

100 kW Nested Hall Thruster System Development

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Abstract: Large scale cargo transportation to support human missions to the Moon and Mars will require very high power Solar Electric Propulsion (SEP) systems operating between 200 and 400 kW. Aerojet Rocketdyne's NextSTEP program is developing and demonstrating a 100 kW EP system, the XR-100, using a Nested Hall Thruster (NHT) designed for powers up to 200 kW, a modular power processor and a modular flow controller. The three year program objective is to operate the integrated EP system continuously at 100 kW for 100 h, advancing this very high power Electric Propulsion (EP) system to Technology Readiness Level (TRL) 5. With our University of Michigan, Jet Propulsion Laboratory and NASA Glenn Research Center teammates, Aerojet Rocketdyne has completed the initial phase of the program, including operating the thruster at up to 30 kW to validate the thermal models and developing and operating multiple power processor modules in the required series/parallel configuration. The current phase includes completing a TRL 4 integrated system test at reduced power to validate all system operating phases. Design upgrades to demonstrate the TRL 5 capabilities are underway. This paper will present the high power XR-100 capabilities, overall program and design approach and the latest test results for the 100 kW EP system demonstration program.

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Nomenclature

AR	=	Aerojet Rocketdyne
DMC	=	Discharge Master Controller
DSU	=	Discharge Supply Module
EP	=	Electric Propulsion
GRC	=	Glenn Research Center
HCT	=	Hall Current Thruster
IF	=	Input Filter
JPL	=	Jet Propulsion Laboratory
LEO	=	Low Earth Orbit
LVTF	=	Large Vacuum Test Facility
MFC	=	Mass Flow Controller
NASA	=	National Aeronautics and Space Administration
NextSTEP	=	Next Space Technologies for Exploration Partnerships
NHT	=	Nested Hall Thruster
OFB	=	Output Filter Board
PEPL	=	Plasmadynamics and Electric Propulsion Laboratory
PFCV	=	Proportional Flow Control Valves
PM	=	Power Modules
PMU	=	Propellant Management Unit
PPU	=	Power Processing Unit
SEP	=	Solar Electric Propulsion
TRL	=	Technology Readiness Level
VF	=	Vacuum Facility
UM	=	University of Michigan
USAF	=	United States Air Force

I. Introduction

IN recent years, high power Electric Propulsion (EP) systems (>100 kW) have been identified as a high-priority technology for development as discussed in the *2012 NASA Space Technology Roadmaps and Priorities*.¹ Use of EP either for transporting astronauts or the infrastructure they need to complete their mission (e.g., SEP cargo tug) drives the requirement for high-power EP. Solar electric propulsion (SEP) cargo delivery systems can transport substantially more mass than a chemical system for a given initial mass in low Earth orbit (LEO) at the expense of trip time and vehicle dry mass. In fact, studies have shown that an SEP cargo tug operating in the range of 3000 s specific impulse can deliver over twice the amount of payload to the lunar surface as compared to a cryogenic chemical system at 450 s.² For a Mars cargo mission, it can be shown that EP represents a potential for an 80% spacecraft mass reduction when compared to chemical propulsion. For these cargo missions, a multi-hundred kilowatt power level is desirable to keep transfer times shorter.³ This is where the NASA's *Next Space Technologies for Exploration Partnerships (NextSTEP)*⁴ demonstration of a 100 kW Nested Hall Thruster becomes a key enabling technology. Numerous mission architecture studies have been performed to show the benefit of a mixed Cargo / Crew approach that utilizes the benefits of high-power SEP.^{2,3,5,6,7,8}

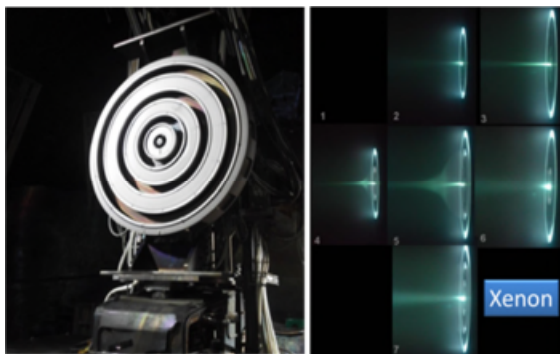


Figure 1. X3 Thruster.

Nested-channel Hall thrusters (NHTs) enable both higher total power and higher power density when compared to single-channel Hall thrusters or clusters thereof. The first publicly available NHT test data was published in 2011 by the University of Michigan's Plasmadynamics and Electric Propulsion Laboratory (PEPL) in a program funded by the Air Force Research Laboratory (AFRL).^{9,10} The X3 thruster (See Figure 1) was subsequently developed at PEPL as part of a joint effort with the AFRL, NASA's Glenn Research Center (GRC), and Jet Propulsion Laboratory (JPL).¹¹

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The NextSTEP program was awarded to Aerojet Rocketdyne in January of 2016. Under the contract, the Aerojet Rocketdyne team will complete the development of the XR-100, a 100 kW Hall Thruster System, including a 200 kW thruster; critical elements of a 100 kW modular Power Processing Unit (PPU); and elements of the modular xenon feed system. The contract includes system integration testing, and will culminate with a NASA TRL 5 demonstration of a 100 kW system for 100 h at thermal steady-state. The specific goals of the NextSTEP project are shown in Table 1, except the thrust objective is not a program goal. Thrust is included in the table for information purposes. The modular nature of these technologies enables system scalability to 200kW with the current thruster design and multi-megawatt power levels with scaled thruster design while meeting the long-term system performance and mass objectives of the project. A spacecraft conceptual model is shown in Figure 2. To perform this contract, there is close collaboration with teammates at Aerojet Rocketdyne (AR), the University of Michigan (UM), the NASA Jet Propulsion Laboratory (JPL), and the NASA Glenn Research Center (GRC).

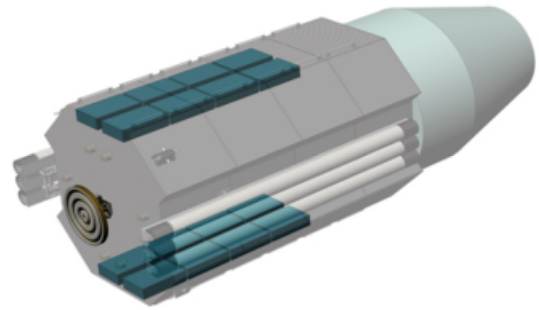


Figure 2. Conceptual 200kW System

The spacecraft conceptual model is shown in Figure 2. To perform this contract, there is close collaboration with teammates at Aerojet Rocketdyne (AR), the University of Michigan (UM), the NASA Jet Propulsion Laboratory (JPL), and the NASA Glenn Research Center (GRC).

Table 1. NASA NextSTEP Program Objectives.

Metric		XR-100 Objective
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
	In-space lifetime capability	>50,000 h
	Operational lifetime capability	>10,000 h
	System efficiency	>60%
	Power per thruster	100 kW
	System kg/kW	<5 kg/kW

These system capabilities provide margin on the performance requirements for Mars cargo transportation. The X3 thruster features the largest throttling capability of any Hall thruster to date, with seven different firing configurations and power levels ranging from 2 kW to 200 kW.¹² Additionally, the X3 is capable of operating over a range of discharge voltages of 200 to 800V. Figure 3 shows the configuration of the XR-100 system, which will use a PPU capable of delivering 100 kW of power to the NHT and of providing closed loop control of the mass flow controllers. The XR-100 feed system consists of a Propellant Management Unit (PMU) and modular Mass Flow Controllers (MFCs) which are based on Aerojet Rocketdyne proprietary designs. The spacecraft feed system would also include propellant tanks. Propellant is fed from the tanks into the PMU that includes the latch valves and filtering required to meet range

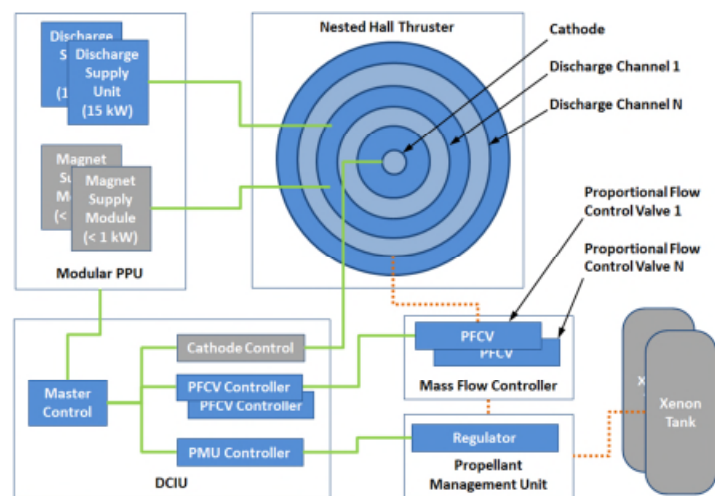


Figure 3. Block diagram of XR-100 system architecture showing modularity chosen to take advantage of NHT throttleability. Blue blocks are being developed as part of the NextSTEP program.

safety and mission assurance requirements. The PMU conditions propellant fed into the MFCs that allow for system scaling and flow rate tailoring for each Hall thruster channel so that it can be optimized by channel for a range of operation. The baseline propellant is xenon gas, which has been shown to be safe, dense, and long-term storable as compared to cryogenic propellants such as hydrogen. The modular PPU approach enables a distributed PPU architecture with scalability to higher powers that allow vehicle designers the flexibility to spread the PPU module mass and thermal loads for optimal placement on spacecraft, even for spacecraft with different physical designs.

This paper summarizes the status of the XR-100 system development program, including design summary of the Nested Hall thruster, power processor, and xenon feed system, as well as the results of testing to date and current development plan.

III. System Architecture and System Test Status

The XR-100 system architecture is shown in Figure 3 on the previous page. As mentioned previously, this architecture allows for unprecedented throttleability based on a flight proven technology. Hall thruster propulsion provides several advantages over other propulsion technologies. Hall systems have flown on dozens of spacecraft for over 40 years,¹³ and spacecraft integration issues have already been resolved. For this reason, scaling up the Hall thruster propulsion system to this power level is a relatively low risk approach to high power SEP system development.

Hall systems present a stable DC electrical load to the spacecraft power system that can be gradually ramped up to avoid large power transients. The XR-100 system is being designed to operate efficiently between 25 kW and 100 kW. Like other Hall thrusters, the X3 requires only propellant, power, and enough heat during periods of eclipse to keep components above their qualified temperatures. The NHT passively radiates all of the heat generated during operation and requires no active or conductive cooling. Because the NHT operates predominately as a DC electric load, the thruster may be located several meters away from the PPU and MFC.

The NHT has a low volume and compact footprint facilitating spacecraft integration. The DC magnetic field strength is typically less than 0.1 Tesla in the center of the discharge channels, and decreases as the inverse square of the distance from the thruster. This low magnetic field strength allows installation of magnetically actuated valves and other devices within close proximity to the NHT, simplifying the spacecraft integration of the propulsion system and limiting impacts on other subsystems.

Another advantage of the XR-100 architecture is that it can benefit from ongoing research in high-power Hall thrusters and cathodes performed at multiple institutions across the country. One system design update not shown in Figure 3 is the use of two propellant flow passages between the MFC and the NHT cathode. The additional propellant line allows the thruster to implement a novel cathode design developed by Chu, Goebel and Wirz with performance and operating life improvements over conventional hollow cathodes.¹⁴

Several components of the system have already been flown and need only be scaled up to match the XR-100 power level and throughput. The NextSTEP program at AR has chosen to focus development efforts on components where there are challenges associated with the increased power and propellant flow rates. The first component under development is the X3 thruster. The second set of components is within the PPU and includes the modular discharge supplies and the mass flow controller valve driver. The third set of components is within the xenon feed system and includes the modular mass flow controller and the propellant management unit.

The NextSTEP program includes a series of design, build and test iterations that methodically grow the system capability and demonstrate successively more challenging test objectives. The test plans and test status of the NHT and components within the PPU and MFC are summarized in Table 2 below. More detailed descriptions of development plans for these components can be found in subsequent sections of this paper.

Table 2. Summary of XR-100 development tests planned for the three-year NextSTEP program

Year	Component	Test Objective	Status
2016	PPU	Demonstrate stable 10 kW operation using a single discharge supply module operating into resistive loads	Successfully completed December 2016
	NHT	Demonstrate stable operation of each discharge channel and characterize thermal behavior	Successfully completed in August 2016
	MFC	Demonstrate proportional flow control capability of the low-cost valve design	Successfully completed September 2016
	MFC & PPU	Demonstrate closed-loop flow control	Successfully completed October 2016
2017	NHT	Demonstrate stable operation of 3 discharge channels operating in parallel at 100 kW total input power	Successfully completed August 2017
	MFC	Demonstrate proportional flow control capability of 5 valves integrated into the MFC manifold	Planned completion in November 2017
	System	Demonstrate stable operation in closed-loop control at 10 kW input power	Planned completion in December 2017
2018	PPU	Demonstrate ability to support power levels up to 100kW via stable 45kW operation using 3 parallel discharge supply modules operating into resistive loads	Planned completion in January 2018
	System	Demonstrate stable operation at 100 kW input power for 100 continuous hours.	Planned completion in August 2018

Component level testing of the DSU and MFC was performed on work benches at Aerojet Rocketdyne’s Canoga Park and Redmond facilities respectively. Component level testing of the NHT was performed at the University of Michigan’s Large Vacuum Test Facility (LVTF) in 2016 and at NASA GRC’s Vacuum Facility 5 (VF-5) in 2017. System testing is planned to be performed at the LVTF in December of 2017 and VF-5 in August of 2018.

The University of Michigan’s LVTF is 9 meters long by 6 meters in diameter. It has seven internal cryopumps capable of pumping 240,000 liters of xenon per second. Figure 4 below shows a photograph and diagram of the LVTF. During the 16 kW thermal characterization testing of the outer discharge channel in 2016, the vacuum chamber pressure reached 9×10^{-5} torr. While higher power operation has been demonstrated in LVTF over short periods, the test results indicated that high power operation of the NHT would be limited by the existing pumping capacity of the facility.¹⁵ The University of Michigan is currently undertaking an effort to greatly improve pumping capacity at the LVTF allowing for higher power testing in December of 2017.

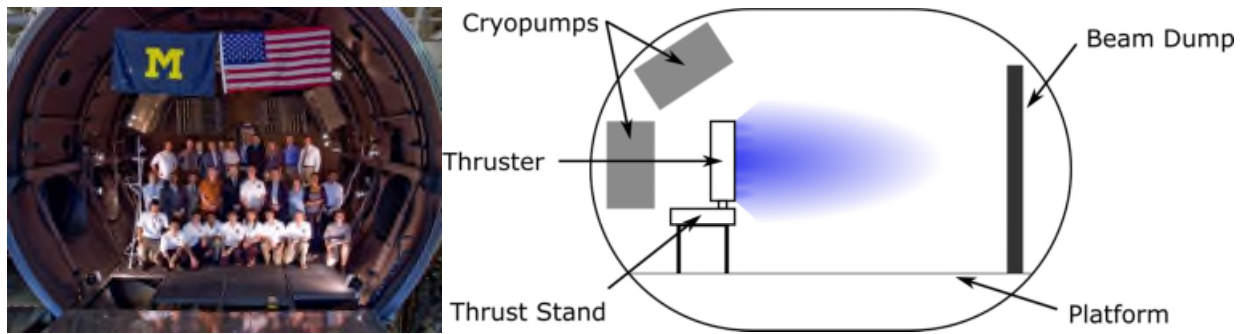


Figure 4. Photograph LVTF with the endcap open, showing the 2009 PEPL group and alumni (left). A schematic diagram of the placement of the thruster, pumps, and beam dump in the chamber (right).

The NASA Glenn Research Center’s VF-5 is 18.3 meters long and 4.6 meters in diameter. It has 33.5 square meters of cryogenic pumping surface area and is capable of pumping 700,000 liters of xenon per second. Figure 5 below shows a photograph and diagram of VF-5. During the 100 kW test of all three discharge channels of the X3 in 2017, the vacuum chamber pressure remained below 6×10^{-5} Torr-Xe. The test mitigated several risks associated with the facility and test equipment, and identified a few areas for improvement in order to demonstrate extended operation of the X3 thruster at 100 kW. Facility and test equipment improvements will be implemented prior to 2018 testing.

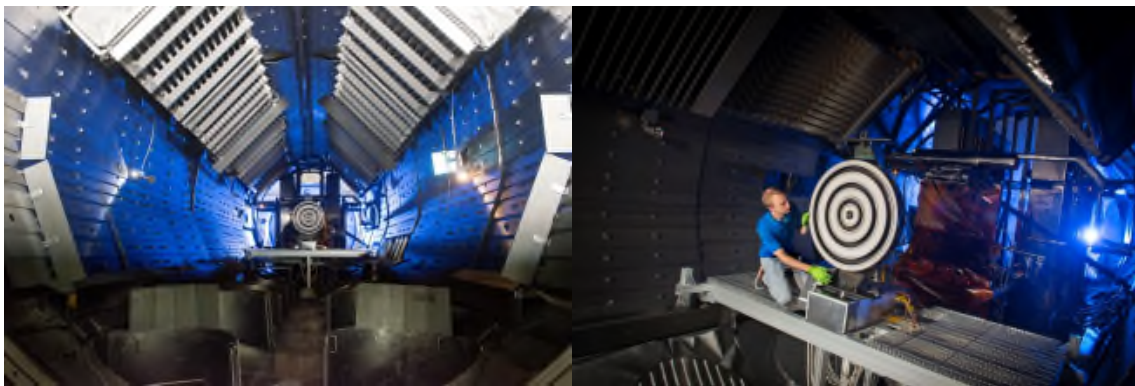


Figure 5. Photograph VF-5 with the endcap open (left) and NHT installed in VF-5 (right)

Thrust measurements were made at both test facilities using a new inverted pendulum style thrust stand developed by the University of Michigan.¹⁵ Direct thrust measurements are typically more accurate than other thrust measurement techniques and have been extensively demonstrated with high power Hall thrusters. Also direct thrust measurements can provide critical, real-time insight into thruster operation at relevant temperatures during long-term, steady-state tests.

Integrated system testing of multiple DSUs, NHT, PMU, and MFCs at 10 kW is planned to complete in 2017. This test will be performed using a single channel of the NHT and will demonstrate stable operation of the integrated system prior to testing at the full 100 kW. In 2018, additional modular hardware will be added to operate multiple channels of the NHT to achieve the 100 kW, 100 h demonstration.

IV. Thruster

Unlike a conventional Hall thruster, the nested Hall thruster (NHT) scales up in power by adding channels that circumscribe the centrally mounted cathode. Each channel is independently controllable enabling throttleability in thrust and power. NHTs have been identified as an important next step in electric propulsion technologies by enabling improved mass and footprint scaling with increased propulsive power.

The X3 NHT builds on the extensive flight heritage of prior Hall thruster propulsion systems. The X2 NHT was developed by the University of Michigan as a proof-of-concept device for nesting two concentric channels as a

means to increase power and throttleability while limiting the increase of thruster mass and footprint. Following the successful demonstration of the X2,^{9,10} the University of Michigan developed the three-channel X3 NHT in collaboration with AFRL, NASA GRC, and NASA JPL. The X3 design heritage traces to the X2 NHT and H6 Hall thruster, and leverages lessons learned in developing the NASA high-power single-channel Hall thrusters (i.e. NASA-457M, -400M and -300M) as well as incorporating a high-current, Lanthanum Hexaboride (LaB6) hollow cathode developed by JPL.^{15,16,17} The X3 NHT is roughly 1 meter in diameter and 10 cm deep and weighs about 250 kg. The X3 was designed to process 200kW without additional radiative surfaces, yielding a potential specific power of 1.25kg/kW for the thruster.



Figure 6. Photographs of X3 installed in University of Michigan's LVTF (left) and operating three channels simultaneously at 30 kW (right).

The X3 NHT incorporates a novel cathode design developed by JPL. The lanthanum-hexaboride hollow cathode has two external gas injectors in addition to the traditional internal flow passage. The external injectors require an additional flow controller in both the PPU and MFC, but provide potential life and performance benefits for the propulsion system.¹²

Plasma and erosion modeling is underway at JPL with the objective of predicting erosion rates and operating life of a multichannel Hall thruster for the first time.¹⁸ Modeling results are expected to show discharge channel erosion rates similar to those of other high power NASA Hall thrusters, yielding an operating life time of several thousand hours. In order to reach the NextSTEP program goal of 10,000 h of operational life, the thruster magnetic circuit will be upgraded to significantly reduce discharge channel erosion. Implementation of AR's zero erosion design¹⁹ with JPL's magnetic shielding modelling^{20,21} would facilitate operating life times greater than $\geq 10,000$ h. Aerojet Rocketdyne's XR-5 Hall thruster already demonstrated 10,000 h of operation in 2009 during an extension of the qualification life test, so these design methodologies are well understood.²²

Thermal analysis of the NHT is also underway at JPL as part of the NextSTEP program. The objective of the thermal analysis is to assess the thruster and cathode thermal margins at a total discharge power of 100 kW at 200 A. Modeling results are expected to show significant positive margin given that the NHT was originally designed for 200 kW. In the event that narrow or negative margins are identified, design solutions will be implemented in the engineering development phase on future programs.

In August 2017, the X3 demonstrated continuous 80 kW operation for two hours and demonstrated continuous 100 kW operation for about 10 minutes. 100 kW operation was halted due to a thermal expansion issue, which will be resolved in time for the 100 kW, 100 continuous hour demonstration test in 2018. Also of note, the X3 demonstrated 250 A total discharge current during three channel operation at 100 kW using the LaB6 hollow cathode provided by JPL. This represents the highest discharge current ever achieved in a Hall thruster.

The operating duration at 100 kW was insufficient to optimize performance, but the X3 demonstrated very good performance at lower power where thermal expansion was not yet an issue. The X3 achieved 66% total thruster efficiency and a total specific impulse of 2580 seconds while operating three channels concurrently at a total discharge current of 125 A and a discharge voltage of 500 V. This performance is comparable to the highest 500 V performance demonstrated by the HERMeS thruster, a state-of-the-art NASA thruster that has already incorporated magnetic shielding.²³

Future work includes the demonstration of 100 h of continuous operation at 100 kW in 2018. This test will demonstrate the ability of X3 NHT to operate at steady-state hot temperatures. Data from this test will help correlate existing thermal and plasma models, which will then be used to estimate maximum operating limits and lifetime capability.

Even though testing of the X3 is incomplete, design improvements have already been planned. Future design iterations will implement a more capable cathode design developed JPL²⁴ and upgrades to the thruster magnetic circuit discussed above. Other design improvements will focus on raising the Technology Readiness Level (TRL) of the NHT. These improvements include upgrades to the structural and thermal capabilities of the thruster enabling successful testing of qualification-level loads imposed by dynamic and thermal environments expected in future missions.

V. Power Processor

The NextSTEP PPU is required to power three thruster power channels (the inner, middle and outer) providing 13.6kW, 32 kW and 55.2 kW respectively for a total of 100 kW. While the final PPU will incorporate low power supplies for the cathode, heaters and magnets, the current focus of the NextSTEP PPU effort is the discharge supply since this was the most challenging part of the PPU. The discharge supply uses a modular design that can support multiple configurations for a single Discharge Supply Unit (DSU) or multiple DSUs in parallel and power each of the 3 NHT channels. This architecture offers greater flexibility and can easily expand to greater power levels. Shown in Figure 7, the Discharge Supply system inner channel will have a single DSU, the middle channel will have three DSUs, and the outer channel will have four DSUs; requiring 8 DSUs in total for the 100 kW EP system. This architecture will be used for the 100 h 100 kW test, which is planned for 2018.

Each DSU consists of a Discharge Master Controller (DMC), input filter (IF), output filter board (OFB) and four power modules (PM). The PMs each provide up to 400V and 3.45 kW of power and can be configured in parallel mode or a series/parallel mode. The configuration selection is accomplished with selection switches on the OFB. The DMC communicates with laboratory control computer (Space Craft C&DH simulator) receiving set point command and providing telemetry for display and data logging. The DMC controls each PM with base the S/C setpoint commands. The input filter has a disconnect switch to provide a controlled power sequence during multiple DSU configuration testing.

During the 1st year, a single DSU was designed, built and tested. Each DSU is capable of delivering 13.8 kW of power from an input voltage of 95V to 140V. The controls architecture was devised to allow multiple DSUs to operate in parallel on a single thruster anode channel with the returns tied to the one common cathode. The DSU is capable of delivering 13.8 kW at 350V-400V to maximize thrust or 700V-800V to maximize ISP.

The testing successfully verified over 10 kW operation at output voltages between 400V and 800V. Figure 8 shows the breadboard test bed and Figure 9 shows a snapshot of the test results. After this successful demonstration, lessons learned were incorporated into the design to build a 100 kW EP system.

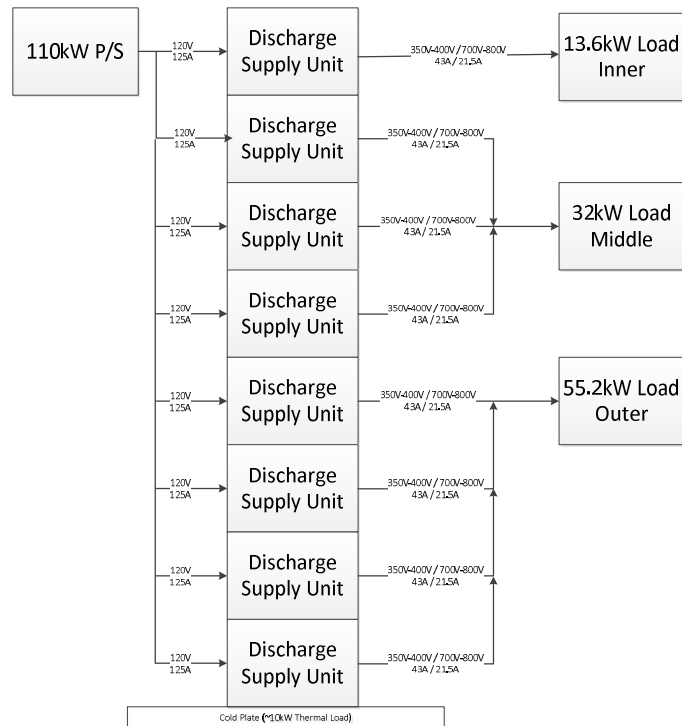


Figure 7. 100kW Module Discharge Supply

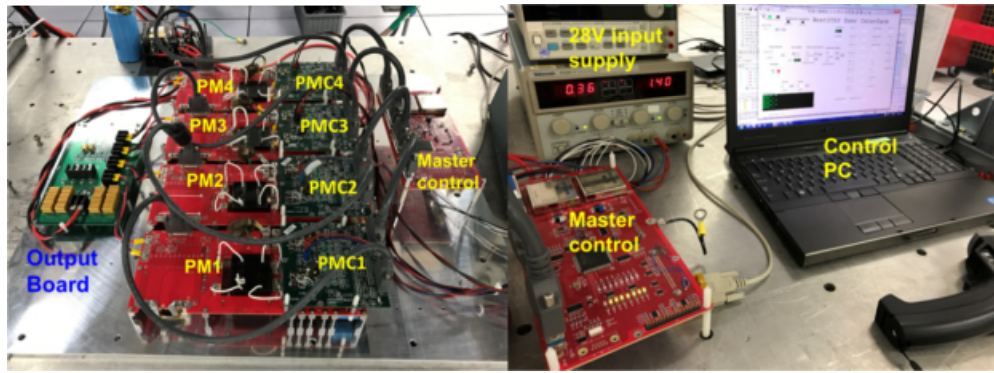


Figure 8. 2016 DSU Demonstration Test Bed

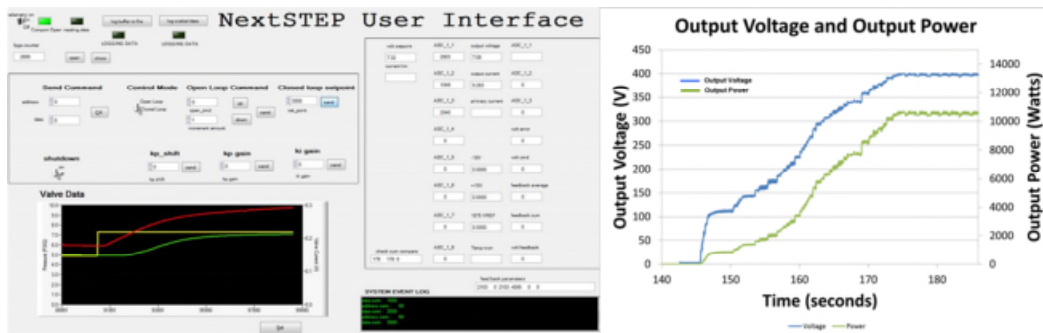


Figure 9. 2016 DSU Demonstration Test Results

A Mass Flow Control (MFC) valve driver was developed during 2016. Integrated flow control testing of a single valve demonstrated successful closed-loop operation of the MFC. This test is discussed in more detail in the feed system section. In 2017 the MFC valve driver will be expanded to drive five valves required for the 100 kW TRL 5 test. The S/C simulator will provide closed loop control between the xenon flow and discharge current for each of the 3 discharge channels.

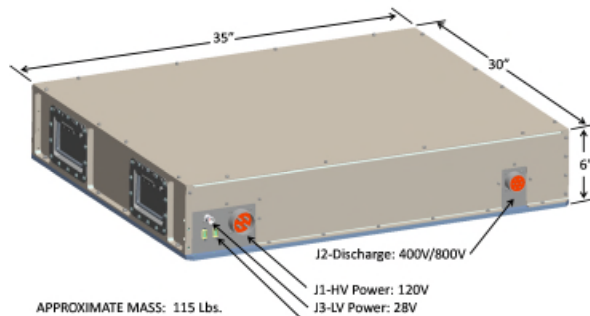


Figure 10. DSU Assembly

In 2017, several modifications were made from the first bread board unit to a demonstration unit. The control system was updated to allow operation of multiple DSUs in parallel. Some of the magnetics had to be modified to reduce excessive power losses and provide adequate heat sinking to the baseplate for the 100 h test in a vacuum. Thermal modeling and analysis was completed to ensure proper thermal conduction to the base plate. Figure 10 shows the final design model.

An integrated system test of a single DSU and mass flow controller with the NHT and feed system will occur at the end of 2017. A 100 kW integrated system demonstration with eight DSUs powering the three NHT channels will occur in 2018.

VI. Feed System - Mass Flow Controller and Propellant Management Unit

The NextSTEP feed system consists of a Mass Flow Controller (MFC) and a Propellant Management Unit (PMU) that control the flow of xenon from the pressurant tank to the NHT. The PMU regulates pressure to the MFC while the MFC controls the flow rate of xenon to the NHT.

The MFC has five Proportional Flow Control Valves (PFCV); one PFCV for each for the three anode channels and the two cathode channels of the NHT. Each flow circuit has an absolute pressure transducer to provide a pressure signal for closed loop flow rate control. The pressure transducer can also provide telemetry for the purpose of monitoring flow rate throughout the mission.

The PFCVs are voice-coil linear actuators that provide full proportional flow rate control. The MFC valves operate at a regulated pressure of 40 psia while the PMU electronic regulator steps the tank pressure of 2000 psia down to 40 psia.

The maximum flow rate of each flow circuit is metered by a Lee restrictor sized for the flow rate demands of each NHT channel. The target flow is achieved by controlling the back pressure to Lee flow restrictors through a closed loop Proportional–Integral–Derivative (PID) circuit in the MFC control board of the PPU that adjusts the input current until the flow target is met.

The MFC and PMU were designed with low cost as the primary objective and are based on AR proprietary designs. The voice-coil PFCVs utilized design features that allow the detail parts to be manufactured with wide dimensional tolerances, with no valve body weldments typical of aerospace solenoids, and with no need for tight stroke and load adjustment during assembly.

Further cost advantages are realized when the PMU and MFC utilize the same internal components such that economy of scale is achieved even within a single MFC and PMU assembly. The same PFCV design serves as a proportional flow controller, an electronic regulator and as a service valve. Flight assemblies may even integrate MFC and PMU into a single additively manufactured manifold.

The net result is that the MFC and PMU can be assembled at a single station, with minimal tools and completed within a few hours. The MFC is treated as a single component and the PFCVs are assembled into the MFC or PMU from bins of detail parts.

The prototype MFC, shown in Figure 11, has a machined manifold while flight MFC will take advantage of additive manufacture to contour out “dead mass” in the manifold to reduce the overall mass.



Figure 11: 5-Valve Mass Flow Controller

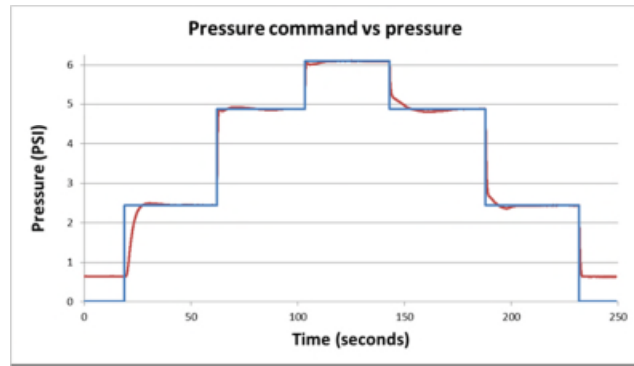


Figure 12: MFC Bench Unit in Test (left) and Closed Loop Pressure (Flow) Response (right)

The performance of the PFCV design was demonstrated on a two-valve bench unit shown in the left photo of Figure 12. Open loop tests were performed on this bench test unit to map the flow performance of this design against input current. The MFC successfully demonstrated precise and stable closed loop flow control with the NextSTEP control board as shown in right graph of Figure 12.

Future work includes demonstration of the 5-valve MFC in an integrated system hot fire test with the PMU regulating an inlet pressure of 2000 psia.

VII. Conclusions

The NextSTEP program has completed the first phase of the system demonstration program and is well on its way to completing the second. In the first year of the program, components of the XR-100 system (NHT, DSU, PMU, and MFC) were developed and tested. This testing included gathering NHT performance and thermal data to mature analytical models, bench tests of the DSUs, PMU, and MFCs, and closed loop control of an MFC.

Information from the testing was used to mature the components for the second year. This year the various components will be tested as an integrated system at 10 kW. This test is planned to complete by the end of November 2017. The program is on track to complete the required 100 kW for 100hr demonstration in 2018. The demonstrated system will be scalable to megawatt powers and builds on long-established long-life flight Hall thruster system design and spacecraft integration methodologies.

VIII. Acknowledgments

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IX. References

- ¹ 2012 NASA Space Technology Roadmaps and Priorities
- ² Spores, R.J., et. al., "A Solar Electric Propulsion Cargo Vehicle to Support NASA Lunar Exploration Program," IEPC Paper No. IEPC-2005-320, 25th International Electric Propulsion Conference, Princeton, NJ, October 31 to November 4, 2005.
- ³ Cassady, Joseph and Smith, William, "A Highly Efficient Cargo Transportation System for Flexible Path Human Exploration Missions," IAC – 10.C4.6.3, 61st International Astronautical Congress, Prague, CZ
- ⁴ NASA, Next Space Technologies for Exploration Partnerships Broad Agency Announcement NNH15ZCQ001K, Oct. 2014.
- ⁵ Myers, R and Carpenter, C, "High Power Solar Electric Propulsion for Human Space Exploration Architectures," IEPC 2011-261, 32nd International Electric Propulsion Conference, Wiesbaden, Germany, September 11 – 15, 2011
- ⁶ Strange, N., Landau, D., Polk, J., Brophy, J., and Mueller, J., "Solar Electric Propulsion for a Flexible Path of Human Space Exploration," Presented at the 61st International Astronautical Congress, IAC-10.A5.2.4, Prague, Czech Republic, Sep.-Oct., 2010.
- ⁷ Brophy, J., Gershman, R., Strange, N., Landau, D. F., Merrill, R., and Kerslake, T., "300-kW Solar Electric Propulsion System Configuration for Human Exploration of near-Earth Asteroids," AIAA Paper 2011-5514, 2011.
- ⁸ Strange, N., Merrill, R., Landau, D., Drake, B., Brophy, J., and Hofer, R., "Human Missions to Phobos and Deimos Using Combined Chemical and Solar Electric Propulsion," AIAA Paper 2011-5663, July 2011.
- ⁹ Liang, R. and Gallimore, A. "Far-Field Plume Measurements of a Nested-Channel Hall-Effect Thruster," 49th AIAA Aerospace Sciences Meeting, 2011-1016, January, 2011.
- ¹⁰ Liang, R. and Gallimore, A. "Constant-Power Performance and Plume Measurements of a Nested-Channel Hall-Effect Thruster," 32nd International Electric Propulsion Conference, Wiesbaden, Germany, 2011-049, September, 2011.
- ¹¹ Florenz, Roland E., Scott J. Hall, et al "First Firing of a 100-kW Nested-channel Hall Thruster," IEPC-2013-394, 33rd International Electric Propulsion Conference, The George Washington University, Washington, D.C., USA October 6 – 10, 2013.
- ¹² Scott J. Hall, Sarah E. Cusson, and Alec D. Gallimore, "30-kW Performance of a 100-kW Class Nested-channel Hall Thruster," IEPC-2015-125, 34th International Electric Propulsion Conference, Hyogo-Kobe, Japan, July 4-10, 2015.

- ¹³ Kim, Popov, Arkhipov, Murashko, Gorshkov, Koroteyev, Garkusha, Semenkin, and Tverdokhlebov, "Electric Propulsion Activity in Russia," 27th International Electric Propulsion Conference, Pasadena, CA, 15-19 October, 2001.
- ¹⁴ Chu, E., Goebel, D. M., and Wirz, R. E., "Reduction of Energetic Ion Production in Hollow Cathodes by External Gas Injection," *Journal of Propulsion and Power*, Vol. 29, No. 5, 2013, pp. 1155–1163.
- ¹⁵ Florenz, R., Gallimore, A, and Peterson, P., "Developmental Status of a 100-kW Class Laboratory Nested Channel Hall Thruster," IEPC-2011-246, 32nd International Electric Propulsion Conference, Wiesbaden, Germany, September 11 – 15, 2011.
- ¹⁶ Goebel, D. M. and Chu, E., "High-Current Lanthanum Hexaboride Hollow Cathode for High-Power Hall Thrusters," *Journal of Propulsion and Power* 30, 1, 35-40 (2014).
- ¹⁷ Goebel, D M, Becatti, G, Tilley, K, Hall, S, "High Current Lanthanum Hexaboride Hollow Cathode for 50-200 kW Hall Thrusters," IEPC-2017-303
- ¹⁸ Mikellides, I. G., Lopez Ortega, A., "Numerical Simulations of a 100-kW Class Nested Hall Thruster with the 2-D Axisymmetric Code Hall2De," IEPC-2017-220, 35th International Electric Propulsion Conference, Atlanta, GA, October 9-12, 2017.
- ¹⁹ Mikellides, I. G., Katz, I., Hofer, R. R., Goebel, D. M., De Grys, K. H., and Mathers, A., "Magnetic Shielding of the Acceleration Channel in a Long-Life Hall Thruster," *Physics of Plasmas* 18, 033501 (2011).
- ²⁰ Mikellides, I. G., Katz, I., Hofer, R. R., and Goebel, D. M., "Magnetic Shielding of a Laboratory Hall Thruster Part I: Theory and Validation," *Journal of Applied Physics* 115, 043303 (2014).
- ²¹ Hofer, R. R., Goebel, D. M., Mikellides, I. G., and Katz, I., "Magnetic Shielding of a Laboratory Hall Thruster Part II: Experiments," *Journal of Applied Physics* 115, 043303 (2014).
- ²² Kristi de Grys, Alex Mathers, Ben Welander, and Vadim Khayms. "Demonstration of 10,400 Hours of Operation on 4.5 kW Qualification Model Hall Thruster", 46th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, Nashville, TN, July 25-28, 2010.
- ²³ Kamhawi, H., Huang, W., Haag, T., Yim, J., Herman, D., Peterson, P. Y., Williams, G., Gilland, J., Hofer, R., and Mikellides, I., "Performance, Facility Pressure Effects, and Stability Characterization Tests of NASA's Hall Effect Rocket with Magnetic Shielding Thruster," AIAA-2016-4826, July 2016.
- ²⁴ Goebel, D. M., Becatti, G., Tilley, K., and Hall, S., "High Current Lanthanum Hexaboride Hollow Cathode for 50-200 kW Hall Thrusters," IEPC-2017-303, 35th International Electric Propulsion Conference, Atlanta, GA, October 9-12, 2017.