Overview and Performance Characterization of Northrop Grumman's 1 kW Hall Thruster String

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Northrop Grumman (NG) Tactical Space Systems Division has embarked on the development and qualification of a high throughput, low power Hall Thruster String (HTS) using hardware designed and built in-house. Following the success of Mission Extension Vehicles 1 and 2, NG is currently developing the next generation in its lineup of satellite servicing capabilities, the Mission Robotics Vehicle (MRV) and Mission Extension Pod (MEP). MEP's mission profile imposes highly demanding requirements upon the electric propulsion system. When surveying the industry for available systems, NG was unable to identify any mature Hall thruster systems that could satisfy the performance and lifetime requirements for MEP. Eventually, it was decided to vertically integrate the EP development process, partnering with NASA Glenn Research Center to leverage ongoing development at GRC of a high throughput, low power Hall thruster.

The components of the HTS have successfully passed PDR and are currently in the engineering development and test phase. Based on performance characterization testing of the development hardware, NG's low power Hall thruster, dubbed the NGHT-1X, promises to deliver state-of-the-art performance and lifetime for a sub-kW Hall thruster, achieving total efficiencies of 50-55% over a wide range of throttle conditions. Results of a series of characterization tests including integrated systems testing with the PPU are presented. Qualification methodology and thruster lifetime verification is also discussed. Environmental qualification of the HTS components is expected to complete in mid-2023 with a first flight in mid-2024.

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Figure 1. The Mission Robotics Vehicle (MRV) installing a Mission Extension Pod (MEP) onto a client vehicle. On MRV and MEP, the Hall thrusters are located at the ends of the long boom arms shown in the image.

I. Introduction

Northrop Grumman (NG) Tactical Space Systems Division (TSSD) has embarked on the development and qualification of a low power Hall Thruster String (HTS) using hardware designed and built in-house. Recently, NG has seen the success of its GEOStar-3 and Mission Extension Vehicle (MEV) Electric Propulsion (EP) systems, which utilize Aerojet Rocketdyne's XR-5 Hall thruster at 3 kW of discharge power [1][2][3]. In the emerging satellite servicing market, NG is currently the industry leader, with two MEVs on orbit providing life-extension services to active Intelsat communications satellites. The MEV performs a rendezvous with a communications satellite near its end of life (EOL) in geostationary (GEO) orbit, docks with the vehicle, and subsequently performs both attitude control and orbit maintenance functions for the Client Vehicle (CV) [3]. This type of mission is only made possible with the use of high-specific impulse electric propulsion.

Following the success of MEV, NG is currently developing the next generation in its line of satellite servicing capabilities, the Mission Robotics Vehicle (MRV) and Mission Extension Pod (MEP). The MRV leverages the heritage RPOD system of MEV as well as the same EP system and adds the incremental capability of a robotics module. This unique spacecraft represents an evolution of the MEV product line, which expands and addresses new space logistics markets. The primary application of the MRV is to transport and install MEPs or other augmentation payloads to client vehicles. Utilizing its space robotics system, the MRV can perform this operation under near transient free conditions, thereby allowing the client to continue normal operations during the installation process. Additional applications cover the full spectrum of potential robotics-based services, such as detailed inspection and repair of a crippled spacecraft [3].

The MEP, on the other hand, is significantly smaller than MEV, though its ultimate purpose is largely the same. Like the MEV, the MEP carries power and an electric propulsion system for CV station keeping. It also enables CV momentum management by means of off-pointing the thrust vector from the center of gravity of the combined stack using a patent-pending algorithm. Based on the CONOPS and requirements, it was decided early on that the EP system should use a low power Hall Thruster String (HTS), due to Hall thrusters' balance of thrust and specific impulse. MEP is designed nominally for a 6-year mission life but can carry a xenon load that permits even longer servicing lifetimes depending on the CV mass and the orbit delivery method. To optimize the overall on-orbit servicing architecture, the MEP uses its own EP system to propel itself from a launch vehicle injection orbit into an orbit near the CV, where the MRV rendezvous with and captures the MEP for installation onto the CV. By using the MRV, the MEP does not require its own RPOD sensor suite, thereby reducing its system complexity, mass, and cost.

However, the demands on the MEP electric propulsion system are not insignificant. To perform both orbit raising and 6 years of station keeping, the EP system must undergo approximately 8,000 on-off cycles and deliver nearly 3,000 m/s of delta-V, part of which is delivered while pushing both MEP and a 2,000+ kg CV. This results in a per-thruster

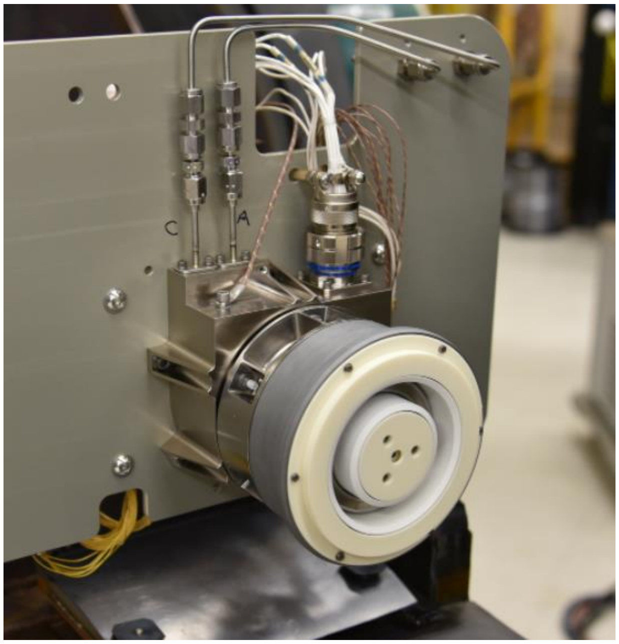

Figure 2. Engineering Model NGHT-1X.

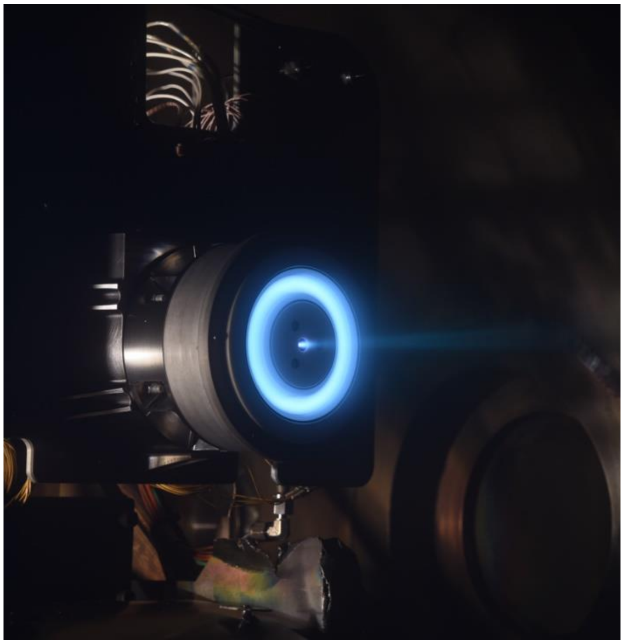

Figure 3. NGHT-1X firing in NASA's VF-8 facility.

throughput requirement in excess of 130 kg of xenon and an operating lifetime of approximately 13,000 hours, equating to a total impulse of approximately 2.1 MNs. Additionally, due to the small size of the MEP, the EP system is limited to 600-900 W of discharge power [3].

When combining these requirements and surveying the industry for available systems, NG was unable to identify any mature Hall Current Thruster (HCT) system that could satisfy the performance and lifetime requirements for MEP. Eventually, it was decided to vertically integrate the EP development process, partnering with NASA Glenn Research Center (GRC) to leverage ongoing developments at GRC of a high throughput, low power Hall thruster [4][5]. NG obtained a non-exclusive license to GRC's high throughput, small spacecraft electric propulsion technology suite, and began evolving the design to a flight-worthy thruster. NG also worked closely with NASA GRC on the development of a 1 kW Power Processing Unit (PPU), basing the discharge supply module on a NASA-provided design.

Table 1. Basic Thruster Requirements for MEP [3].

Parameter	Requirement
Anode Power	600 – 900 W
Specific Impulse	> 1600 s
Thrust-to-Power	> 58 mN/kW
Total Impulse	> 2.1 MNs
On-Off Cycles	> 8,000 cycles

An early integrated systems test was performed in Q4 2020 with an NG breadboard PPU and XFC and a NASA GRC lab thruster, in order to retire PPU and system architecture risk early on. The preliminary design phase of the HTS and its components was kicked off in earnest in Q1 2021, leveraging the lessons learned from the work performed prior to this point. Preliminary Design Reviews (PDRs) for the HTS, the HCT, and the PPU, as well as for the Xenon Flow Controller (XFC) and thruster harnessing, were successfully completed in early Q3 2021. Following PDR, procurement began for Engineering Model (EM) hardware builds, and EM characterization testing for all components began in Q1 2022. Testing was performed both at NASA GRC and NG's Dulles, VA facilities.

Critical Design Reviews (CDRs) for all components are scheduled for summer 2022. Environmental qualification of all components is expected to be complete in mid-2023, in advance of an expected MEP launch date of mid-2024. Thruster life testing will still be ongoing at the time of MEP launch as the life test will take several years to complete.

In Section II, a high-level description of the 1 kW HTS and its components is provided. In Section III, test facilities are briefly discussed, and in Section IV the results of thruster and system characterization testing is presented in detail. In Section V, qualification methodology for the system is discussed including the thruster life test approach. Lastly, conclusions are found in Section VI.

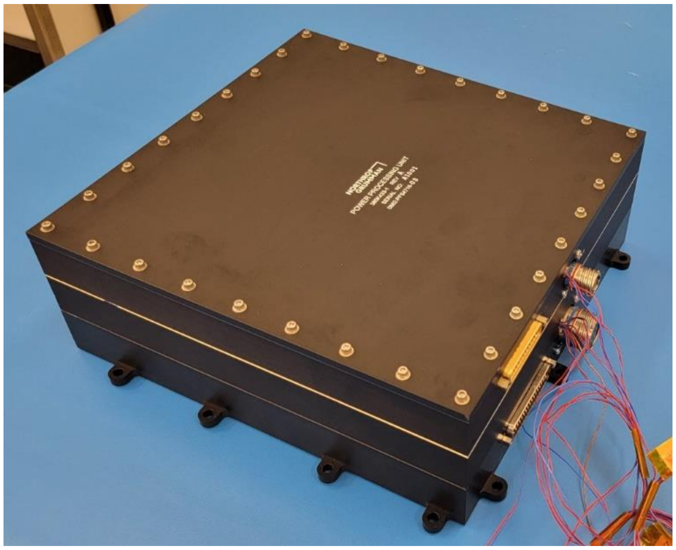

Figure 4. Engineering Model PPU.

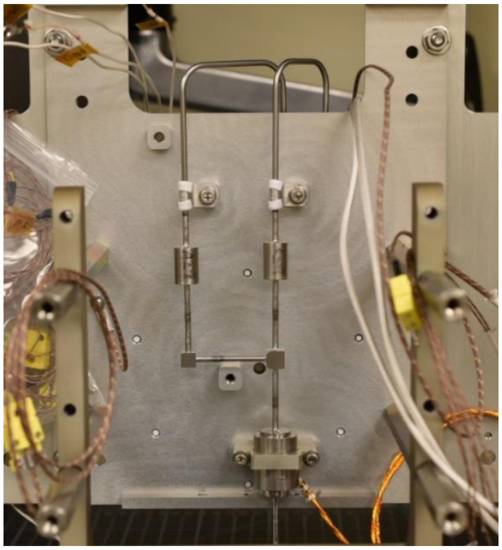

Figure 5. Engineering Model XFC.

II. Hall Thruster String Description

The 1 kW Hall Thruster String is designed to receive regulated xenon pressure from an upstream propellant management system and 24-34 V unregulated bus voltage for the PPU. Flow to the thrusters is controlled by Proportional Flow Control Valves (PFCVs) and fixed flow restrictors. Due to the nature of the control methodology within the PPU, the system is not overly sensitive to inlet pressure and can be tuned to operate with stability over a wide range of regulated pressures. Technically, the PFCV and HTS are even capable of operating in a blow-down mode from tank pressures up to 2700 psia, but this introduces complexity to the control scheme and was decided against for MEP during early architecture trade studies.

Images of the HCT are shown in Figure 2 and Figure 3. The HCT, referred to as the NGHT-1X (Northrop Grumman Hall Thruster, 1 kW, Xenon-fueled), is a partially magnetically shielded Hall thruster based on NASA Glenn Research Center's H71M thruster. NASA began the design evolution process by generating an initial Engineering Model design, retaining key performance-determining features such as the magnetic circuit, anode/propellant distributor design, and cathode configuration of the H71M. NG then took the initial EM design and evolved it further to improve manufacturability and to be able to withstand the structural and thermal environments required for MEP. The result is a well-packaged thruster that is simple and robust for handling, integration, and operation.

The nominal intended operating range of the NGHT-1X is from 600-1000 W and 300-400 V, though it has demonstrated stable operation over a wide range of throttle conditions from 200-1100 W and 200-400 V. Performance is class-leading and is discussed in more detail in Section IV. Internal thermal isolation limits the amount of heat conducted to the spacecraft without complicating the mounting interface. The amount of isolation was carefully chosen to minimize radiator size requirements for the spacecraft while avoiding the need for internal survival heaters at a minimum interface temperature of -24ºC. The propellant and electrical interfaces are hard mounted to the thruster base and are accessible from a single side for robustness and ease of integration. The EM1 NGHT-1X has a mass of 3.1 kg.

An image of the PPU is shown in Figure 4. The PPU is a radiation-hard electronics box designed to operate from an unregulated bus voltage of 24-34 V. Several internal supplies provide the various functions required of the PPU: discharge supply module; heater-ignitor-keeper supply; magnet supply; PFCV supply; microcontroller; and AUX supply. Communication between the PPU and the spacecraft is accomplished through an RS-422 interface. The EM1 PPU has a mass of 6.1 kg.

Nominally, the PPU discharge supply module is designed to output up to 1000 W at 200-400 V. In the discharge module, a zero-volt-switching full-bridge converter topology converts the input voltage to high output voltage. An internal microcontroller handles the output controls, sequencing, and fault detection responses for each supply within the PPU. Utilizing software-based controls as opposed to FPGAs enables substantial flexibility and complexity in the PPU's operating sequences. All of the operating sequences needed to run the HCT are programmed into the PPU and are called by a single command from the spacecraft. However, the PPU can also accept individual commands from the spacecraft

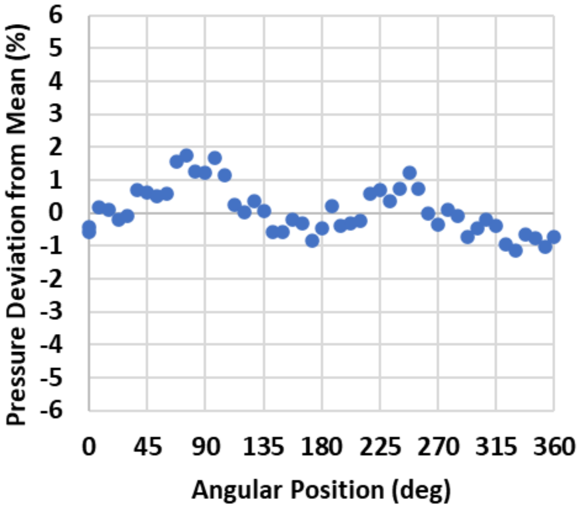

Figure 6. Anode flow symmetry at the channel centerline in the discharge channel exit plane.

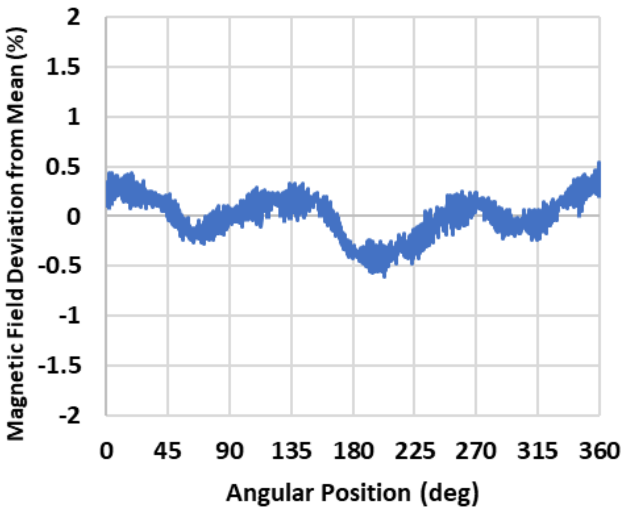

Figure 7. Magnetic field strength symmetry at the peak field location along the channel centerline.

to perform operations step by step, which is a useful feature for troubleshooting of potential in-flight anomalies.

An image of the XFC is shown in Figure 5. The XFC is a compact welded manifold with PFCV-based control, which is common in many Hall thruster and other electric propulsion systems [6][7][8]. Control of the PFCV is performed through the PPU via closed-loop control of the HCT discharge current. Downstream of the PFCV, two flow restrictors control the flow split between the anode and cathode of the HCT. These restrictors are sized to provide a fixed cathode flow fraction across the entire operating range of the HCT. Fluid connection to the HCT is accomplished using Omnisafe torque-elimination fittings.

III. Characterization Test Facilities

A. VF-8 (NASA GRC)

All performance, systems, thermal, and wear testing described in this paper was performed in NASA GRC's VF-8 facility. VF-8 is a 1.5-m diameter, 4.5-m long vacuum chamber which has a pumping speed of 120,000 L/s on N_2 and a base pressure of 7×10^{-8} torr. During thruster firing, chamber background pressure varied from approximately 20-35 μtorr. To measure thrust, the facility is equipped with a null-type, inverted-pendulum thrust stand of heritage NASA GRC design [9][10]. The thrust uncertainty for the data presented herein is approximately ± 0.5 mN.

Anode and cathode flow rates are controlled separately through mass flow controllers, however, during performance testing, the cathode flow was set to the same percentage of the anode flow at all conditions to mimic the nominal cathode flow fraction as controlled by the XFC. The flow controllers are calibrated and have an uncertainty of approximately ± 0.5% of the reading.

B. Environmental Test Lab (NG TSSD)

Vibration and shock testing were performed in Northrop Grumman's Environmental Test Lab in Dulles, VA. Due to relatively high vibration level requirements, testing was performed on the large T4000 shaker table which is used for spacecraft-level vibration testing. The HCT was mounted to an adapter bracket for axes parallel to the mounting interface. During testing, the HCT was instrumented with multiple external accelerometers to monitor and record vibration responses.

IV. Test Results

A. Anode Flow Symmetry and Magnetic Field Distribution

Prior to completion of the first thruster assembly, subassembly testing was performed on the anode and magnetic circuit to verify that their performance met requirements. Symmetric flow distribution within the discharge channel is critical to achieving efficient and stable discharge performance in Hall thrusters [11]. To measure the anode flow

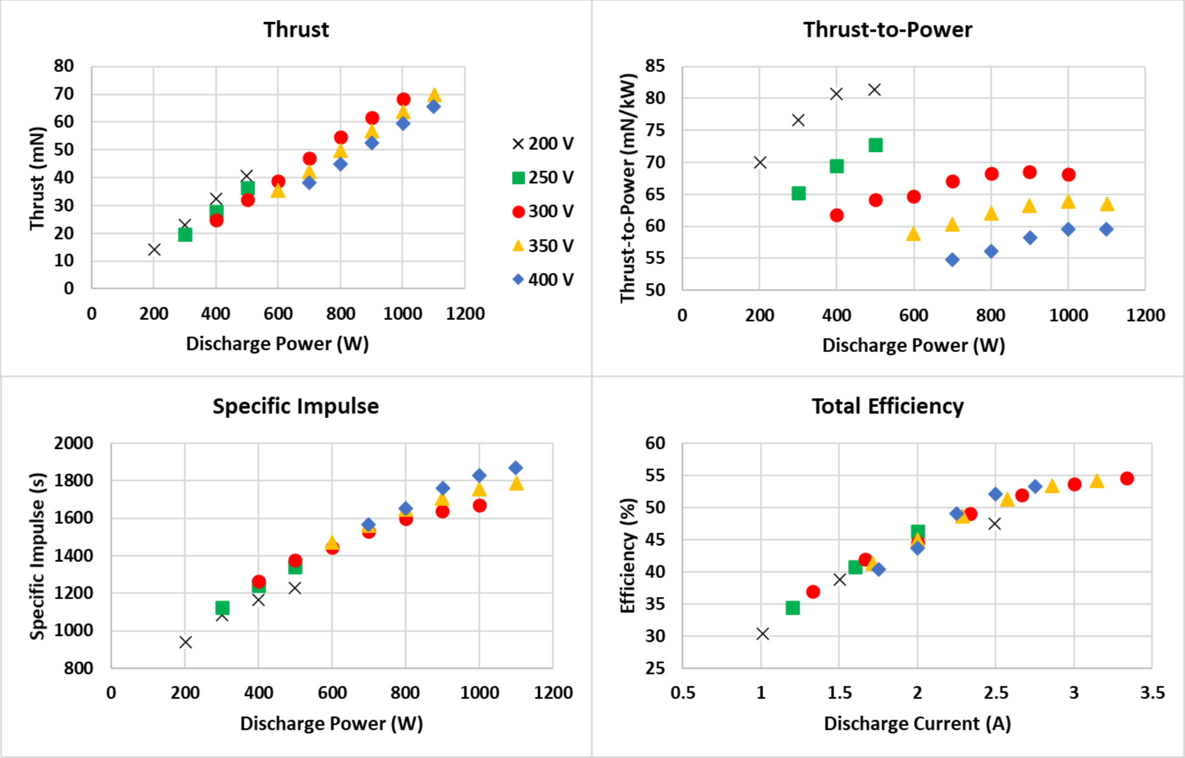

Figure 8. NGHT-1X performance, measured in NASA's VF-8 facility after a 500-hour wear test.

distribution symmetry, the anode subassembly was mounted in an aluminum discharge channel analog and installed in NASA GRC's VF-8 facility. With xenon flowing through the anode at normal operational flow rates, pressure within and downstream of the channel was measured with a specialized probe at various axial and radial locations. Data at the discharge channel exit plane at the radial centerline is shown in Figure 6. Overall flow symmetry based on pressure measurements is within ± 2% of the average. ± 5% is considered an acceptable level of flow symmetry by NASA [12], so this data demonstrates the effective gas distribution design developed by NASA GRC. Based on the anode design and process controls in place, NG expects this level of flow symmetry to be repeatable across flight units.

Similar to flow distribution, the symmetry of the magnetic field plays an important role in the performance of Hall thrusters. To measure the magnetic field distribution, the magnetic circuit assembly was placed on a Senis magnetic field mapping system equipped with a rotation stage, and the magnet coils were powered on to generate a magnetic field. 1D axial, 1D azimuthal, and 2D radial-axial probe sweeps were taken and all show good agreement with expectations based on simulations. Azimuthal symmetry at the axial location of the peak field strength, measured along the channel centerline, is shown in Figure 7. Radial field strength at this axial location is within ± 0.5% of the average across all azimuthal locations, which is extremely tight and reflects the robust design of the magnetic circuit. This high degree of symmetry plays a key role in the performance and stability of the NGHT-1X.

B. Thruster Performance

A detailed Current-Voltage-Magnetic Field map, or IVB map, was performed in NASA GRC's VF-8 facility to establish thrust, specific impulse, and discharge stability across a range of throttle conditions and magnetic field settings. This test was performed both before and after the 500-hour wear test described in Section IV-E, in order to characterize performance change as the thruster channel and pole covers erode. Over a range of 200 to 1100 W and 200 to 400 V, at each condition, performance data was taken at multiple magnetic field strengths to determine optimal field strength for that condition. For all data points, cathode flow fraction was fixed at the same value.

Figure 8 shows the thrust, thrust-to-power ratio, total specific impulse (including cathode flow), and total efficiency (including magnet power and cathode flow) of the NGHT-1X as measured in VF-8 following the 500-hour wear test. Performance is shown at the optimal magnetic field setting at each throttle condition as determined by the IVB map. As discussed in Section IV-E, this post-wear test data set, as opposed to Beginning-of-Life (BOL) data, is expected to be representative of mission-average performance. Within the nominal operating range of 600-1000 W and 300-400

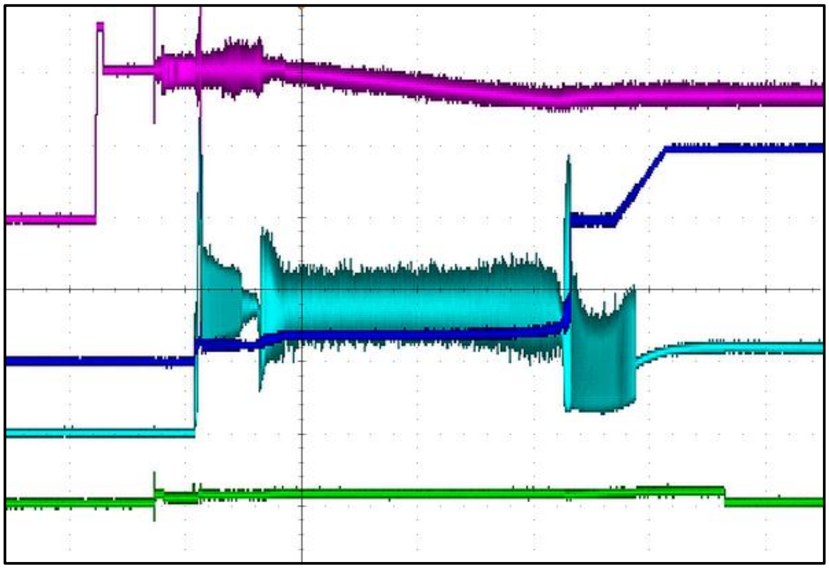

Figure 9. Example ignition from integrated systems testing. Top (magenta) – PFCV current; Middle-top (blue) – Discharge voltage; Middle-bottom (cyan) – Discharge current; Bottom (green) – Keeper voltage. Axis scales are omitted to protect proprietary information.

V, peak thrust-to-power is 68.6 mN/kW, which is achieved at 900 W 300 V. Peak total efficiency is 54.6% at 1 kW 300 V, and peak specific impulse is 1830 s at 1 kW 400 V. At most conditions within this nominal operating range, the discharge current oscillation amplitude remained less than 500 mA peak-to-peak. Overall, this performance is exceptional and class-leading for a thruster of this size and power range.

The lower-right quadrant of Figure 8 illustrates the current-fed nature of Hall thrusters. Total efficiency is almost solely dependent on discharge current, showing little to no sensitivity to discharge voltage. At low currents in particular, beyond a certain point, specific impulse cannot be increased by increasing discharge voltage at a fixed discharge power due to the loss in efficiency associated with the reduction in current. This is an important point for deep-space, Hall thruster-based missions which become power-limited far from the sun while also needing to maximize specific impulse. The importance of maintaining sufficient discharge current is even more dramatically illustrated in the performance results of the MaSMi-DM, whose performance is comparable to the NGHT-1X. In some cases, specific impulse actually decreases when increasing voltage at a fixed power due to the significant drop in efficiency concomitant with the reduction in discharge current [12].

C. Thermal Characterization

To characterize the NGHT-1X's thermal performance at various operating conditions, the thruster was instrumented with a number of internal and external thermocouples during assembly. Thermal testing was performed in NASA GRC's VF-8 facility. During the test, the NGHT-1X was mounted to an interface plate equipped with two heaters used to regulate the interface temperature to the required maximum capability of 105^{o}C. After the desired throttle condition was set, the thruster was allowed to fire for several hours in order to reach thermal steady state, defined as <3^{o}C change per hour on all thermocouple channels. While it would still be valuable for the purposes of thermal model correlation to not apply additional heating to the interface plate, doing so imparted the maximum expected thermal stresses on the thruster, which ensured that no critical temperature limit was missed during the modeling process.

Once steady state was achieved, thermal and electrical data were recorded. Thrust data was not collected during this test since the large number of thermocouples exceeded the number of connections available through the thrust stand. The primary temperatures of interest were the inner coil, outer coil, and discharge channel base. During all throttle conditions tested, with an interface temperature of 105^{o}C, the inner coil remained under 400^{o}C; the outer coil under 425^{o}C; and the discharge channel base under 500^{o}C. These key temperatures have appreciable margin on their respective limits, especially considering the elevated interface plate temperature (which will rarely be reached in operation), which demonstrates the efficient heat rejection of the NGHT-1X design. Thermal data collected in this test was used for detailed correlation of the NGHT-1X thermal model in preparation for CDR.

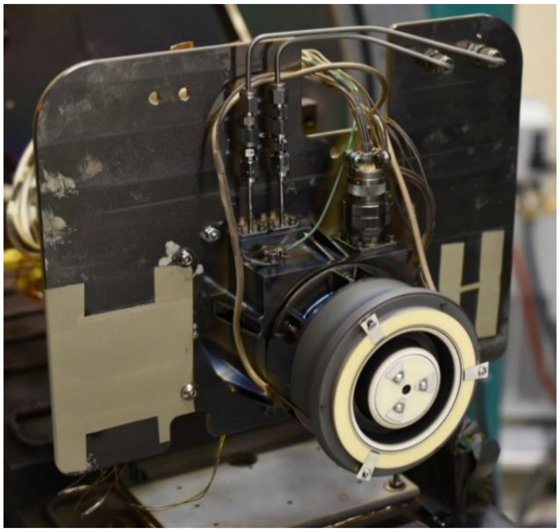

Figure 10. The EM1 NGHT-1X after the short duration wear test (SDWT).

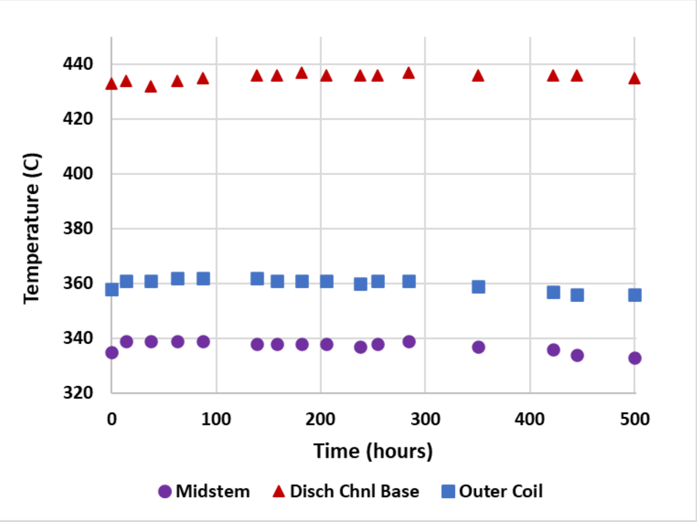

Figure 11. Several key thruster temperatures throughout the 500-hour SDWT.

D. Integrated Systems Testing

All testing described up to this point focused on characterizing thruster performance and was conducted using laboratory power supplies and mass flow controllers. In order to characterize and optimize system-level operation, an integrated systems test was performed using an EM XFC and EM PPU. Multiple individual tests were performed in this configuration: thruster ignition sequence and PFCV PID constant optimization; cold and hot start comparisons; high and low inlet pressure ignitions; steady-state firing in normal conditions; steady-state firing with intentionally induced high-amplitude discharge current oscillations; and extended duration firing. These tests were intended not only to characterize and optimize the system under nominal operating conditions, but also to demonstrate stability under a variety of worst-case conditions with respect to thermal environments, component variations, and thruster behavior.

Throughout the integrated systems test, over 50 thruster ignition sequences were performed without any failed ignitions or unintentional shutdowns due to improper control or sequencing. An example ignition is shown in Figure 9. Ignitions were repeatable at cold and hot start conditions. Ignitions were also consistent at high- and low-pressure extremes without adjusting PFCV PID constants or ignition sequencing. The pressure extremes were chosen to simulate worst-case combinations of component variability and system temperatures without having to actually adjust those parameters, which would be quite impractical in the case of component variability. Additionally, the PPU demonstrated stable output regulation during discharge current oscillations with peak-to-peak amplitudes as high as 200% of the RMS discharge current. Overall, the HTS exhibited reliable and robust operation over its entire operational envelope.

E. Short Duration Wear Testing

In order to characterize pole cover erosion, which is the primary life-limiting factor in magnetically shielded Hall thrusters [13][14], a 500-hour Short Duration Wear Test (SDWT) was performed on the EM1 NGHT-1X in NASA GRC's VF-8 facility. The inner and outer pole covers were masked in three azimuthal locations to provide reference surfaces when taking post-test profilometer measurements of the pole covers. Additionally, various areas of the thrust stand bracket were masked in order to characterize facility backsputter rate, which were measured to be more than an order of magnitude less than the thruster erosion rates. Wear testing was conducted at the 700 W, 300 V throttle condition which, based on measured pole cover erosion trends on the HERMeS thruster, is expected to be one of the highest erosion conditions in the nominal operating envelope [15][16]. More SDWTs are planned at other throttle conditions to verify or refute this expectation. Based on erosion data gathered to date, the NGHT-1X is expected to satisfy its throughput requirement of 2.1 MNs with margin.

An image of the thruster after the SDWT is shown in Figure 10. Throughout the test, all thruster temperatures remained steady to within a few degrees of their averages for the entire test duration, which is shown graphically in Figure 11. Upon inspection after completion of the SDWT, in contrast to the large amounts of deposition on external surfaces from facility backsputter, the thruster internals showed little signs of outgassing or degradation, which affirms the careful design and material selection that went into the NGHT-1X.

Thrust data was not collected continually throughout the test, but rather only during pre- and post-SDWT IVB

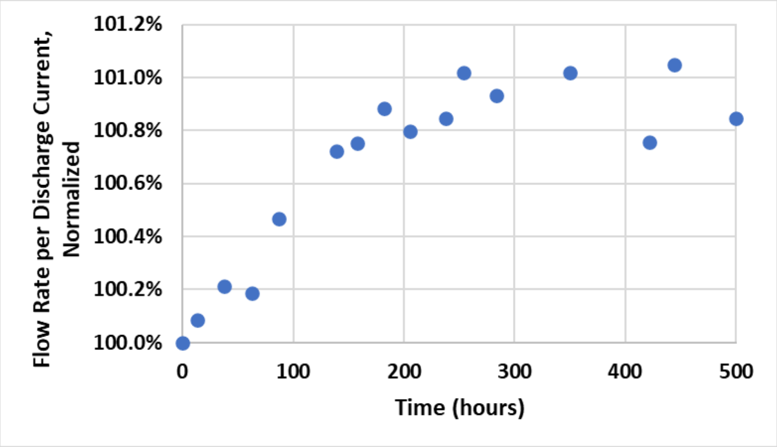

Figure 12. Ratio of flow rate to discharge current, normalized, throughout the duration of the 500-hour SDWT.

maps. However, performance change over time due to channel erosion can be partially inferred from the amount of xenon flow required to maintain the same discharge current, shown graphically in Figure 12. Over the first 250 hours of the test, the flow rate required to maintain 2.33 A of discharge current increased by ~1%, indicating a slight drop in specific impulse. Between 250 and 500 hours, the trend was flat, which suggests that the rate of discharge channel erosion slowed significantly after 250 hours. This result was expected and is an intended consequence of the partially magnetically shielded topology. Because performance change seems to have stabilized, the data presented in Section IV-B is expected to be representative of mission-average performance, which is why it is presented in this paper as opposed to BOL performance.

F. Environmental Testing

To retire structural risk, a second EM NGHT-1X was fabricated specifically to undergo a structural environmental test campaign. First, random and sinusoidal vibration testing was performed at acceptance levels. Following this test, an abbreviated IVB map will be performed both to gather data on unit-to-unit performance variation and also to expose the thruster to its operational thermal environments. The latter point is important in order to expose any potential thermally induced structural deficiencies that would otherwise be missed in a standalone structural test. Lastly, random and sinusoidal vibration as well as shock testing will be performed at qualification levels to fully vet the structural design of the NGHT-1X.

Environmental testing was performed in NG's Environmental Test Lab (ETL) in Dulles, VA. The lowest modal frequency of the thruster observed in the acceptance-level test was approximately 600 Hz, which is substantially higher than typical spacecraft structural modes that could couple to the thruster. Pre- and post-structural mode frequencies and amplitudes were nearly indistinguishable from each other, demonstrating great structural integrity of the thruster design. Following the vibration test, the HCT was shipped to NASA GRC for hot fire testing in the VF-8 facility. Once performance testing is complete, the unit will be shipped back to Dulles for qualification-level vibration and shock testing.

V. Future Testing and Thruster Qualification Methodology

Engineering Model testing will continue through Q2 and Q3 2022. Performance and plume data has recently been taken with the EM1 NGHT-1X in NASA GRC's VF-11 facility and is still being analyzed. VF-11 has a higher pumping speed than VF-8 and achieved background pressures of 4-6 μtorr during thruster firing, providing a valuable understanding of how the NGHT-1X's performance is affected by background pressure and other facility effects. Following this, several more SDWTs are planned to measure erosion rates at different throttle conditions and with pole covers modified to represent its current eroded state after the first SDWT. As stated in the previous section, at the time of writing this paper, the EM2 NGHT-1X is ready to undergo hot fire performance testing in VF-8, after which it will return to NG Dulles for qualification-level vibration and shock testing.

Regarding thruster lifetime qualification, because of the requirements typically demanded from EP systems, namely thousands of operating hours and thousands of on-off cycles, lifetime qualification presents a unique challenge to the thruster manufacturer and to the spacecraft prime contractor. To the former, how does one perform the testing in a way that sufficiently verifies that the thruster can meet its requirements, given that the life of the thruster often exceeds several years of continuous firing and that ground test facilities are known to impact thruster behavior compared to the space environment? To the latter, how should the thruster's requirements be defined so as to mitigate the financial and temporal burden of lifetime testing while still ensuring the thruster can accomplish its mission(s)? As both the thruster manufacturer and the end user, Northrop Grumman must address both questions.

These challenges have been explained with great clarity in Dankanich's 2009 Lifetime Qualification Standard for Electric Thrusters [17] and expanded upon in 2018 by Polk and Brophy [18], who were co-authors on the 2009 paper. The essential problem is that, because thruster lifetimes are so long (and because propellant can be so expensive), it is prohibitively time-consuming and costly to conduct more than one life test and to conduct that one life test for substantially longer than the actual mission requirement, resulting in no statistical information about the wear-out failure mode(s). As described in [17] and [18], an appropriate combination of a full life test, supplemental shorter tests, and experimentally verified models is key to establishing a qualified lifetime for an electric propulsion thruster.

Northrop Grumman intends largely to follow the recommendations laid out in these papers. An EM3 NGHT-1X will be built in Q3 2022 which will undergo a Long Duration Wear Test (LDWT). The LDWT will be conducted to no less than 100% of the mission requirement, though if funding allows the test will be carried out to failure. The SDWTs that will be completed in 2022 will supplement the LDWT with information on erosion variability between throttle conditions and other factors. Additionally, NG has in-house EP plasma plume simulation capability that will be leveraged in developing the lifetime qualification model [19][20].

The EM3 thruster for the LDWT will be built prior to the qualification and flight units but will possess all the key features of the final design that dictate discharge behavior and erosion, such as the propellant distributor design and magnetic field topology. This approach is consistent with the standard laid out in [17]. In fact, because of the diligence of the thruster development team and the resulting success of the EM test campaign so far, very few design changes are anticipated from PDR to CDR, so EM3 will be almost fully representative of the qualification and flight units.

Once CDR and procurement of hardware have completed, a Qualification Model (QM) thruster will be built and tested. This QM thruster will be identical to the flight units and will undergo a full environmental qualification campaign including vibration, shock, and TVAC testing to qualification levels, interspersed with multiple hot fire performance tests. Testing of flight and qualification thrusters is expected to begin in early 2023.

In parallel with the LDWT and environmental qualification, cycle tests will be performed on the two primary cycle-life-limited components, the cathode heater and magnet coils. A batch of six cathode heaters will undergo cycle testing in NASA GRC's heater cycle test facility. The heaters will be tested to failure, or to a cycle count that is substantially higher than the mission requirement such that further cycling is deemed unnecessary. In a separate facility, three sets of inner and outer magnet coils will undergo thermal cycle testing in a test rig specially designed by NASA GRC to facilitate deep thermal cycles. The magnet coils have significantly more thermal mass than the cathode heaters, which results in substantially longer test cycle times and thereby limits the number of cycles that are practical to test. NG intends to test the magnet coils to no less than 100% of the mission requirement, and further if funding allows.

VI. Conclusions

Preliminary characterization of Northrop Grumman's NGHT-1X low power Hall thruster and associated hardware shows best-in-class performance and has demonstrated robust operation over a wide range of throttle points and environmental conditions. Once environmental qualification is complete in 2023, the NGHT-1X will define the state-of-the-art in flight-ready, commercially available Hall thrusters in the sub-kW power class, suitable for applications ranging from satellite servicing to medium-sized GEO comsats and even to deep space SmallSat missions. The first mission application of the NGHT-1X system will be onboard Northrop Grumman's Mission Extension Pod, which is slated for first launch in 2024, and several other applications are already under consideration in addition to the MEP.

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References

[1] Glogowski, M. J., Pilchuk, J. W., Kodys, A. D., Molinsky, J. M., Rahal, G. E., Eskenazi, M. I., and Tam, W. H., “Electric Propulsion Systems Development & Integration Activity at Orbital ATK,” 35th International Electric Propulsion Conference, Atlanta, GA, 2017.

[2] Kodys, A., Pilchuk, J., Glogowski, M., Trescott, J., Pucci, J., and Koch, B., “Initial Flight Operations of the GEOStar-3 Electric Propulsion System,” 2018 Joint Propulsion Conference, Cincinnati, OH, American Institute of Aeronautics and Astronautics, 2018. https://doi.org/10.2514/6.2018-4719.

[3] Glogowski, M. J., Anderson, J. D., Herbert, G. A., Kodys, A. D., and Llorens, W. A., “Application of Solar Electric Propulsion in the Emerging Satellite Servicing Industry,” 36th International Electric Propulsion Conference, Vienna, Austria, 2019.

[4] Benavides, G. F., Kamhawi, H., Liu, T., Pinero, L. R., Sarver-Verhey, T. R., Rhodes, C. R., Yim, J., Mackey, J., Gray, T. G., Butler-Craig, N. I., Myers, J. L., and Birchenough, A. G., “Development of a High-Propellant Throughput Small Spacecraft Electric Propulsion System to Enable Lower Cost NASA Science Missions,” AIAA Propulsion and Energy 2019 Forum, American Institute of Aeronautics and Astronautics, 2019. https://doi.org/10.2514/6.2019-4162.

[5] Kamhawi, H., Liu, T. M., Benavides, G. F., Mackey, J., Server-Verhey, T., Yim, J., Butler-Craig, N. I., and Myers, J., “Performance, Stability, and Thermal Characterization of a Sub-Kilowatt Hall Thruster,” 36th International Electric Propulsion Conference, Vienna, Austria, 2019.

[6] Bushway, E., and Perini, R., “Proportional flow control valve (PFCV) for electric propulsion systems,” 36th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, American Institute of Aeronautics and Astronautics, 2000. https://doi.org/10.2514/6.2000-3745.

[7] Kerl, T., Lenguito, G., Aghazadeh, F., Malone, S., Snyder, S., and Chaplin, V. H., “Maxar Electric Propulsion Development for Deep Space,” AIAA Propulsion and Energy 2020 Forum, American Institute of Aeronautics and Astronautics, 2020. https://doi.org/10.2514/6.2020-3605.

[8] Stanley, S. B., Chew, G., Rapetti, R., Tofil, T., Herman, D. A., Allen, M.,Welander, B., Jackson, J., and Myers, R., “Development of a 13 kW Hall Thruster Propulsion System Performance Model for AEPS,” 53rd AIAA/SAE/ASEE Joint Propulsion Conference, American Institute of Aeronautics and Astronautics, 2017. https://doi.org/10.2514/6.2017-4726.

[9] Haag, T. W., “Thrust Stand for High-Power Electric Propulsion Devices,” Review of Scientific Instruments, Vol. 62, No. 5, 1991.

[10] Mackey, J. A., Haag, T. W., Kamhawi, H., Hall, S. J., and Peterson, P. Y., “Uncertainty in Inverted Pendulum Thrust Measurements,” NASA/TM—2018-219952.

[11] Ding, M., Li, H., Ding, Y., Liu, H., Yu, D., and Wang, X., “Experimental study of the effect of propellant asymmetrical distribution on anode current in a Hall effect thruster,” Physics Letters A, Vol. 383, Issue 25, 2019, Pages 3108-3113, ISSN 0375-9601. https://doi.org/10.1016/j.physleta.2019.07.008.

[12] Conversano, R. W., Reilly, S. W., Kerber, T. V., Brooks, J. W., and Goebel, D. M., “Development of and Acceptance Test Preparations for the Thruster Component of the Ascendant Sub-kW Transcelestial Electric Propulsion System (ASTRAEUS),” 36th International Electric Propulsion Conference, Vienna, Austria, 2019.

[13] Mikellides, I. G., Lopez Ortega, A., and Jorns, B., "Assessment of Pole Erosion in a Magnetically Shielded Hall Thruster," AIAA 2014-3897, 50th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, 2014. https://doi.org/10.2514/6.2014-3897.

[14] Jorns, B., Dodson, C. A., Anderson, J. R., Goebel, D. M., Hofer, R. R., Sekerak, M. J., Lopez Ortega, A., and Mikellides, I. G., "Mechanisms for Pole Piece Erosion in a 6-kW Magnetically-Shielded Hall Thruster," AIAA 2016-4839, 52nd AIAA/SAE/ASEE Joint Propulsion Conference, 2016. https://doi.org/10.2514/6.2016-4839.

[15] Polk, J. E., Lobbia, R., Barriault, A., Guerrero, P., Mikellides, I., Lopez Ortega, A., "Inner Front Pole Cover Erosion in the 12.5 kW HERMeS Hall Thruster Over a Range of Operating Conditions," 35th International Electric Propulsion Conference, Atlanta, GA, 2017.

[16] Frieman, J. D., Gilland, J. H., Kamhawi, H., Mackey, J., Williams Jr., G. J., Hofer, R. R., and Peterson P. Y., "Wear trends of the 12.5 kW HERMeS Hall thruster", Journal of Applied Physics 130, 143303, 2021. https://doi.org/10.1063/5.0062579.

[17] Dankanich, J. W., Brophy, J. R., and Polk, J. E., "Lifetime Qualification Standard for Electric Thrusters," AIAA 2009-5095. 45th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, 2009. https://doi.org/10.2514/6.2009-5095.

[18] Polk, J. E. and Brophy, J. R., "Life Qualification of Hall Thrusters by Analysis and Test," Space Propulsion 2018 Conference, Seville, Spain, 2018.

[19] Bermudez, L. M., Noushkam, N., Basak, D., and Glogowski, M. J., "High Fidelity Numerical Simulations for the Characterization of Plasma Plume Interaction Effects on Geostationary Satellites," AIAA SPACE 2015 Conference and Exposition, American Institute of Aeronautics and Astronautics, 2015. https://doi.org/10.2514/6.2015-4641.

[20] Bermudez, L. M., Barnhart, K. J., Agathon-Burton, C. A., Basak, D., and Glogowski, M. J., "A Comprehensive Numerical Approach to the Modeling and Simulation of Plume Interaction Effects on Solar Electric Propulsion Spacecraft," 35th International Electric Propulsion Conference, Atlanta, GA, 2017.