High Power Demonstration of a 100 kW Nested Hall Thruster System

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The XR-100 team successfully completed high power system testing of a Nested Hall Thruster system made up of the X3 Nested Hall Thruster, a modular Power Processing Unit, and a 5 valve Mass Flow Controller as the culmination of work performed under a NASA NextSTEP program. The test campaign attained several key records to date, including highest directly measured thrust of an electric propulsion (EP) string, highest demonstrated current of an EP string, and highest power operation of an EP string at thermal equilibrium published to date. Most importantly, the XR-100 system testing demonstrated that a 100 kW-class Nested Hall Thruster system has comparable performance and behavior to current state-of-the-art mid power Hall Thrusters, validating that the heritage technology can be scaled up to 100+ kW class. In addition to the outlined accomplishments and corresponding system demonstration, design improvements for future development and testing are discussed.

I. Nomenclature

AR	=	Aerojet Rocketdyne
DSU	=	Discharge Supply Unit
GRC	=	NASA Glenn Research Center
HPST	=	High Power System Test
Isp	=	Specific Impulse
LaB_6	=	Lanthanum Hexaboride
MFC	=	Mass Flow Controller
NextSTEP	=	Next Space Technologies for Exploration Partnerships
NHT	=	Nested Hall Thruster
PEPL	=	Plasmadynamics and Electric Propulsion Laboratory
PFCV	=	Proportional Flow Control Valve
PPU	=	Power Processing Unit

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SFC	=	System Flow Controller
TRL	=	Technology Readiness Level
UM	=	University of Michigan
VF-5	=	Vacuum Facility 5
XR-100	=	100-kW class Nested Hall Thruster propulsion system
X3	=	3-Ring Nested Hall Thruster

II. Introduction

NASA's Next Space Technologies for Exploration Partnerships (NextSTEP) program aims to mature key technologies that will enable human space exploration [1]. Under the NextSTEP program, Aerojet Rocketdyne (AR) led a team composed of NASA Glenn Research Center (GRC), NASA Jet Propulsion Laboratory (JPL), and the University of Michigan (UM) to advance the development of the XR-100, a 100-kW class Hall Thruster propulsion system [2]. The XR-100 propulsion system consists of UM's X3 Nested Hall Thruster (NHT), AR's modular Power Processing Unit (PPU), AR's modular Mass Flow Controller (MFC), and JPL's high current hollow cathode. The XR-100 is intentionally designed for modularity to accommodate continued scaling of the capability as needed. Powers as high as 300 kW or more could be achieved in the future with the addition of more discharge channels to the NHT, more Discharge Supply Units (DSU's) to the PPU, and more Proportional Flow Control Valves (PFCV's) to the MFC. The goal of the program was to advance the XR-100 to Technology Readiness Level (TRL) 5, establishing the viability of the technology at the 100-kW class. This was to be demonstrated in a program-culminating test campaign with the objective of operating the propulsion system at 100 kW for 100 continuous hours. The central goals driving these quantitative metrics were to 1) demonstrate the technology can achieve high power as a system, 2) can achieve thermal steady state, and 3) can maintain stable operation beyond thermal equilibrium. Many propulsion technologies work well at low TRLs as a thruster alone or for short durations, but issues with the underlying physics become more apparent at full power, at the system level, and for extended durations up to and beyond thermal equilibrium. By exercising the system in this way, the NextSTEP program could evaluate whether the high power capability has fundamental limitations or if further technology maturation is feasible.

In the case of the XR-100 NHT propulsion system, the 100 kW-class capability is based on proven flight technology – Hall thruster systems. The first Hall thrusters were flown by the Soviet Union in 1972 [3], and Hall thrusters continue to be chosen to this day to support satellite operations for their high efficiency and long life. All of the subsystem designs making up the XR-100 system are based on heritage designs [4-7]. The expectation is that the XR-100 Nested Hall Thruster system will behave like a flight state-of-the-art Hall thruster system – with some unique challenges - allowing the team to utilize lessons learned and experience on other Hall thruster systems to inform development activities.

In the preceding three years of the program, risk reduction activities were performed at the subsystem and system level in preparation for the final high power system demonstration. These risk reduction activities included standalone NHT testing up to 100 kW [4], a 10 kW integrated system test [5], a 45 kW PPU test [6], high current cathode development and testing [7], and NHT plasma and thermal modeling at JPL [2, 8-10]. The X3 was designed to operate at discharge powers up to 200 kW, but in its prior development program, it had only been demonstrated up to 30 kW [11]. In 2017, the X3 was operated up to 100 kW discharge power at GRC in the same facility using the same test equipment as the final system test. It validated that the facility could handle the high flow rates and thermal load for short and midterm durations and demonstrated that the X3 NHT could reach high power as designed [4]. Lessons learned from the 100 kW NHT testing also drove improvements to the thruster to better support high power operation. The 10 kW integrated system test performed in early 2018 at UM's Plasmadynamics and Electric Propulsion Laboratory (PEPL) validated that UM's X3, AR's PPU, and AR's MFC could all operate together as an EP string successfully [5]. The 10 kW system test operated a single channel of the NHT with a single DSU in the PPU using three of the valves in the MFC (one for the channel and two for the hollow cathode) [5]. The 10 kW system test demonstrated closed-loop control of the NHT for current and flow rate and operated the system at low voltage (400 V) and high voltage (700 and 800 V). Lessons learned from this test drove design improvements to the MFC, circuit adjustments in the DSU, and software updates in the System Flow Controller (SFC). The 45 kW PPU test, preceded by tests of a single DSU up to 15 kW, validated that 3 DSU's could work together in a master-slave relationship to power a single resistive load [6]. It also validated that the control architecture could properly control and balance the power load across multiple DSU's. In parallel, JPL tested and refined their lanthanum hexaboride (LaB_6), high-current hollow cathode design to support high power operation of the NHT [7]. Thermal models and plasma modeling with JPL's OrCa2D code were used to drive design improvements to the thermal management of the cathode, allowing for higher cathode currents and longer lifetimes. These cathodes were used during all NHT subsystem and system tests. And in support of the many test activities described, JPL performed the first-ever simulation of a Nested Hall thruster using their Hall2De code [2, 8, 9]. JPL also developed a multi-channel thermal model of the NHT and the hollow cathode that were used to interpret thruster test results and guide development of the hollow cathode [10]. Each test and analysis performed over the course of the program burned down risk, identified design improvements, characterized subsystem performance, and/or defined the test conditions for the final high power system test.

III. System Test Overview

The XR-100 high power system test (HPST) was performed at NASA GRC in Cleveland, Ohio in early 2019. Fig. 1 provides a simplified block diagram of the system test set up and location of the subsystems inside and outside of the vacuum chamber facility. Objects in the diagram are not to scale.

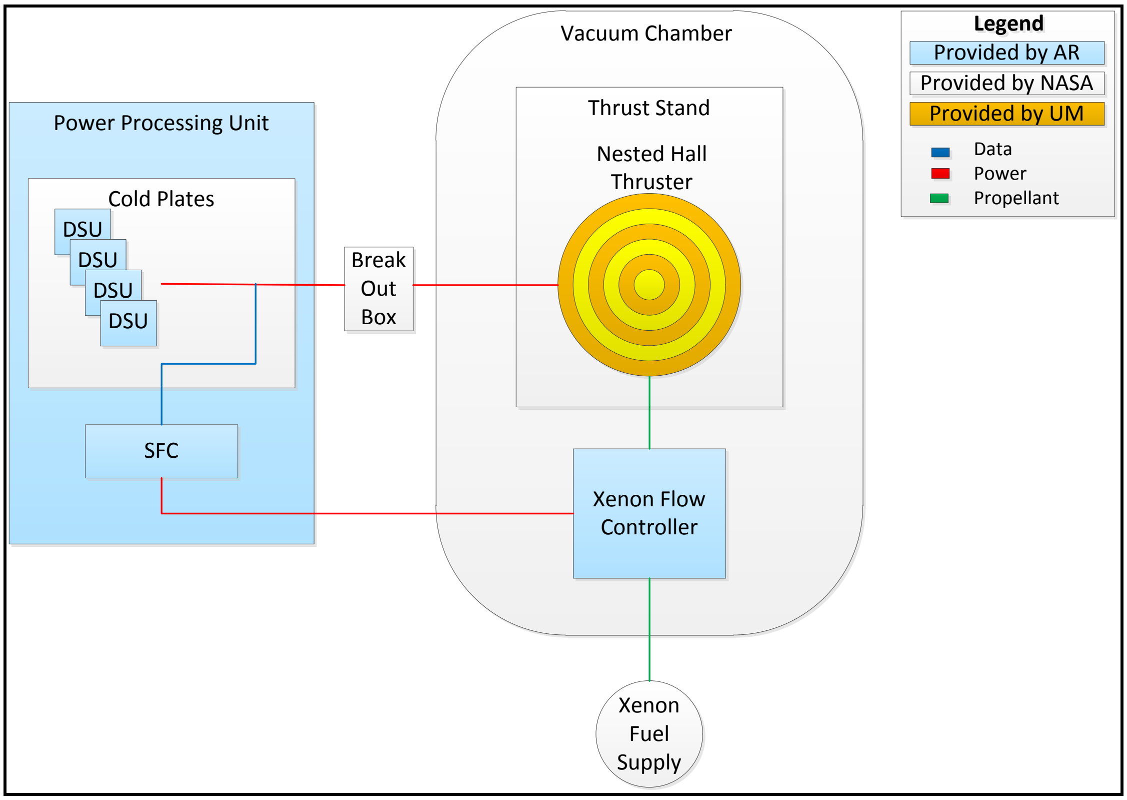

Fig. 1 Simplified block diagram of the XR-100 High Power System Test (not to scale).

A. X3 Nested Hall Thruster

The University of Michigan's X3 NHT is made up of three concentric discharge channels with a center-mounted cathode and was designed to operate up to 200 kW discharge power [12]. It was designed to operate at discharge voltages from 200 to 800 V and discharge current up to 250 A. The lanthanum hexaboride (LaB_6) hollow cathode was designed, tested, and provided by JPL and can support discharge currents of greater than 300 A [7]. It utilizes external gas injectors to support high flow, high current operation. The X3 NHT was first built by UM under another program in partnership with NASA GRC, JPL, and the Air Force Research Laboratory (AFRL) [12]. The design builds off of NASA GRC's experience with high power Hall Thrusters, particularly the NASA-457M thruster that achieved 97 kW thruster operation [13-15]. The X3 NHT is radiation cooled, with no active water cooling employed during any of the thruster testing. Fig. 2 shows the X3 NHT installed in the vacuum facility prior to the system test.

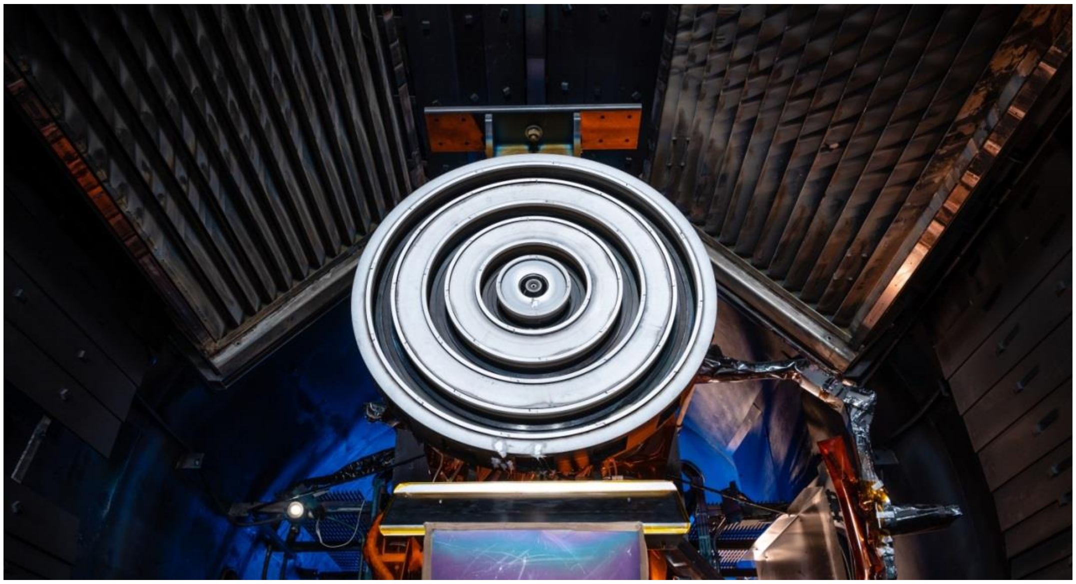

Fig. 2 X3 Nested Hall Thruster installed on a thrust stand in VF-5.

B. Power Processing Unit

Aerojet Rocketdyne's PPU is composed of 15 kW Discharge Supply Units (DSU's) modules - a sibling to AR's Advanced Electric Propulsion System (AEPS) DSU design [6,16] - and a System Flow Controller (SFC) to control the MFC. Each DSU is made up of 1 input filter, 1 output filter, 4 power modules, 4 power module controllers, and 1 master control board. The DSU was designed to operate optimally at 350-400 V and 700-800 V, with switchable configuration of the power modules allowing for both high efficiency (high voltage) and high thrust (low voltage) system operation.

Fig. 3 Three Discharge Supply Units mounted on cold plates in a rack.

As shown in Fig. 1, the PPU was located outside of the vacuum chamber. This is consistent with AR standard practices, lowers risk, and allows for access to the PPU without having to open the chamber. That last point is especially relevant, as the EM-level design of the DSU has a manual switch to change power module configuration for low voltage or high voltage operation. Separate vacuum testing of a single DSU was performed to validate that the design can achieve thermal equilibrium while operating in a vacuum environment. For the HPST, each DSU was installed on a cold plate, with facility water run through a chiller before flowing to the heat exchangers on the cold plates. Each chiller supplied water to two DSU's in series. Fig. 3 shows three DSU's mounted on cold plates in a rack. These racks were used to efficiently co-locate the many DSU's required for the high power system test.

As demonstrated in the 10 kW system test [5], the Inner discharge channel of the Nested Hall Thruster can be operated like a state-of-the-art Hall thruster system, employing a single DSU to supply discharge power. For the Middle and Outer discharge channels, modular groupings of DSU's were employed to deliver the higher discharge power required. In those cases, one DSU in the group controls the other DSU's in a master-slave relationship previously demonstrated in the 45 kW PPU test in 2018. At the beginning of the HPST, the DSU's were distributed as 1 DSU for the Inner channel, 2 DSU's for the Middle channel, and 4 DSU's for the Outer channel. Later, the DSU's were redistributed as 3 DSU's for the Middle channel and 4 DSU's for the Outer channel. The final three channel system operation was run in this configuration, with a 30 kW lab power supply used to supply the Inner channel discharge power. Had another DSU been available, that would have been employed in place of the lab power supply, but schedule limitations precluded the team from building an additional DSU in time.

For the HPST, the SFC controlled the MFC through closed-loop current control. The operator would command a discharge current through the graphical user interface (GUI), and the SFC would send a small level of drive current to the PFCV to open the valve. Feedback measurements from the laboratory breakout box (BoB) of that channel's discharge current informed the SFC to send more or less drive current to the valve to increase or decrease the flow until it reached and maintained the commanded discharge current. For the cathode PFCV's, flow rates were calibrated to the downstream pressure as measured by the integrated MFC pressure transducers prior to system operation and closed-loop controlled on this measured pressure by the SFC.

C. Mass Flow Controller

Aerojet Rocketdyne's MFC is made up of five PFCV's – one for each anode channel and two for the hollow cathode. The MFC design features a pressure transducer integrated downstream of each PFCV that can be used for closed-loop pressure control. Prior to the HPST, characterization tests were performed on the MFC to characterize the pressure curves and drive current required for each PFCV to deliver the required flow rates. The MFC was installed next to the X3 NHT on the same platform, as shown in Fig. 4 in the yellow box on the right. The body of the MFC maintained contact with the metal platform during testing, experiencing passive conductive cooling through the platform.

Fig. 4 X3 Nested Hall Thruster (left) and Mass Flow Controller (squared right) inside the vacuum chamber.

D. Vacuum Facility and Test Equipment

The HPST was performed in Vacuum Facility 5 (VF-5) at NASA GRC. VF-5 is a 4.6-m diameter, 18.3-m long cylindrical vacuum chamber that contains 33 m^2 of cryogenic pump surfaces which provide a pumping speed of approximately 700,000 L/s on xenon. The cryogenic panels and facility walls are covered in graphite panels to minimize backsputter during thruster operation. Facility pressure was monitored with an ionization gauge mounted approximately 1.5 m from thruster centerline, in-plane with thruster exit and facing downstream. Facility base pressures were typically on the order of $1x10^{-7}$ Torr. At the highest flow rates demonstrated, the maximum operating pressure observed was approximately $6x10^{-5}$ Torr-Xe.

Much of the testing infrastructure was previously used during the 2017 risk reduction testing of the X3 NHT in VF-5 [4, 17], with certain changes for system operation. As described above, the thruster discharge was operated off of the AR DSU's. The cathode heater and keeper and the thruster electromagnets were operated off of separate laboratory supplies as in 2017. Xenon flow to the MFC was measured using a 2000-sccm commercial flow controller and was controlled using the AR MFC described above. Otherwise, the test apparatus remained unchanged from the 2017 configuration, as follows. Electric propulsion-grade xenon propellant was provided through the MFC to the thruster using electro-polished stainless steel feed lines. Thruster telemetry was monitored at approximately 0.5 Hz using the breakout box and data logger implemented for the 2017 testing. Low frequency measurements were taken of the discharge voltage and current of each discharge channel, cathode to ground voltage, magnet voltage and current, and DSU input and output voltage and current. Commercial oscilloscopes and high-speed current and voltage probes were used to monitor the high frequency behavior of the discharge current and voltage of each of the three channels of the NHT.

Thermocouples were placed throughout the thruster, on each magnet coil, on the MFC valve body, and on each DSU to monitor system temperatures and verify thermal equilibrium. Three cameras were employed looking at the front, back, and long range view of the thruster to visually monitor the thruster behavior, and end-on high resolution photos of the NHT were taken periodically through a viewport in the vacuum chamber.

E. Thrust Stand

Thrust was directly measured using an inverted-pendulum thrust stand capable of measuring up to 8 N of thrust. This stand was previously used during the 2017 NHT risk reduction testing and was based on a thrust stand developed at the University of Michigan for X3 NHT testing there [4, 18]. The thrust stand operates in null mode, is calibrated in-situ using a string of known masses, features active inclination control, and is held at a fixed temperature using water coolant to prevent thermal drift, following industry best practices [19-21]. As described by Hall [17], the stand features design modifications to accommodate the large mass and high thrust of the X3 NHT but still operates with the same principles as other inverted-pendulum stands. A cable "waterfall" was developed specifically for the high-current and multi-channel requirements of the NHT, and was designed to minimize hysteresis in the thrust measurement. This waterfall was successfully used in the 2017 NHT risk reduction testing. In-situ calibrations were performed at the beginning of each test day, and zeros were collected an additional 1-3 times throughout the day as testing allowed. Thermal drift (as characterized by zero drift) was found to be between 1-2% of the measured thrust value across a day of testing. This thermal drift was accounted for in post-processing of the thrust values. Using the analysis technique developed by Mackey [22], which includes effects such as calibration variation, the weight of the thruster and stand, and inclination uncertainty, the uncertainty of the measurements reported here was determined to be approximately 0.8% of the highest measured thrust of this campaign, or approximately 36 mN. This value is dominated by uncertainty and resolution of the inclination control.

F. Test Objectives

As discussed in Section II, the objective of the HPST was to operate the system at 100 kW for 100 continuous hours to demonstrate the viability of the high power capability at relevant operating conditions for long duration. Based on the pump saturation capacity of the VF-5 vacuum pumps, the XR-100 test would have to be run at 800 V to achieve 100 continuous hours of system operation. However, the X3 NHT had not been previously demonstrated at high powers at high voltages. The 2017 thruster-only testing operated the NHT in VF-5 at 300 V, 400 V, and 500 V at high powers up to 100 kW but did not reach thermal equilibrium or high voltage [4]. The 10 kW System test in early 2018 operated the Inner channel of the thruster at 700 V and 800 V to demonstrate the system could handle high voltage operation for short duration [5]. In 2019, additional X3 NHT testing was done at PEPL Large Vacuum Test Facility (LVTF) to demonstrate thruster thermal steady state at 400 V, 30 kW. A thruster anomaly ended the test approximately one hour shy of thermal equilibrium. The HPST was therefore reprioritized to demonstrate system thermal equilibrium at high power greater than 50 kW, something that had yet to be demonstrated at the thruster or system level. Data from a test like this would help inform future design work and would provide validation that the technology can achieve a stable and passively manageable thermal steady-state during operation. Following demonstration of system thermal equilibrium, the second objective would be to demonstrate system operation at 100 kW.

IV. System Test Results

Integrated system testing was initially unable to maintain operation for long durations: the Middle channel was not operating in a thermally stable way at the lower current density provided by 2 DSU's. To address this, the Inner channel DSU was reconfigured to be a third Middle channel DSU and the system was run as a two-channel test. Once the system achieved thermal equilibrium on two channels, the Inner channel was added back in on a lab power supply to demonstrate three channel system operation and attempt to reach 100 kW.

A. Thermal Equilibrium Operating Point

As discussed in Section IIIF, the HPST was reprioritized to demonstrate system thermal equilibrium at high power (>50 kW). The lowest risk operating condition was chosen in support of this new objective, and testing was performed at 300 V running the Middle and Outer channels off of 7 DSU’s. The NHT had been previously demonstrated at high powers at 300 V [4], Hall thrusters were historically more stable at lower voltages, and 300 V was near the design range of the DSU’s. Discharge current was limited to 80 A on the Middle channel, as that was the highest current that had been previously demonstrated on that channel, and there were known and unknown risks beyond 80 A that had not been fully vetted. The Outer channel discharge current was limited to 140 A for a number of reasons: first, it was near the output current limitations of the DSU’s; second, it was near the highest flow rate ever output through the PFCV; and third, the combined (planned) Inner, Middle, and Outer channel flow rates were nearing the highest flow rates ever run in VF-5. Operation at such high flow rates had not been run in VF-5 for long duration, and there was a risk that the sustained high flow rates along with the heat load might crash the vacuum pumps. The facility risk was balanced against the lower system risk, so the 300 V, 220 A two channel operating point was chosen, for a 66 kW discharge power and 73.5 kW total system power.

B. Thermal Equilibrium Results

The XR-100 successfully reached thermal equilibrium with two channels operating at 73.5 kW total system power following magnet bakeout and thruster conditioning. A picture of the XR-100 operating at this condition is shown in Fig. 5. The dark spot on the left side of the image is an obstruction in the camera field of view. This is the highest power operation of an EP string at thermal equilibrium published to date.

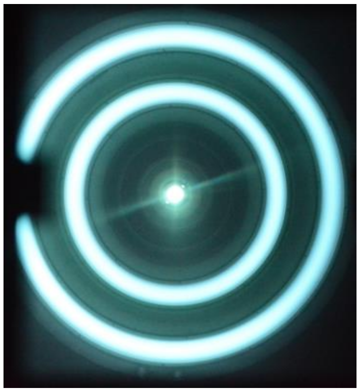

Fig. 5 XR-100 Nested Hall Thruster Propulsion System operating two channels at 73.5 kW.

Thermal equilibrium is defined in this test program as temperature changes less than 1 degree Celsius per hour. As discussed in Section III and shown in Fig. 6, thermocouples were placed throughout the thruster and monitored over the course of the test to characterize the thermal behavior of the thruster. Once the 73.5 kW operating point was reached at t+6 hours in Fig. 6, all thruster temperatures equilibrated within 6 hours. The DSU temperatures stabilized within 1 hour of reaching the 73.5 kW operating point; this thermally stable behavior was repeated during the single DSU vacuum testing at 10.5 kW discharge power into a resistive load.

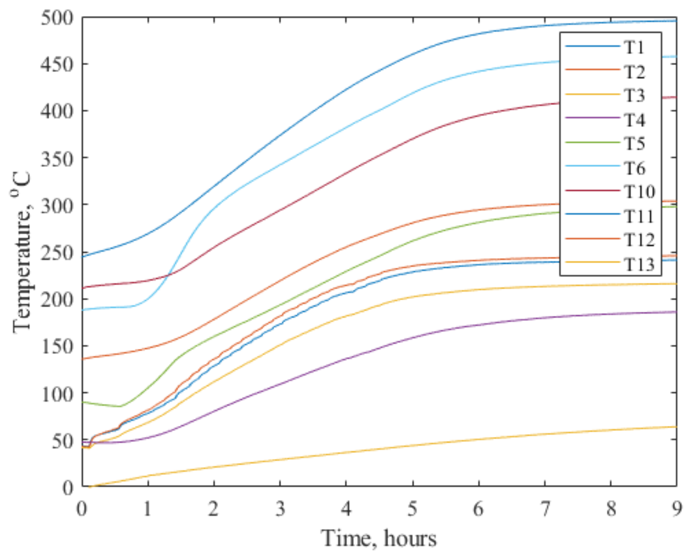

Fig. 6 Temperatures at various thruster locations during ramp up and steady state operation during thermal equilibrium testing.

Cathode to ground voltage is shown in Fig. 7. This voltage is an indication of cathode coupling and, indirectly, of thruster voltage utilization efficiency. A smaller cathode to ground voltage magnitude indicates improved cathode/thruster coupling and that a larger portion of the applied discharge voltage is available for beam ion acceleration. Typically, cathode to ground voltage in Hall thrusters is expected to be in the range of -5 to -15 V. As is shown in Fig. 7, cathode to ground was approximately -9.3 V throughout the 73.5 kW dwell. The magnitude of the voltage is in family with previous X3 NHT test results from the 2017 testing [4], and the fact that it stays constant indicates that the thruster was operating consistently throughout the run. Though plasma diagnostics would be needed to further interrogate thruster operation, this value—and the fact that it matches those found during previous testing where plasma diagnostics were used to measure thruster utilization efficiencies [4, 17]—can be seen as a simple indication of the health of the thruster during this run.

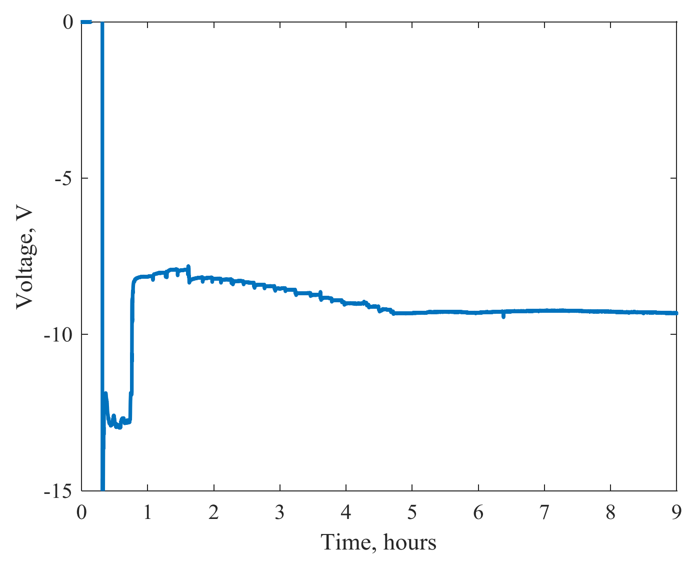

Fig. 7 Cathode to Ground Voltage measured during thermal equilibrium testing.

The PPU evenly distributed the power load across all power modules during ramp up and while at steady state operations up to and beyond system thermal equilibrium. Fig. 8 and Fig. 9 show the distributed load for both voltage and current across all 16 power modules within the 4 DSU's supplying discharge power to the outer channel of the X3 NHT during the thermal equilibrium test run.

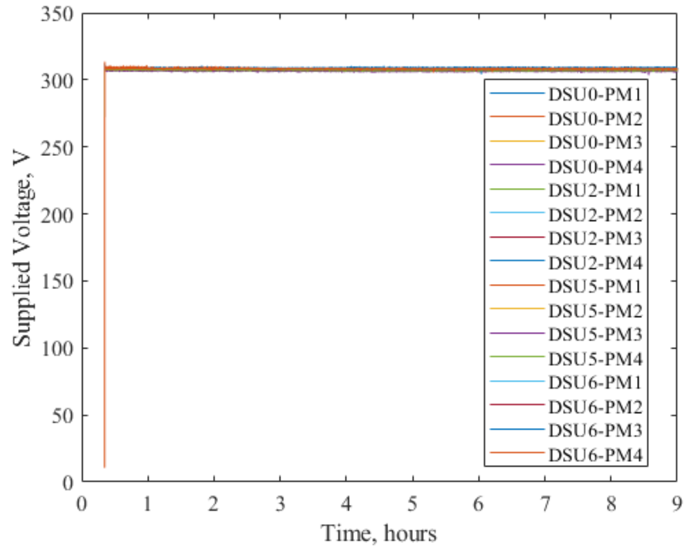

Fig. 8 Equally distributed discharge voltage across all power modules supporting the Outer channel during thermal equilibrium testing.

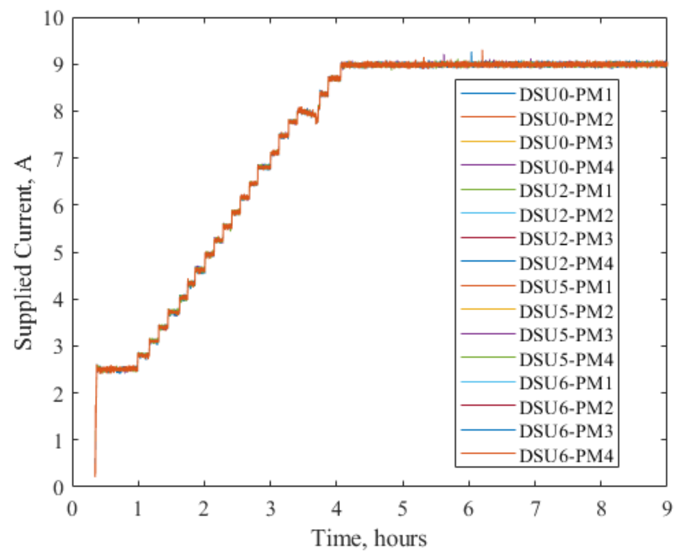

Fig. 9 Equally distributed discharge current across all power modules supporting the Outer channel during thermal equilibrium testing.

The XR-100 system was controlled by the PPU's SFC using closed-loop current control on the discharge channels and closed-loop flow control on the cathode throughout the test run. This control architecture was employed throughout the test sequences, which included soft start procedures, ramp up on current, and steady state dwell operation to thermal equilibrium and beyond. All four valves (two anode, two cathode) were controlled independently and maintained constant outputs, illustrated in Fig. 10 for the Outer discharge channel. As the PFCV operates for long duration and reaches higher temperature, the valve requires less drive current to maintain a constant flow rate output, so the blue line representing Outer valve drive current decreased while the black line representing Outer channel discharge current remains constant.

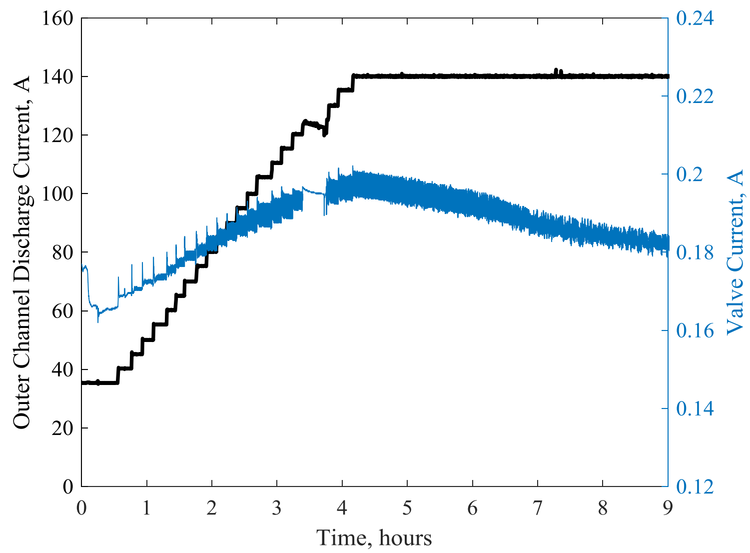

Fig. 10 Closed-loop current control of the Outer channel discharge current (black) by varying the valve current (blue).

C. Three Channel High Power Results

Following demonstration of system thermal equilibrium, the second objective of the HPST was to demonstrate system operation with all three channels at high power. As mentioned in Section IIIB, a 30 kW lab power supply was used for the Inner channel at the end of the test campaign to support three channel operation. Had a spare DSU been available in the short test timeframe, it would have been implemented instead. The lab power supply was limited to 25 A current output, for a total discharge current with all three rings at 245 A. This is just below the highest flow rate previously demonstrated in VF-5 for short durations during the 2017 NHT test [4]. First, the XR-100 was tested with all three rings at 300 V and 245 A to demonstrate stable system operation with all three channels. Fig. 11 is an end-on view of the NHT as the system operated all three channels at 300 V, 80 kW total system power. The dark spot on the left side of the image is an obstruction in the camera field of view.

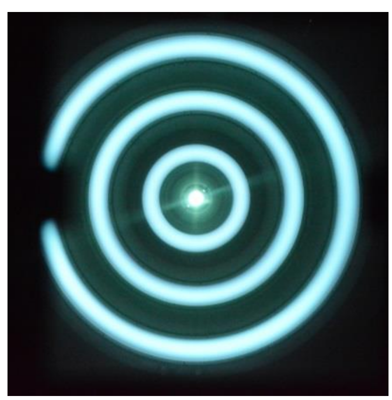

Fig. 11 Three channel operation of the XR-100 system at 300 V, 80 kW total power.

Once stable three channel operation of the system was demonstrated at 80 kW total power, testing moved on to the third objective: 100 kW total power operation. Because of the flow rate concerns for the facility and aforementioned current limitations on each channel, increased power could only be achieved by increasing discharge voltage. Once the three channels were operating stably at 300 V and 245 A total discharge current, the voltage was increased in 10 V increments, as illustrated in Fig. 12. System performance was measured at 310 V (82.3 kW total power) and 320 V (85.4 kW total power), and system operation was briefly demonstrated up to 350 V (~94 kW total power) before a high current event ended the test campaign. Ultimately, the system was demonstrated at total system powers above 85 kW for short durations, though not to thermal equilibrium.

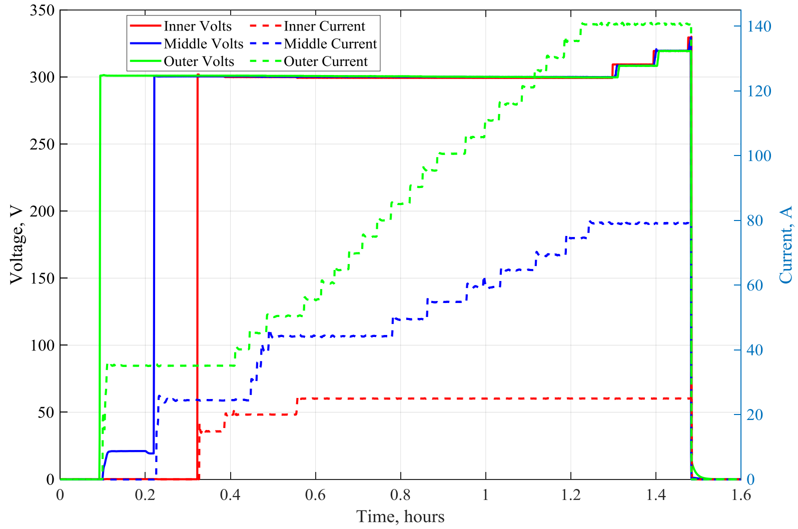

Fig. 12 Three channel operation of the XR-100 system ramping up to high power. Solid lines are voltage measurements, dashed lines are current measurements.

D. Summary of System Performance

Thruster and PPU performance were measured throughout the test campaign. Table 1 gives a summary of the system performance measured during this test campaign at low discharge voltage and high power.

Table 1 Summary of XR-100 System Performance at Low Voltage

Inner	Middle	Outer	Total Power	Thrust [mN]	Isp [s]	System Efficiency
-	300V/79.3A	301V/141A	73.7 kW	4100	1976	56.9%
-	300V/79A	300V/141A	73.7 kW	4080	1951	56.0%
299V/25A	300V/78.9A	300V/141A	80.1 kW	4574	1960	56.1%
309V/24.9A	308V/78.7A	308V/140A	82.3 kW	4600	1974	55.5%
319V/25A	320V/79.2A	319V/141A	85.4 kW	4658	2012	55.3%

The first three columns give the discharge voltage and discharge current as measured at the breakout box for the Inner, Middle, and Outer discharge channels. Total Power is the total system input power calculated at that operating point, which includes magnet power and PPU input power. The methodology to calculate thrust, total specific impulse (Isp), and thruster efficiency are the same as was used during the 2017 NHT standalone testing and are fully detailed in Hall et. al. [4]. Thrust measurements were averaged over a 60 second period and corrected for zero drift and inclination using best practices as outlined in Section II. The PPU demonstrated greater than 95% efficiency throughout low voltage operations, and the combination of thruster efficiency and PPU efficiency was used to calculate system efficiency for each operating point. The XR-100 NHT system demonstrated system efficiency between 55-57% at low voltage, with higher system efficiency expected at higher voltages and with the implementation of magnetic field optimization [17].

V. Discussion

A. Major Accomplishments

The system test achieved thermal steady state at the highest power of an EP string to be published – in this case, at 73.5 kW total system power [3, 23, 24]. This thermal equilibrium data set is valuable for several reasons: it provides empirical anchoring for the JPL multi-channel thermal model to help better understand multi-channel thermal interactions, it demonstrates that the system can achieve a thermally stable operating point at high power, and it identifies areas of improvement to support future programmatic requirements like 1000 hour continuous operation. This test campaign also demonstrated the highest directly-measured thrust of an EP string – 4.1 N during thermal equilibrium with two channels, and 4.6 N when operating three channels with the Inner channel on a lab power supply. The system test also demonstrated the XR-100 system with all three channels at high current – in this case, two channels at 220 A on DSU's only and three channels at 245 A with the Inner channel on a lab power supply. This is the highest current operation of an EP string to be published to date. Much of the development efforts in the EP community have been focused on the thruster alone, but the system-level focus of NASA's NextSTEP program drove the development of the other subsystems of the XR-100 EP string to support 100 kW system operation. The development of the high power PPU was a major accomplishment on its own, and this system test was also the highest power PPU demonstration published to date – up to 87.7 kW output power for short duration and 66 kW output power for long duration. The modular demonstration of the PPU design throughout the program at both the subsystem and system level validated that the PPU can support operation from 10 kW to almost 100 kW while maintaining efficiencies in the mid 90% [5]. These results support the future application of this design architecture to support even higher power operations up to 250 kW and beyond with continued high performance.

B. Hall Thruster System

A key observation from the high power system test was that the XR-100 Nested Hall Thruster propulsion system acts like a state-of-the-art Hall thruster. Thruster performance results were compared at approximately 75 kW discharge power from both the 2017 standalone NHT test and the XR-100 HPST, presented in Table 2 [4].

Table 2 Comparison of thruster performance during the 2017 NHT test (gray) and 2019 XR-100 HPST.

Inner	Middle	Outer	Discharge Power	Thrust [mN]	Isp [s]	T/P [mN/kW]
299V/25A	300V/78.9A	300V/141A	73.4 kW	4574	1960	62.0
298.4V/33.6A	300.1V/78.6A	298.1V/138.5A	74.9 kW	4640	2020	61.9
309V/24.9A	308V/78.7A	308V/140A	75.0 kW	4600	1974	60.5
319V/25A	320V/79.2A	319V/141A	78.3 kW	4658	2012	59.2

The thruster performance observed during this system test is comparable to the thruster-only results from 2017, with differences attributed to the slightly richer cathode flow fraction (CFF) used in the system test and the measurement uncertainties of the thrust stand and flow meter. As previously discussed by Hall et. al., these efficiency and thrust-to-power (T/P) values are comparable to other NASA high-power Hall thrusters [4]. The NHT operated at the same magnetic field strengths as mid power state-of-the-art Hall thrusters, demonstrated in-family cathode-to-ground voltage, and preferred to operate at similar current densities [25]. Though plasma diagnostics were not employed during this HPST campaign, the JPL plasma models [8, 9] and the 2017 standalone NHT test plume measurements showed comparable values to state-of-the-art Hall thrusters for most probable ion voltage, plasma potential, charge state distribution, and utilization efficiencies [17].

During both the low power and high power system tests, the PPU utilized the same control architecture as was used during the early integrated system test of AEPS [26]. This control architecture successfully demonstrated closed-loop current control for one, two, and all three discharge channels independently and simultaneously. Modifications were made to the software to drive the master-slave relationship between multiple DSU's supplying a single discharge channel, but power distribution performance across multiple power modules was consistent with single DSU systems. Similar soft start and shutdown procedures were also utilized, though the order of the discharge channels is a unique consideration for an NHT. And while the general behavior of the thruster was consistent and on the same order of magnitude as mid power Hall thrusters, unique to such a high power system was the magnitude of current events and fluctuations that the electrical components were exposed to and had to withstand.

C. Design Improvements

Though the XR-100 Nested Hall Thruster propulsion system was able to achieve thermal equilibrium at high power, ultimately it was unable to demonstrate 100 kW operation for 100 continuous hours. However, key design improvements have been identified to enable operation for 100 hours and onward to 1000 hours or more for higher TRL development efforts. Any future development efforts will include modification of the thruster magnetic circuit to reduce thermal loading and to implement magnetic shielding. This latter effect will improve performance by orders of magnitude as the XR-100 approaches a more flight-like design [27-30]. Additional modifications will include improved electrical isolation for thruster components, which will also enable long duration high power operation to 100 continuous hours and beyond.

Additionally, the initial DSU baseline design was optimized for discharge voltage ranges of 350 to 400 V and 700 to 800 V. This is not aligned with the range of voltages the thruster can and prefers to operate at: for example, the X3 NHT can operate at 500 V, but that is outside of the preferred output voltages for the DSU's and might cause inefficient operation or even overheating of the power modules. As noted in previous papers [5, 20], the next iterations of the transformer design within the DSU will incorporate better heat transfer from the transformer into the baseplate. This will help the DSU's operate at less efficient design points without a risk of overheating. The DSU's may also be modified to operate in output ranges more consistent with the X3 so the two subsystems are more aligned to support high power, long duration system operation. Furthermore, the PPU circuit components will be built to withstand higher current events that may occur during high power system operation.

VI. Conclusion

The XR-100 Nested Hall Thruster propulsion system under NASA's NextSTEP program has made significant progress maturing the capability to one day support manned and cargo missions to Mars and deep space. Throughout the three year program, the team led by Aerojet Rocketdyne validated that the XR-100 Nested Hall Thruster propulsion system fundamentally acts like heritage Hall Thruster systems, clearing the path for continued development beyond TRL 5. Additionally, performance directly measured during both thruster-only testing and integrated system testing is comparable to state-of-the-art Hall Thruster performance. During the final activity of the program, the XR-100 team performed integrated system testing at high power up to thermal equilibrium, the highest power integrated system test at steady state published to date. It also demonstrated the highest current and highest directly measured thrust of an EP string test published to date. The team has identified manufacturing and design improvements for the NHT, PPU, and integrated system that will be implemented in future development programs, but no fundamental physics have been found that would limit further development of the XR-100 100-kW class Nested Hall Thruster propulsion system.

Acknowledgments

The high power system test was supported by a large team across Aerojet Rocketdyne, the University of Michigan, NASA Glenn Research Center, and NASA Jet Propulsion Laboratory. The authors would like to thank the following people for their support in the planning, preparation, and execution of the system test: Sam Hablitzel, Jerry Jackson, Brian Koch, John Pace, Aaron Poehls, Erich Soendker, Arturo Tolentino, and Benjamin Welander from Aerojet Rocketdyne; Sarah Cusson, Marcel Georgin, Leanne Su, and Joshua Woods from the University of Michigan; James Gilland, Chad Joppeck, Thomas Liu, Eric Pencil, Taylor Varouh, and all of the facility technicians at VF-5 from NASA Glenn; and Alejandro Lopez Ortega, Ioannis Mikellides, and Sean Reilly from NASA JPL. The first author would also like to thank the following Aerojet Rocketdyne interns for their contributions to the test planning, data analysis, and literature reviews: Jordan Marshall, Samar Mathur, Alex Mundahl, Adam Patel, Nick Simon, and Henry Steiner.

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