

NASA's Evolutionary Xenon Thruster (NEXT) Long-Duration Test as of 736 kg of Propellant Throughput

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The NASA's Evolutionary Xenon Thruster (NEXT) program is developing the next-generation solar-electric ion propulsion system with significant enhancements beyond the state-of-the-art NASA Solar Electric Propulsion Technology Application Readiness (NSTAR) ion propulsion system to provide future NASA science missions with enhanced mission capabilities. A Long-Duration Test (LDT) was initiated in June 2005 to validate the thruster service life modeling and to qualify the thruster propellant throughput capability. The thruster has set electric propulsion records for the longest operating duration, highest propellant throughput, and most total impulse demonstrated. At the time of this publication, the NEXT LDT has surpassed 42,100 h of operation, processed more than 736 kg of xenon propellant, and demonstrated greater than 28.1 MN·s total impulse.

Thruster performance has been steady with negligible degradation. The NEXT thruster design has mitigated several lifetime limiting mechanisms encountered in the NSTAR design, including the NSTAR first failure mode, thereby drastically improving thruster capabilities. Component erosion rates and the progression of the predicted life-limiting erosion mechanism for the thruster compare favorably to pretest predictions based upon semi-empirical ion thruster models used in the thruster service life assessment. Service life model validation has been accomplished by the NEXT LDT. Assuming full-power operation until test article failure, the models and extrapolated erosion data predict penetration of the accelerator grid grooves after more than 45,000 hours of operation while processing over 800 kg of xenon propellant. Thruster failure due to degradation of the accelerator grid structural integrity is expected after groove penetration.

Nomenclature

BOL	=	beginning-of-life
CRA	=	center radius aperture
DCA	=	discharge cathode assembly
DSDRM	=	deep space design reference mission
ELT	=	extended life test
EM	=	engineering model
EM3	=	engineering model 3 thruster
GRC	=	NASA Glenn Research Center
HiPEP	=	High-Power Electric Propulsion
IPS	=	ion propulsion system
J_B	=	beam current, A
J_{NK}	=	neutralizer keeper current, A
LDT	=	long-duration test
\dot{m}_M	=	main plenum mass flow rate, sccm
\dot{m}_C	=	discharge cathode mass flow rate, sccm

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\dot{m}_N	=	neutralizer cathode mass flow rate, sccm
NCA	=	neutralizer cathode assembly
NEARER	=	Near Earth Asteroids Rendezvous and sample Earth Returns mission
NEXT	=	NASA's Evolutionary Xenon Thruster
NSTAR	=	NASA Solar Electric Propulsion Technology Application Readiness
P_{IN}	=	input power, kW
PM	=	prototype model
SSR	=	surface sample return
TL	=	throttle level
TT10	=	throttle table10
V_A	=	accelerator grid voltage, V
V_B	=	beam power supply voltage, V
VF	=	vacuum facility
WT	=	wear test
ϕ	=	aperture or orifice diameter

I. Introduction

NASA identified the need for a higher-power, higher-specific impulse, higher-thrust, and higher-throughput capable ion propulsion system (IPS) beyond the state-of-the-art NASA Solar Electric Propulsion Technology Applications Readiness (NSTAR) IPS employed on the Deep Space 1 and Dawn missions.¹⁻⁴ To fill this need, the NASA's Evolutionary Xenon Thruster (NEXT) ion propulsion system, led by the NASA Glenn Research Center (GRC), was competitively selected in 2002. The NEXT IPS has been in advanced technology development under the NASA In-Space Propulsion Technology Program. The highest fidelity NEXT hardware planned has been built by the government/industry NEXT team including: a true engineering model (referred to as prototype model) thruster, an engineering model power processing unit, engineering model propellant management assemblies, a prototype gimbal, and control unit simulators.⁵ Each of the units have been extensively tested separately, have completed environmental testing (with the exception of the power processing unit), and have been tested together in system integration testing.⁶⁻⁹ The status of the NEXT project, results from IPS component testing, and results of integration testing can be found in Refs. 5 – 15.

The NEXT thruster service life capability is being assessed via a comprehensive service life validation scheme utilizing a combination of testing and analyses. The approach is consistent with the lifetime qualification standard for electric thrusters.¹⁶ The NEXT ion thruster is an evolution of the NSTAR thruster design. The understanding of plasma physics and erosion processes gained from the NSTAR development program also applies to the NEXT thruster. The NEXT thruster, as a second generation deep-space ion thruster, made use of over 70,000 hours of ground and flight test experience (not including the hours accumulated by the NSTAR IPS on the ongoing Dawn mission) in both the design of the NEXT thruster and evaluation of thruster wear-out failure modes. A NEXT service life assessment was conducted at NASA GRC employing several models to evaluate all known failure modes with high confidence based upon the substantial amount of ion thruster testing dating back to the early 1960s.^{17,18} The NEXT service life assessment also incorporated the results of the NEXT 2,000 h wear test conducted on a NEXT laboratory model (referred to as engineering model) ion thruster at 6.9 kW input power.^{17,19} The transparency between the laboratory model (referred to as engineering model) and engineering model (referred to as prototype model) thruster wear characteristics has been demonstrated by a short-duration prototype-model wear test.^{20,21} The NEXT service life assessment references explain the thruster performance and erosion modeling analyses.^{17,18}

The NEXT Long-Duration Test (LDT) was initiated to validate the NEXT thruster service life model and qualify the NEXT thruster lifetime. The goals of the NEXT LDT were to: demonstrate the initial project qualification propellant throughput requirement of 450 kg, validate thruster service life modeling predictions, quantify thruster performance and erosion as a function of engine wear and throttle level, and identify unknown life-limiting mechanisms. After demonstration of the qualification propellant throughput, 450 kg of xenon, in December 2009 the first listed goal has been redefined to test to failure of the thruster.

II. NEXT Long-Duration Test Background

The NEXT LDT is being conducted in VF16 at NASA GRC with an engineering model ion thruster, designated EM3, shown in Fig. 1. The EM3 thruster has been modified to a flight-representative configuration by incorporating prototype-model (PM) ion optics, delivered by industry partner Aerojet Corporation, and a graphite discharge

cathode keeper electrode.²² The NEXT thruster is nominally a 0.5 – 6.9 kW input power xenon ion thruster utilizing 2-grid, dished-out ion optics. The technical approach for the NEXT design is a continuation of the derating philosophy used for the NSTAR ion thruster. A beam extraction area 1.6 times that of NSTAR allows higher thruster input power while maintaining low voltages and ion current densities, thus maintaining thruster longevity. Descriptions of the NEXT EM3 thruster design and vacuum facility 16 (VF16) can be found in Refs. 1, 20, and 23 – 27.

Critical ion engine component erosion rates are monitored by 6 in-situ, charge-coupled device cameras. The cameras record the downstream neutralizer keeper and cathode orifice plates, the discharge keeper and cathode orifice plates, accelerator grid apertures at various radial locations from centerline, and the cold grid-gap of the thruster ion optics. The cameras are mounted to a single-axis positioning system that moves the cameras radially in front of the thruster, typically while the thruster is not operating. Additional testing diagnostics include: a data acquisition system that monitors thruster telemetry at 15 Hz permitting autonomous operation, staggered planar probes to monitor beam profiles and divergence, a quartz-crystal microbalance to monitor backspattered efflux, and a far-field ExB probe to measure the charge-state signature of the plume. Descriptions of the testing and facility diagnostics can be found in Refs. 27 and 28.

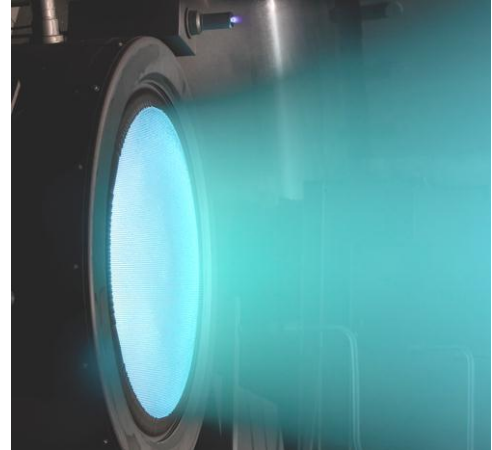


Figure 1. NEXT EM3 operating at full power during the Long-Duration Test.

III. NEXT Long-Duration Test Results – Metrics and Overall Performance

A. Status and Test Metrics

The NEXT IPS was designed for solar electric propulsion applications that experience variable input power as solar flux changes at various distances from the sun throughout the mission. To accommodate this variation in available power, the IPS can be throttled from 0.5 to 6.9 kW with varying specific impulse and thrust values. The EM3 thruster is being operated in the NEXT LDT at discrete operating segments for sufficient durations to characterize erosion rates and performance as a function of time for each condition used in validating the thruster service life models. The NEXT LDT throttling profile, illustrated in Table 1 and described in detail in Ref. 29, was completed in May 2010 and the go-forward plan is to continue thruster operations at full-power until failure. Detailed thruster characterizations are performed periodically to assess performance over 11 of the 40 operating conditions in the NEXT throttle table. Thruster assessment includes overall thruster and component performance including the performance of the discharge chamber, ion optics, and neutralizer cathode. The NEXT throttle table 10 (TT10) inputs, used for the LDT, are defined in the Appendix and the entire throttle table detailed in Ref. 30.

As of July 17, 2012, the NEXT EM3 thruster has accumulated 42,100 hours of operation, processed 736 kg of xenon, and demonstrated a total impulse of 28.1 MN·s. The NEXT LDT has set electric propulsion records for the most hours of operation, highest propellant throughput processed, greatest total impulse demonstrated, and longest hollow cathode operation. The project-level qualification throughput (i.e., thruster service life measured in kg of xenon propellant processed) was determined based upon the maximum individual thruster requirement from proposed missions that would utilize the NEXT IPS with 50% margin added. The NEXT LDT demonstrated the project-level thruster throughput requirement of 450 kg in December 2009, achieving one of the goals of the LDT.³¹ This goal was subsequently redefined to demonstrate the thruster service life capability by operating the thruster to failure. The throttling profile was completed in May 2010. Figure 2 shows the propellant throughput as a function of elapsed time with reference to the NSTAR Extended Life Test (ELT), the requirements from various mission analyses conducted using NEXT propulsion, and the original target NEXT qualification level throughput of 450 kg.³²⁻³⁹ One motivation for the continuation of the NEXT LDT is highlighted by the missions requiring thruster throughput capability in excess of 300 kg. As the thruster demonstrates greater throughput capability, new NEXT mission applications are enabled and existing mission concepts that carried additional strings to meet a lifetime requirement can be simplified reducing both spacecraft complexity and cost. The NEXT LDT exceeded the total impulse demonstrated by the 30,352 h NSTAR ELT in less than 1/3rd the thruster operating duration, shown in Fig. 3. The NEXT LDT has demonstrated more than 3 times the total propellant throughput demonstrated by the NSTAR ELT. Operating durations for all throttle table conditions and testing duty cycle (currently at 67%) are shown in Figs. 4 and 5, respectively.

Table 1. NEXT Long-Duration Test mission-like throttling strategy. Since throttling profile completion, the thruster has been operated at full input power (TL40) and plan to continue at TL40 until failure.

Throttle Segment	Throttle Level	Input Power, kW	Operating Condition (J_B , V_B)	Segment Duration, kh	End of Segment Date
1	TL40	6.9	3.52 A, 1800 V	13.0	11/17/2007
2	TL37	4.7	3.52 A, 1179 V	6.5	12/23/2008
3	TL05	1.1	1.20 A, 679 V	3.4	06/24/2009
4	TL01	0.5	1.00 A, 275 V	3.2	12/15/2009
5	TL12	2.4	1.20 A, 1800 V	3.1	05/05/2010

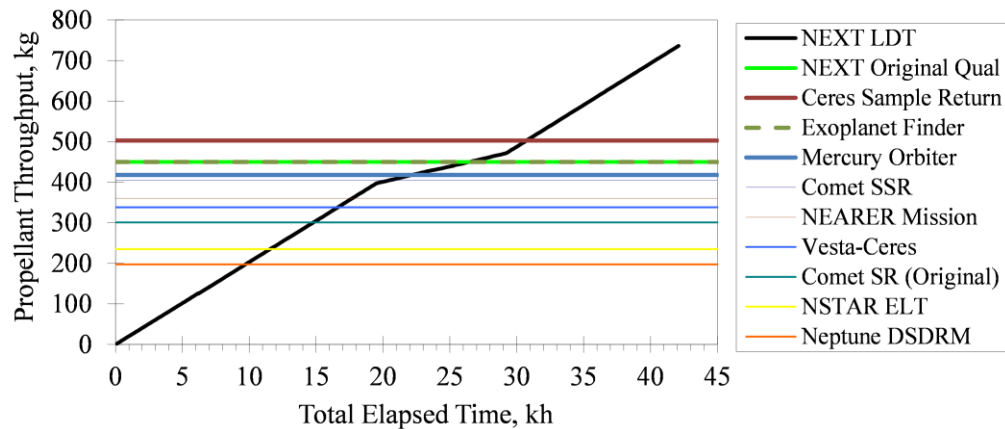


Figure 2. NEXT LDT propellant throughput as a function of time with reference milestones. NEXT project qualification throughput (450 kg) was demonstrated in December 2009.

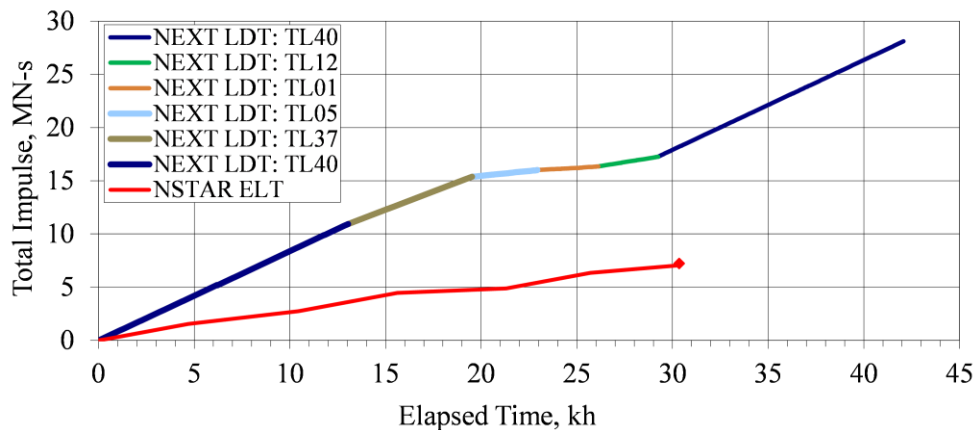


Figure 3. NEXT LDT and NSTAR ELT total impulse demonstrated as a function of testing duration.³⁴

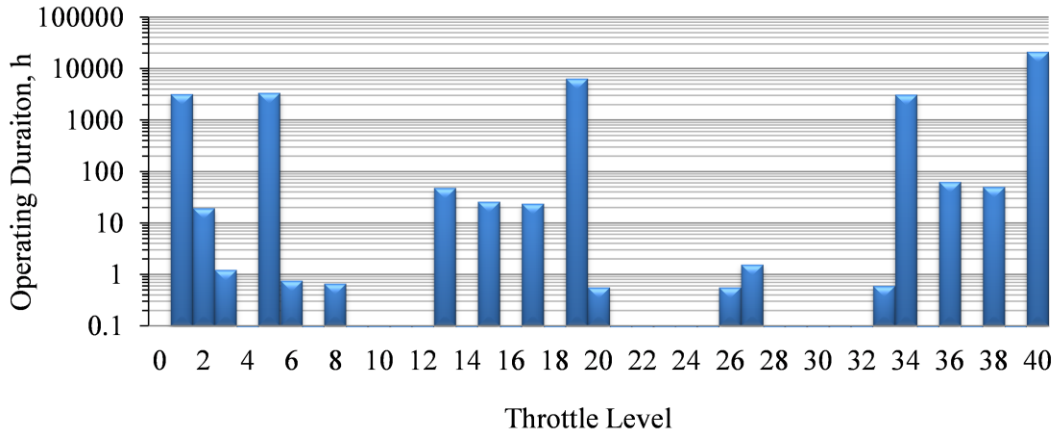


Figure 4. NEXT LDT semi-log chart of operating duration as a function of throttle level.

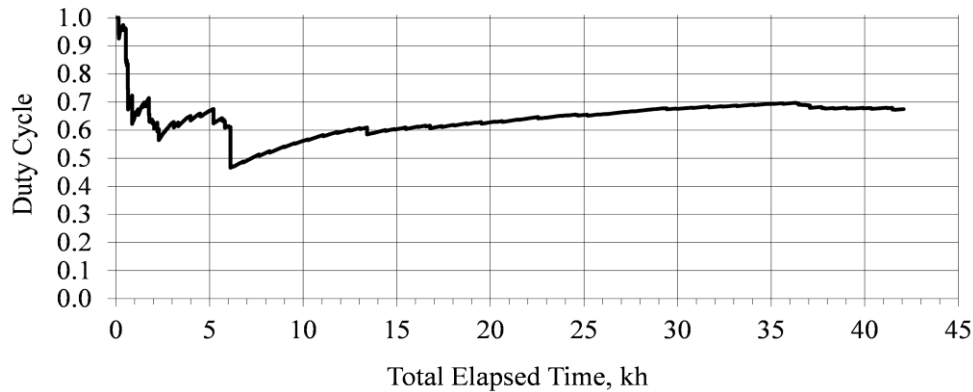


Figure 5. NEXT LDT testing duty cycle as a function of test duration.

B. Thruster Performance

Performance of the EM3 thruster has been steady with minimal degradation. Calculated thrust has remained constant while thruster input power has increased by a maximum of 30 W due to increasing discharge losses, less than 0.5% increase from beginning-of-life. Thruster performance measurement, calculation methodology, and assumptions are described in detail in Refs. 20, 23, 40, and 41. A summary of key thruster performance parameters comparing beginning-of-life performance to performance after processing 300 kg (lifetime requirement) and 450 kg (qualification – 150% lifetime requirement) were presented in Refs. 31 and 42. Plots of overall thruster performance including calculated thrust, specific impulse, thrust efficiency, and input power can be found in Ref. 29. Recent thruster data continue to show negligible performance degradation after 42,100 hours of operation.

At full-power, calculated thrust and specific impulse have remained constant at values of 237 ± 3 mN and 4170 ± 70 s, respectively. After 13,042 hours, thrust efficiency decreased from the beginning-of-test value of 0.709 to 0.706 due to an increase in input power to the thruster from 6.83 kW to 6.86 kW. This increase was a result of increasing thruster discharge losses. The indicated uncertainty in performance values are discussed in Ref. 43. Slight increases in specific impulse and thrust efficiency were realized after the beginning-of-test characterization due to an intentional decrease in neutralizer flow to improve overall propellant utilization efficiency. It was later discovered that the neutralizer flow setpoints were insufficient to maintain spot-mode operation of the neutralizer throughout the NEXT LDT. An updated throttle table, TT10, with increasing neutralizer flow rate as a function of propellant throughput processed, has been used to ensure sufficient flow margin during the NEXT LDT.

Trends at all operating conditions are similar: constant thrust, constant specific impulse after the neutralizer flow decrease at beginning-of-test, slightly increasing input power due to increasing discharge losses, and slightly decreasing efficiency after beginning-of-life (BOL) neutralizer flow decrease due to increasing input power. The maximum thruster performance variations are 2.5% of thrust efficiency and 4.2% change in specific impulse. For

reference, the NSTAR ELT experienced measured degradations of less than 9%, for both thrust efficiency and specific impulse.⁴⁴

IV. NEXT Long-Duration Test Results – Performance, Erosion, and Model Validation

The following sections describe the model predictions for thruster erosion, measured erosion data, and thruster performance resulting from extended operating duration. The relevant erosion data with comparison to model predictions and other ion thruster wear test data (NSTAR, NEXT, or other) will be discussed.

A. Discharge Chamber

Most of the performance changes during the NEXT LDT occurred during the first 10 kh of operation at full-power. Thruster discharge losses with time, which are the primary cause for increasing thruster input power, are plotted in Fig. 6. At full-power, the thruster discharge loss has increased from 122 to a maximum of 132 W/A over the testing duration. Discharge losses stabilized after approximately 10 kh of operation, consistent with observed trends in accelerator aperture erosion. The NEXT LDT discharge loss increase is likely caused by the decrease in neutral density due to accelerator aperture chamfering, increased thermal conductance from the cathode emitter due to barium migration, and surface condition changes of the cathode emitter and anode wall.²¹ Discharge voltage and discharge current data are shown in Figs. 7 and 8, respectively. Modest increases in discharge losses, less than 6% of pretest values, are observed for all operating conditions. Higher discharge loss variability is observed for low power conditions that operate at higher discharge propellant utilization efficiencies where discharge loss variation is more sensitive to subtle flow variations. There has not been an observable change in discharge characteristics that would indicate changes in the magnetic field topology.²⁶

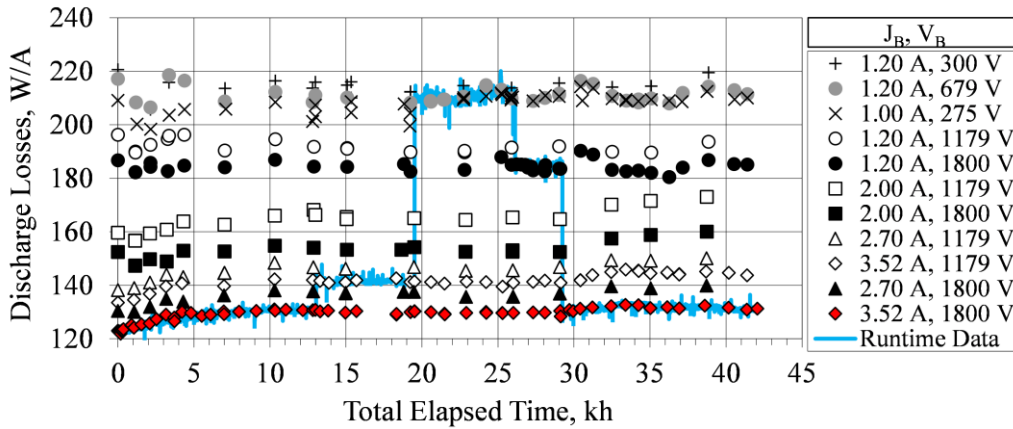


Figure 6. NEXT LDT thruster discharge loss data as a function of time.

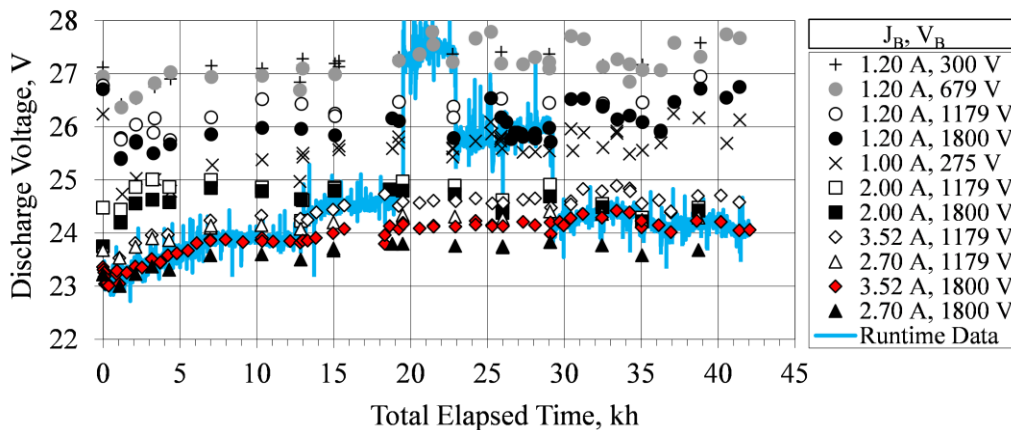


Figure 7. NEXT LDT discharge voltage across the throttle table as a function of test duration.

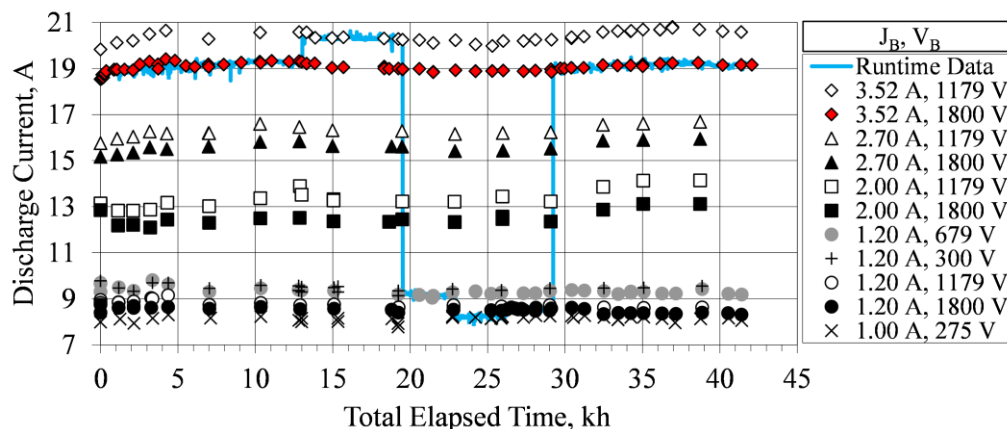


Figure 8. NEXT LDT discharge current across the throttle table as a function of test duration.

B. Discharge Cathode Assembly

The total operating duration on the NEXT LDT discharge hollow cathode is currently 42,561 hours. Severe erosion of the discharge cathode assembly was observed during the NSTAR ELT. After 15,000 hours of operation, the NSTAR keeper electrode eroded sufficiently to fully expose the cathode heater, radiation shielding, and cathode orifice plate.⁴⁵ The NSTAR ELT keeper erosion was characterized by a widening of the keeper orifice in contrast to the NEXT 2,000 h and NSTAR 8,200 h wear tests, in which the most severe erosion was focused towards the mid-radius of the keeper faceplate.^{19,46,47} Post-test examination of the NSTAR ELT discharge cathode revealed complete removal of the cathode orifice plate weld joint, shown in Fig. 9. The orifice plate was only held on the cathode tube by a 20 – 50 micron area of thermally induced fusion between the cathode tube and orifice plate.⁴⁴ Because of the severe NSTAR ELT discharge cathode erosion, additional potential failure modes were uncovered including cathode failure due to cathode heater erosion and unclearable grid-to-grid short or rogue hole formation due to flaking of the discharge cathode radiation shielding.⁴⁴

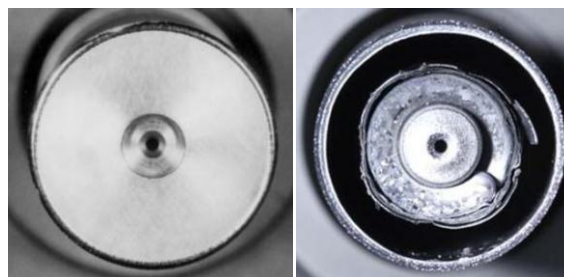


Figure 9. NSTAR ELT discharge cathode assembly BOL (left) and after 30,352 h (right).⁴⁴

The primary function of the discharge cathode keeper is to protect the discharge cathode from excessive sputter erosion. The EM3 keeper material was changed to graphite, which has a sputter yield an order of magnitude lower than that of molybdenum at 50 eV.⁴⁸ Figure 10 shows the beginning-of-life and most recent discharge cathode images for the NEXT LDT. The NEXT discharge cathode faceplate has become slightly textured, but the discharge cathode orifice and keeper orifice diameters have not changed within the measurement error, as shown in Fig. 11, normalized by the beginning-of-test values. While the LDT results confirm that no enlargement of the keeper orifice has occurred, the erosion of the downstream face of the keeper cannot be measured in-situ. Discharge cathode keeper downstream surfaces from the NSTAR 8,200 h and NEXT 2,000 h wear tests were qualitatively similar with the deepest erosion at a radii of 55-60% and 40% of the total keeper radius, respectively.^{19,46,47} Scaling the NEXT 2,000 h wear test molybdenum discharge keeper erosion rate (depth of 17% of the keeper thickness after test) with the decrease in sputter yield of graphite compared to molybdenum gives a conservative estimate of wear through of the keeper after > 100 kh at full-power (>2000 kg).^{17,18,47-49} It is estimated that the NEXT LDT keeper thickness near mid-radius has diminished by roughly 30% (see Fig. 13).^{18,19}

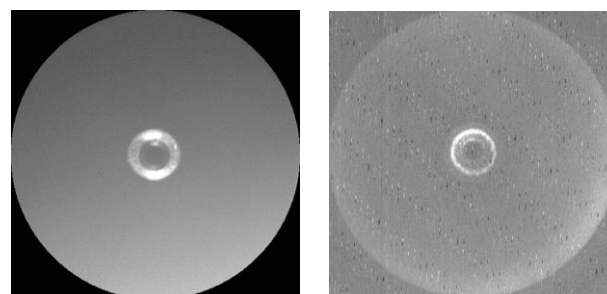


Figure 10. NEXT LDT discharge cathode assembly in-situ images after (left) 0 h and (right) 42,071 h.

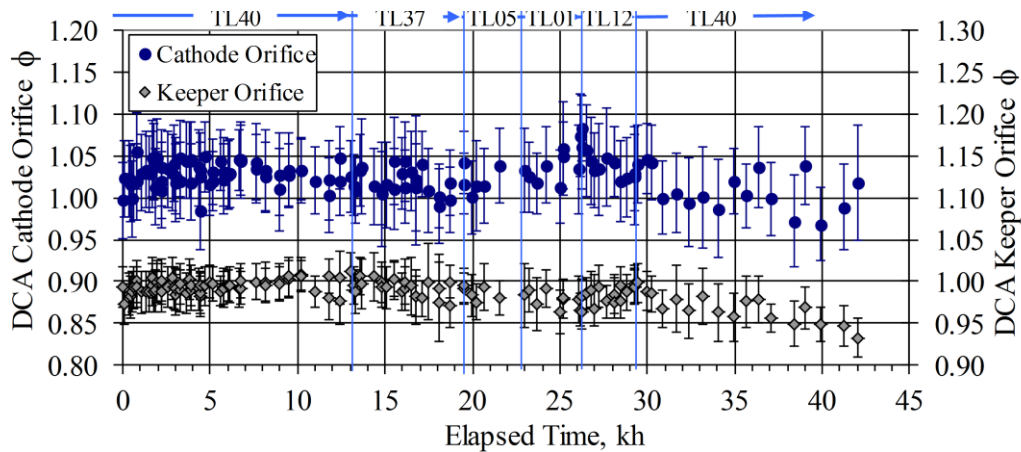


Figure 11. NEXT LDT discharge cathode and keeper orifice diameters normalized to beginning-of-life.

Shorting of the discharge keeper to cathode was observed during the NSTAR ELT and coincided with the onset of the anomalous discharge cathode assembly erosion.⁴⁴ The electrical shorting of the NEXT LDT discharge keeper to cathode was an expected event based upon the findings from the NEXT 2,000 h and the High Power Electric Propulsion (HiPEP) 2,000 h wear tests performed at NASA GRC.^{19,50} Post-test analyses measured tungsten material deposits on the upstream surface of the keeper faceplate near the orifice of 40 μm and 70 μm thicknesses for the NEXT and HiPEP wear tests, respectively.^{50,51} Assuming linear growth, extrapolation of these coating thicknesses for extended duration would have resulted in bridging the estimated operating gap between the NEXT LDT keeper and cathode face after an operating duration on the order of 10 to 30 kh. Intermittent thermally-induced discharge keeper-to-cathode shorting appeared after 13,875 hours of operation (833 hours after throttling to TL37). Discharge keeper voltage data are shown in Fig. 12. The NEXT lifetime assessment also predicted a priori this shorting event and considered its impact on thruster service life.^{17,18}

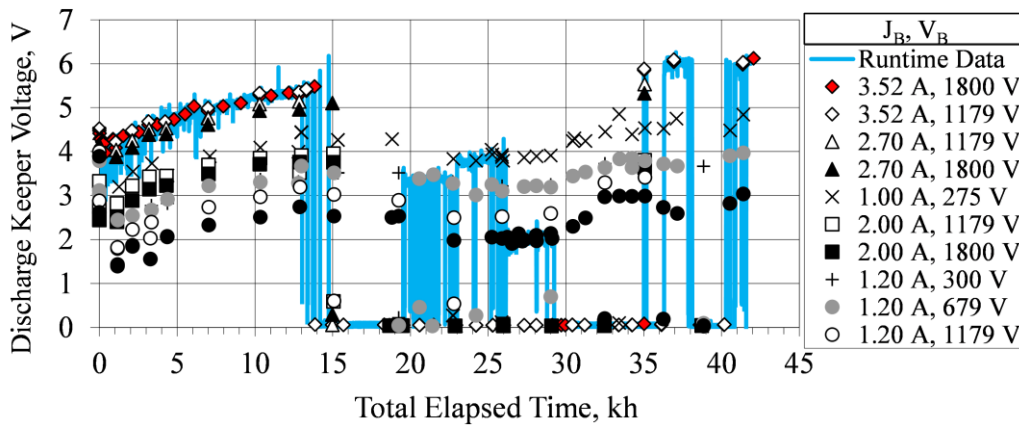


Figure 12. NEXT LDT thruster discharge keeper voltage data as a function of time.

There have been 312 discharge cathode ignitions with an average duration of 4.5 minutes between application of the heater current and ignition. The discharge cathode ignition durations beyond the nominal 3.5 – 6 minute durations have been attributed to: absorbed moisture during facility regenerations (eliminated by a 4 sccm purge during vacuum facility regenerations), thermally-induced heater open-circuits due to loss of current return path (eliminated by a hard current return on the PM discharge cathode design), and thermally-induced keeper shorting to cathode.²⁸ Model predictions for other cathode wear-out modes such as barium depletion and keeper erosion are shown in Fig. 13 indicating at most 50% barium depletion for either cathode by the time accelerator grid groove penetration is predicted.^{17,18}

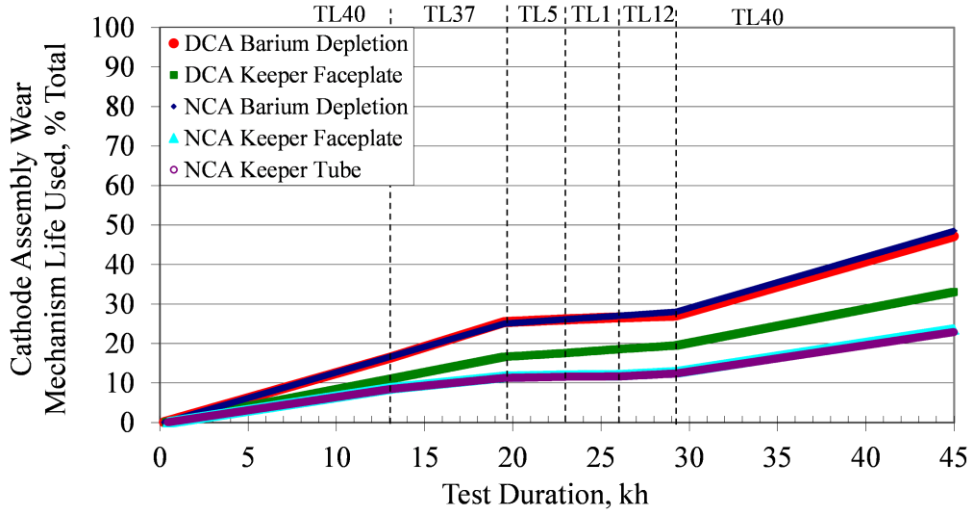


Figure 13. NEXT LDT cathode wear-out mode progressions based upon NEXT service life assessment.

C. Neutralizer Cathode Assembly

The total operating duration on the neutralizer cathode is 42,599 hours, making it the longest hollow cathode test. The neutralizer keeper voltage and the coupling voltage between neutralizer cathode and the vacuum facility ground are shown in Fig. 14. The keeper voltage demonstrated a slight decrease over 19.5 kh of operation during operation at fixed emission current and flow rate.²⁶ The voltage decreased from 11.2 to 10.7 volts during the first 10 kh at full-power. This minor decrease is likely due to erosion of the neutralizer cathode orifice plate. The application of a two-dimensional axisymmetric model of the plasma and neutral gas in electric propulsion hollow cathodes for the NEXT LDT neutralizer reveals that the anticipated erosion of the cathode orifice channel is sufficient to cause the observed keeper voltage drop with time.⁵² While in-situ cameras image the minimum neutralizer orifice diameter, detailed erosion orifice channel profile data cannot be determined using the NEXT LDT cameras. Post-test measurements will have to be made. A decreasing nominal keeper voltage of similar magnitude was observed at full-power during the NSTAR ELT as well.^{34,44} The NEXT coupling voltage has been steady at $-10.2 \text{ V} \pm 0.2 \text{ V}$ at full-power. Spikes in the keeper and coupling voltages are due to thruster shutdown and restart events where steady-state conditions do not exist for the neutralizer; these can be ignored. There have been 310 neutralizer ignitions all within 6 minutes of application of the heater current. Typical ignition durations are between 3.5 – 4.0 minutes.³⁰

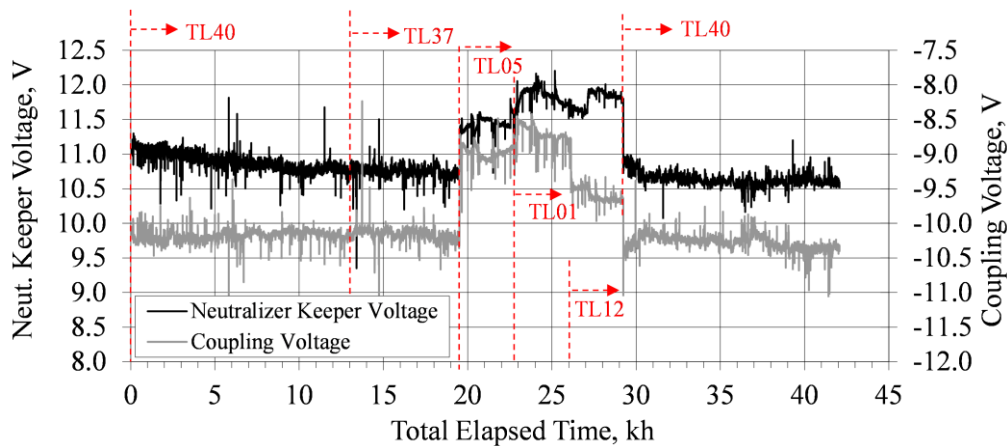


Figure 14. NEXT LDT neutralizer keeper and coupling voltage data as a function of time.

At low power levels, the beam current set points, and hence neutralizer emission currents, are at their lowest for engine operation. Neutralizer orifice clogging at low neutralizer emission currents is difficult to predict requiring experimental investigation. Clogging of the neutralizer has not been observed for any operating condition, including a total of 9,700 consecutive hours at low emission current conditions, shown in Fig. 15. Figure 16 illustrates the measured neutralizer orifice and keeper orifice diameters measured throughout the NEXT LDT.

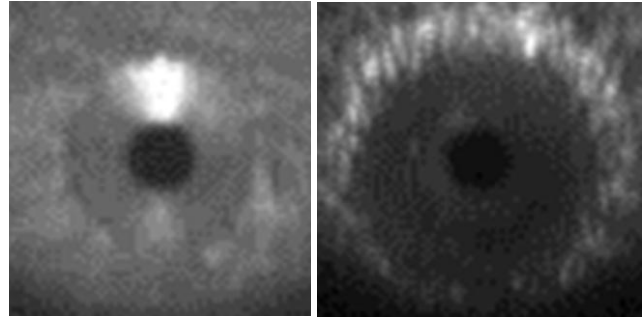


Figure 15. NEXT LDT neutralizer cathode orifice at beginning-of-life and after 42,071 h.

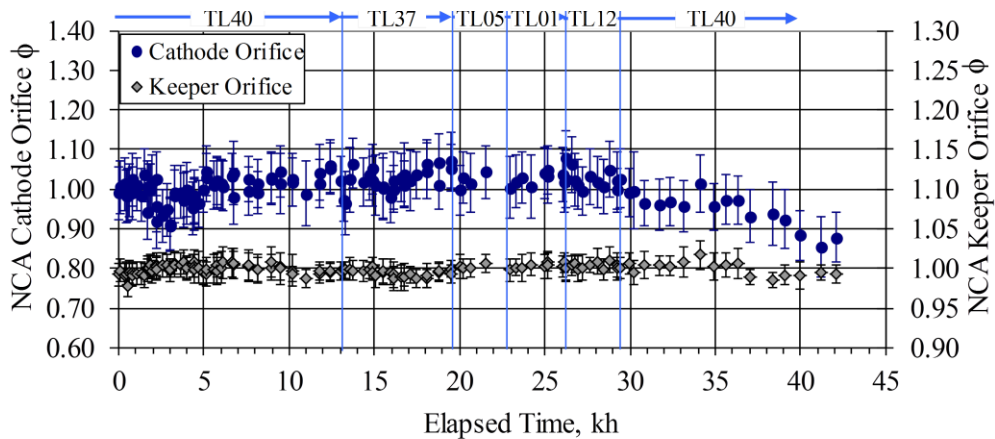


Figure 16. NEXT LDT thruster neutralizer cathode and keeper orifice diameter data as a function of time (normalized to beginning-of-life).

The main observed NEXT LDT thruster performance degradation is the loss of neutralizer flow margin with testing duration. Relative to the NEXT technology development throttle table at the inception of the NEXT LDT, a loss in neutralizer flow margin had been observed. Flow margin has decreased, based on beginning-of-life neutralizer flow rates, for all beam current conditions over the test duration.³⁰ Motivated by the engineering model (EM) neutralizer low flow margin at beginning-of-life, design modifications have been incorporated into the prototype model (PM) neutralizer design yielding higher flow margin at low-power.¹³ The design changes also caused a slight decrease in flow margin at high emission currents, where substantial beginning-of-life margin exists, and an approximate one volt increase in the magnitude of the coupling voltage.¹³ A new throttle table (TT10) was released to address the observed degradation experienced during the LDT and is now the baseline throttle table for the technology program and for mission analyses.³⁰ The new throttle table, partially shown in the Appendix and detailed in Ref. 30, increases the neutralizer flow rate from beginning of life as a function of propellant throughput processed. To determine neutralizer flow margin for a flight thruster utilizing a PM neutralizer, the LDT data was shifted based upon the difference between the pretest characterization data from the EM3 neutralizer and two PM neutralizers.^{13,20,30} The changes made were a shift up in flow margin of the LDT data at low power of up to 0.5 sccm and a shift down at full-power by 0.3 sccm. Figure 17 shows the predicted flow margin of a flight-like neutralizer operated in the NEXT LDT throttling profile. The flow set points, used to calculate flow margins, are from TT10. As the figure illustrates, there would have been a positive flow margin of at least 0.4 sccm for all operating conditions throughout the NEXT LDT had it utilized a PM neutralizer and updated TT10 neutralizer flow rate inputs. The neutralizer keeper current could also have been increased to provide additional flow margin, if necessary. The NEXT TT10 has demonstrated sufficient neutralizer keeper current and flow margin to prevent neutralizer orifice clogging and maintain sufficient flow margin from plume-mode even at low-power levels.

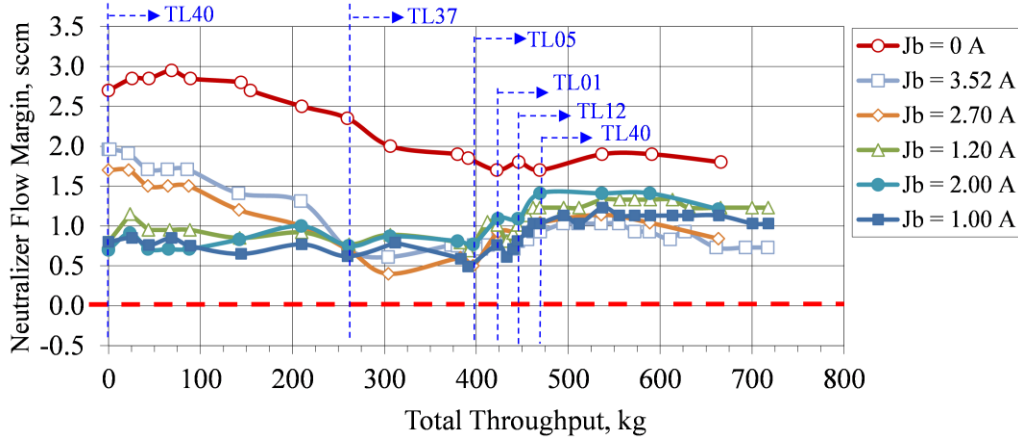


Figure 17. Anticipated NEXT PM neutralizer flow margin data as a function of time operated in the NEXT LDT throttling profile. Measurement error is ± 0.1 scm.

D. Ion Optics Assembly

An initial decrease in accelerator current was observed at the beginning of the test due to accelerator grid erosion – primarily restricted to outer radii accelerator grid aperture enlargement.²⁶ The overall trend has been a slight decrease in observed accelerator currents as the downstream diameters of the apertures are chamfered, as shown in Fig. 18. Since throttling the thruster back to full-power at 29,240 hours, accelerator grid current has increased slightly as the over-focused outer-radii erosion when operating at TL12 is filled in with back-sputtered carbon. Electron backstreaming and perveance margins throughout the wear test are plotted in Figs. 19 and 20, respectively. Electron backstreaming limit, impingement-limited total voltage (perveance limit), and screen grid ion transparency measurement techniques are defined in Ref. 53. At full-power and after completion of the throttling profile, the electron backstreaming margin was within one volt of the beginning of test value, i.e., within the measurement uncertainty. In comparison, the NSTAR first failure mode was electron backstreaming, encountered during the ELT after 25,700 hours (211 kg throughput), preventing full-power operation.³⁴ The NSTAR first failure mode has been mitigated by the improved, second-generation NEXT discharge chamber and ion-optics designs. There has been a modest, but discernable trend in electron backstreaming margin while the thruster was operating at full-power for significant duration. The two full-power (TL40) run segments, operation up to 13 kh and after 29.2 kh, have demonstrated increasing electron backstreaming margin that is attributed to back-sputtered carbon deposition inside the bulk of the accelerator grid apertures causing a slight decrease in the cusp diameter. Each full-power run segment has been for roughly 13 kh and the electron backstreaming margin increased by 6 V and 10 V during the first and second run segments, respectively. This second order behavior is due to ground-based testing and is not expected in flight where the electron backstreaming margin is predicted to remain constant because of the lack of accelerator grid aperture cusp erosion or change in ion optics' grid gap.

Perveance margins have increased as expected due to the downstream erosion (chamfering) of the accelerator apertures, similar to that observed during the NSTAR ELT.³⁴ Screen grid ion transparencies exhibited a slight decrease of a few percentage points during the both the first and second full-power run segments, shown in the Fig. 21. This decreasing screen grid ion transparency is speculated to be caused by deposits on the screen grid, but post-test measurements will have to be made. Changes in electron backstreaming limit, perveance limit, and screen grid ion transparencies are not significant enough to degrade the ion optics' performance and are less than or equal to those exhibited by the NSTAR ion optics during the 8,200 h wear test and NSTAR ELT.^{44,46}

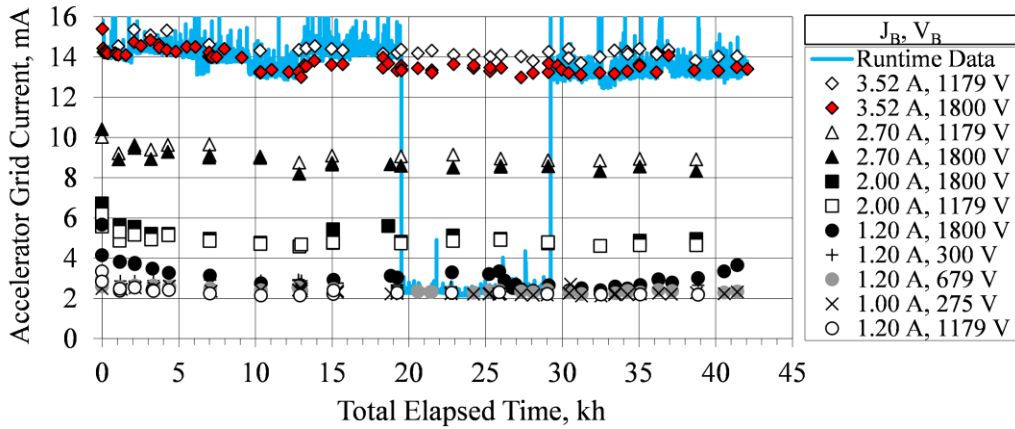


Figure 18. NEXT LDT accelerator grid current data as a function of time.

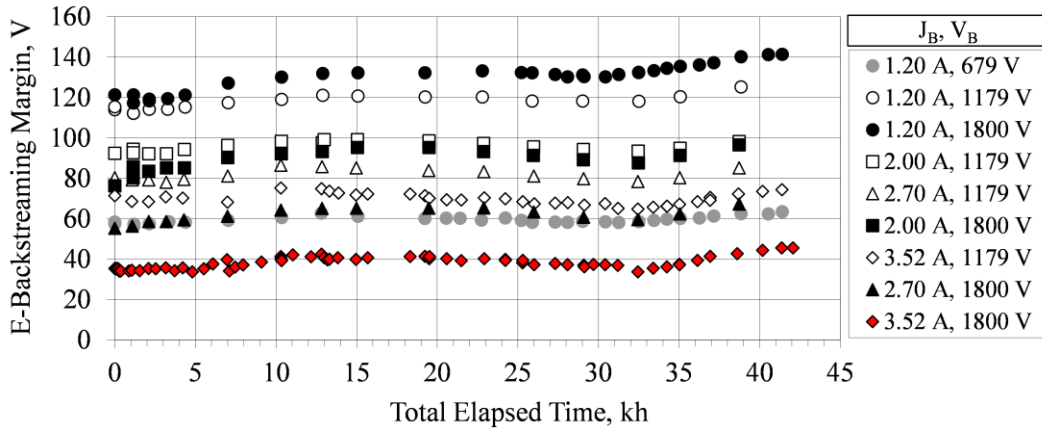


Figure 19. NEXT LDT electron backstreaming margin data as a function of time.

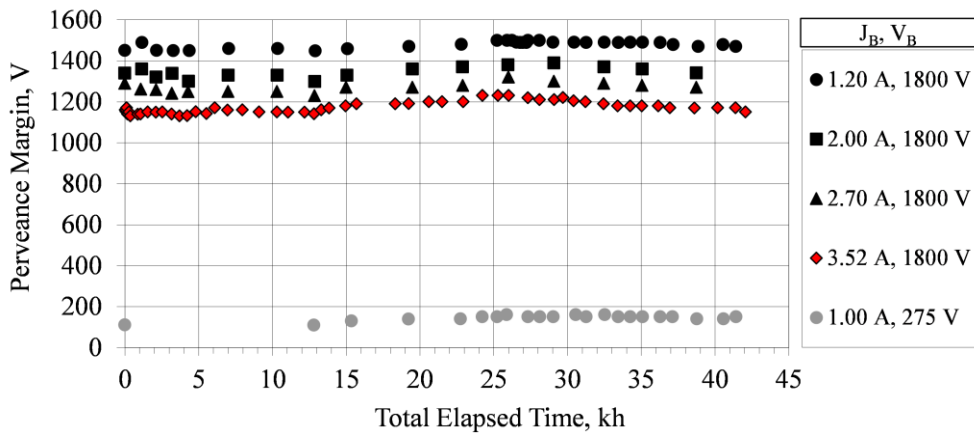


Figure 20. NEXT LDT perveance margin data as a function of time.

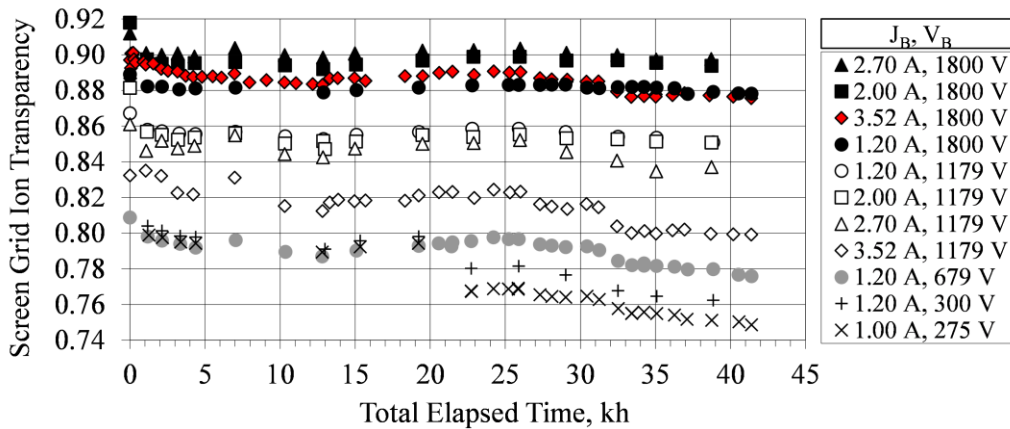


Figure 21. NEXT LDT screen grid ion transparency as a function of test duration.

The accelerator grid aperture erosion is monitored throughout the NEXT LDT and the data shown in Fig. 22. The lack of aperture barrel erosion was expected based upon the semi-empirical model predictions. The predicted NEXT accelerator aperture diameter erosion can be found in Ref. 18 and is negligible due to the significantly decreased maximum beam current density for the NEXT compared to NSTAR. Centerline aperture diameters were measured pre- and post-test of the NEXT EM1 and PM1R wear tests indicating negligible enlargement as well.^{19,21,47}

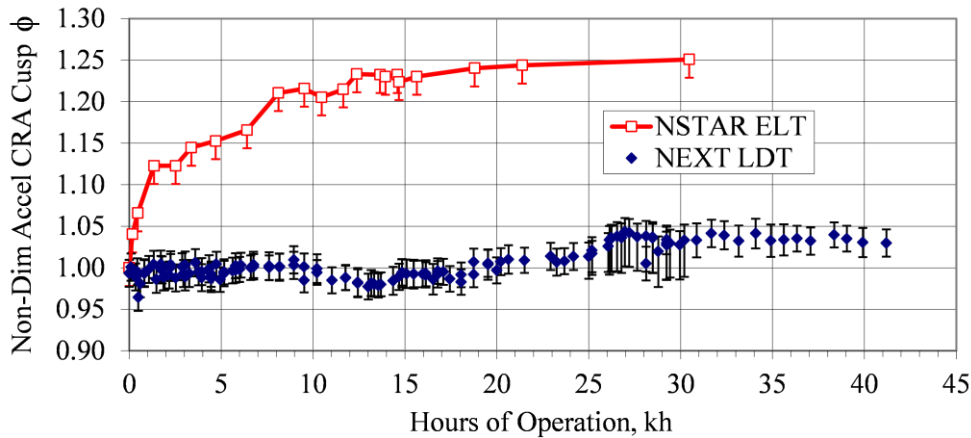


Figure 22. Accelerator grid center aperture cusp diameters from NEXT LDT and NSTAR ELT.³⁴

The first failure mode encountered during the NSTAR ELT was the inability to prevent electron backstreaming. The elimination of the NSTAR first wear-out mechanism in the NEXT design can be primarily attributed to the lack of enlargement of the accelerator grid apertures and elimination of the decreasing grid-gap of the NSTAR ion optics.^{44,46} Decreases in grid-gap cause an increase in the electric field between the grids resulting in reduced electron backstreaming margin and increased arcing between the grids. Pre- and post-test grid-gap measurements from the NSTAR ELT and 8,200 h wear test indicated 30% and 12% reduction in the cold grid-gap, respectively.^{34,44,46} How the grid-gap varied over the course of the tests is not known because no data are available. Analysis of electron backstreaming data indicates the grid-gap change probably occurred slowly over the duration of the test.³⁴ A decrease in the cold grid-gap of 7% was also observed following the NEXT 2,000 h wear test, which utilized EM ion optics. To address this undesirable change, the PM ion optics assembly and mounting scheme were modified from the EM design specifically to address and eliminate the observed decreasing cold grid-gap with thruster operation. A camera images the centerline cold grid-gap periodically throughout the LDT, which is assumed to trend with any changes in the operating ion optics' grid-gap. Within the measurement uncertainty, there has been no observed change in the NEXT LDT cold grid-gap, shown in Fig. 23. The EM3 thruster utilizes PM ion optics. The cold ion optics' grid-gap was last measured after 36,334 hours of operation and can no longer be measured due to degradation of the lighting within the vacuum facility.

The electron backstreaming margin has remained constant over the test duration, shown in Fig. 19. The improved beam flatness of the NEXT design and elimination of the changing ion optics' grid-gap have successfully addressed the first failure mode encountered in the NSTAR design. The NEXT design improvements push the thruster wear-out mode to another mechanism that progresses at a slower rate resulting in a substantial improvement in thruster service life capability.

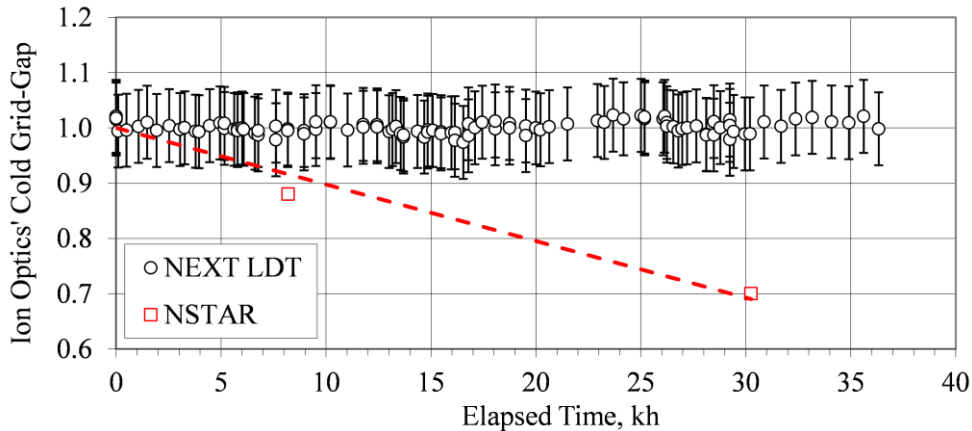


Figure 23. NEXT LDT and NSTAR cold ion optics' grid-gap, normalized to pretest measurements, as a function of testing duration.^{45,46}

Having demonstrated mitigation of the NSTAR first failure mode and discussed the main source of performance degradation, the main concern for full-power operation is the progression of the accelerator grid pit-and-groove erosion. The NEXT full-power operating condition has the highest accelerator grid groove erosion rate with time owing to the combination of high beam current density and magnitude of accelerator grid potential.^{17,18} Accelerator grid groove depth was measured via an optical diagnostic between 7.6 – 35.6 kh of operation and the results are shown in Fig. 24.⁵⁴ The linear trend of accelerator downstream erosion with time for a fixed operating condition was also observed for the pit depth measured via laser profilometer during the NSTAR ELT.³⁴ The NEXT semi-empirical model predictions demonstrate excellent agreement with the LDT data and the maximum groove depth from post-test laser profilometer measurements following the NEXT EM1 2,000 h wear test.^{19,47} The agreement between modeling and experimental data is extremely important because the NEXT LDT data is the major source of modeling validation, though NSTAR data were used extensively during the model development. The accelerator grid groove depth can no longer be measured because of degraded lighting and shadowing of the groove due to the depth of the groove and lighting angle.

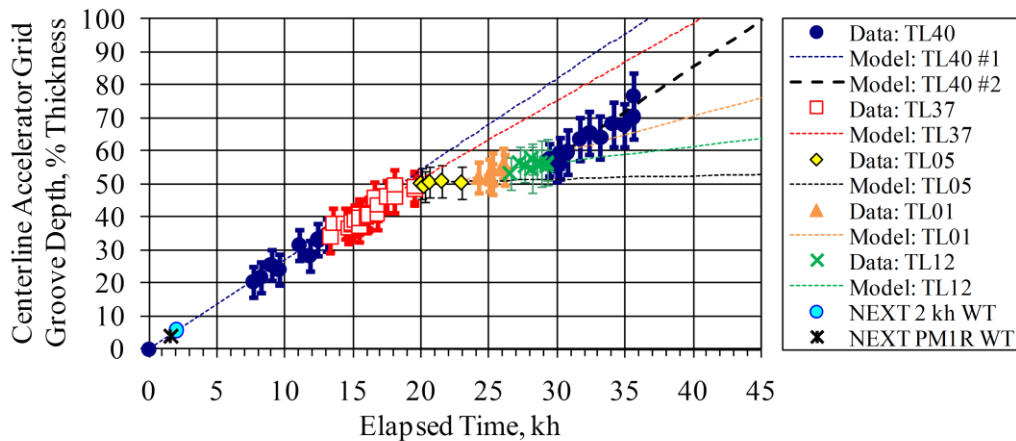


Figure 24. NEXT centerline accelerator grid groove penetration depth as a function of operating duration. Model predicts groove penetration after 45 kh assuming continued 6.9 kW operation.

V. NEXT Long-Duration Test-to-Failure Prediction

The NEXT thruster has successfully built upon the NSTAR development and flight programs. The NEXT thruster design has successfully mitigated several issues and wear out modes encountered during the NSTAR thruster development and flight programs. Upon completion of the 30,352 hours of operation for the NSTAR ELT: the thruster could no longer operate at full-power due to the inability to prevent electron backstreaming; the keeper electrode of the discharge cathode was completely eroded away leading to erosion of the heater coil, radiation shielding, and cathode orifice plate; and charge-exchange erosion had penetrated the accelerator grid thickness at the pits in the hexagonal pit-and-groove pattern. These findings led to additional thruster failure modes for the NSTAR thruster relating to the erosion processes as described in the NSTAR ELT report.^{34,44} With the NEXT thruster, which attempted to mitigate these issues, it has been the case that after 42,100 hours of operation the NEXT LDT can operate at any condition on the throttle table, has negligible discharge keeper erosion, and pit-and-groove erosion depths have an estimated 90% of the accelerator groove thickness. Additionally, many of the undesirable issues observed during the NSTAR wear tests have been addressed by the NEXT design.

The first failure mode anticipated for the NEXT LDT is loss of structural integrity of the accelerator grid due to charge-exchange erosion. The measured data during the LDT validate the NEXT thruster groove penetration model. The operating condition with the worst groove erosion rate as a function of time is full-power operation due to the high beam current density and high magnitude accelerator grid potential. The NEXT thruster service life model is used to predict the penetration of the grooves in the accelerator grid assuming test-to-failure of the NEXT LDT at full-power and the results are shown in Figs. 24 and 25. These graphs indicate groove penetration after more than 45 kh of operation and processing more than 800 kg of propellant throughput for the NEXT LDT throttling profile. This would result in a total impulse demonstrated of 30.7 MN·s, *by far the highest total impulse ever demonstrated by any electric propulsion device.*

The agreement between post-test measurements of pit-and-groove patterns and maximum groove depth from the EM1 and PM1R short-duration wear tests at full-power have been compared to the measured NEXT LDT groove depth at full power for the TL40 operating segment.^{19,21,47} The data of Fig. 25 show excellent agreement even though all three tests took place in difference vacuum facilities. The EM1 2,000 h wear test was conducted in VF6 at NASA GRC: a 7.6 m diameter x 22.9 m long facility outfitted with 12 cryogenic pumps providing 220,000 L/s pumping speed on xenon next to the ion thruster. The backspattered film thickness measured post-test yielded an average back-sputter rate of 1.5 $\mu\text{m}/\text{kh}$.¹⁹ The full-power back-sputter rate in VF16 is twice that of VF6, 3.0 $\mu\text{m}/\text{kh}$ measured by a quartz-crystal microbalance in the same plane as the thruster exit. The groove depth data from the two tests with a factor of 2 variation in back-sputter rate indicate that pit-and-groove erosion rates in regions of high beam current density are minimally influenced by the back-sputtered carbon deposition over the indicated range. The combined effects of elevated background pressure in the test facility and backspattered carbon deposition are estimated to cancel out, and therefore the LDT groove wear is expected to be representative of thruster operation in space.

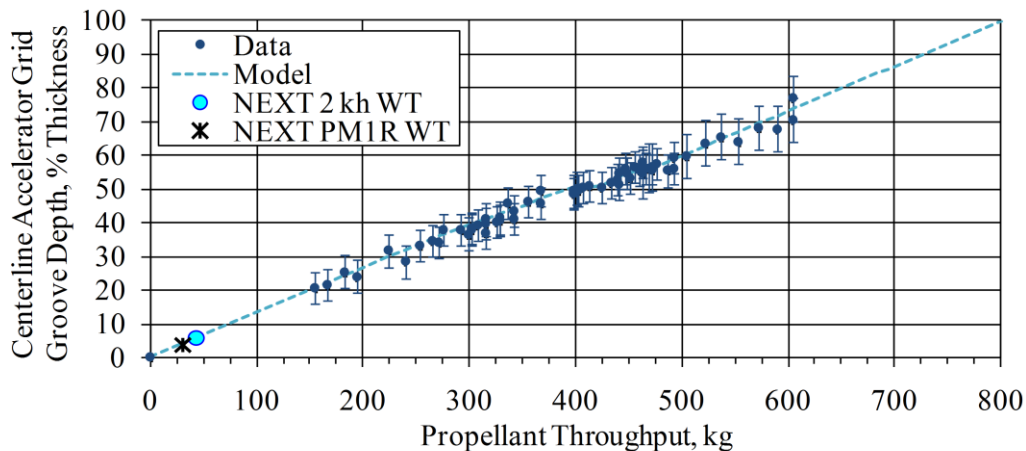


Figure 25. NEXT centerline accelerator grid groove penetration depth as a function of propellant processed. Model predicts groove penetration after 800 kg assuming continued 6.9 kW operation.

Predictions for accelerator grid aperture geometries, cathode orifice geometries, and electron backstreaming margin are output by the NEXT service life assessment for a given throttling profile. For the case of the NEXT LDT, where the accelerator apertures across the grid face have eroded to their worst-case final geometries, no additional changes in aperture geometries are expected. This prediction, combined with the lack of a change in the cold ion optics' grid-gap, leads to negligible change in the electron backstreaming margin for the remaining duration of the NEXT LDT. Thus, the NSTAR first failure mode of electron backstreaming will not be an issue with NEXT thrusters.

As the NEXT LDT test article approaches failure, attempts will be made to capture as much relevant data to characterize the failure as possible without unduly disrupting the execution of the test. The predicted NEXT first failure mode is expected after groove or groove and pit penetration, but may not coincide. This penetration, especially in the groove regions, may be detectable with the in-situ cameras and techniques such as back-lighting the image with the discharge plasma. Penetration of the accelerator grid will be checked approximately every 350 hours of operation going forward. In addition, penetration of the accelerator grid is expected to result in undercutting erosion (pit) or changes in the operating grid-gap (groove). Accelerator pit penetration and undercutting erosion may result in increased deposits within the ion optic's grid gap.³⁴ It may be possible to detect this deposition by obtaining and tracking the emission behavior of the grids when the thruster is not operating via Fowler-Nordheim equations. This data will be obtained and monitored every facility regeneration (roughly every 700 hours of operation). Accelerator groove penetration leading to structural degradation of the accelerator grid may be detectable by monitoring the operating grid gap. If the grid-gap changes, this might be captured by measuring both electron backstreaming and perveance margins at full-power, which will be checked every 350 hours of operation. In addition to the thruster telemetry, all this data may provide a method for detecting thruster behavior as failure is approached which will be important for the NEXT program and potential flight opportunities.

VI. Conclusion

The NEXT LDT is the major test component of the comprehensive thruster service life assessment that combines multiple wear tests and modeling. The NEXT LDT holds the electric propulsion records for the longest operation duration (42,100 h), highest propellant throughput demonstrated (736 kg), the highest total impulse (28.1 MN·s), and the longest duration test of a hollow cathode (42,599 h). The thruster surpassed the initial project qualification propellant throughput (450 kg) in December 2009. The throttling profile for thruster modeling validation was completed in May 2010. The NEXT LDT has validated the thruster service models across the broad throttle range of the NEXT thruster. The go-forward plan is to operate the thruster at full-power until failure. Demonstrating higher throughput capability enables new NEXT mission concepts to close and reduces complexity and cost of existing NEXT mission concepts that had additional thruster strings to meet operating thruster lifetime requirements. The test has demonstrated that multiple NSTAR failure modes, including the NSTAR first failure mode, have been mitigated by the NEXT design. The NEXT LDT test article is predicted to reach its first failure mode, predicted to be loss of structural integrity of the accelerator grid due to charge-exchange ion impingement, after more than 45 kh and processing greater than 800 kg of xenon propellant. By the end of the LDT, the total impulse demonstrated should exceed 30.7 MN·s. Understanding the thruster behavior as the first failure mode is approached and confirming the predicted first failure mode is important for the NEXT program and mission applications.

Appendix

Table A1. NEXT beginning-of-life throttle table (TT10) inputs for LDT performance operating conditions. Full-power wear test condition in bold.

TL Level	P_{IN} , kW [†]	J_B , A	V_B , V	V_A , V	\dot{m}_M , sccm	\dot{m}_C , sccm	\dot{m}_N , sccm	J_{NK} , A
40	6.86	3.52	1800	-210	49.6	4.87	4.01	3.00
37	4.71	3.52	1180	-200	49.6	4.87	4.01	3.00
32	5.29	2.70	1800	-210	37.6	4.26	3.50	3.00
29	3.64	2.70	1180	-200	37.6	4.26	3.50	3.00
22	4.01	2.00	1800	-210	25.8	3.87	2.50	3.00
19	2.78	2.00	1180	-200	25.8	3.87	2.50	3.00
12	2.44	1.20	1800	-210	14.2	3.57	3.00	3.00
9	1.70	1.20	1180	-200	14.2	3.57	3.00	3.00
5	1.12	1.20	679	-115	14.2	3.57	3.00	3.00
2	0.669	1.20	300	-410	14.2	3.57	3.00	3.00
1	0.545	1.00	275	-350	12.3	3.52	3.00	3.00

[†] Nominal values at beginning of life.

Table A2. NEXT throttle table (TT10) neutralizer flow rate inputs as a function of propellant throughput for LDT performance operating conditions. Full-power wear test condition in bold. After each throughput milestone is surpassed, the new flow rate becomes the set point.

TL Level	P_{IN} , kW [†]	J_B , A	Neutralizer flow rate (\dot{m}_N), sccm					
			0 kg	100 kg	200 kg	300 kg	400 kg	450 kg
40	6.86	3.52	4.01	4.01	4.01	4.01	4.01	4.33
37	4.71	3.52	4.01	4.01	4.01	4.01	4.01	4.33
32	5.29	2.70	3.50	3.50	3.50	3.50	3.82	4.14
29	3.64	2.70	3.50	3.50	3.50	3.50	3.82	4.14
22	4.01	2.00	2.50	2.82	3.14	3.46	3.78	4.10
19	2.78	2.00	2.50	2.82	3.14	3.46	3.78	4.10
12	2.44	1.20	3.00	3.00	3.32	3.64	3.96	4.28
9	1.70	1.20	3.00	3.00	3.32	3.64	3.96	4.28
5	1.12	1.20	3.00	3.00	3.32	3.64	3.96	4.28
2	0.669	1.20	3.00	3.00	3.32	3.64	3.96	4.28
1	0.545	1.00	3.00	3.00	3.32	3.64	3.96	4.28

[†] Nominal values at beginning of life.

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