AIAA Propulsion and Energy Forum
July 9-11, 2018, Cincinnati, Ohio
2018 Joint Propulsion Conference

10.2514/6.2018-4418

Update on the Nested Hall Thruster Subsystem for the NextSTEP XR-100 Program

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Under the NextSTEP program led by Aerojet Rocketdyne in collaboration with NASA Glenn Research Center, the University of Michigan, and the Jet Propulsion Laboratory, the XR-100 100 kW Electric Propulsion system is being developed to Technology Readiness Level 5. As part of this program, the X3, a Nested Hall Thruster designed to operate at powers up to 200 kW, is being further developed through parallel modeling and experimental efforts with the ultimate goal of supporting a 100 kW-100 hr system test in the final year of the NextSTEP program. Recent developments for the X3 subsystem are presented including a summary of testing and modeling results and design updates in anticipation of a risk reduction test scheduled for the summer of 2018.

Nomenclature

AR	=	Aerojet Rocketdyne
GRC	=	Glenn Research Center
JPL	=	Jet Propulsion Laboratory
LVTF	=	Large Vacuum Test Facility
MFC	=	Mass Flow Controller
NHT	=	Nested Hall Thruster
PPU	=	Power Processing Unit
SEP	=	Solar Electric Propulsion
TRL	=	Technology Readiness Level
UM	=	University of Michigan

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I. Introduction

Large-scale cargo transportation to support human missions to the Moon and Mars will require next-generation, high-power Solar Electric Propulsion (SEP) systems capable of operating between 200 and 400 kW. In an effort to spur technological innovation to meet this future need, the NASA NextSTEP program awarded three contracts in 2015 to companies for the purpose of advancing three high-power electric propulsion systems to a higher Technology Readiness Level (TRL). [1] The three-year objective of the NextSTEP program, projected to be completed in 2018, is to operate each selected EP system (including a power processing unit and flow controllers) continuously at 100 kW for 100 h, thereby demonstrating a TRL of 5. As one of the grant recipients, Aerojet Rocketdyne (AR) is developing the XR-100, a 100 kW EP system in partnership with the NASA Glenn Research Center (GRC), the University of Michigan (UM), and the Jet Propulsion Laboratory (JPL).[2] The XR-100 system builds off the X3, a 200 kW Nested Hall Thruster (NHT), [3]–[9] with the addition of AR-developed modular Power Processing Unit (PPU) and modular Mass Flow Controller (MFC) whose designs can scale up to the required 100 kW and beyond. The requirements and goals of the XR-100 system are shown in Table 1.

Table 1: NASA NextSTEP Program Objectives

Metric		**XR-100 Goal**
Requirement	TRL 5 demonstration power	100 kW
	TRL 5 steady state operation time	100 h
Objective	Specific Impulse	~2,000 to ~5,000 s
	Thrust per thruster	> 5 N
	Operational lifetime capability	> 10,000 h
	System efficiency	>60%
	Power per thruster	100 kW
	System specific mass	< 5 kg/kW

Over the past two years of effort, the XR-100 team has worked to prepare the NHT subsystem for the 100 h demonstration test in Year 3 through a series of risk-reduction activities. These have included analysis through modeling,[10]–[12] moderate design changes and optimization studies, and a series of short-term experimental test campaigns.[7], [8], [13] The purpose of this paper is to provide an overview of these most recent activities on the NHT development. To this end, in the first section, we describe the X3 thruster and its design capabilities. In the second section, we discuss modeling efforts related to the X3. In the third section, we provide a summary of the testing results from Year 2 of this project including a 100 kW risk reduction test performed at NASA GRC and a 10 kW system demonstration test at UM. In the final section, we conclude with an overview of the design updates that were motivated by the Year 2 tests and a discussion of a final upcoming risk reduction test planned for Summer 2018.

II. Thruster Overview

The X3, a three-channel NHT, is the baselined thruster subsystem for the XR-100 program. In contrast to traditional Hall thrusters that consist of a single, annular channel in which a plasma is created and accelerated, NHTs employ multiple concentrically aligned annular channels (Fig. 1). This geometric configuration enables both increased throttling and a higher power density at high power levels (> 50 kW) than single channel thrusters. At the same time, even though NHTs are a relatively new technology, many of the guiding design principles that have emerged over forty years of single channel Hall thruster research can be directly applied to its implementation. By leveraging these lessons-learned from this mature, flight-proven technology, NHTs thus can be built for high performance as well as the high-power goals of NextSTEP.

The X3 thruster is the result of a collaboration started in 2009 among the Air Force Research Lab, the Air Force Office of Scientific Research, NASA GRC, NASA JPL, and ElectroDynamic Applications.[9] Its design builds on heritage from multiple previous experimental thrusters including a two-channel precursor NHT, the X2,[14] as well as high-power single channel Hall thrusters built by NASA: the NASA-400M, the NASA-300M, and the NASA-

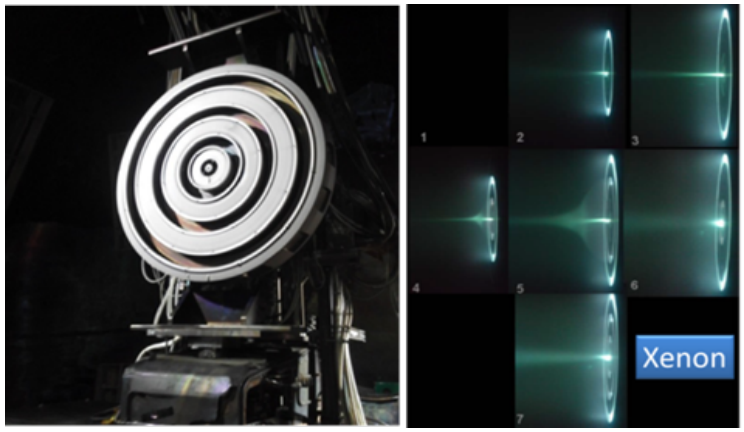

*Figure 1: **Left**: The X3 installed in the Large Vacuum Test Facility (LVTF) at the University of Michigan. **Right**: The X3 in six possible channel configurations.*

457M-v1 and NASA-457M-v2.[15]–[18] The X3 is the highest-power NHT developed to date, designed to have a wide throttling capability (2-200 kW, and 1600-3200 s specific impulse with xenon as a propellant) while maintaining high performance (> 60% overall efficiency). These performance metrics are sufficient to satisfy the NextSTEP programmatic goals (Table 1).

We summarize here key aspects of the X3 design and construction. A more complete description can be found in Refs. [8] and [9]. The X3 employs three independently-operated, annular discharge channels, concentrically placed around a center-mounted LaB_6 hollow cathode. The channels can be operated in seven different configurations: all firing concurrently, each channel firing individually, or any combination of two channels firing (Fig. 1). It is this versatility which contributes to the wide throttling range of this system. The X3 is capable of operating on both krypton and xenon, though for the XR-100 program, it exclusively has used the latter. The anode and the majority of the discharge chamber for each channel are comprised of one continuous cup of stainless steel. This cup, which is held at anode potential, is in turn insulated from the thruster body by segmented boron nitride rings mounted on the downstream ends. Each channel's magnetic field is generated by a set of two concentrically-wrapped electromagnetic coils (six coils in total). Iron magnetic poles between the channels serve to guide and shape the magnetic field generated by each coil pair. These pole pieces are shared between channels except at the innermost and outermost poles. The magnetic topography in each channel is configured in a lens shape though not with so-called magnetic shielding (c.f. Ref [19]). The overall thruster diameter is approximately 80 cm with a total mass of 230 kg. It is passively cooled—even at its highest design power of 200 kW.

The electron source for the NHT is provided by a 250-A class, centrally-mounted hollow cathode (Fig. 2) constructed by NASA JPL [20]. This element employs a molybdenum cathode tube, a tungsten orifice plate, and a graphite keeper. It can support gas flow through three regions: the central cathode bore, external flow injectors mounted around the keeper, and internal auxiliary injectors that flow gas through the gap between the keeper and cathode tube. The hollow cathode operates at a flow rate of 7% of the total flow through the anode during standard X3 operation. However, due to concerns about emitter erosion that can be precipitated at high internal flow rates, the maximum flow through the central bore of the cathode is capped at 20 sccm. At operating conditions where the total required xenon flow through the cathode exceeds this maximum, the auxiliary flow injectors are employed. The presence of this external flow has the additional benefit of reducing keeper wear that is known to onset at high discharge currents (see Sec. IV.C).

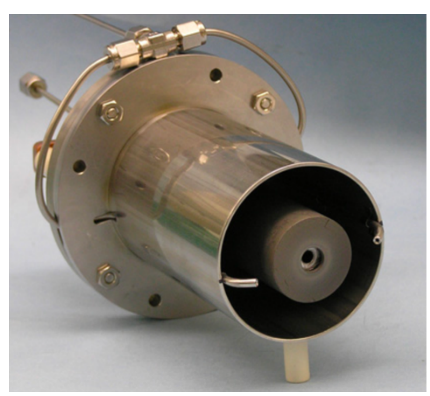

Figure 1: 250-A class LaB_6 hollow cathode from NASA JPL with external flow injectors

III.Modeling Overview

There have been several modeling activities in Years 1 and 2 of the XR-100 program in support of the X3 development. These include thermal analysis, plasma-based physics models, and magnetic models. [10]–[12] This section summarizes the major conclusions from these efforts.

A. Thermal Modeling

At the outset of the NextSTEP program, NASA JPL undertook an effort [10] to improve and refine the thermal model of the X3 that had originally been developed for its design. [9] The JPL model was intended to not only increase confidence moving into the 100 hr demonstration test at thermal equilibrium but also could be used as a numerical tool for exploring future design iterations. This model was constructed in the NX-SST software and consisted of a full Finite Element Mesh (FEM) generated from CAD drawings of the thruster. Although it incorporated a high degree of detail, there were still a number of undetermined parameters in this model relating to uncertainty about plasma thermal loading and thermal interfaces. It was originally planned that these parameters could be calibrated using experimental temperature data from Year 1 thermal testing of the thruster. Ultimately, it was found that the thermal data from these tests could not be used for this purpose—the thruster had not actually reached thermal equilibrium. Thus, although there are some preliminary and insightful results from the thermal model, it still requires additional experimental input. There is an upcoming final risk reduction test planned for Summer 2018 in which this data will be generated (see Sec. V).

B. Magnetic Field Modeling

The magnetic field topography in each channel of the X3 is intended to be implemented in the "plasma lens" configuration (see Fig. 3). This topology leverages design insights that emerged in the past two decades as to how to optimize the performance of Hall thrusters—particularly at high-specific impulse.[21], [22] Achieving this plasma lens configuration requires a judicious choice of current magnitudes and ratios in the electromagnetic coils adjoining each channel. In the X3, this tailoring of the magnetic field is complicated by the fact that the magnetic

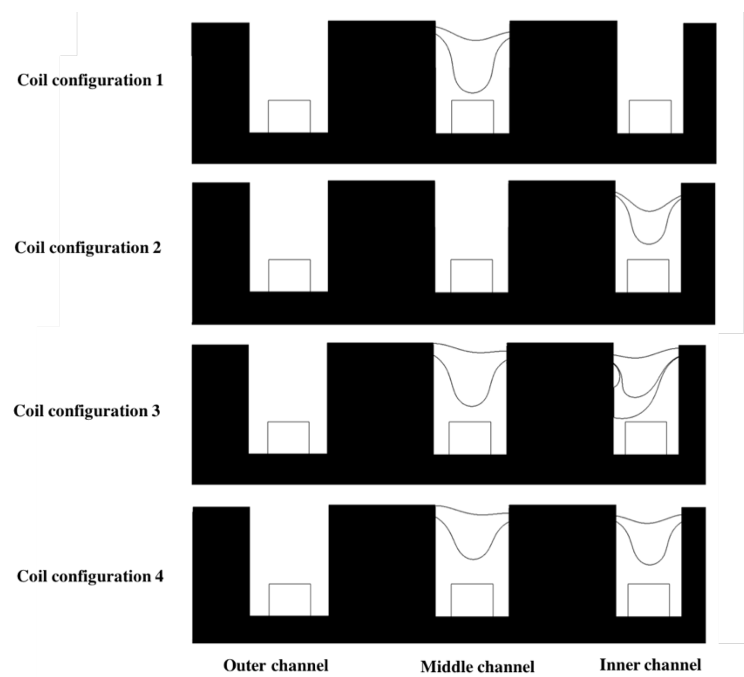

Figure 3: Illustration of consequences of magnetic core sharing in the X3. Configuration 1: only the electromagnetic coils for the inner coil are energized to create a lens shape; Configuration 2: only the electromagnetic coils for the middle coil are energized to create a lens shape; Configuration 3: The same current values through each set of coils are used from Configuration 1 and 2 but energized at the same time. Configuration 4: The coil settings have been adjusted to recover lensing in both channels. Figure adapted from Ref. [12] .

cores for shaping the magnetic flux are shared among channels. For example, the outer pole of the inner channel is the inner pole for the middle channel. There thus is a high-degree of coupling between the magnetic fields. This has led to the observation (Fig. 3) that in order to maintain a plasma lens shape, different current coil settings are required depending on the operating condition (i.e. single channel vs. multichannel).

In an effort to determine how to correct for this cross-channel coupling, team members from NASA JPL, NASA GRC, and UM implemented a high-fidelity magnetic field model of the X3. This consisted of simulating the thruster geometry in Infolytica's MagNetv7.7 while employing best practices for the convergence and accuracy of this software as applied to Hall thrusters.[23] The simulations outputs were then qualitatively validated against experimental measurement and used to inform the tailoring of the magnetic field to optimize performance for both single and multichannel operation. [12]. The optimized magnetic field settings that emerged from this study were employed in a test campaign conducted in Year 2 at NASA GRC. As discussed in Sec. IV.A, this test showed performance levels (> 60% efficiency) commensurate with state of the art Hall effect thrusters that employ the plasma lens topography.

C. Plasma Modeling

One of the design objectives (though not requirements) for the NextSTEP XR-100 program is to demonstrate a capability of 10,000 hours of operational lifetime (see Table 1). In order to assess the life of the X3 subsystem against this benchmark, team members from NASA JPL implemented a high-fidelity numerical plasma model of the thruster in the NASA JPL code, Hall2De. [11] Hall2De is an RZ, multi-fluid solver capable of tracking multiple ion fluids and electrons while simulating a full-scale thruster geometry. The X3 model implemented in Hall2De is, to our knowledge, the first full-scale simulation of a multi-channel Hall thruster. Figure 4 shows a sample output of the simulation of the X3 operating at 800 V and 100 kW.

The performance predictions from Hall2De were benchmarked against experimental measurements from one three-channel operating condition of the X3—a discharge voltage of 400 V and output power of 49.6 kW. The predicted thrust and anode specific impulse were shown to be within 5% of the measured values while the efficiency was within 10%. The preliminary erosion estimates from the code indicated that the downstream wear of the boron nitride rings is the dominant wear mechanism of the thruster with a projected erosion rate at 100 kW and 800 V of approximately 10^{-3} mm/h. Although this result would indicate the thruster in its current form may not achieve a 10,000 hour lifetime, we emphasize that these simulations for the X3 at this operating condition are subject to a high-degree of uncertainty. [11] Moreover, the X3 is a laboratory model and could be iterated upon to achieve higher life (c.f. Ref. [19]). Indeed, this numerical plasma model is just the type of numerical tool critical for such an undertaking.

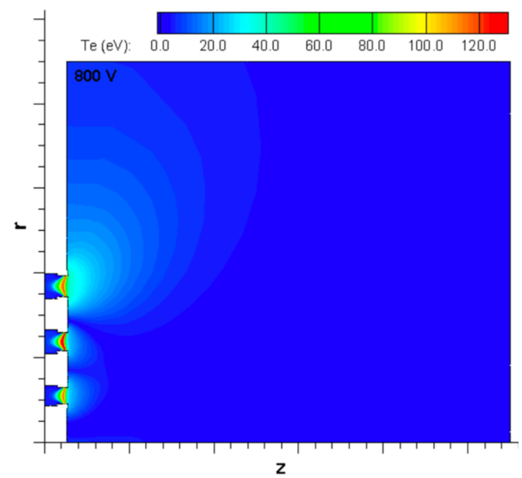

Figure 4: Sample of output from simulation of the X3 generated by JPL's thruster code, Hall2De. The data shown is electron temperature at the 800 V, 100 kW condition. Figure taken from Ref. [11].

IV.Thruster Testing

There were a series of risk reduction tests performed on the X3 in Years 1 and 2 of this program in preparation for the Year 3 100 kW-100 hr demonstration. We focus here on a summary of the Year 2 activities. These consisted of a risk reduction teste performed at NASA GRC, a system-level test at UM, and a cathode demonstration test at NASA JPL. These experimental campaigns in turn have informed minor design iterations to the thruster which will be validated in a final, reduced-power thermal equilibrium test conducted at UM in the summer of 2018.

A. 100 kW Risk Reduction Test

As part of the Year 2 effort, team members from UM and NASA GRC conducted a risk reduction test in the summer of 2017 in the VF5 vacuum facility at NASA GRC (Fig. 5). [8] There were both facilities-related and

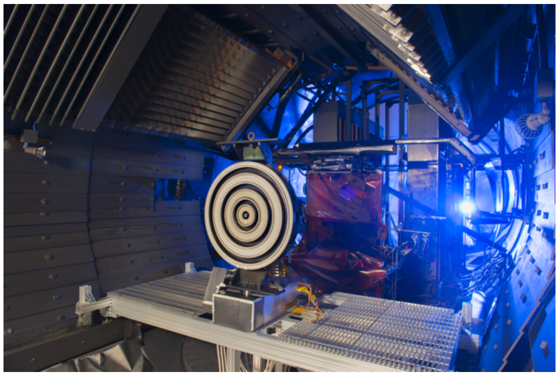

Figure 5: The X3 thruster installed in the VF5 facility at the NASA Glenn Research Center before the 2017 risk reduction test.

thruster subsystem-related goals for this campaign. With respect to the facility, the purpose was to identify any modifications or adjustments necessary to accommodate the high-power loading and large quantity of xenon throughput anticipated for the 100 kW-100 hr test. With respect to the X3, the primary objective was to identify any actions or modifications necessary to prepare the thruster for extended operation at 100 kW for the Year 3 test. This latter requirement was largely driven by the fact that due to the limited pumping capabilities of UM's Large Vacuum Test Facility (LVTF) at the time of the original development of the X3, the thruster had not yet been operated to 100 kW.

The performance of the X3 was successfully demonstrated over a wide range of operating conditions during this risk reduction test. These included discharge voltages from 300-500 V, discharge powers from 5-102 kW, and a maximum discharge current of 247 A. Key performance measurements for the thruster are shown in Fig. 6. The reported power levels in these plots correspond to different combinations of channels. The lowest power configurations (e.g. < 10 kW) consist of just the inner channel firing while the full power conditions (~100 kW) correspond to all three channels operating concurrently. As Fig. 6 shows, the maximum measured thrust for the system was 5.4 $\pm$ 0.1 N at 98.4 kW discharge power (400 V, 247 A). The maximum demonstrated specific impulse for this system at 100 kW was ~2600 s at a peak efficiency of 67 $\pm$ 0.03%. Referring to Table 1, we can see that this demonstrated thruster specific impulse, efficiency, and power level all satisfy the program objectives. They similarly allow for a PPU efficiency as low as 90% (the demonstrated system exceeds this [13]) while still achieving the 60% overall system efficiency objective. This campaign thus has established the capabilities of the X3 subsystem and increased confidence in the ability of the thruster and system to meet performance goals heading into the Year 3 test.

This risk reduction test also helped identify minor design changes in anticipation of the Year 3 test. Indeed, during a short-term, three-hour thermal soak at 80 kW, it was found that the gaps between the segmented boron nitride insulator rings (Sec. II) expanded as the thruster heated. The gaps eventually became sufficiently large that they posed a potential risk for allowing arcing from the thruster plasma to the body. This finding led to a design change in the ring configuration (discussed in Sec. V) to mitigate this effect. This new design will be tested in

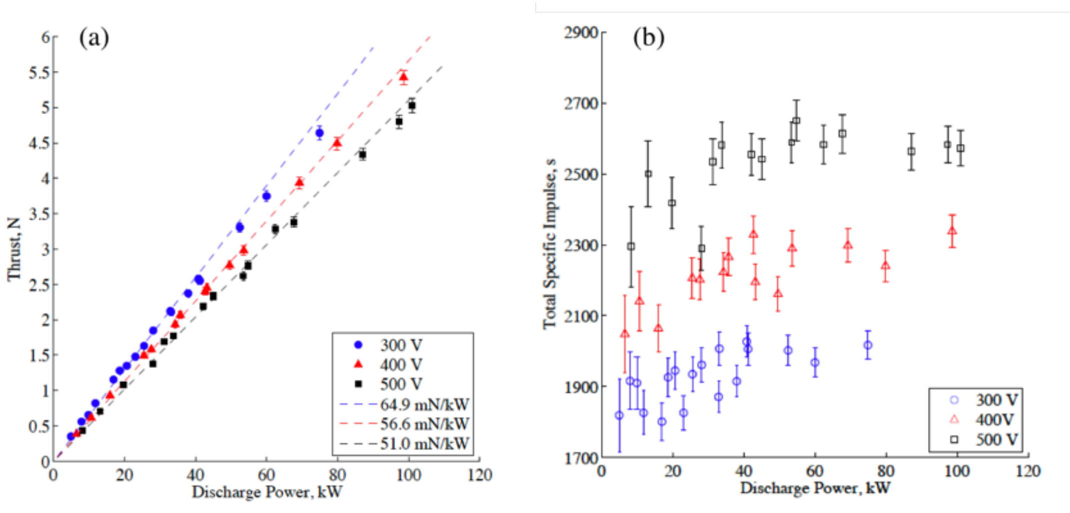

Figure 6: Performance measurements from X3 risk reduction testing at NASA GRC. a) Thrust as a function of discharge power for three discharge voltages. The dotted lines denote best fits to the linear trends. b) Measured total specific impulse as a function of discharge power for three discharge voltages. Fig. adapted from Ref. [8].

summer 2018.

B. 10 kW System Level Test

One of the programmatic goals of Year 2 of this program was to perform an end to end integrated system test with the X3, one of the modular PPUs developed by AR, and the modular MFC developed by AR. The major success criteria for this campaign, conducted in January 2018 in the LVTF at UM, were to demonstrate the ability of the MFC and PPU to operate the thruster at low power and at low and high voltage conditions. During this test, the MFC and PPU from AR controlled the thruster channels while the hollow cathode heater and keeper as well as the thruster magnets were operated on laboratory supplies. This is consistent with the intended configuration for the Year 3 100 hr test.

Overall, the system-level test met all of its objectives and provided increased confidence moving into Year 3 testing. As Fig. 7 shows, the PPU and MFC successfully operated the X3 at 10 kW at voltages ranging from 300 V to 800 V. For the results shown here, the PPU commanded the voltage while the MFC was operated in manual control mode. Later in the test campaign, the PPU also demonstrated closed-loop control capability of the thruster discharge power.

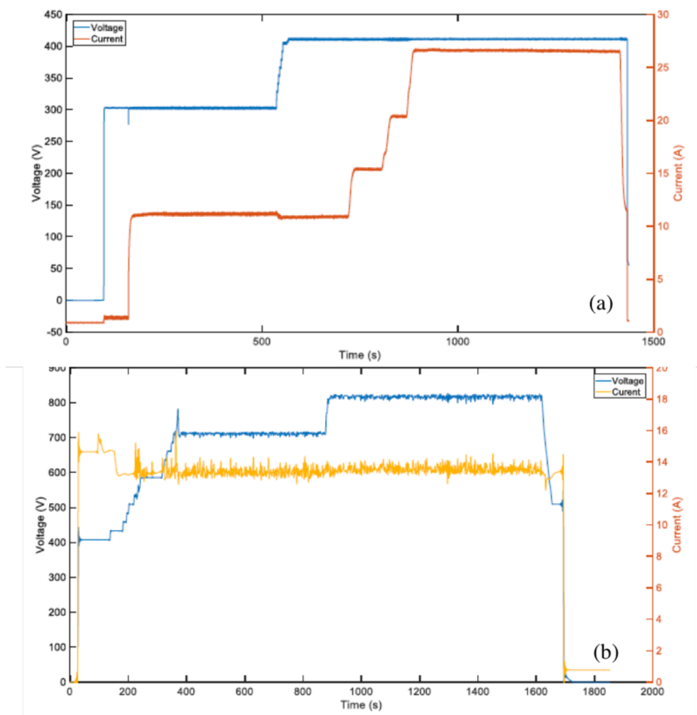

Figure 7: Discharge voltage and current from 10 kW systems test where the X3 was controlled by the AR PPU and MFC. a) Throttling up to 400 V conditions; b) Throttling up to 800 V. Figure adapted from Ref. 13.

In addition to the benefits and insight learned from the system level test, this campaign also highlighted the need for a few additional adjustments to the X3 itself. In particular, it was noted that at high-voltage operation, the thruster exhibited frequent (1-2 per minute) transient spikes (10-100 A) in the current. These events are represented qualitatively as the hash in discharge current in Fig. 7b. The amplitudes here (~2 A) are lower than the actual observed amplitude of the spikes (100 A) due to the low time-resolution of this particular dataset. The cause of these transients was not identified in this campaign, though in the opinion of the test operators, these were believed to be attributed to material erosion from the wear bands on the insulator rings. As discussed in Sec. V, for the 100-hr test, new discharge rings have been fabricated and installed. The fresh rings should mitigate this current spiking issue. The efficacy of this solution will be tested in the Year 3 thermal test at UM. We also briefly note here that even though these transients occurred, the PPU and MFC recovered after each event and the system continued to operate.

C. Hollow Cathode Testing

A third-generation 250 A LaB_6 hollow cathode was developed by JPL in Year 2 of this effort to support the upcoming Year 3 test. This cathode was implemented after the GRC risk reduction test and integrated on the X3 for the system level test (Sec. IV.B). Although there was no concern that the previous generations of cathodes used with the X3 would be able to support the 100 kW-100 hr demonstration test, the purpose of performing this cathode iteration was to demonstrate extensibility to the desired program objectives of NextSTEP (i.e. the 10,000 hour lifetime outlined in Table 1). To this end, design efforts were undertaken to reduce the two dominant life-limiting mechanisms of this device: emitter erosion from evaporation and keeper erosion by ion bombardment. For the

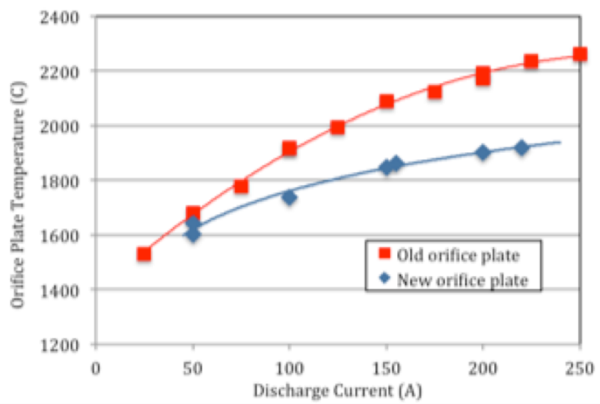

Figure 8: Cathode orifice plate temperature for the previous and third-generation LaB6 cathodes. Figure from Ref.8.

former concern, the cathode orifice diameter was expanded. This produced a larger view factor to the internal emitter and therefore facilitated enhanced radiative cooling of this surface. For the latter concern, two auxiliary gas injector mechanisms were added to the cathode to damp erosion-causing energetic ions in the plume. One scheme supplied gas through externally mounted tubes directed toward the near-field of the cathode while the other supplied gas through the gap between the concentric keeper electrode and cathode bore tube.

The efficacy of both upgrades are discussed in full detail in Ref. [20]. We outline here briefly the major findings. First, as shown in Fig. 8, it is evident that the increase in cathode size did effectively reduce the cathode temperature, thereby reducing the risk of failure through emitter erosion. For the second concern, both external injection schemes were shown to yield comparable capabilities in reducing the energetic content of ions downstream. Taken together, these two measures for prolonging lifetime were estimated to yield a cathode life at the full current required for the NextSTEP program (250 A) in excess of 10,000 hours.

V. Remaining Risk Reduction Activities and Testing for X3

As discussed in the preceding sections, both the modeling and experimental investigations in Year 2 have led to the need for minor design modifications to the X3 and additional risk reduction testing. Most notably, it is necessary to validate a new segmented insulator ring design that was implemented to ameliorate arcing concerns at high-temperatures. The tests conducted to validate this design simultaneously will serve the purpose of providing critical calibration data for the thermal model discussed in Sec. II.A.

With this in mind, we briefly discuss here the ring modifications to address the ring gap concerns. During the GRC risk reduction test, it was found that at the 80 kW power level after three hours of operation, the gaps between the segmented insulator rings expanded sufficiently that a conductive path formed from the discharge plasma to the thruster body. Although this type of gap growth was anticipated and had been observed in previous experimental campaigns conducted at lower power operation, the degree of spreading at high-power operation had not been anticipated. In order to mitigate this effect, a new ring design borrowing heritage from the NASA-457M [18] was implemented for each channel of the X3. This configuration is contrasted to the original ring configuration in Fig. 9. The principle of this new design is that even if the rings do spread laterally apart, there is sufficient overlap between the segments that the thruster body remains isolated from the plasma. Additional gasket material (not shown) also helps conserve the insulating barrier.

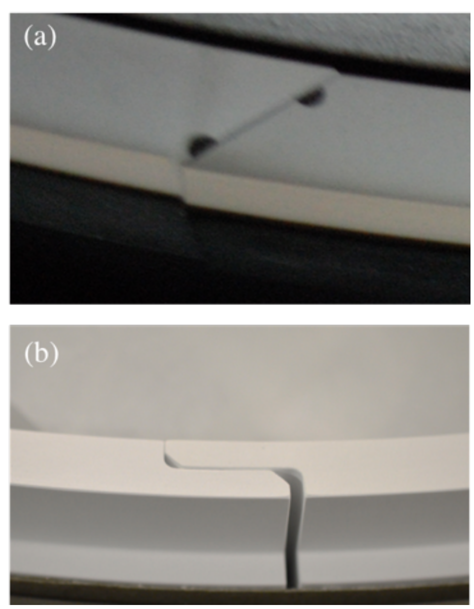

Figure 9: Segmented ring implementations with the a) old design and b) new design.

There is a need to test this new design modification in advance of the 100-hr test scheduled for Year 3. To this end, a reduced power risk reduction test is scheduled to be completed at UM in summer of 2018. This campaign will be conducted at 40 kW in the LVTF at UM. The major objectives of this test are:

- to demonstrate that the ring modifications do not change the global operating conditions, e.g. discharge current and oscillation characteristics
- to wear in the new rings at a high-voltage, high-specific impulse operating condition (> 700 V) in anticipation of the Year 3 wear test
- to demonstrate thermal steady-state operation of the thruster up to 40 kW with a maximum of 800 V on each channel.

This final task will also provide the required necessary measurements to inform the thermal model discussed in Sec. II.A. As of the submission of this article, this test is slated to conclude by July 2018.

VI. Conclusions

In this paper, we have outlined the efforts—both simulation and experimental—to prepare the X3 subsystem for the upcoming Year 3 test in support of the NextSTEP XR-100 program. From the perspective of performance targets, the X3 has now been operated to a level exceeding the full required power (102 kW) with demonstrated metrics commensurate with the program objectives, i.e. an efficiency > 60% and a specific impulse > 2000 s. From a system level test, we have demonstrated that the X3 subsystem can be integrated with the system architecture (PPU and MFC) that will form the basis of the Year 3 test. The results from both the system level and risk reduction tests pointed to a potential risk associated with the thruster operation: thermal spreading of the gaps between the segmented discharge chamber insulating rings. A new ring design, leveraging heritage from the high-power NASA-457M program, was implemented on the thruster to mitigate this effect. This modification, in addition to some final thermal steady-state testing, is slated to be completed and validated in an experimental campaign in summer 2018. In parallel with these experimental efforts, a significant modeling capability—including thermal, magnetic field, and plasma modeling—has been developed in support of this program. This modeling has already guided some optimization studies of the thruster, and it is anticipated that it will provide critical insight for follow-on efforts to adapt the XR-100 system for the next-level goals—including 10,000 hours of projected life.

In summary, the X3 subsystem is on track to be integrated into the Year 3 testing of the XR-100 system, and the combination of risk-reduction tests and modeling efforts have provided increased confidence in the success of the upcoming 100 kW-100 hr continuous operation test.

Acknowledgements

The authors would like to acknowledge funding and engineering support from the project leader, Aerojet Rocketdyne. Special thanks to Sarah Shark and Benjamin Welander from AR. The authors also would like to acknowledge the invaluable contributions of the students and staff of the Plasmadynamics and Electric Propulsion (PEPL) laboratory at UM to both testing and thruster development.

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