

Overview of Electric Propulsion Projects at NASA Glenn Research Center

IEPC-2019-A-949

*Presented at the 36th International Electric Propulsion Conference
University of Vienna • Vienna, Austria
September 15-20, 2019*

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Abstract: NASA Glenn Research Center (GRC) is currently leading the development of multiple electric propulsion (EP) systems to flight readiness. The Advanced Electric Propulsion System (AEPS) is a 12.5-kW Hall thruster system that is being developed by the Solar Electric Propulsion Technology Demonstration Mission (SEP TDM) project. NASA's Evolutionary Xenon Thruster-Commercial (NEXT-C) is a 7-kW-class gridded ion thruster system. NASA GRC is also providing EP discipline support to the Power and Propulsion Element (PPE) and the Double Asteroid Redirection Test (DART) missions, which will be the first applications for these technologies, respectively. Lower technology readiness level (TRL) projects are underway for applications including CubeSats, small spacecraft, and Mars exploration vehicles. NASA GRC has performed numerous independent verification and validation (IV&V) tests of CubeSat-class EP systems in support of a growing number of small U.S. businesses that are developing these systems. Lastly, three technology development efforts focused on 100-kW EP strings led by Aerojet Rocketdyne, Ad Astra, and MSNW were recently completed.

I. Introduction

Electric propulsion (EP) has been an active area of research and development at NASA Glenn Research Center (GRC) since the late 1950s,¹ and the Center is the lead organization for EP within NASA, with support provided by NASA's Jet Propulsion Laboratory (JPL). To support EP research and development at NASA GRC, significant facility investments were made in the early 1960s. Today more than ever, these facility capabilities are enabling the advancement of EP systems for a range of missions. Although the investments in EP started approximately 60 years ago, only recently has the technology gained a strong foothold in both the commercial and Government sectors. The initial commercial applications started with EP systems providing station keeping on large communications satellites.² Success of those systems has led to the development of a new class of all-electric-propulsion-based communication satellites, which is rapidly changing the economics of the industry. Initial operational use of EP by NASA started with gridded ion thrusters for Deep Space 1 and Dawn planetary missions. Because of an attractive combination of thrust and specific impulse, as well as modest system-level complexity, NASA began investigating Hall thruster technologies in the early 1990s. Originally developed in the Soviet Union, several collaborative efforts were conducted during this time with multiple Russian institutes to evaluate and demonstrate Hall thruster technology.³⁻⁵ After two decades of development, Hall thruster technology was deployed on the Advanced Extremely High Frequency communications satellite for the U.S. Air Force. The growth in EP continues across all scales of satellite and transportation systems, from the CubeSat regime to the new high Power and Propulsion Element (PPE) and future NASA missions. This paper will highlight the contributions of NASA GRC in supporting both industry and NASA missions over the last 2 years.

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II. Space Technology Mission Directorate Solar Electric Propulsion Technology Demonstration Mission

In 2010 NASA began developing large, deployable photovoltaic solar array structures for high-power electrical power generation and high-power EP technologies.⁶⁻¹¹ The maturation of the critical technologies required for the high-power solar electric propulsion (SEP) vehicle has made mission concepts utilizing high-power SEP viable.¹² The high-power EP investments were in areas having high technical risks and/or long lead times.

A. In-House Technology Development

Beginning in 2012, NASA initiated the technology development of a 13-kW Hall thruster system that included the Hall Effect Rocket with Magnetic Shielding (HERMeS) and a 120-V input/800-V output power processing unit (PPU). This technology development effort was performed to demonstrate the feasibility of high-power, high-throughput Hall thruster technology and reduce risk for the qualification and acquisition of flight units under a contract with U.S. industry. Three high-fidelity technology development unit (TDU) thrusters, one of which is shown in Fig. 1, and the HP-120V/800V PPU were produced under this effort. An extensive test campaign of this hardware was initiated in 2015 that included demonstrating thruster performance, verifying magnetically shielded operation at high specific impulse, and affirming that the internally mounted cathode minimizes the effects of facility pressure on performance; and demonstrating TDU thruster compliance to qualification-level environments.¹³⁻²²

Recently, a series of wear tests were conducted to identify erosion phenomena and the associated failure modes, as well as serve to validate the service-life models. The Long Duration Wear Test, which was the third in this series of tests, accumulated over 3,500 h of operation on the TDU-3 thruster and served as a pathfinder for the planned life and qualification testing of the Advanced Electric Propulsion System (AEPS) hardware that will be delivered to NASA under a contract with Aerojet Rocketdyne (AR).²³

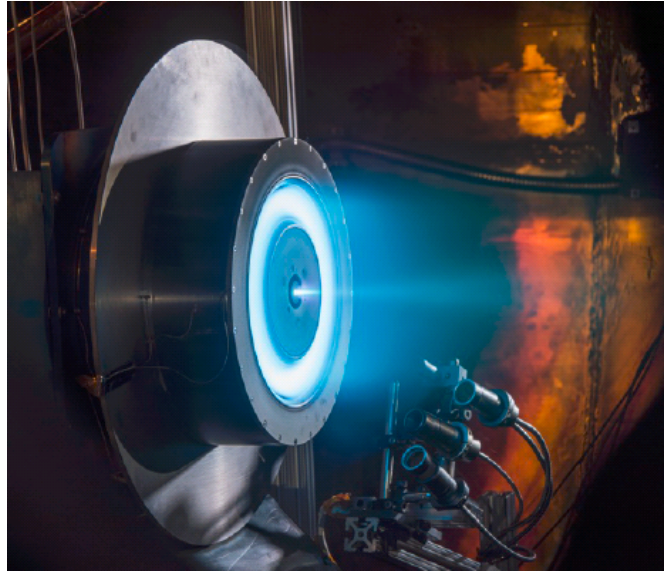


Figure 1. 12.5-kW Hall-Effect Rocket with Magnetic Shielding (HERMeS) operating in Vacuum Facility 5 at NASA GRC.

B. Advanced Electric Propulsion System

The AEPS contract was awarded in 2016 to AR as the prime with major subcontractors ZIN Technologies and VACCO Industries. Management of the contract is being led by NASA GRC. The thruster and PPU designs produced by NASA under the technology development effort served as a reference and the point of departure for the AEPS components. The AEPS EP string consists of the Hall Current Thruster, a PPU (including digital control and interface functionality), xenon flow controller (XFC), string harnesses, and a command and data handling system for the safe operation of the AEPS string in ground-based operation. Initially, the contract deliverables included an engineering development unit (EDU) EP string and optional qualification model (QM) and flight model (FM) hardware delivery within 3 years.²⁴ Subsequently, requirement changes resulted in contract modifications, including replacement of the EDU hardware with engineering test unit (ETU) components. This change was made to align the AEPS hardware delivery schedule with the PPE, on which two AEPS strings will be flown.

AR has completed the fabrication of the first of two ETU Hall thrusters. ETU-1, which is shown in Fig. 2, was designated for environmental tests and has undergone acceptance-level random vibration testing at AR. The unit has been delivered to NASA JPL where hot-fire testing will be performed in the Owens test facility prior to qualification-level random vibration testing at AR and qualification-level shock testing at an AR subcontractor facility. Hot-fire testing will then be repeated at NASA JPL followed by deep thermal-vacuum cycle testing and system-level radiated electromagnetic interference (EMI) testing at The Aerospace Corporation (TAC). The fabrication of ETU-2 is nearly completed and is scheduled for delivery to NASA GRC in September 2019. The ETU-2 thruster is designated for full performance, stability, thermal, plume, and wear characterization tests, which will be conducted at NASA GRC in Vacuum Facility 5 (VF-5). Following detailed characterization testing, the thruster will undergo two 250-h wear

segment tests to assess pole cover erosion rates at two selected thruster operating points. Then an integrated system test with the ETU PPU and XFC will be performed. Laser-induced fluorescence (LIF) measurements will also be made, and the data used for model validation purposes. Finally, the ETU-2 string will be utilized for a 1,000-h wear test. These tests will be completed in advance of the AEPS Critical Design Review (CDR) that is currently scheduled for July 2020.

ETU and EDU PPUs are being manufactured by the AEPS project. The ETU PPU will undergo functional and thermal bench tests at AR and will then be shipped to NASA GRC for integrated tests with the ETU-2 thruster. Once the ETU PPU is delivered to NASA GRC, it will be utilized in the remaining ETU-2 thruster tests including the LIF testing and 1,000-h wear test. The EDU PPU will undergo functional tests at AR, and then the unit will be shipped to NASA GRC for thermal cycle and burn-in tests. The unit will then undergo a random vibration test at NASA GRC's Structural Dynamic Laboratory (SDL), after which qualification-level shock testing will be performed at an AR subcontractor facility. After completing the shock test, the EDU PPU will be returned to NASA GRC for electromagnetic conductance and power quality tests. Integrated thermal-vacuum testing will then be performed with the ETU-1 thruster at JPL followed by EMI testing at TAC.

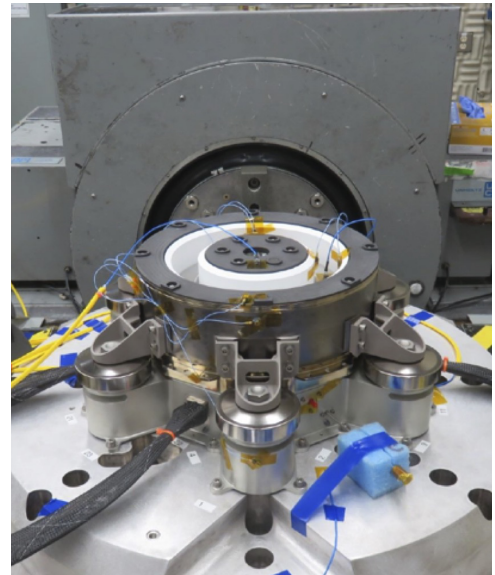


Figure 2. Advanced Electric Propulsion System (AEPS) engineering test unit ETU-1 thruster during vibration test at Aerojet Rocketdyne (AR).

C. Plasma Diagnostics Package

A flight plasma diagnostics package (PDP) is being designed, developed, and implemented on NASA's PPE. A notional representation of the PDP shown in Fig. 3, will be provided as Government-furnished equipment (GFE) to the PPE spacecraft provider. The PDP will collect on-orbit plasma plume data from the high-power EP system, which will be used to assess differences in the on-orbit operating performance characteristics compared to ground test data. The PDP data will be utilized to refine the plume models to mitigate risks associated with the spacecraft-plasma plume interaction for the PPE and Gateway. The PDP will also provide necessary data that will enhance high-power SEP extensibility to higher power SEP systems envisioned by NASA. In addition, the PDP improves on-orbit understanding of high-power EP systems to accelerate adoption for future NASA, other Government Agencies, and commercial missions.

The current PDP architecture consists of one thruster probe assembly (TPA), a main electronics package (MEP), and associated wiring harnesses (that connect the TPA to the MEP). The TPA includes the following 10 sensors:

- Five planar probes: these obtain time-resolved ion flux, electron temperature, and plasma potential
- Three high-speed retarding potential analyzers (HS-RPAs): these obtain ion energy distribution and time-resolved/energy-filtered ion characterizations
- Two hemispherical potential analyzers (HPAs): these obtain ion energy distribution

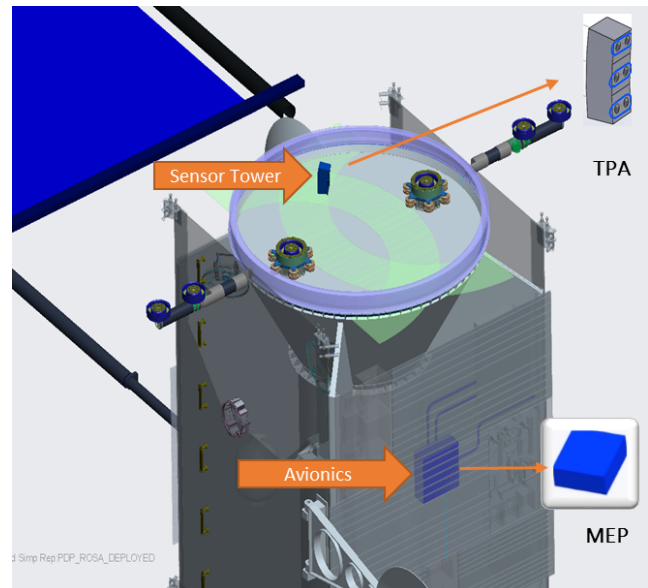


Figure 3. Notional arrangement of the plasma diagnostics package (PDP) on the Power and Propulsion Element (PPE) spacecraft.

The System Requirements Review was successfully completed in May 2019, and the project is progressing with component-level breadboard testing and the preliminary design activities.

III. Power and Propulsion Element

The Power and Propulsion Element (PPE), the first major element of NASA's Gateway, was recently awarded to Maxar Technologies. The PPE is a 50-kW SEP spacecraft (Fig. 4), which is an increase of nearly 3 times the current state of the art (SOA). The PPE will serve Gateway as a mobile command and service module, providing a communications relay for human and robotic expeditions to the lunar surface. To achieve the 50 kW of EP, the vehicle will utilize two different systems: two strings of the 12.5-kW Hall thruster AEPS currently under development by AR and four strings of a 6-kW Hall thruster system under development by Busek Co. Inc. and Maxar Technologies. The contract for spacecraft development was awarded to Maxar in May 2019, and NASA is targeting launch of the PPE on a commercial rocket in late 2022.

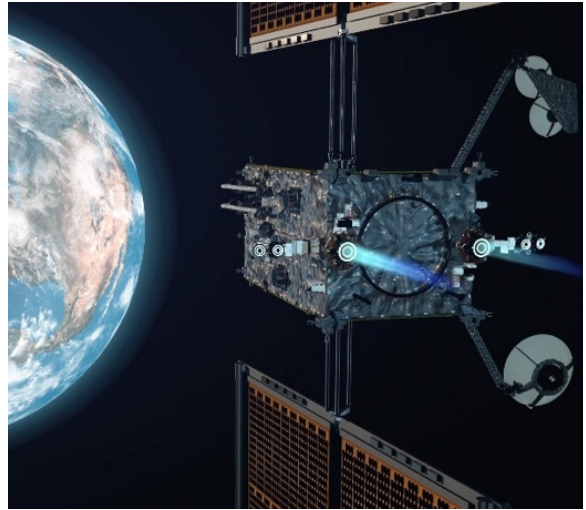


Figure 4. Maxar concept for the Power and Propulsion Element for Gateway.

IV. NASA's Evolutionary Xenon Thruster

A. NASA's Evolutionary Xenon Thruster-Commercial

The development of NASA's Evolutionary Xenon Thruster (NEXT) gridded ion thruster propulsion system began in 2002 as a follow on to the successful NASA Solar Electric Propulsion Technology Applications Readiness (NSTAR) program.²⁵ NEXT was conceived to operate at higher power and total impulse capability compared to NSTAR, consistent with the needs of flagship-type outer-planet missions. Under this effort, the development of a 7-kW gridded ion thruster, high-efficiency PPU, propellant management system (PMS), thruster gimbal, and digital control interface unit (DCIU) were undertaken. The Phase I effort resulted in the design and fabrication of multiple engineering model (EM) thrusters; characterization of EM thruster performance; completion of a 2,000-h wear test; development of a breadboard PPU, PMS, and DCIU simulator; and a system integration test of the NEXT system.²⁶⁻²⁸ During Phase II, hardware development of a prototype model (PM) thruster and PMS were completed as well as an EM PPU and breadboard gimbal. A long-duration test (LDT) was also conducted to validate the thruster service life model and quantify the NEXT thruster wear rates over an extended mission's power-throttling profile. The LDT was voluntarily terminated in 2014, at which time the thruster had accumulated over 51,000 h of operation and processed 918 kg of propellant.²⁹

In April 2015, NASA GRC awarded the NASA's Evolutionary Xenon Thruster-Commercial (NEXT-C) contract to AR with major subcontractor ZIN Technologies. The contract scope included completion of the PPU development to TRL 6 and the fabrication, test, and delivery of two NEXT-C flight thrusters and PPUs. NASA GRC provided subject matter expertise and continuity to the previously completed technology development effort as well as insight and oversight of the contracted work and delivered flight-qualified hollow cathode heaters for the discharge and neutralizer hollow cathode assemblies. Component- and system-level testing is also scheduled to occur at NASA GRC. The NEXT-C CDR was conducted in April 2018, and following a successful PPU gate review to address open issues, the PPU was determined to be TRL 6. The fabrication of the first of two NEXT-C flight thrusters is nearly complete, with delivery to NASA GRC expected in September 2019. Protoflight testing of this thruster will be performed by AR personnel at GRC immediately following delivery and will include performance and environmental (thermal-vacuum and vibrational) testing. A single-string test with the first flight PPU will follow the environmental testing of the thruster, both tailored to Double Asteroid Redirect Test (DART) mission-specific requirements. These tests will utilize VF-6, VF-18, and the SDL at GRC. All testing of the first string is scheduled to be completed in 2019 in support of the DART mission.

B. High Thrust-to-Power NEXT Thruster Assessment

To address the broader interests of the U.S. propulsion community, an activity was convened to assess the capability of an unmodified flight-representative NEXT thruster to operate at higher thrust and power densities, and ultimately higher thrust-to-power, than has been qualified to date for NASA's deep space missions. This was undertaken through a vetting process involving representatives from the commercial space sector who assisted in defining the performance requirements. Multiple throttle-level performance goals were defined for the thruster, all of which operate at 1.7 to 2 times higher current densities, and some of which operate at up to 2 times higher thrust and power densities, than those conditions associated with the standard NASA throttle table.

Many of these operating conditions had been previously demonstrated with EM NEXT thruster hardware, including power and thrust levels up to 13.6 kW and 466 mN, respectively. However, the most challenging throttle level "TL1B" (at 7.0 kW, 3,060 s specific impulse I_{sp} , and 324 mN thrust) had not. Resources were secured to conduct a brief series of tests on high-fidelity NEXT thruster hardware at TAC to address operations at TL1B. The objective of the test was to evaluate the existing NEXT flight thruster design gaps relative to operation at TL1B; and from this, identify potential hardware modifications that may be required.

A NEXT flight-like thruster configuration was characterized over power levels ranging from 4.2 to 7.7 kW, while constrained within a fairly narrow range of about 620 s I_{sp} : 2,890 to 3,510 s. The operating condition that most closely approximated the TL1B performance goal was at 6.5 kW input power and 3,080 s I_{sp} , producing about 275 mN thrust. The shortfall in processed power and thrust was associated with the lower-than-desired maximum beam current of 5.4 A (vs. 7.0 A target). Causes of this shortfall, associated with the ion optics assembly (as configured for NASA planetary missions) and discharge magnets were identified. Modest changes to NASA's NEXT thruster hardware configuration used for planetary missions, intended to capture TL1B and other high-thrust and high-power density conditions, were discussed. Activities to define and verify these modifications are the subject of ongoing efforts.

C. Annular Ion Engine Development Efforts

In FY19 resources were applied to continue development of the Annular Ion Engine (AIE) concept. Activities included the build of a second-generation 40-cm thruster with reconfigured magnetics and ion optics, applying lessons learned from the GEN1 engine.³⁰ This engine is presently being prepared for discharge chamber tests with simulated beam extraction scheduled for September 2019. Concurrent activities include magnetics modeling to improve electrical efficiency, and ion optics modeling to improve perveance and increase thrust-to-power ratio. Modeling tasks are being performed both at GRC and at University of Michigan under a NASA contract.

Additionally, discussions with TAC identified the benefit of developing a subscale (18-cm beam diameter) AIE to more readily address physics- and manufacturing-based issues identified with the full-scale 40-cm thruster. This subscale AIE may also provide a design solution for propulsion requirements for small spacecraft platforms with available power for EP. To this end, two subscale AIE designs have been completed utilizing a common ion optics design and applying two discharge chamber magnetic circuit approaches. The AIEs are presently in fabrication with testing scheduled to begin in the fall of 2019.

D. Double Asteroid Redirect Test

The NEXT ion propulsion system will be utilized on the Double Asteroid Redirection Test (DART) mission (Fig. 5), which is led by the Johns Hopkins Applied Physics Laboratory (APL). The DART mission will be the first-ever asteroid deflection demonstration using a kinetic impact method. The target of the DART mission is the binary asteroid system Didymos. The spacecraft will impact the 160-m-diameter moonlet Didymos B, and Earth-based telescopes will measure its corresponding change in orbit. An auxiliary 6U CubeSat will also provide information on the plume ejecta and impact crater, which will provide a wealth of physical composition information. The NEXT system provides flexibility in mission operations and will nominally be used for trajectory control maneuvers (as well as several short "neutral burns").

The DART mission recently passed its mission CDR. A number of risk-reduction tests have been conducted by the NEXT/APL team to characterize the propulsion system across anticipated flight conditions.^{31,32} The NEXT system is currently at TRL 6, and delivery of the flight thruster and PPU (to NASA GRC) will occur in late summer of 2019. The system will undergo acceptance tests, which includes performance, structural, and thermal-vacuum tests. The system will then be delivered to AR prior to integration on the spacecraft. The mission has a nominal launch date in July 2021, with the asteroid impact occurring in September 2022.

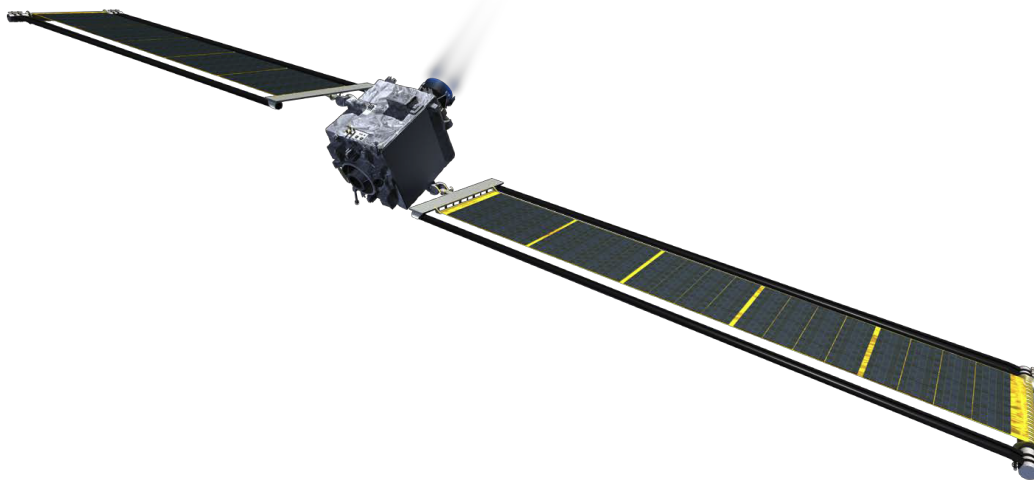


Figure 5. Double Asteroid Redirection Test (DART) spacecraft with NASA’s Evolutionary Xenon Thruster (NEXT) gridded ion propulsion system.

V. High-Power Electric Propulsion

NASA, while returning to the Moon with the Gateway, is also looking towards exploration of Mars. For lunar missions, a 50-kW SEP vehicle is sufficient to meet the mission needs; however, for a Mars mission, vehicles on the scale of 300 kW or greater are envisioned. At that scale, the option exists to increase the individual thruster power level up to 100 kW per string. In 2015 under the NextSTEP Broad Area Announcement (BAA), NASA selected three propulsion subsystems for development: (1) Ad Astra: VASIMR (Variable Specific Impulse Magnetoplasma Rocket), (2) MSNW, LLC: ELF-250 (electrodeless Lorentz force), and (3) AR: 100-kW nested Hall thruster. The primary goal for each system was to demonstrate 100 h of continuous, steady-state operation of the propulsion subsystem at 100 kW. The subsystems included thruster, PPU, feed system, and other key components. As the period of performance for the contracts ends, each effort has been unable to achieve the desired performance; however, the lessons learned will be valuable building blocks for future developments.

A. XR-100

As part of the NextSTEP project, a team lead by AR and partners NASA GRC, NASA JPL, and the University of Michigan sought to advance the maturity and demonstrate the XR-100 operations at 100 kW. Based on the University of Michigan’s X-3, the XR-100 shown in Fig. 6 is a nested Hall thruster configuration consisting of three concentric rings of discharge chambers with a centrally mounted cathode. The system is designed to operate between 200 and 800 V discharge voltage and up to 250 A discharge current. The testing conducted in early 2019 was the culmination of a 3-year development effort under the NextSTEP project. The focus of the testing was to complete 100 h of continuous operation at 100 kW to demonstrate stable operation and thermal steady state. Ultimately the testing was able to achieve 73.5 kW total system power at thermal steady state. Although short of the goal, the testing provided substantial information for future design improvements and data for the anchoring of empirical models.³³



Figure 6. XR-100 installed in NASA Glenn Research Center Vacuum Facility 5 vacuum chamber.

VI. Small Spacecraft Propulsion

An area of continued growth is EP for small spacecraft from 3U CubeSats up to spacecraft <450 kg. However, whereas the class of Evolved Expendable Launch Vehicle (EELV) Secondary Payload Adapter (i.e., “ESPA-class”) satellites (<450 kg) are rapidly growing in both utility and popularity, they still lack the high delta-v propulsive capabilities currently available in the larger SOA all-electric spacecraft buses. The addition of EP to these systems can greatly expand their utility for a variety of missions. In particular, small spacecraft with EP are an option for enhanced space and ground communication networks for Earth, Moon, and Mars missions. More recently, a number of promising science missions have been proposed where the combination of small spacecraft and CubeSats can now provide valuable science in a smaller, more affordable package. To support the development of EP for small spacecraft, NASA has undertaken a variety of efforts to advance the SOA and evaluate the performance of new concepts.

A. Sub-Kilowatt Hall Thrusters

In FY18, NASA GRC led an effort to develop a high-propellant-throughput small-spacecraft EP system that included a sub-kilowatt Hall-effect thruster, a PPU, and a xenon feed system³⁴ (Fig. 7). The effort was in support of NASA’s strategic goal to increase the use of small spacecraft to accomplish its science goals.³⁵ The propulsion system performance goals were achieved by leveraging past NASA investments in Hall thruster technologies. The thruster design included a number of advanced features previously demonstrated on higher power systems, including optimized magnetic shielding, which enabled high-propellant throughput and long life (reduced wear); a centrally mounted hollow cathode, which enabled improved thruster electrical stability; a hollow cathode design, incorporating features from the NASA GRC-designed hollow cathode assemblies flown on the International Space Station that have been the industry standard for EP; and a patented propellant manifold assembly design that is more robust than the SOA. The PPU design focused on scalability, deep space reliability, and cost appropriate to support anticipated NASA small spacecraft on a variety of scales, inclusive of the operating requirements of a variety of domestic Hall thrusters between 200 W and 1 kW. At project completion, the laboratory model thruster had demonstrated 443 h of operation and a total thruster efficiency between 47% and 53%, depending on the operating condition. The PPU’s breadboard discharge converter was successfully demonstrated, powering the thruster discharge in an integrated system test. The measured electrical conversion efficiency of the discharge converter was between 92% and 95% across an input voltage range of 24 to 34 V and output power range of 200 W to 1 kW at 350 V. Initial discharge wear measurements indicate an operational lifetime in excess of 10,000 h is achievable. Performance and thermal results of the thruster and PPU were consistent with pretest predictions and validated the system design philosophy.

Testing is underway at NASA GRC with Busek on a 600-W Hall thruster. This work was competitively selected under the 2017 Space Technology Mission Directorate Announcement of Collaborative Opportunity (ACO) NNH17ZOA001K solicitation. Testing focuses on performance and wear over an extended operating period to meet a variety of potential mission scenarios.

B. CubeSat Propulsion

There are a number of emerging EP systems attempting to meet the growing industry and NASA mission needs. The challenges for the NASA missions, compared to industry applications, include the operation beyond low earth orbit (LEO) and reliability requirements for missions supporting science and exploration. In an effort to help evaluate these technologies for NASA applications, GRC has been working closely with the Small Spacecraft Technology Program to conduct evaluation tests on a number of promising technologies.

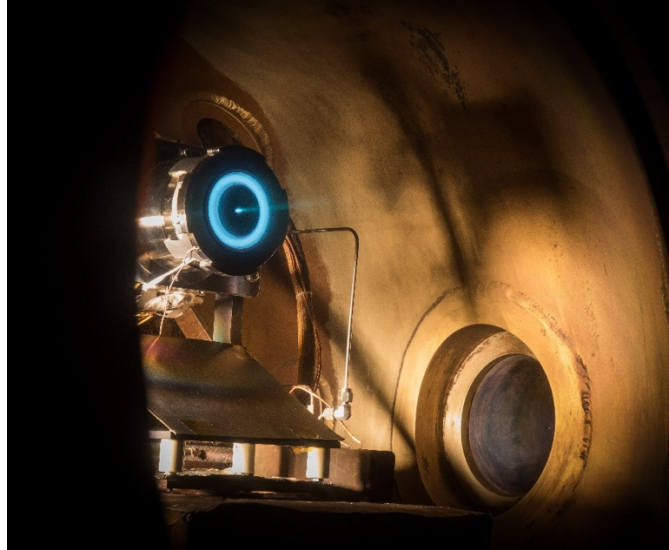


Figure 7. 500-W Hall thruster in testing at NASA Glenn Research Center.

1. Busek Ion Thruster BIT-3

Busek's ~3-cm ion thruster BIT-3 is a small radiofrequency ion thruster that uses iodine propellant; designed to enable low cost deep space missions. An EM system was developed under a Small Business Innovative Research (SBIR) contract. Subsequently, the BIT-3 was selected as the payload system for the Moorehead State University Lunar IceCube and the Arizona State University LunaH-Map CubeSats that will be launched from the Space Launch System during the Artemis-1 mission.

2. Alameda Applied Science Corporation Metal Plasma Thruster

Multiple performance tests has been completed in Vacuum Facility 3 (VF-3) at NASA GRC, to characterize the metal plasma thruster (MPT) CubeSat propulsion system. The MPT thruster was operated on a high-precision torsional thrust stand with three separate solid fuels that included niobium, palladium, molybdenum, carbon, and aluminum. Testing consisted of firing single pulses from the MPT thruster and measuring the impulse bits using the thrust stand. Data on over 1,200 impulse bits was obtained and covered a range from 0.1 to 0.6 mNs/pulse. Estimates of measured impulse bits agreed well with predicted values, and impulse behavior followed operating parameters as expected. The testing functionally demonstrated successful performance of a new CubeSat-sized propulsion system.

3. Enpulsion GmbH IFM Nano Thruster

NASA GRC is currently performing test preparations for independent verification and validation (IV&V) testing of the IFM Nano Thruster technology. The IFM is an integrated field emission electric propulsion (FEEP) module that uses high electric fields to extract and accelerate indium ions for thrust generation. The plan is to conduct a range of tests in the GRC VF-3 to characterize performance by direct measurements and evaluate operational stability. Testing is expected to be completed in late fall of 2019.

VII. Facility Investments

As the NASA lead for EP, GRC maintains a significant specialized EP test infrastructure that can be applied to the evaluation of a broad range of EP devices. To meet the increasing demands, NASA and the Center continue to invest in improving both test capabilities and test capacity. In the past 2 years, several investments have been completed and others are in the planning stages.

Vacuum Facility 11 (VF-11): Because of the increasing demand for test facilities, the Center recently reactivated VF-11 (Fig. 8), which had been underutilized for several years. At 2.2 m diameter $\times$ 8.25 m long it is well suited for low- and moderate-power EP devices. Over the past year the facility supported customer testing that was awarded by a NASA competitive solicitation.

Vacuum Facility 3 (VF-3): One of the growing areas of need is the IV&V of CubeSat and small spacecraft propulsion systems. At 1.5 m diameter $\times$ 4.5 m long, VF-3 has been utilized for a number of test programs on multiple types of propulsion systems. The chamber is equipped with a torsional thrust stand with a thrust resolution of approximately 10 μ N. A commercial mass/energy analyzer is being implemented to enable mass spectra; energy spectra; and time-of-flight measurements of cations, anions, and neutrals of up to 500-amu mass and 1-keV energy to be obtained. Along with a refurbished oil diffusion pumping system, a turbopump and dry scroll pump combination was implemented to provide operational flexibility for conducting certain types of testing.

Vacuum Facility 8 (VF-8): This is a flexible facility (Fig. 9) that is used for both EP component-level testing that includes hollow cathodes, thrusters, and PPUs, as well as integrated system testing. Recently the oil diffusion pumps have been replaced with cryogenic pumps to improve the overall reliability and provide a completely oil-free test environment. The thrust stand has also been upgraded to enable null mode operation as opposed to displacement mode.



Figure 8. Recently reactivated Vacuum Facility 11 vacuum chamber with thrust stand installed.

Vacuum Facility 6 (VF-6): One of the largest facilities (Fig. 10) at NASA GRC has recently been converted back to an EP test facility. Because of the large volume at 6.7 m diameter $\times$ 18.3 m long, it is ideally suited for higher power systems or devices with sensitivity to back-sputtered chamber material. However, it has been limited by a modest test pumping capacity at 310 kL/s of xenon. Currently a design activity is underway to improve the pumping speed by 3 times to nearly 960 kL/s. The improvement would make it the largest, highest pumping speed capacity facility in the world and well positioned to meet the Nation's needs well into the future as higher power systems are developed.



Figure 9. Exterior view of Vacuum Facility 8 vacuum chamber.

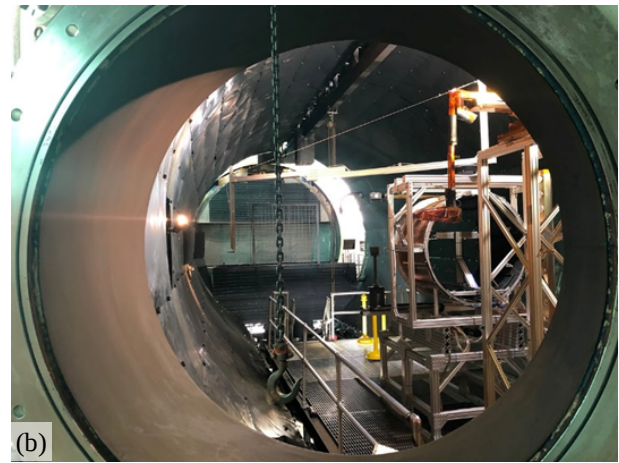
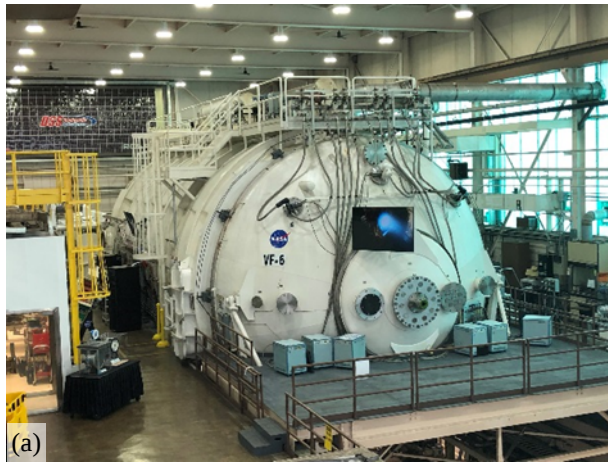


Figure 10. Vacuum Facility 6 vacuum chamber. a) Exterior. b) Interior.

VIII. Summary

The past 2 years at NASA Glenn Research Center (GRC) has been an active period with a number of significant accomplishments. The field of electric propulsion (EP) continues to grow in support of NASA missions and across the broader commercial satellite sector. The advancements, as reflected in the scope of work, are across the entire spectrum of EP—from CubeSats to large transport vehicles for Mars missions. NASA GRC continues to be at the forefront of the advances with internal development of technologies to supporting infusion into the broader commercial community. In addition, NASA GRC continues to invest in facility capabilities to support the growth both by bringing previously underutilized facilities online and continually improving existing vacuum facilities. The future continues to look promising for EP, and NASA GRC is excited to be at the forefront of this growth.

Acknowledgments

The authors would like to thank all the members of the NASA Glenn Research Center Electric Propulsion Systems Branch, Power Management and Distribution Branch, Thermal Systems and Transport Processes Branch, Facilities Test Division, and the NASA Jet Propulsion Laboratory Electric Propulsion Group, without whose dedication and hardware these accomplishments would not have been possible.

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