Sensitivity Testing of the NSTAR Ion Thruster

IEPC-2007-010

Presented at the 30[th] International Electric Propulsion Conference, Florence, Italy
September 17-20, 2007

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Abstract: During the Extended Life Test of the DS1 flight spare ion thruster, the engine was subjected to sensitivity testing in order to characterize the macroscopic dependence of discharge plasma production on operating conditions and component wear with runtime. The discharge chamber sensitivity to ±3% variation in main flow, cathode flow, and beam current, and to ±5% variation in beam and accelerator voltage, was determined for the minimum- (TH0), half- (TH8), and full-power (TH15) throttle levels. 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 parameters—discharge voltage, discharge current, discharge loss, double-to-single-ion current ratio, and neutralizer-keeper voltage—to the variations in the independent parameters—main flow, cathode flow, beam current, and beam voltage. The sensitivities of each dependent parameter with respect to each independent parameter were determined using a least-squares fit routine. Variation in these sensitivities with thruster runtime was recorded over the duration of the ELT, to determine if discharge performance changed with thruster wear. 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 for the NSTAR configuration plasma production is limited by primary electron input due to the 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 also be presented to illustrate beam ion production and content sensitivity to the discharge chamber operating parameters.

Nomenclature

NSTAR	=	NASA Solar Electric Propulsion Application Readiness
ELT	=	Extended Life Test
BOL	=	Beginning of Life
TH	=	Throttle Level
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 operation[1]. 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 periodically assessed on the FT2 NSTAR ion engine via a series of sensitivity tests over the course of the 30,000 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). 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 ±3% variation in main flow, cathode flow, and beam current, and to ±5% variation in beam and accelerator voltage, was determined for the minimum- (TH0), half- (TH8), and full-power (TH15) 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. 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.

II. Experimental Setup

A. Test Article and Facility

The flight spare engine 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].

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 5.3x10-4 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 power processing unit, 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].

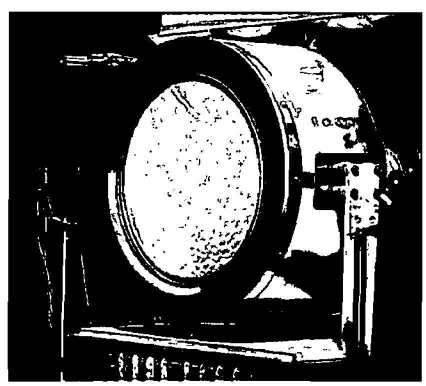

Figure 1. FT 2 thruster in JPL Endurance Test Facility

B. Experimental Procedure

Experimental characterization of the discharge chamber performance as a function of operating condition was performed on the FT2 NSTAR ion engine via a series of sensitivity tests. 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), 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 ±3% variation in main flow, cathode flow, and beam current, and to ±5% variation in beam and accelerator voltage, was determined for the minimum- (TH0), half- (TH8), and full-power (TH15) 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]. The 16x5 matrix of data was used instead of a full factorial matrix to reduce runtime and operational costs of the engine at these off nominal, sometimes stressful conditions.

Experiment	$\dot{m}_{main}$ (sccm)	$\dot{m}_{cath}$ (sccm)	$\dot{m}_{neut}$ (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]

The engine was allowed to reach steady state operation at each of these off nominal conditions before the discharge electrical parameters were recorded. 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.

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 Power[6].

Sensitivity results, i.e. the partial derivatives, will be presented as a function of power level in the following sections. A sample of the beginning of life sensitivities is shown in table 2.

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. This is because both the discharge voltage and discharge current are highly sensitive to changes in main flow. As the main flow is increased, the discharge voltage and discharge current decrease (Figure 1 and 2). Therefore, increasing main flow lowers the required cathode discharge power (J_DV_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. Specifically, the sensitivity of required discharge power to changes in 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 time[4]. The net result, however, is that the discharge loss sensitivity to changes in flow and beam current increased with runtime.

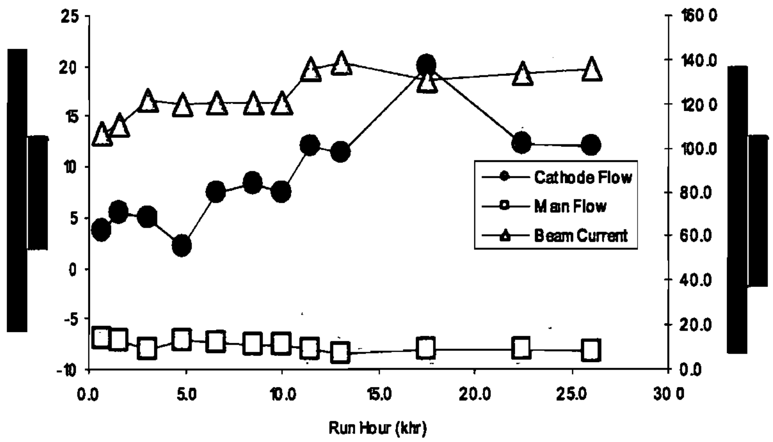

Figure 1. Discharge-Loss Sensitivity at Full Power (TH15)[6].

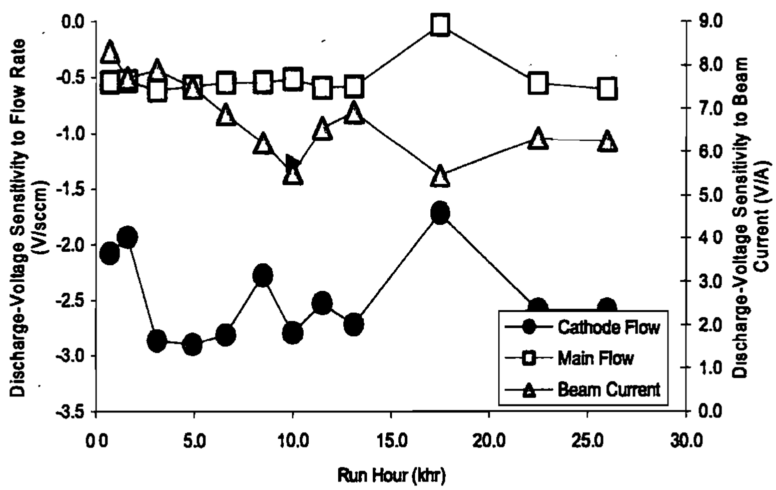

Figure 2. Discharge-Voltage Sensitivity at Full Power (TH15)[6].

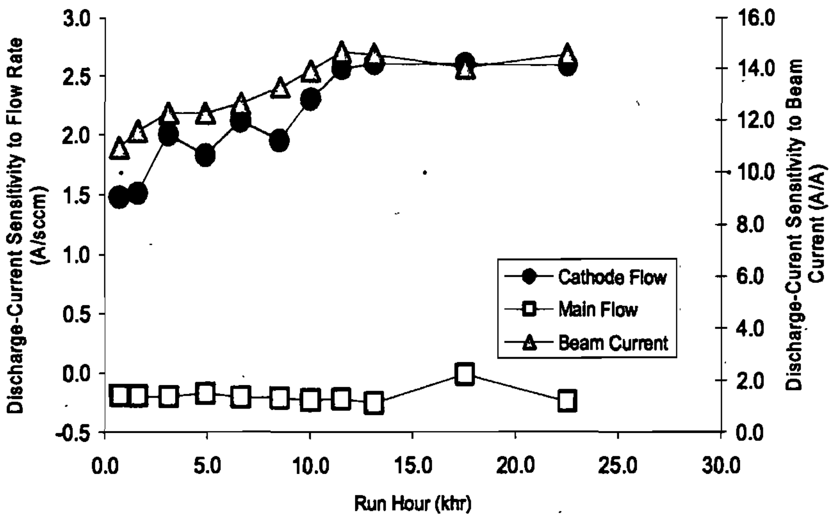

Figure 3. Discharge-Current Sensitivity at Full Power (TH15)[6].

B. Full 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 sensitivity of discharge current and voltage to beam current and flow rate was variable with runtime. In fact, after 25,000 hours of operation, the BOL and EOL discharge loss was roughly the same.

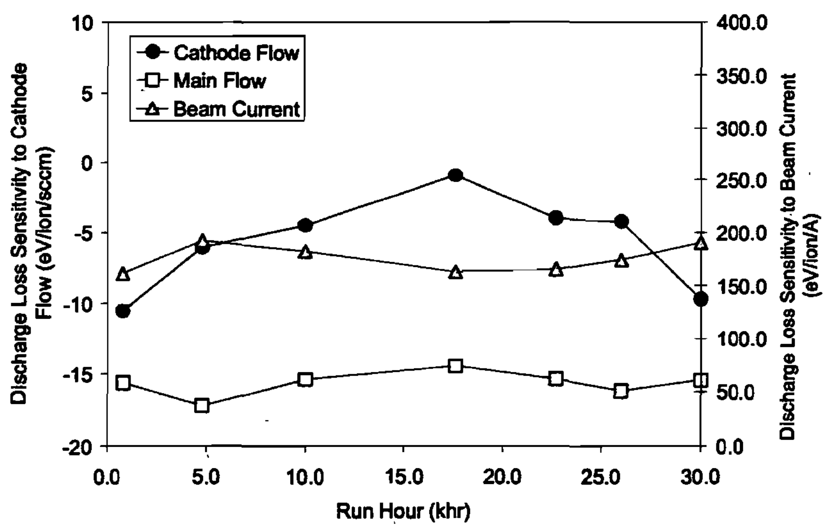

Figure 4. Discharge-Loss Sensitivity at Full Power (TH8)[6].

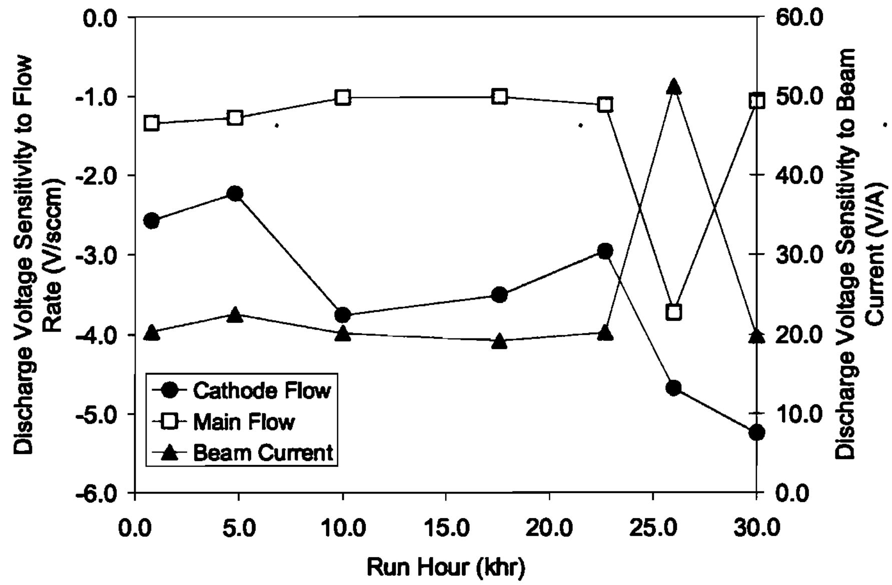

Figure 5. Discharge-Voltage Sensitivity at Full Power (TH8)[6].

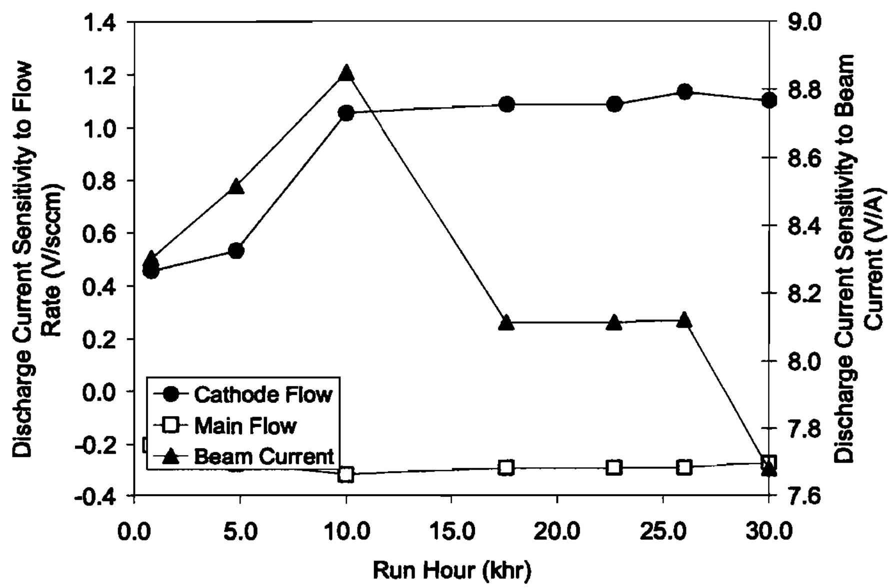

Figure 6. Discharge-Current Sensitivity at Full Power (TH8)[6].

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 is discharge voltage decreased the required discharge power. In terms of sensitivity to thruster wear, the sensitivity of discharge current and voltage to flow rate and beam current, respectively, increased over time. As such, the discharge power and loss sensitivity also increased with thruster wear.

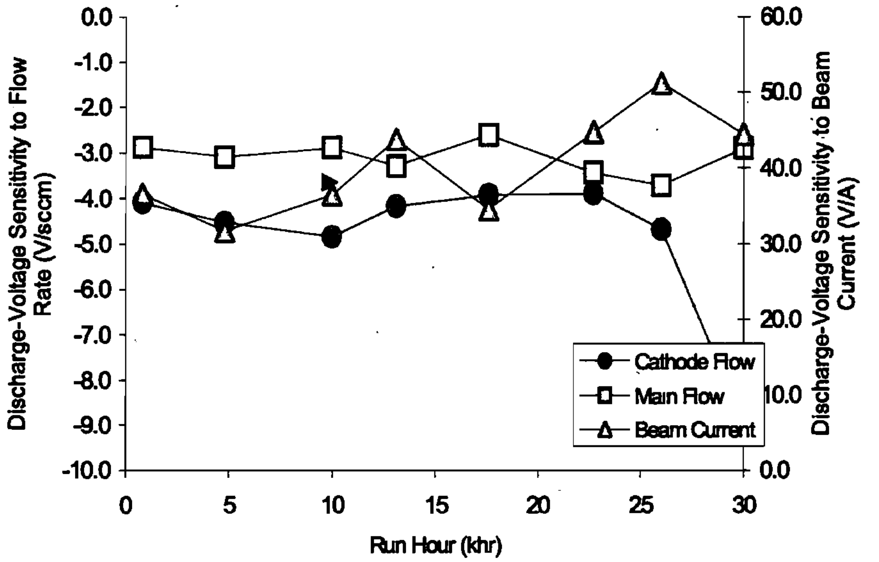

Figure 7. Discharge-Loss Sensitivity at Full Power (TH0)[6].

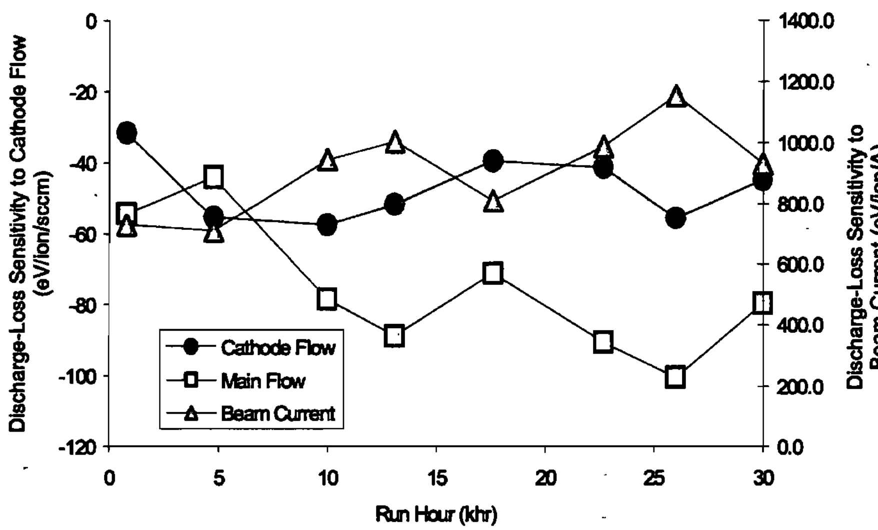

Figure 8. Discharge-Voltage Sensitivity at Full Power (TH0)[6].

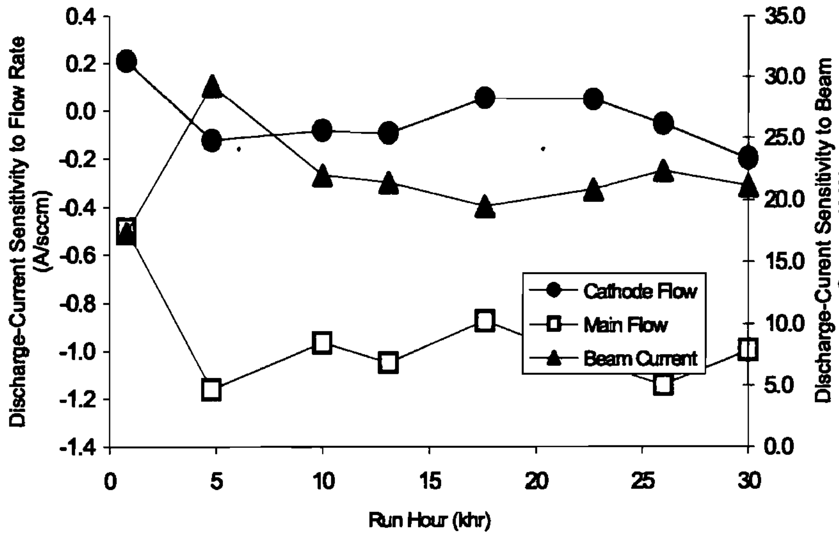

Figure 9. Discharge-Current Sensitivity at Full Power (TH0)[6].

D. Electric Field Sensitivity for all Power Levels

The ±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.

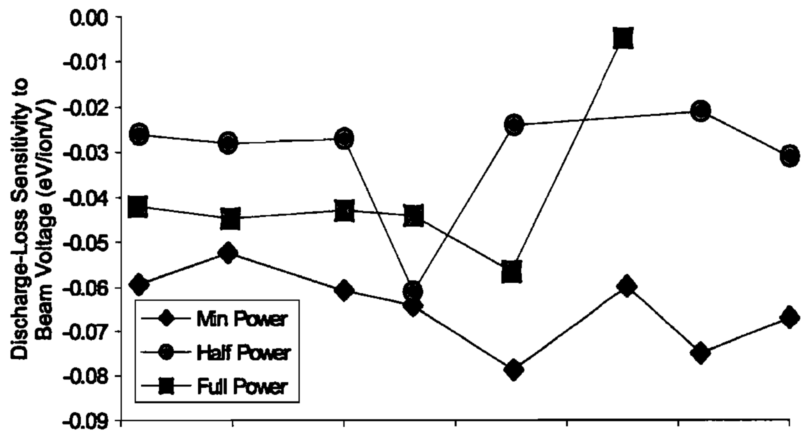

Figure 10. Discharge-Loss Sensitivity to Beam Voltage at All Power Levels[6].

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 testing[7]. 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 reduces 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 hours[3].

IV. Discussion

Overall, the sensitivity data suggests that discharge operation is most sensitive to changes in cathode flow rate. 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 plenum[8910]. 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 also indicates little variation with thruster wear. As was confirmed by the destructive post test inspection, this suggests a healthy discharge cathode operation and magnetic field in spite of over 30,000 hours of operation[11].

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 to a lesser degree 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.

Acknowledgments

The authors would like to acknowledge Al Owens, Ray Swindlehurst, Jay Polk, Bob Toomath, and Dennis Fitzgerald of the Jet Propulsion Laboratory for assisting in the conduct of this test program. The Jet Propulsion Laboratory, California Institute of Technology carried out the research described in this paper, under a contract with the National Aeronautics and Space Administration.

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