

Sensitivity Testing of the NSTAR Ion Thruster

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Abstract: During the Extended Life Test (ELT) of the DS1 flight spare ion thruster, the engine was subjected to sensitivity testing in order to characterize the dependence of discharge plasma production on operating conditions and component wear. The discharge chamber sensitivity to small variations in main flow, cathode flow, beam current, and grid voltages, was determined for 0.5 to 2.3 kW operation. The degree of variation was consistent with the control band provided by the DS1 PPU and feed system (3-5%). For each power level investigated, 16 high/low operating conditions were chosen to vary the flows, beam current, and grid voltages in a matrix that mapped out the entire parameter space. The matrix of data generated was used to determine the partial derivative or sensitivity of the dependent discharge parameters to the variations in the independent parameters (throttle set points). The sensitivities of each dependent parameter with respect to each independent parameter were determined using a least-squares fit routine. Several key findings have been ascertained from the sensitivity testing. Discharge operation is most sensitive to changes in cathode flow and to a lesser degree main flow. The data also confirms that the NSTAR thruster plasma production is limited by primary electron input for a fixed neutral population. Key sensitivities along with their change with thruster wear (operating time) will be presented. In addition double ion content measurements with an ExB probe will be presented to illustrate beam ion content sensitivity to discharge chamber operating parameters.

Nomenclature

<i>NSTAR</i>	=	NASA Solar Electric Propulsion Application Readiness
<i>ELT</i>	=	Extended Life Test
<i>BOL</i>	=	Beginning of Life
<i>TH</i>	=	Throttle Level
<i>PPU</i>	=	Power Processing Unit
J_B	=	Beam Current
J_D	=	Discharge Current
V_D	=	Discharge Voltage
ϵ_d	=	Discharge Loss
\dot{m}	=	Flow Rate

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I. Introduction

The Extended Life Test (ELT) of the Deep Space 1 (DS1) flight spare ion thruster (FT2) is the longest operation of an ion thruster on record, processing over 235 kg of xenon propellant and accumulating 30,352 hours of operation during its five year run¹. 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. The objectives of the test were to characterize known failure modes, identify unknown failure modes, and measure performance degradation with thruster wear. Thruster performance data and operational characteristics over the full DS1 throttle range were collected and analyzed extensively during the course of the test. Experimental characterization of the discharge chamber performance as a function of operating condition was also periodically assessed via a series of sensitivity tests roughly every few thousand hours of operation. Sensitivity tests were used to determine the functional dependence of plasma production, ionization efficiency, and hollow cathode efficiency on the extracted ion fraction, primary electron input, and neutral density input to the discharge chamber and hollow cathode (main and cathode flow rates). A matrix of sensitivity operating points was generated to map out the sensitivity of discharge variations in the throttle set points. The level of parameter variation was based on the control band provided by the DS1 PPU and feed system. There was a need to understand how such variation would affect engine performance and to measure the extent to which nominal fluctuations in the control system might place the engine in an overstressed condition. The computed sensitivities or partial derivative of the dependant discharge parameters to throttle table set points will be presented along with a discussion of their implications on discharge chamber plasma production and thruster wear.

II. Experimental Setup

A. Test Article and Facility

The flight spare engine (FT2) used in the ELT was fabricated by Boeing, formerly Hughes Electron Dynamics (HED). The thruster employs a conical-cylindrical discharge chamber with a three-ring cusp magnetic field design. A two-grid molybdenum optics system focuses and electro-statically accelerates the ionized xenon propellant, to produce thrust. A tungsten impregnated 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. Details on the 30-cm thruster can be found in reference 2.

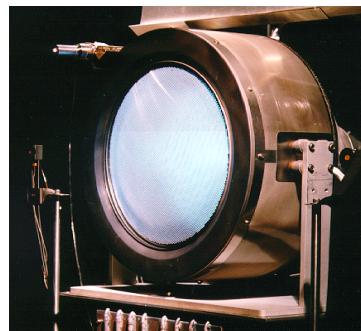


Figure 1. FT2 thruster in JPL Test Facility.

The ELT was conducted in the Jet Propulsion Laboratory Endurance Test Facility; a 3-m by 10-m-long vacuum chamber with a total xenon system pumping speed of 100 kL/s. The vacuum system provided a base pressure of less than 5.3×10^{-4} Pa at the full power flow rates. The pumping surfaces were regenerated periodically, but the engine was kept under vacuum for the duration of the test. The chamber was lined with graphite panels to minimize the amount of material back sputtered onto the engine and test diagnostics. The propellant feed system consisted of two mass flow meters in series for each of the cathode, neutralizer, and main lines, each independently controlled. Laboratory power supplies, with similar capabilities to the DS1 flight PPU, were used to run the thruster. A computer data acquisition system was used to monitor the engine and test facility. Details of the test facility and electrical system can be found in reference 3 and 4. Several diagnostics were used to measure the ion beam characteristics as well as general engine performance parameters. Specific details on the operation and design of the diagnostics can be found in references 3 and 4.

B. Experimental Procedure

As mentioned previously, sensitivity tests were used to determine the functional dependence of plasma production, ionization efficiency, and hollow cathode efficiency on the extracted ion fraction (J_B), primary electron input (J_D), grid potential, and neutral density input to the discharge chamber and hollow cathode (main and cathode flow rates). Specifically, a matrix of sensitivity operating points was generated to map out the sensitivity of discharge voltage, discharge current, double ion production, and discharge loss to variations in main and cathode flow rate, beam current, applied electric field, and power level. The discharge chamber sensitivity to $\pm 3\%$ variation

in main flow, cathode flow, and beam current, and to $\pm 5\%$ variation in beam and accelerator voltage, was determined for the minimum (TH0, 0.5kW), half (TH8, 1.1 kW), and full-power (TH15, 2.3kW) points. For each power level investigated, 16 high/low operating conditions were chosen to vary the flows, beam current, and grid voltages in a matrix that mapped out the entire parameter space in accordance with the Taguchi theory of experiments (Table-1)⁵. A 16x5 matrix of data was used instead of a full factorial matrix to reduce runtime and operational costs at these off nominal, sometimes stressful conditions.

The engine was required to reach steady state, which was approximately an hour of operation, at each of these off nominal conditions, before the discharge electrical parameters were recorded. It should also be noted that the thruster operated in beam control mode, meaning that the discharge current is varied by the DAQ system to maintain a beam current set point. This is required to maintain a given thrust and specific impulse.

The 16×5 matrix of data generated was used to determine the sensitivity of the dependent parameters—discharge voltage, discharge current, and discharge loss,—to the variations in the independent parameters—main flow, cathode flow, beam current, and beam voltage. The sensitivities or partial derivatives of each dependent parameter with respect to each independent parameter were determined using a least-squares fit routine based on a singular value decomposition method.

III. Experimental Results

DISCHARGE PARAMETER	SENSITIVITY TO MAIN FLOW	SENSITIVITY TO CATHODE FLOW	SENSITIVITY TO BEAM CURRENT
J_d	$-0.19 \frac{A}{sccm}$	$1.48 \frac{A}{sccm}$	$10.94 \frac{A}{A}$
V_d	$-0.54 \frac{V}{sccm}$	$-2.08 \frac{V}{sccm}$	$8.31 \frac{V}{A}$
ϵ_b	$-7.01 \frac{W/A}{sccm}$	$3.71 \frac{W/A}{sccm}$	$107.0 \frac{W/A}{A}$

Table 2. BOL TH15 Engine Sensitivities to Flow and Beam Current at Full Power⁶.

Sensitivity results or the partial derivatives of dependent parameters to the throttle set points, are presented as a function of power level in the following sections. A sample of the beginning of life sensitivities at the full power point are shown in table 2 for preliminary discussion. At TH15, the BOL sensitivities indicate cathode flow has a significant effect on primary electron production as indicated by the increase in discharge current and discharge loss per sccm of cathode flow. Increasing main flow reduces primary electron production and discharge loss. Sensitivities to beam current indicate the NSTAR engine is operating in a neutral limited state, and attempting to

Experiment	m_{main} (sccm)	m_{cath} (sccm)	m_{neut} (sccm)	V_B (V)	J_B (A)
1	+3%	-3%	-3%	+5%	-5%
2	-3%	-3%	-3%	-5%	-5%
3	+3%	-3%	+3%	+5%	-5%
4	-3%	+3%	+3%	+5%	+5%
5	+3%	+3%	+3%	-5%	+5%
6	-3%	+3%	-3%	-5%	+5%
7	+3%	-3%	-3%	-5%	+5%
8	-3%	-3%	-3%	+5%	+5%
9	+3%	+3%	-3%	+5%	+5%
10	-3%	+3%	+3%	-5%	-5%
11	+3%	-3%	+3%	+5%	+5%
12	-3%	-3%	+3%	+5%	-5%
13	+3%	-3%	+3%	-5%	-5%
14	-3%	-3%	+3%	-5%	+5%
15	+3%	+3%	-3%	-5%	-5%
16	-3%	+3%	-3%	+5%	-5%

Table 1. Sensitivity testing matrix.⁶

generate more ionization without increasing flow rate is costly in terms of discharge chamber wear (higher discharge voltage) and electrical efficiency (discharge loss).

A. Full Power Sensitivity

Figures 1 through 3 are plots of the discharge-loss, voltage, and current sensitivities at full power (TH15) versus runtime. The plots indicate that increasing main flow from the nominal set-point reduces discharge loss. As the main flow is increased, the discharge voltage and current decrease. Therefore, increasing main flow lowers the required cathode discharge power ($J_D V_D$) for a given level of ionization, thus reducing the discharge loss for a given beam current set-point. Increasing cathode flow, however, increases discharge loss. Although increasing cathode flow also reduces discharge voltage, the cathode operates less efficiently at cathode flow rates above the nominal set-point. As seen in figure 3, increasing cathode flow increases discharge current, to such an extent that the discharge power increases with increasing cathode flow. Therefore, for a fixed beam current, discharge loss increases for a high cathode flow rate set-point. Increasing the beam current also increases discharge loss. In order to create more ions, the discharge current and voltage must be increased.

Comparison of the sensitivity of discharge loss to runtime indicates that wear of the thruster components does affect discharge performance. The sensitivity of discharge power to cathode flow increases with thruster wear. This is likely due to the enlargement of the keeper orifice, as well as increasing neutral loss from accelerator grid aperture enlargement as was observed at this time⁴. The net result, however, is that the discharge loss sensitivity to changes in flow and beam current increased with runtime.

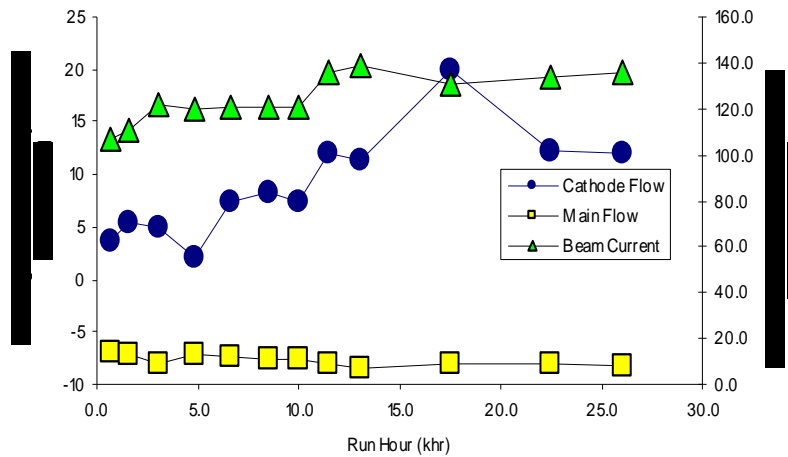


Figure 1. Discharge-Loss Sensitivity at Full Power (TH15)⁶.

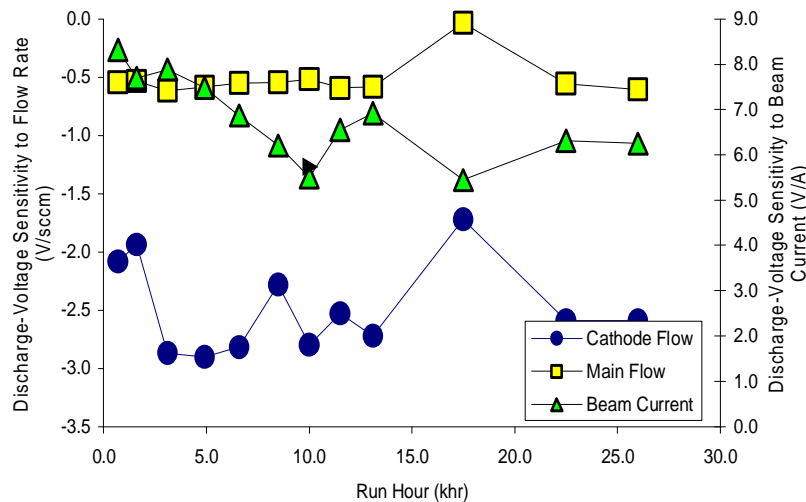


Figure 2. Discharge-Voltage Sensitivity at Full Power (TH15)⁶.

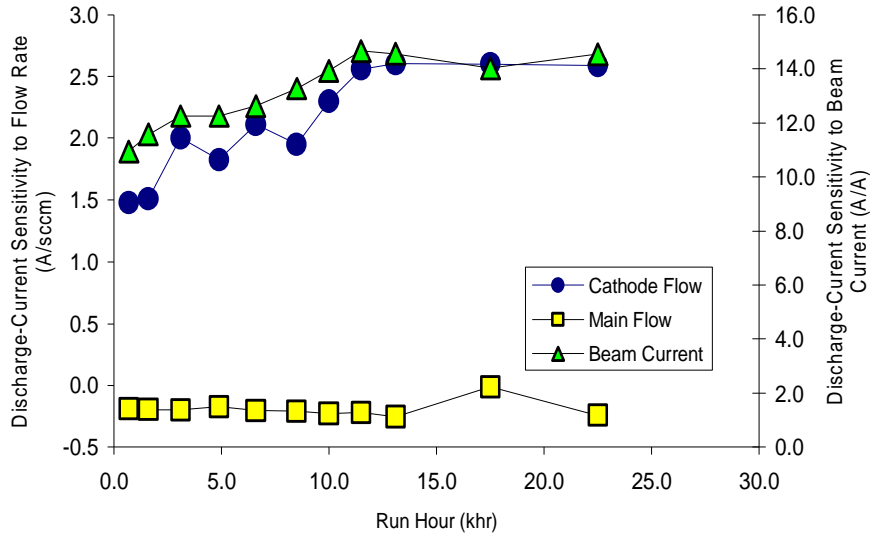


Figure 3. Discharge-Current Sensitivity at Full Power (TH15)⁶.

B. Half Power Sensitivity

Figures 4 through 6 are plots of the discharge-loss, -voltage, and -current sensitivities at half power (TH8) versus runtime. As with TH15 operation, increasing main flow reduces the discharge power for a given beam current, and therefore reduces the discharge loss. However, unlike TH15 operation, increasing cathode flow reduces discharge loss. At TH8, the sensitivity and reduction in discharge voltage due to increasing cathode flow, outweighs the effect of increasing discharge current due to increasing cathode flow. Therefore, the product of current and voltage, the discharge power, decreases for increased cathode flow, as does the discharge loss. Similar to TH15, increasing beam current increased discharge loss, as more electrons (discharge current) are required to create the level of ionization necessary to support the increased beam current requirements.

Comparison of TH8 sensitivity with runtime indicates that all sensitivities to main flow did not change with runtime. Sensitivity of discharge loss to cathode flow and beam current also did not change from BOL to EOL. The sensitivity of discharge current and voltage to cathode flow increased with runtime, but with opposite signs. The sensitivity of discharge current to beam current decreased with runtime and discharge voltage to beam current remained unchanged. The cause of the dip in discharge voltage sensitivities at 25khr is not understood.

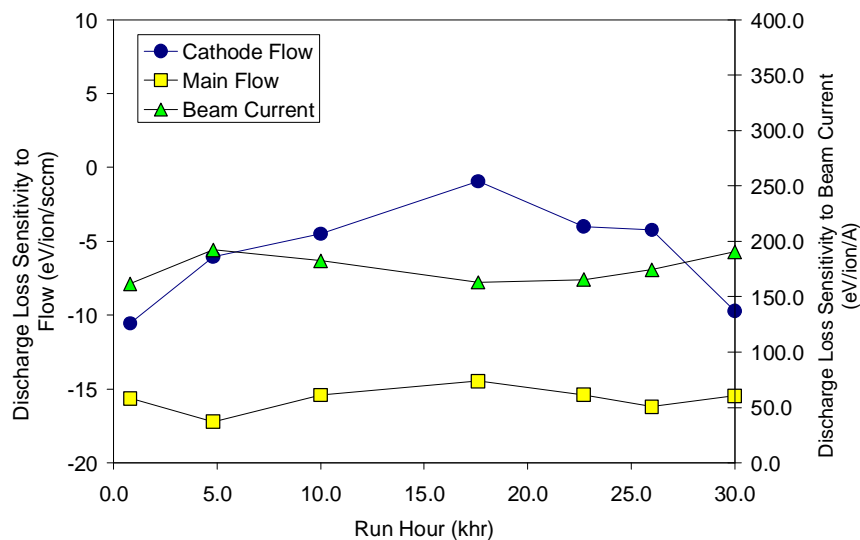


Figure 4. Discharge-Loss Sensitivity at Half Power (TH8)⁶.

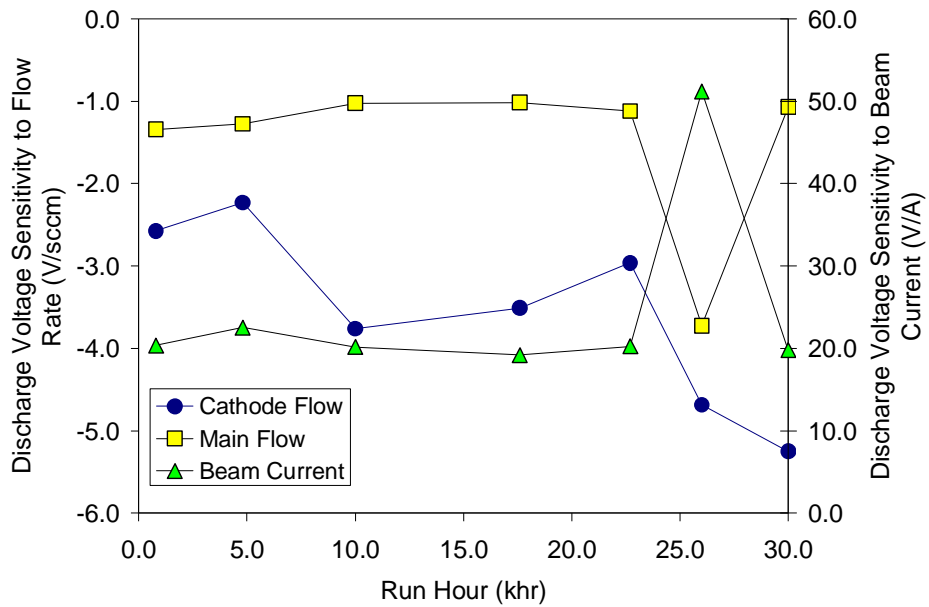


Figure 5. Discharge-Voltage Sensitivity at Half Power (TH8)⁶.

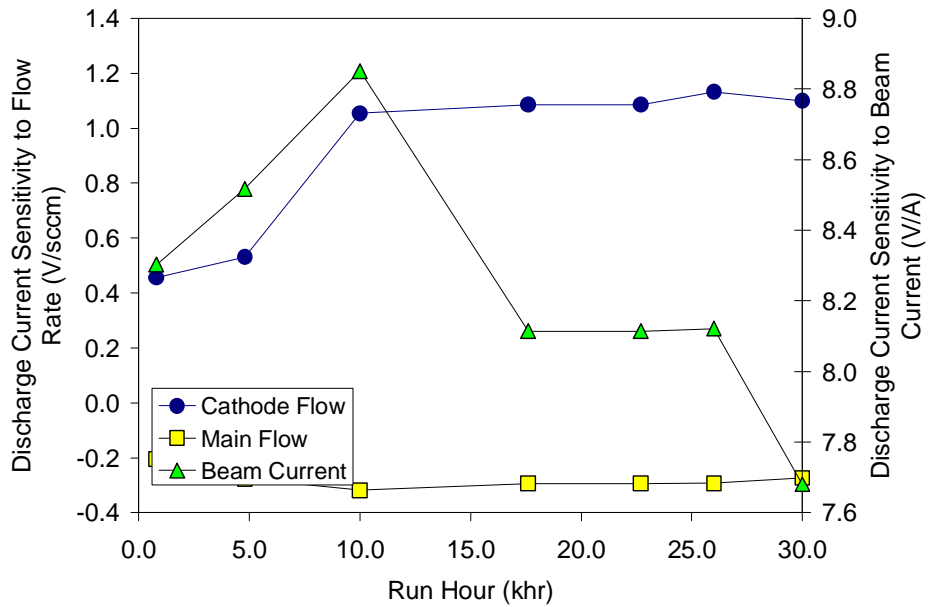


Figure 6. Discharge-Current Sensitivity at Half Power (TH8)⁶.

C. Minimum Power Sensitivity

Figures 7 through 9 are plots of the discharge-loss, -voltage, and -current sensitivities at minimum power (TH0) versus runtime. As with TH15 and TH8 operation, discharge loss was reduced with increasing main flow, and increased with increasing beam current. Similar to TH8 operation, increasing cathode flow also reduced discharge loss. However, TH0 discharge current operation was not particularly sensitive to changes in cathode flow; therefore the reduction in discharge voltage decreased the required discharge power. In terms of sensitivity to thruster wear, the sensitivity of discharge loss to flow rate and beam current increased slightly over time. Sensitivity of discharge current to beam current and flow changed most notably over the first five thousand hours of operation and remained relatively stable through to EOL. The sensitivity of discharge current to cathode flow reversed during this time period. The sensitivity of discharge voltage to flow and beam current remained relatively stable from BOL to 25khrs. Sensitivity of discharge voltage to cathode flow and beam current increased during the last 5khrs of the test.

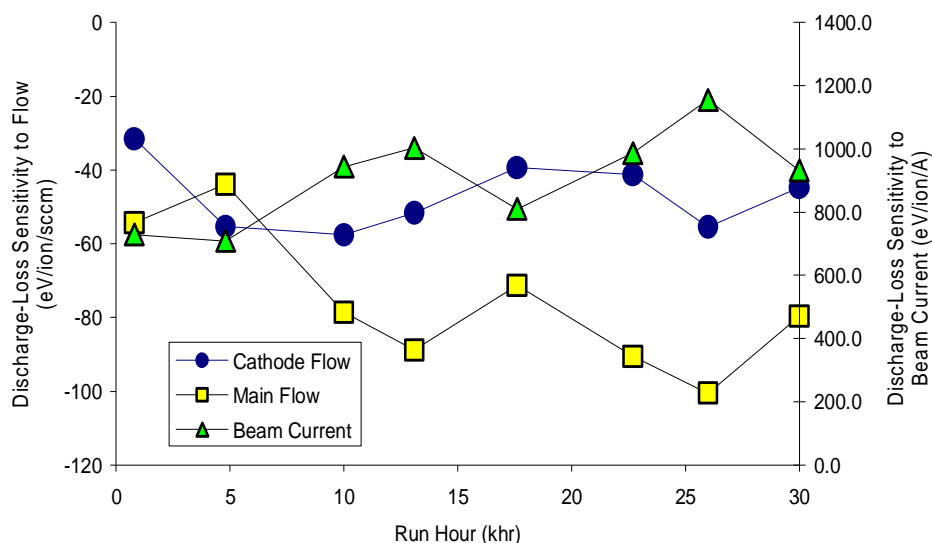


Figure 7. Discharge-Loss Sensitivity at Minimum Power (TH0)⁶.

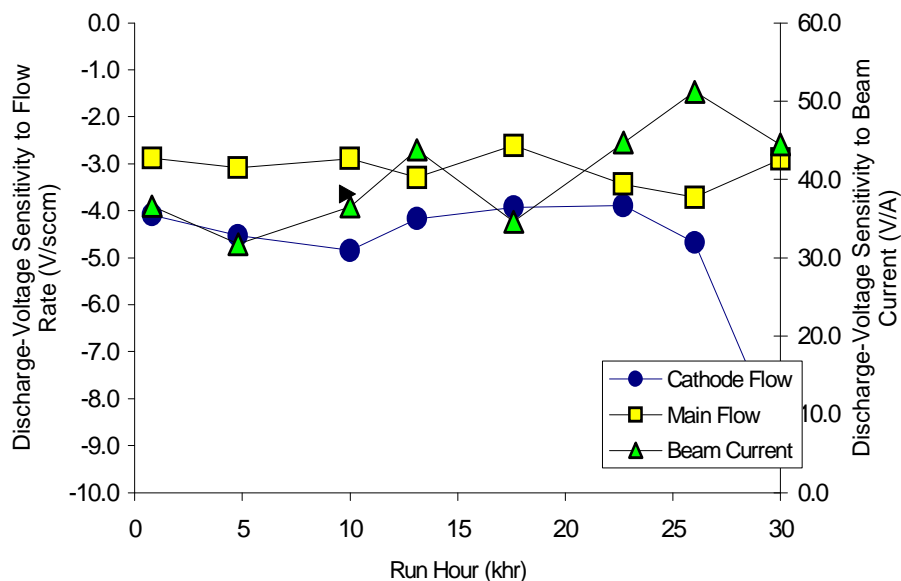


Figure 8. Discharge-Voltage Sensitivity at Minimum Power (TH0)⁶.

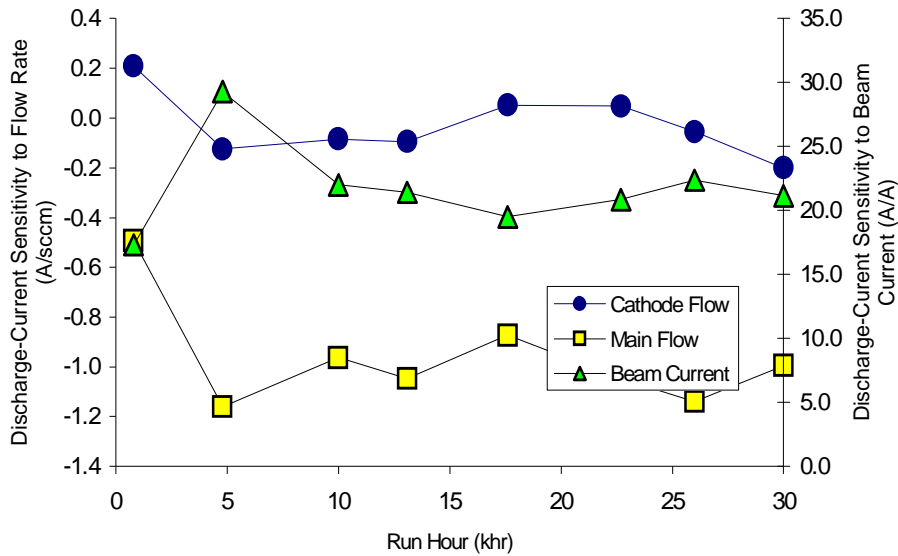


Figure 9. Discharge-Current Sensitivity at Minimum Power (TH0)⁶.

D. Electric Field Sensitivity for all Power Levels

The $\pm 5\%$ variation in accelerating voltage did not have a measurable effect on any discharge parameters for the three power levels investigated. Variation in beam voltage had a measurable effect only on discharge loss. Figure 10 shows the sensitivity of discharge loss to beam voltage versus runtime for the three power levels investigated. Increasing the beam voltage by 100 V tended to reduce discharge loss by 3–8 eV/ion, suggesting that a more focused beam improved the screen transparency.

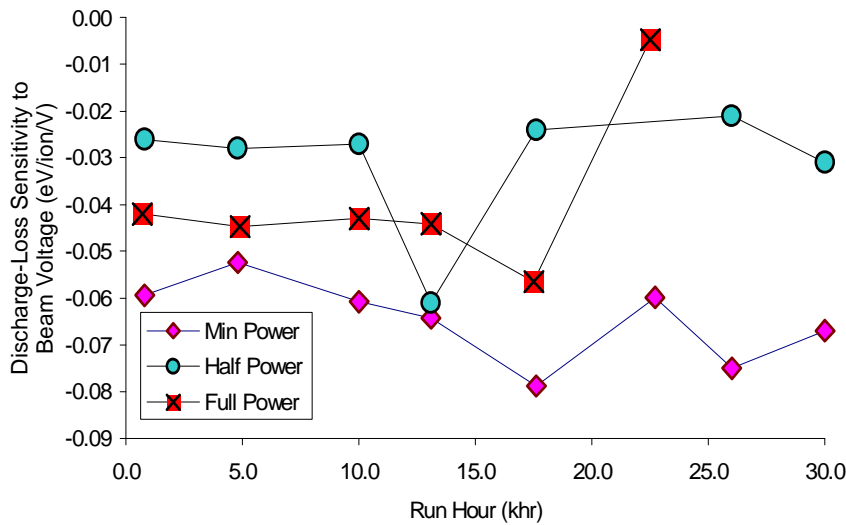


Figure 10. Discharge-Loss Sensitivity to Beam Voltage at All Power Levels⁶.

E. Double Ion Fraction Sensitivity for all Power Levels

The double-to-single-ion current ratio is a parameter directly related to discharge chamber performance and wear and was measured with an ExB probe during sensitivity testing⁷. The general trend in the ExB data was an increased double production with an increase in primary electron input. Similarly, an increase in cathode flow reduced the

double content, by increasing the neutral population. The TH8 condition had the highest double content and sensitivity to changes in cathode flow rate and discharge current as compared to TH0 and TH15. This increase in doubles production has been suggested as a potential mechanism for the rapid cathode keeper erosion observed during the TH8 operational segment of the ELT from 10,000 to 15,000 hours³.

IV. Discussion

Overall, the sensitivity data suggests that discharge operation is most sensitive to changes in cathode flow rate and more so at the half and minimum power points. As Langmuir probe traces have shown, much of the ionization in the nominal NSTAR engine occurs along the thruster centerline, in the cathode plume, with the primary neutral source being cathode flow rate, and not the main flow from the plenum⁸⁹¹⁰. Although increasing main flow above the nominal set point reduces discharge voltage and discharge loss, that effect must be traded with reduced propellant utilization, which reduces the total engine efficiency. Plasma production and discharge voltage increase with beam current, as in order to increase ion production for a fixed neutral population, primary electron input must increase. Similarly, increasing the primary electron content, by increasing the discharge current for a fixed neutral input, increases the plasma's resistivity, manifesting itself as an increase in the discharge voltage. Discharge plasma production was not highly sensitive to increasing the electric field strength between the grids, suggesting the current NSTAR grid configuration is sufficiently optimized in terms of the screen grid's transparency to ions.

Comparison of the beginning and end of life sensitivities indicates variation with thruster wear, with the trend to increasing sensitivity of the discharge plasma to changes in flow and beam current. Although the changes in sensitivity were measurable, they did not appear that effect the engine's performance or indicate off nominal hollow cathode operation. As was confirmed by the destructive post test inspection, a stable discharge suggests a healthy discharge cathode, magnetic field, and screen grid in spite of over 30,000 hours of operation¹¹.

V. Conclusion

Several conclusions can be drawn from the sensitivity testing during the Extended Life Test Program. Discharge operation is most sensitive to changes in cathode flow rate and to a lesser degree main flow. This provides a propellant utilization efficient means of mitigating cathode wear issues. This also leaves open the possibility of an improved throttle table to maximize primary electron input with a better understanding of the cathode flow rate needed to mitigate neutral depletion. Increasing main flow above the nominal set point reduces the discharge voltage and discharge loss but with a higher propellant usage cost. Double ion content measurements indicate a lean cathode flow rate set-point leads to more significant changes in doubles production with small changes in discharge parameters; this being most apparent at the TH8 throttle point. The change of engine sensitivity with time was also minimal which suggests consistent performance of the NSTAR engine for long duration missions and confirms the health of both the discharge chamber and cathode at the conclusion of the test.

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References

¹Sengupta, A., et. al., "An Overview of the Results from the 30,000 Hr Life Test of Deep Space 1 Flight Spare Ion Engine," *AIAA-2004-C3608*, presented at the 40th AIAA Joint Propulsion Conference, Ft. Lauderdale, FL, Jul. 2004.

² Christensen, J., et al., "Design and fabrication of a Flight Model 2.3 kW Ion Thruster for the Deep Space 1 Mission," *AIAA-98-3327*, July 1998.

³ Anderson, J. R., et al., "Results of an On-going Long Duration Ground Test of the DS1 Flight Spare Ion Engine," *AIAA-99-2857*, June 1999.

⁴ Sengupta, A., et al., "Performance Characteristics of the Deep Space 1 Flight Spare Ion Thruster Long Duration Test After 21,300 Hours of Operation", *AIAA-2002-3959*, July 2002.

- ⁵ Taguchi, G., Chowdhury, S., and Wu, Y., *Taguchi's Quality Engineering Handbook*, John Wiley & Sons, Inc., New Jersey, 2005.
- ⁶ Sengupta, A., "Experimental and Analytical Investigation of a Ring Cusp Ion Thruster: Discharge Chamber Physics and Performance," Ph.D. Dissertation, Dept. of Aerospace Engineering, University of Southern California, Los Angeles, CA, 2005.
- ⁷ Polk, J. E., et al., "An Overview of the Results from an 8200 Hour Wear Test of the NSTAR Ion Thruster," *AIAA-99-2446*, June 1999.
- ⁸ Sengupta, A., "Experimental and Analytical Investigation of a Modified Ring Cusp NSTAR Engine," *IEPC-2005-160*, presented at the 29th International Electric Propulsion Conference, Princeton, NJ, November 2005.
- ⁹ Herman, D.A. et al., "Comparison of Discharge Plasma Parameters in a 30-cm NSTAR Type Ion Engine with and without Beam Extraction", *AIAA-03-5162*, presented at the 39th Joint Propulsion Conference, Huntsville, AL, July 2003.
- ¹⁰ Herman, D.A., "The Use of Electrostatic Probes to Characterize the Discharge Plasma Structure and Identify Discharge Cathode Erosion Mechanisms in Ring-Cusp Ion Thrusters," Ph.D. Dissertation, Dept. of Aerospace Engineering, University of Michigan, Ann Arbor, MI, 2005.
- ¹¹ Sengupta, A., "Destructive Physical Analysis of Hollow Cathodes from the Deep Space 1 Flight Spare Ion Engine 30,000 Hr Life Test", *IEPC-2005-026*, Presented at the 29th International Electric Propulsion Conference, Princeton, NJ, October 2005.