

Post-test Inspection of NASA's Evolutionary Xenon Thruster Long-Duration Test Hardware: Discharge and Neutralizer Cathodes

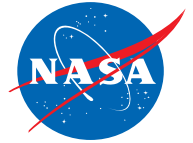
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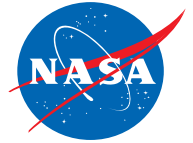
July 25, 2016

Additional NEXT Publications



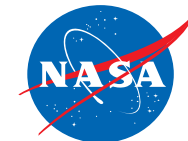
- LDT Companion Papers
 - Post-test Examination of NASA's Evolutionary Xenon Thruster Long-Duration Test Hardware: Discharge Chamber, AIAA-2016-4630
 - EP-09 3:30 – 4:00 PM on 7/25 in 250 D
 - Post-test Examination of NASA's Evolutionary Xenon Thruster Long-Duration Test Hardware: Ion Optics, AIAA-2016-4632
 - EP-09 4:30 – 5:00 PM on 7/25 in 250 D
- Development and Validation of Autonomous Operational Sequences for the NEXT System, AIAA-2016-5077
 - ITAR-04 5:00 – 5:30 PM on 7/27 in 151 DE
- Status of the Development of Flight Power Processing Units for the NASA's Evolutionary Xenon Thruster - Commercial (NEXT-C) Project, AIAA-2016-4519
 - APS-01 10:30 – 11:00 AM on 7/25 in 150 DE

Presentation Outline



- NEXT Long-Duration Test (LDT) Background
- Discharge Cathode
 - Keeper Electrode
 - Cathode Orifice Plate
 - Keeper-Cathode Electrical Short Resolution
 - Heater/Radiation Shield
- Neutralizer Cathode
 - Keeper Electrode
 - Cathode Orifice Plate
 - Heater/Radiation Shield
 - Neutralizer Common-GND Low Impedance Resolution
- Summary and Future Work

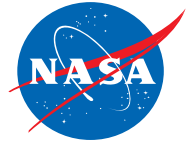
NEXT LDT Background



- NEXT LDT initiated in June 2005 as part of comprehensive thruster service life assessment
- Goals of test were to
 - Qualify thruster throughput capability to initial value of 450 kg
 - Validate thruster service life models
 - Characterize thruster performance over test duration
 - Measure critical thruster components erosion rates
 - Identify any unknown life-limiting mechanisms
- Test voluntarily terminated in February 2014 after demonstrating:
 - 51,184 hour of HV operation
 - 918 kg throughput
 - 35.5 MN-s total impulse
- Thruster vented to atmospheric conditions in April 2014 with post-test inspection initiated shortly thereafter
- Post-test inspection is presently nearing completion – this paper/presentation discusses pertinent results to-date on both cathodes
 - Results on other components covered in companion papers

Throttle Segment	Operating Condition (J _B , V _B)	Input Power, kW	Segment Duration, kh	End of Segment Date
1	3.52 A, 1800 V	6.9	13.0	11/17/2007
2	3.52 A, 1179 V	4.7	6.5	12/23/2008
3	1.20 A, 679 V	1.1	3.4	06/24/2009
4	1.00 A, 275 V	0.5	3.2	12/15/2009
5	1.20 A, 1800 V	2.4	3.1	05/05/2010
6	3.52 A, 1800 V	6.9	21.9	02/28/2014

NEXT LDT Post-test Inspection

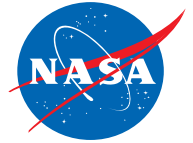


- Post-test inspection of NEXT LDT thruster hardware largely followed similar methods and procedures as what was used for NSTAR ELT
- Comparisons made (when appropriate) to results from several prior life tests
- Focus placed on previously identified wear-out failure modes, including:
 - Excessive wear of discharge keeper orifice plate
 - Excessive wear of neutralizer keeper tube
 - Excessive wear of cathode orifice plates
- Intended to verify that design changes implemented based on prior NEXT 2 kh WT had intended effects
- Also needed to resolve a number of issues encountered during test, including:
 - Discharge cathode-keeper electrical short
 - Discharge cathode intermittent heater open circuit
 - Loss of neutralizer flow margin
 - Low impedance between neutralizer common and facility ground



DISCHARGE CATHODE

Discharge Cathode Keeper



- Primary purpose of discharge keeper in NEXT is to protect cathode components (cathode tube, heater etc.) from discharge plasma
- Have observed significant erosion of downstream surface as well as orifice in prior life tests
 - NSTAR Life Demonstration Test
 - NSTAR Extended Life Test
 - NEXT 2,000 Wear Test
- Had changed material of NEXT keeper after results from 2 kh wear test to reduce sputter yield and increase keeper lifetime



NSTAR ELT after 30,352 hours*



NEXT LDT after 51,184 hours

*Image from Sengupta, A., Brophy, J. R., and Goodfellow, K. D., "Status of the Extended Life Test of the Deep Space 1 Flight Spare Ion Engine After 30,352 Hours of Operation", *39th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit*, AIAA-2003-4558, Huntsville, AL, July 20-23, 2003.

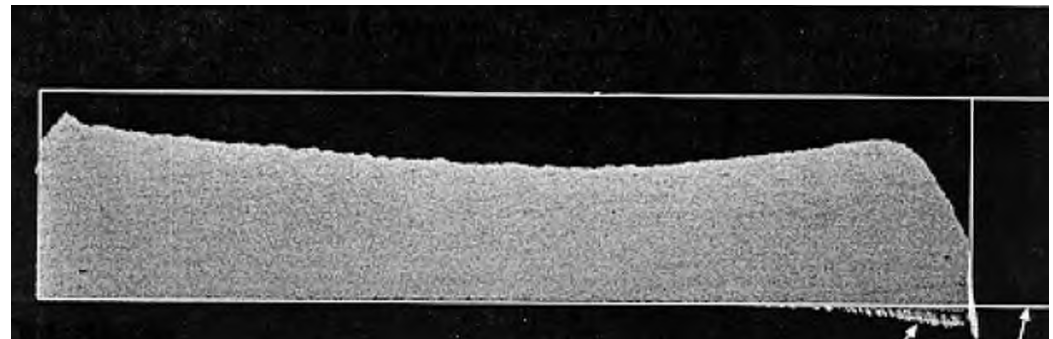
Discharge Cathode Keeper



- Cross section of NEXT LDT keeper indicates maximum erosion was 15.8% of the pretest thickness, at a location of 39% of the total radius
- Results are remarkably close to the NEXT 2 kh wear test – observed maximum erosion of 17% of pretest thickness at location of 40% of total radius
- Minimum orifice diameter did not change significantly
- Deposition observed on upstream surface of orifice plate, similar to previous life tests
- Indicates **substantial** increase in keeper lifetime compared to NSTAR LDT and ELT, as well as NEXT 2 kh WT



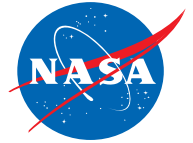
NEXT LDT after 51,184 hours



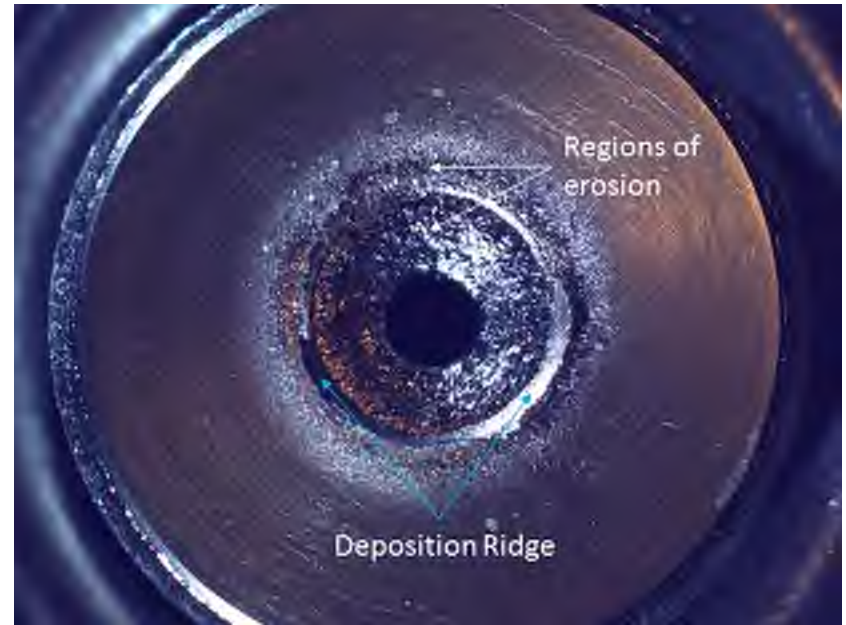
NSTAR LDT after 8,192 hours*

*Image from Polk, J. E., et al., "An Overview of the Results from an 8200 Hour Wear Test of the NSTAR Ion Thruster", *35th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit*, AIAA-1999-2446, Los Angeles, CA, June 20-24, 1999.

Discharge Cathode Orifice Plate

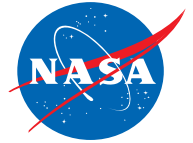


- No wear observed on downstream surface of cathode orifice plate outside of area exposed by keeper orifice
- Presence of a deposition “ridge” in the general location of the keeper orifice circumference
 - Regions of net erosion on both sides of this ridge

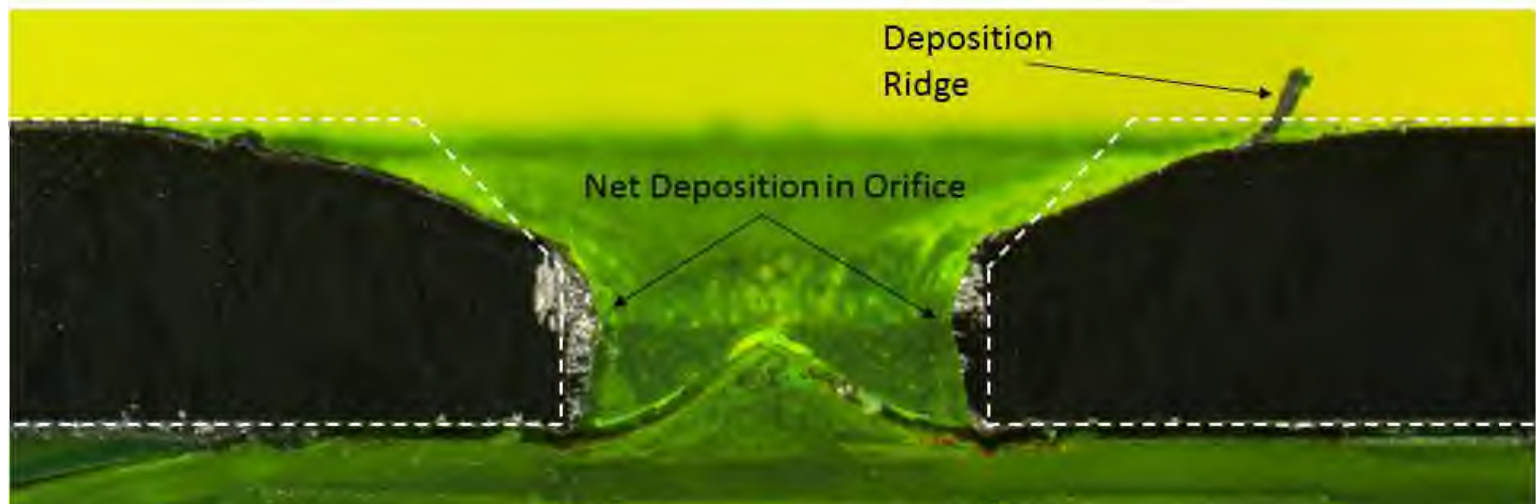


- Significant improvement over wear observed in NSTAR ELT
 - Discharge keeper erosion exposed cathode orifice plate, leading to only a 20-50 μm wide fused area attaching the plate to the cathode tube
 - Reduced keeper erosion in NEXT led to successful protection of cathode orifice plate for over 51 kh with ample keeper lifetime remaining

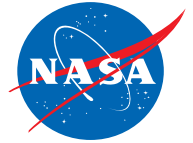
Discharge Cathode Orifice Plate



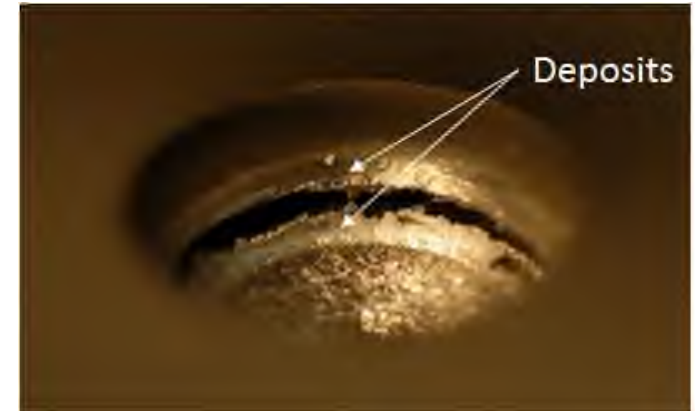
- Cross-sectioned orifice plate reveals net erosion of chamfer area as well as downstream area exposed by keeper orifice
- Deposition observed within cylindrical portion of orifice, reducing diameter by 13% compared to measured pretest diameter
 - Found to be material either from orifice plate or emitter
 - Reduced diameter also observed on NEXT 2 kh WT and NSTAR LDT
- Deposition ridge in middle of eroded area found to be cause of keeper-cathode short



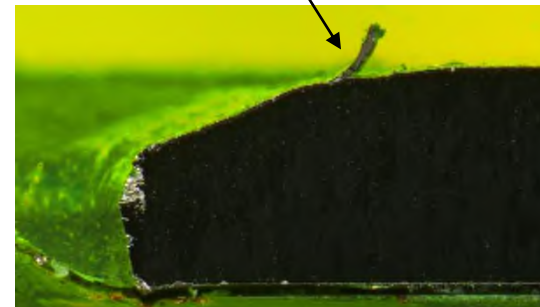
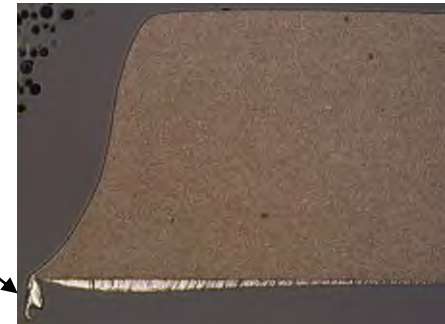
Keeper-Cathode Electrical Short



- A thermally-induced electrical short between the keeper and cathode was observed during the LDT
 - Began manifesting during ignitions around 13 kh, and was found to potentially increase discharge cathode ignition times
 - Became a more consistent short around 48 kh
- Short was found to be caused by deposits with keeper cathode gap
 - Material analysis indicates it had come from cathode orifice plate, so will occur in flight
- Likely began growing on upstream side of keeper orifice plate, eventually bonding to cathode orifice plate and subsequently breaking in the middle



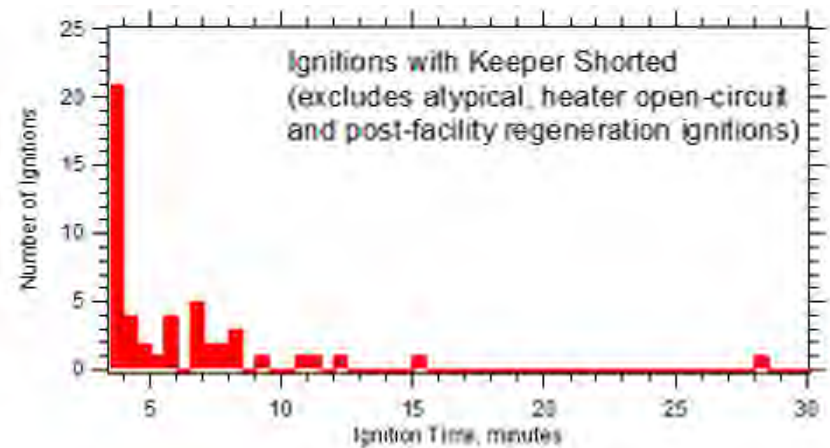
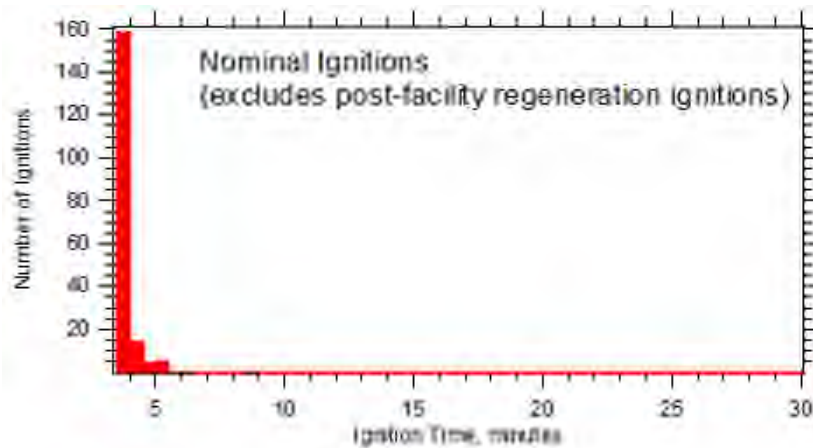
Deposits



Keeper-Cathode Electrical Short

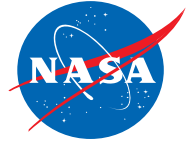


- Discharge cathode ignitions characterized in order to isolate effect of keeper-cathode short on ignition time
- Many factors found to affect ignition time during test, including:
 - Facility regenerations
 - Intermittent heater open circuits
 - Atypical conditions where ignition procedure was not strictly followed
- Isolating effect of keeper short indicates that average ignition time increased by ~ 2.5 minutes from 3 minutes 44 seconds to 6 minutes 5 seconds



- Presently investigating effect of attenuated igniter pulse (by nearly 2X) due to long electrical line lengths between thruster and power supplies

Heater/Radiation Shield



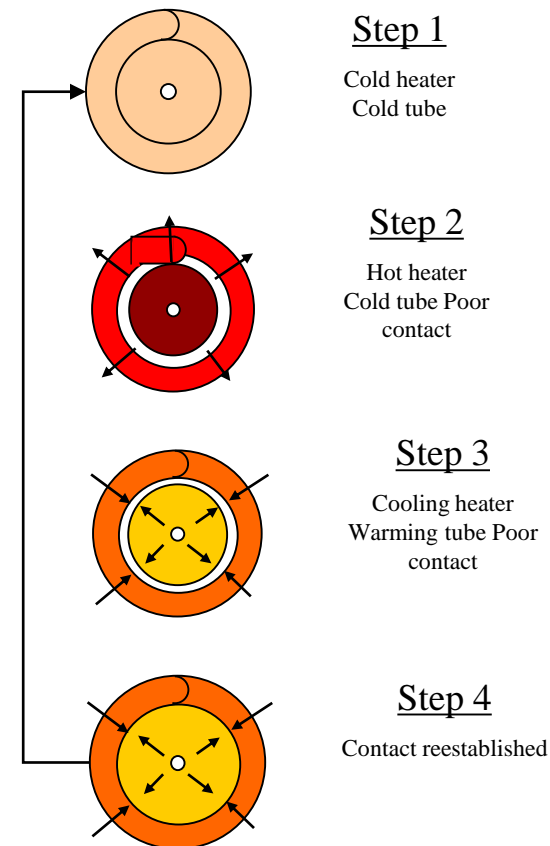
- No visible wear found on discharge heater or radiation shield
 - Significant improvement over NSTAR ELT due to reduced keeper erosion
 - Lack of wear eliminates additional failure modes found in NSTAR such as grid-to-grid shorting due to radiation shield flaking and excessive heater coil erosion
- Heater coil resistance measured during post-test inspection found to be $0.452\ \Omega$, which is in agreement with pretest measurements within the measurement variation



Intermittent Heater Open Circuit



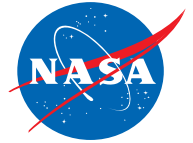
- An intermittent, thermally-induced heater open circuit was observed during the NEXT LDT from ~ 13 – 29 kh
- Speculated cause was poor contact between heater sheath and cathode tube, as a “friction fit” between the components was the only return path for the heater current
- Resistance measurements between cathode components taken during post-test inspection indicate highly variable resistance between heater sheath and cathode tube, sometimes exceeding 20 Ω at room temperature
- Heater easily slipped off when cut and removed from tube, indicating poor contact between components
- Not expected to be an issue for flight cathode due to implementation of more reliable, secure connection between heater sheath and cathode tube



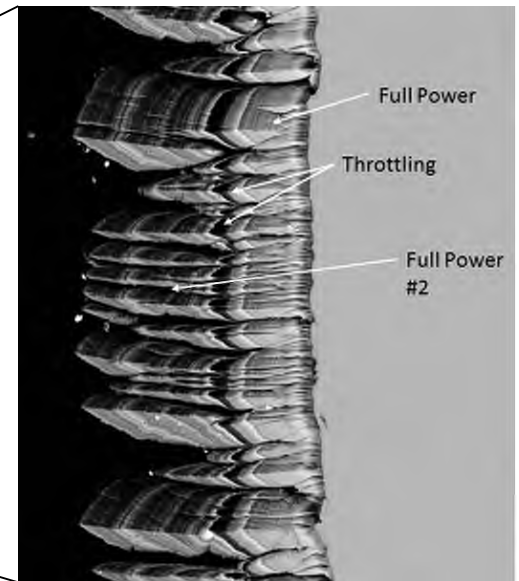
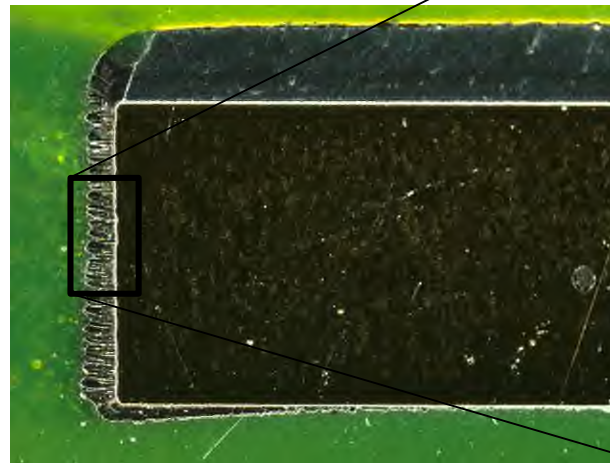


NEUTRALIZER CATHODE

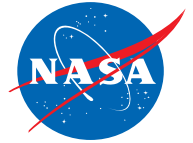
Neutralizer Keeper Electrode



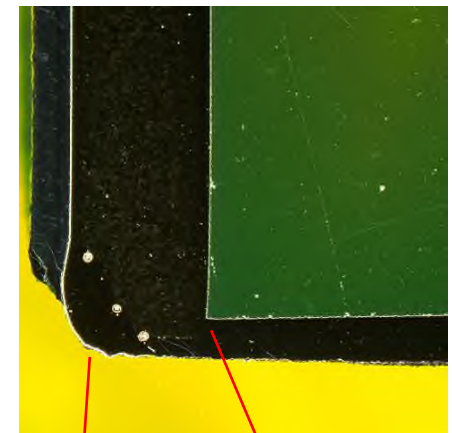
- Deposition found on nearly all surfaces of neutralizer keeper, except for beam side near the downstream end which is susceptible to ion impingement
- Significant deposition layer found on downstream side of orifice plate (27% of pretest thickness) – primarily backspattered carbon from facility
 - Much thicker than what was predicted by QCM measurements
- Deposition within orifice decreased diameter by 6% - combination of carbon from facility and cathode orifice plate material
 - Layered appearance caused by throttling of engine during test
- Effects of deposition on neutralizer flow margin will need to be assessed



Neutralizer Keeper Electrode



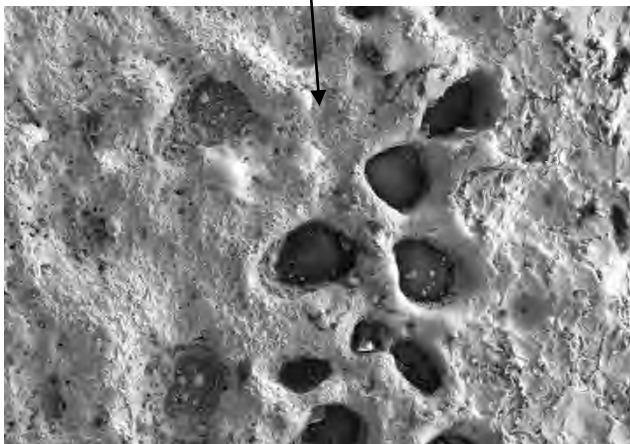
- Net erosion observed on beam side of neutralizer, extending ~ 2.5 orifice plate thicknesses upstream of downstream surface
- At furthest downstream location, orifice plate had eroded by 24% of the tube wall thickness (at location of weld)
- Upstream of orifice plate, tube wall had eroded by maximum of 17% of pretest thickness
- Compare to NEXT 2 kh wear test, which observed a maximum of 7.5% erosion with a total extent of 6.7 plate thicknesses upstream of downstream surface
- Significant reduction in extent of erosion between two tests likely a result of decreased beam extraction diameter from 40 cm to 36 cm
 - Reduced ion flux to the keeper surface
- Flight design increased thickness of keeper tube by 50%, which was not implemented in LDT hardware



24%
eroded

17%
eroded

Neutralizer Cathode Orifice Plate

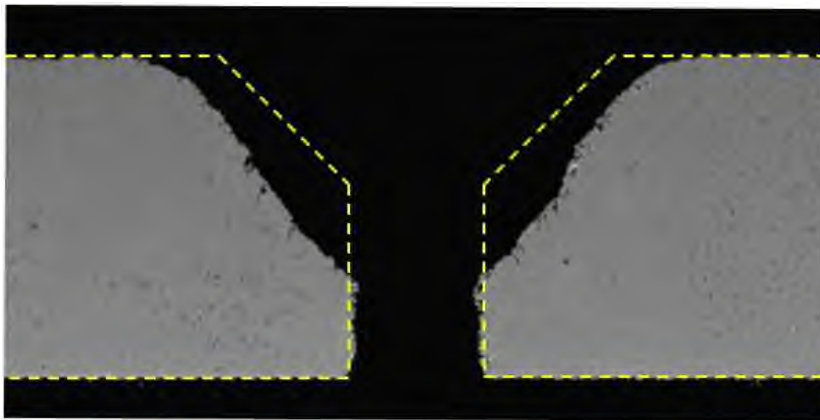


- Texturing of the orifice plate was found, particularly on side closer to ion beam
- Micrographs show that this texturing is actually numerous tiny pits
 - Signs of surface melting also indicate electrical arcing occurred in this area
- Inspection of previously tested neutralizers with NEXT indicate this phenomenon is not limited to the LDT
- Speculated to occur during thruster arcs (“recycles”) when the accelerator grid can reach potentials up to the beam voltage and large currents were found to travel through the neutralizer common line
- Pitting is superficial and did not thin orifice plate
 - Not expected to be an issue
- Orifice plate and weld are fully intact

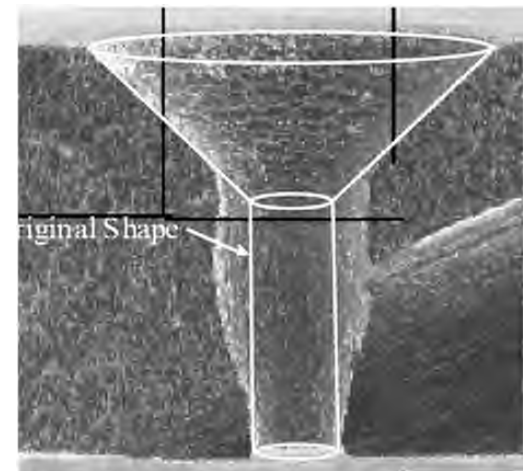
Neutralizer Cathode Orifice Plate



- Significant erosion of orifice chamfer occurred, with surface appearing somewhat porous
 - Indicates either net deposition or pitting similar to downstream surface
- Net deposition found in upstream cylindrical portion, decreasing minimum diameter by 8%
 - Material determined to be either from orifice plate itself or emitter
- Shape differs from what was found in NSTAR ELT, where downstream portion of chamfer remained intact and cylindrical portion exhibited “fluting”
 - Orifice dimensions and operating currents differ between two cathodes



NEXT LDT after 51,184 hours

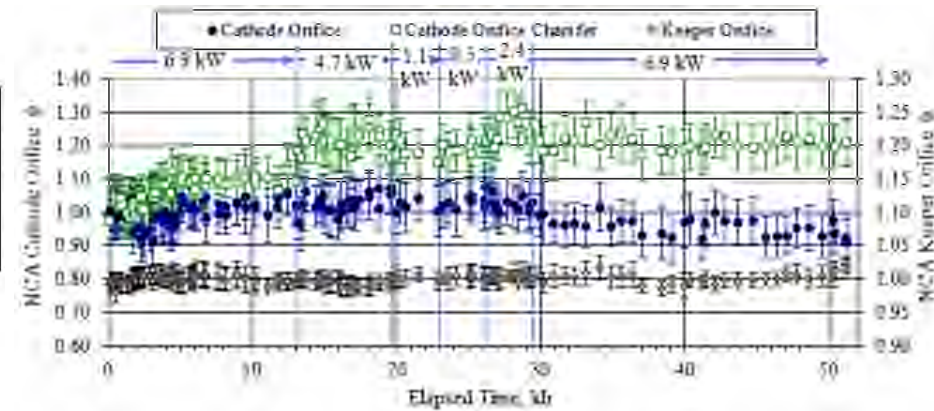
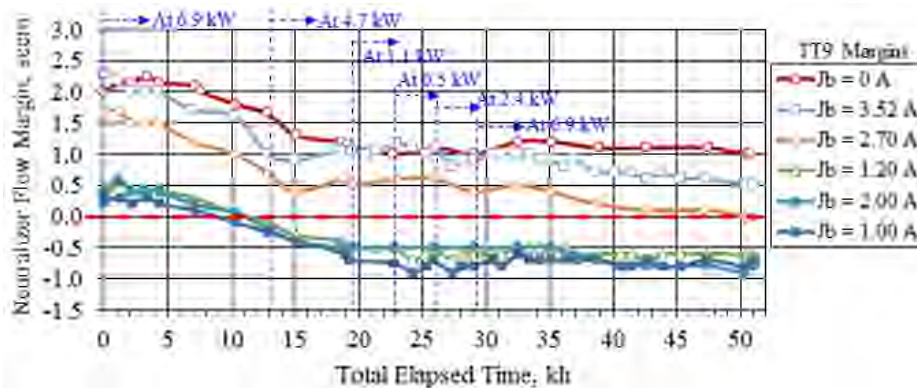
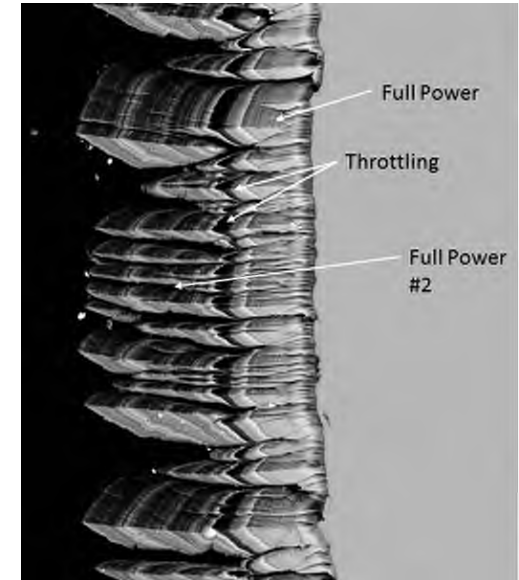


NSTAR ELT after 30,352 hours*

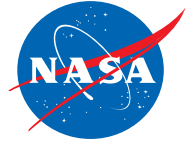
*Image from Sengupta, A., et al., "The 30,000-Hour Extended-Life Test of the Deep Space 1 Flight Spare Ion Thruster," NASA/TP 2004-213391, March, 2005.

Loss of Flow Margin

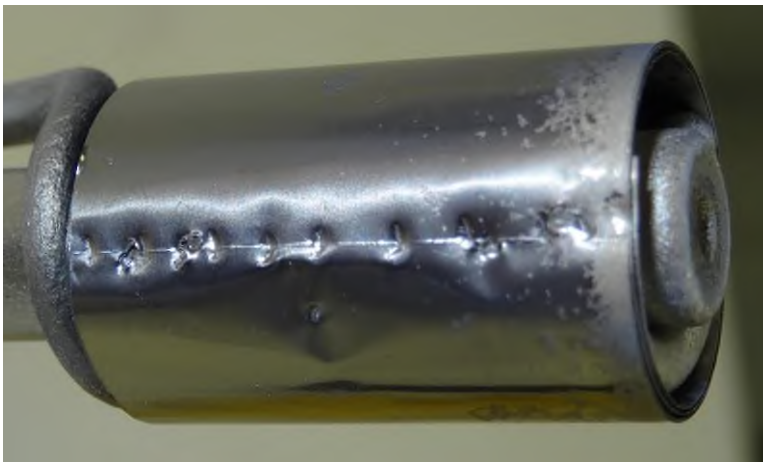
- Loss of flow margin from plume mode observed during NEXT LDT
- Speculated that this loss was tied to changes in cathode orifice geometry
- Cathode simulations performed at JPL show an enlargement of the orifice causes a decrease in neutralizer keeper voltage, which was correlated to flow margin loss during test
- Evidence that erosion of cathode orifice was greatest at higher beam currents, when largest losses to flow margin occurred
- Cathode-keeper gap for flight design was changed and neutralizer flows are adjusted in latest throttle tables to ensure adequate flow margin is maintained throughout lifetime



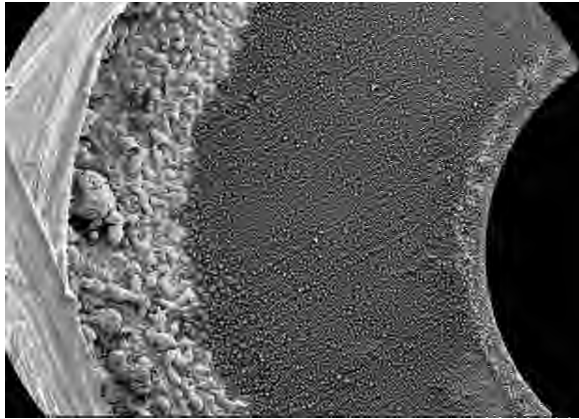
Heater/Radiation Shield



- Neutralizer radiation shield found to be in excellent condition with no sign of wear except for near downstream edge
- Arc tracks found on outermost surface of radiation shield, likely correlated with pitting on cathode orifice plate
 - Also found on NEXT 2 kh WT radiation shield, to a much lesser extent
 - Did not appear to have impact on ignition times or mechanical integrity of shield
- Heater was also found to be excellent condition except for texturing on downstream surface of coil, also likely correlated with pitting phenomenon
 - Resistance of heater found to increase slightly from 0.240 Ω (pretest) to 0.260 Ω (post-test)



Neutralizer Common-GND Low Impedance



- Observed low impedance between neutralizer common and facility ground during test, sometimes as low as $\sim 10 \text{ k}\Omega$
- Found to be caused by deposition within low voltage propellant isolator
 - Deposition found to have come from metallic ends, likely caused by arcing within isolator
- Plasma shield with relatively high open-area fraction downstream of LVPI may allow plasma to seed breakdowns within LVPI
- Evidence of arcing also found in NEXT 2 kh WT LVPI, but not in PM1R
 - PM1R LVPI (and present design) has plasma shield with much lower OAF, potentially mitigating issue



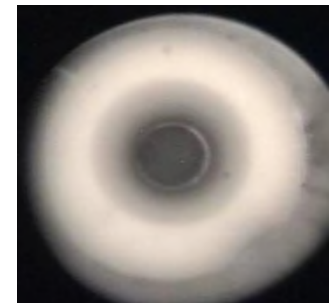
Unused EM LVPI



NEXT 2 kh WT LVPI

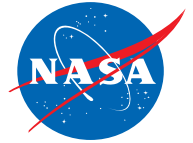


NEXT LDT LVPI



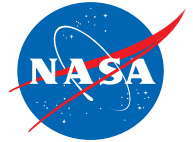
NEXT PM1R LVPI

Summary and Future Work



- Post-test inspection of LDT thruster hardware is nearing completion
- Major findings for discharge cathode
 - Maximum eroded depth of only 16% on keeper indicates substantial improvement in lifetime, successfully protecting internal cathode components from discharge plasma including cathode heater, radiation shield and most of cathode orifice plate
 - Downstream surface of cathode orifice plate exposed by keeper orifice showed significant erosion, creating deposits in keeper-cathode gap which led to observed electrical short
 - Only significant impact of electrical short is ~ 2.5 minute increase (on average) in discharge ignition time, which may have been exacerbated by attenuated ignition pulse
 - Intermittent heater open circuit observed during test caused by poor contact between heater sheath and cathode tube, which will be addressed in flight design

Summary and Future Work



- Major findings for neutralizer cathode
 - Significant deposition found on downstream face and within orifice of keeper electrode – impact of backspattered carbon on neutralizer flow margin will have to be assessed
 - Erosion on beam side of keeper tube was reduced compared to NEXT 2 kh WT, attributed to decrease in beam extraction diameter
 - Cathode orifice found to be enlarged, with shape differing from NSTAR ELT
 - Erosion of orifice has been correlated with observed loss of flow margin from plume mode
 - Evidence of arcing found on cathode orifice plate, heater and radiation shield downstream surfaces
 - Speculated to have occurred during thruster recycles, but did not cause any operational issues or loss of structural integrity
 - Low impedance between neutralizer common and ground caused by arcing within LVPI, and is not expected to occur with flight design
- Future Work
 - Insert analysis including characterization of barium depletion and tungstate formation (ongoing)
 - Consideration of further inspection of heaters such as cross-sectioning

Questions?

