potential are small[14], and subsequently

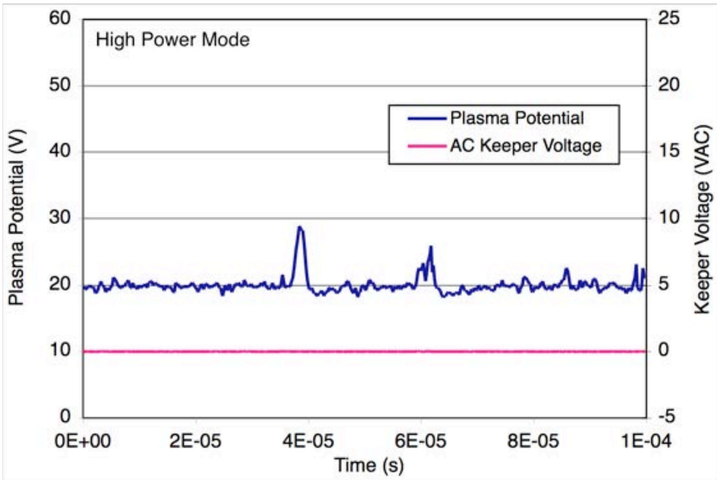

Figure 7. Plasma potential in the cathode plume and AC keeper voltage in the high power mode of the NCA discharge.

the erosion rate is also low because the ions have a low energy.

In the low power mode, the neutralizer cathode provides 1.5 A of electron current to neutralize the ion beam and 1 A of current to the keeper. The plasma potential for this mode measured by the radial probe inserted into the edge of the plasma ball just downstream of the keeper, and the AC keeper voltage, are shown in Figure 8. The time scale in this figure is slightly longer than in Fig. 7 in order to show the characteristics of the oscillations. The keeper voltage oscillation level is nominally about 1 Vpp with occasional larger oscillations of up to 3 Vpp. This is still considered to be in the "spot mode regime" where the AC keeper voltage is nominally below about 5 V peak to peak. However, the plasma potential in the plasma plume close to the axis is found to be significantly higher and characterized by very large oscillations approaching 60 V. The frequency of the large potential spikes in less than 50 kHz, which is indicative of ionization instabilities that can occur in cathode plumes[14]. This behavior is certainly characteristic of the "plume-mode" of a hollow cathode in which the high plasma potentials generated by the oscillations result in energetic ions that cause the observed cathode electrode erosion[14]. It appears that the XIPS neutralizer cathode is in the spot mode in the high power mode, but operates out in the plume mode in the low power mode where the discharge current and flow rates are lower.

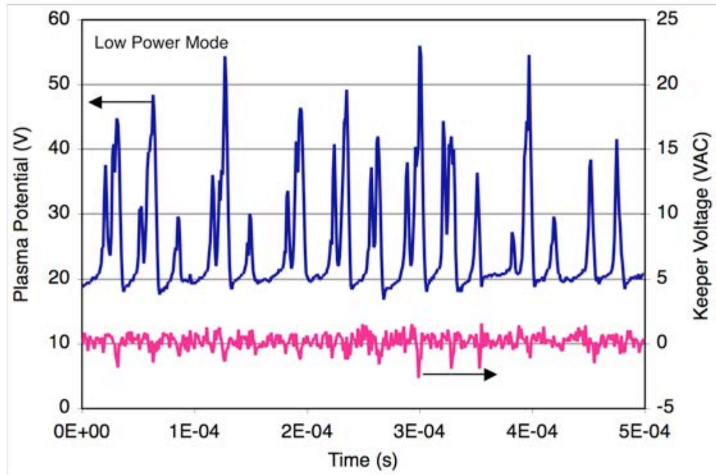

Figure 8. Plasma potential in the cathode plume and AC keeper voltage in the low power mode of the NCA discharge showing large oscillation levels.

While plume mode operation has historically been determined by keeper voltage oscillation measurements, the transition to plume mode cannot be determined accurately solely by a keeper voltage measurement because such a measurement is strongly dependent on the keeper power supply characteristics and the capacitance and inductance in the connections to the cathode. However, direct plasma potential measurement by fast emissive probes, such as those shown in Figure 8, clearly show that the transition to plume mode has already occurred at the low power point, and that higher than expected erosion rates will likely result for this cathode geometry in this operation mode. Despite this operating condition in the Low Power mode, the XIPS 25-cm NCA successfully met all life requirements for the Boeing station keeping missions (2 times the mission life plus margin) and did not experience any performance issues. However, it is a concern for deep space missions where longer life is required.

This distinct difference in the operating mode between the high power and low power points is well illustrated by examining the radial dependence of the plasma potential from the cathode plume axis. Figure 9 shows the plasma potential measured versus distance from the axis of the discharge and 3 mm downstream of the keeper exit for the high and low power modes from the scanning emissive probe. The high power mode has a well behaved potential profile without significant oscillations. In contrast, the low power mode features outbursts of high frequency oscillations, especially in the near-cathode plume region close to the keeper exit.

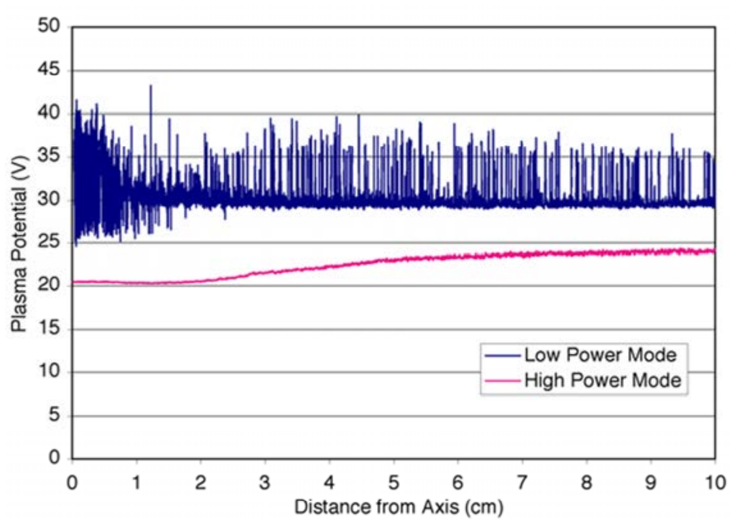

Figure 9. Radial plasma potential profile for the high power and lower power operating points showing the plume mode onset in the XIPS NCA in the low power mode.

V. Oscillation Mitigation

Plume mode operation for a given cathode design at a given discharge current is normally mitigated by increasing the gas flow through the cathode[15]. This was tried with the XIPS neutralizer cathode while running in the low power mode. Figure 10 shows the radial plasma potential from the fast emissive probe for three neutralizer gas flow rates. As expected, increasing the neutralizer gas flow decreased the magnitude of the oscillations, and operation with about 2/3rd higher flow pushed the cathode back into spot mode. However, the penalty of increasing the neutralizer gas flow rate by 1 sccm was a reduction in the mass utilization and overall thruster efficiency by almost 3%. This is a significant decrease in performance, and alternative methods are desirable.

In the NSTAR experience with the neutralizer cathode on ELT[1], the cathode orifice was enlarged with time due to ion erosion from the very high-density orifice plasma[23], which is characteristic of very small orifice cathodes. During the DS-1 mission, this resulted in a transition to plume mode during the flight. This problem was solved by increasing the keeper current at a fixed neutralizer gas flow rate. However, this technique did not eliminate the plume mode operation in the XIPS NCA in the low power mode. Figure 11 shows the radial plasma potential profiles from the scanning emissive probe at the nominal gas flow rate in the low power mode for three keeper currents. Increasing the keeper current for a fixed flow and discharge current actually increases the oscillation magnitude. This type of behavior is normally seen in discharge cathodes where increasing the keeper current enhances the oscillation problem.

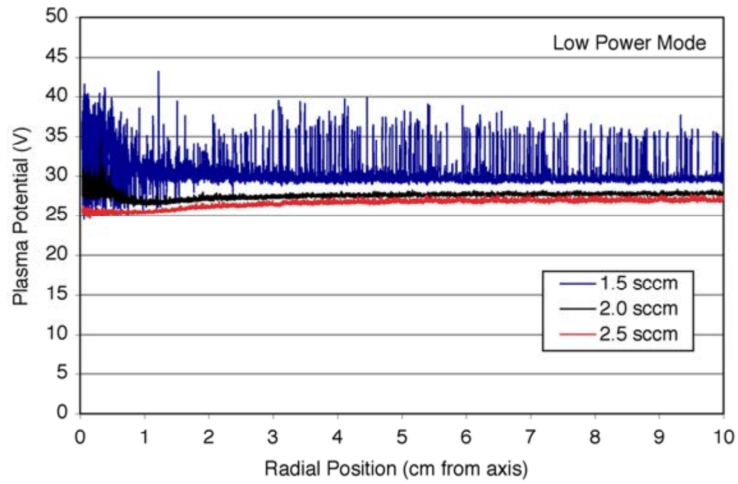

Figure 10. Variation in radial plasma potential for three neutralizer cathode flow rates in the low power mode.

The reason that higher keeper currents do not eliminate plume mode in the XIPS NCA is that this cathode has an orifice diameter that is significantly larger than the NSTAR neutralizer and actually approaches the orifice size found in the NSTAR discharge cathode. This means that the cathode physics is different between the two cathodes because of the different orifice sizes[15]. Neutralizer cathodes with extremely small orifices like NSTAR, which were called Type A cathodes in reference 15, operate at very high pressures and high plasma densities inside the insert and orifice regions. The plasma generation and heating in this case are dominated by resistive effects in the orifice region due to the high collisionality. Increasing the keeper current draws more electron current from high density plasma inside the cathode orifice, which tends to increase the resistive heating of the orifice plasma, increases the local plasma density, and also increases the heating of the orifice plate and thereby the cathode insert. This increase in the plasma density entering the keeper orifice region modifies the characteristics of the plasma in contact with the keeper and the current collection location, and these changes in the plasma properties can impact and reduce the transition to plume mode.

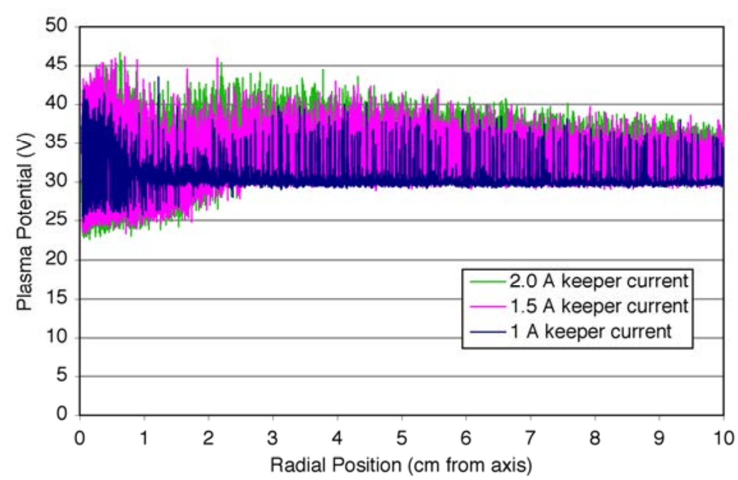

Figure 11. Variation in radial plasma potential for three different keeper currents in the low power mode at the standard cathode flow rate.

In contrast, larger diameter orifices (called Type B in reference 15) produce much lower neutral densities and plasma densities in the insert, orifice and keeper regions. While collisional effects still dominate the insert region and in the upstream entrance of the cathode orifice, the neutral and plasma flows tend to transition to a collisionless regime somewhere inside the cathode orifice length. Increasing the keeper current then increases the demand on the plasma current flowing from the collisional transition upstream in the cathode orifice region through the orifice to the collisionless transition into the keeper region. This then requires a higher ionization rate in the collisionless regime to provide sufficient plasma in contact with the keeper electrode to deliver the required current, which can enhance the oscillation level and plume mode transition.

A way to reduce plume mode operation in neutralizer cathodes at very low discharge currents is to reduce the cathode orifice diameter. A copy of the XIPS NCA was manufactured with the cathode orifice machined to 75% of the diameter of the flight version. Figure 12 shows the radial plasma potential profile measured in the standard high power mode conditions of current and flow for the two cathode orifice diameters. Decreasing the orifice diameter increases the potential slightly, consistent with an increase in the resistive drop in the orifice region associated with the higher neutral density. The plasma potential for the smaller orifice case also has slightly higher oscillation levels with frequencies above about 200 kHz, but these oscillations are small and don't lead to any large spikes associated with plume mode operation. In contrast, Figure 13 shows the plasma potentials for the two cathodes operating in the low power mode at the standard conditions of 1.5 A, 1.5 sccm and 1 A keeper current. The oscillations in the plasma potential are completely eliminated with the smaller orifice diameter, and the overall plasma potential decreased in magnitude. The new cathode is clearly operating in the quiescent spot mode, and the lack of large plasma potential oscillations eliminates energetic ion generation and high erosion rates.

Changes in the cathode orifice diameter also affect the plume plasma density. Figure 14 shows the axial plasma density profiles for the two cathodes operating in the high power mode. In this case, the cylindrical Langmuir probe was corrected for the thick-sheath regime[24,25] encountered at distances

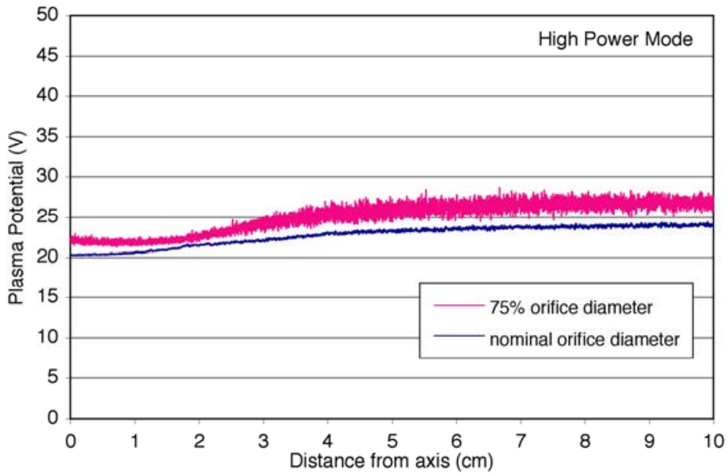

Figure 12. Radial plasma potential profiles for the two cathode orifice sizes in the high power mode.

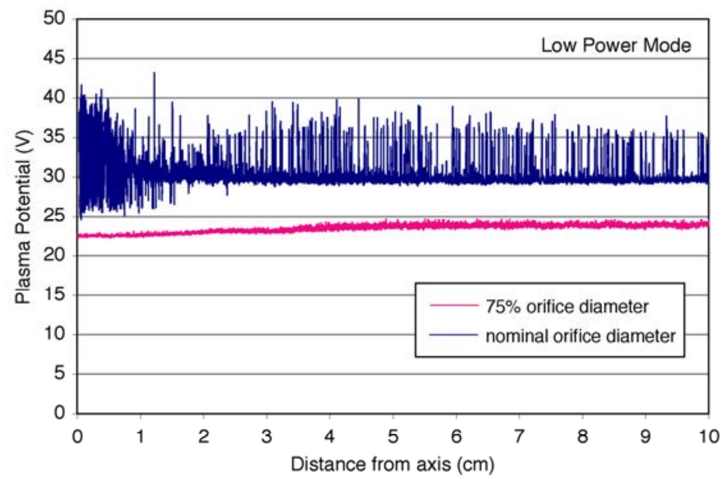

Figure 13. Radial plasma potential profiles for the two cathode orifice sizes in the low power mode.

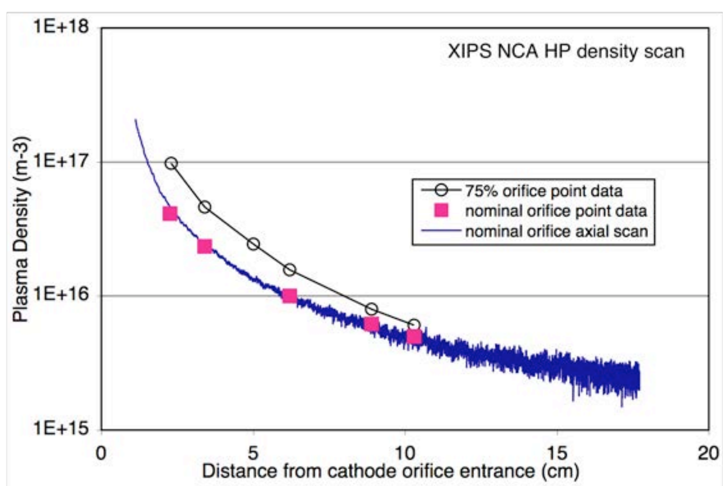

Figure 14. Axial plasma density profiles for the two cathode orifice sizes in the high power mode.

greater than about 5 cm from the cathode keeper exit. The smaller cathode orifice is observed to increase the plasma density in the plume close to the cathode. The densities are then nearly the same at distances greater than about 10 cm from the cathode. The slightly more collimated cathode plume plasma with the higher plasma density tends to disperse with distance from the cathode such that the far-field plasma density is essentially the same for the two cathodes.

The strong keeper and cathode orifice wear observed in the XIPS 25-cm thruster life test is attributed here to the cathode operating in the plume mode at the low power operating point. The plasma-potential oscillations couple into the keeper power supply and produce some level of keeper voltage oscillations that are normally monitored to detect this problem. The fact that the keeper voltage oscillation level for this cathode was below the accepted threshold for plume mode (<5 Vpp) is likely a misunderstanding of the effects of moderate plasma potential oscillation levels on the cathode electrode erosion during extended operation periods and very long life tests. The plume mode threshold of 5 Vpp was determined many years ago, and the impact of operating with keeper-voltage oscillation levels of a few volts peak to peak for durations in excess of 10,000 hours were likely not understood at the time. It is clear that another method must be used, such as plasma potential oscillation monitoring described here, to define plume mode onset and the possibility of unacceptable erosion rates.

Another well known method of mitigating the effect energetic ion bombardment and excessive sputtering is to change the material of the keeper electrode to another with a lower sputtering yield. Recent work at UCSD[26] has shown that tantalum has a lower sputtering yield at low energy in xenon than molybdenum normally used in the XIPS NCA. The smaller orifice neutralizer cathode described above was configured with a tantalum keeper electrode, as shown in Figure 15, and put into a long duration wear test in a dedicated facility at JPL configured similarly to the cathode test facility described above. The plasma potential oscillations just downstream of the keeper exit were measured with a stationary emissive probe inserted into the edge of the cathode plume, and no oscillations were detected. The potential was the same as that shown in Figs. 12 and 13 for the 75% orifice condition, indicating that stable operation in the desired mode had been achieved.

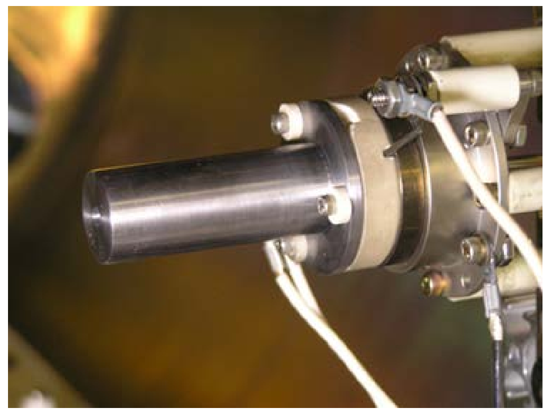

Figure 15. Neutralizer cathode with a tantalum keeper used in a extended wear test.

The extended neutralizer cathode wear test has now been operated for a total of about 3000 hours. The behavior of the discharge current and voltage in the first 2700 hours is shown in Figure 16. The cathode was run in the high power mode for the first 1100 hours, and then operated in the low power mode. In the transition between high and low power, a problem in the feed system reduced the injected gas flow by about 10% below the nominal level, which caused some discharge oscillations and higher discharge voltages than normal for several hundred hours. This problem was detected and corrected, and the cathode removed and inspected at 1570 hours to ensure that no damage had occurred. At 1570 hours, no discernable keeper or cathode orifice plate erosion could be detected, and after installation and standard cathode conditioning was completed the cathode re-started normally. The neutralizer cathode has now been run at the nominal low power conditions for nearly 2000 hours, and will be periodically inspected to measure the erosion rates on the keeper and cathode orifice electrodes. It is anticipated that the combination of the smaller cathode orifice that eliminated the plume mode ionization instabilities and the tantalum keeper electrode will provide a lower erosion rate and sufficient life for deep space missions that can require over 30,000 hours of operation. The longer life is also achieved without impacting the mass utilization efficiency or thruster efficiency, which is very desirable for deep space missions.

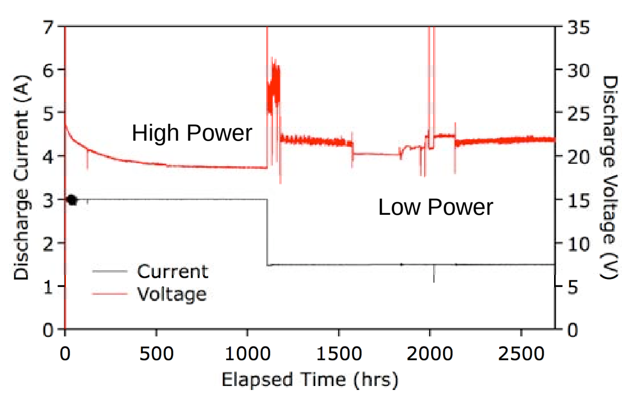

Figure 16. Discharge current and voltage for the tantalum-keeper neutralizer cathode wear test to date.

VI. Conclusion

The 25-cm XIPS ion thruster is a viable candidate for NASA deep space mission and the required life of the thruster can be demonstrated by a combination of testing and modeling. The thruster successfully completed a 16,000 hour wear test at L-3 Communications and easily provides the life required with margin for station keeping and orbit raising applications on communications satellites. Separate efforts have been underway to delta-qualify the thruster for deep space applications[27] that includes evaluations of the life of the discharge cathode[28,29] and the ion acceleration grids[30-31]. In this paper, we described the neutralizer cathode wear observed in the 25-cm thruster life test and determined that it was caused by operating the cathode in the plume mode during the low-power phase of the life test, which produced large plasma potential fluctuations and energetic ions that produced the keeper and orifice plate erosion. Modification of the cathode with a smaller cathode orifice plate diameter eliminated the plume mode behavior, and replacement of the molybdenum keeper with a lower sputtering yield tantalum keeper is projected to greatly reduce the wear rate and increase the cathode life. An on-going wear test of this modified neutralizer cathode is underway to demonstrate this longer life capability for deep space applications.

Acknowledgments

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