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**NASA Progress on the Development and Qualification  
of a 12-kW Hall-Effect, Solar Electric Propulsion Thruster**

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**Abstract**

The National Aeronautics and Space Administration (NASA) continues to evolve the human exploration approach for beyond low-Earth orbit and in a manner involving international, academic, and industry partners. The center of this approach is NASA's Gateway program that will establish a permanent human presence in lunar orbit for human cislunar science, operations, and lunar surface access to eventually land the next American astronauts on the south pole of the Moon. In support of the effort, NASA's Space Technology Mission Directorate (STMD) began a project to increase the state of the art for the Hall-Effect Solar Electric Propulsion (SEP) technology. The resulting Advanced Electric Propulsion System (AEPS) project has developed a 12 kW Hall-effect thruster in support of the Gateway program. The project is managed by the NASA Glenn Research Center (GRC), supported by the NASA Jet Propulsion Laboratory (JPL) with development, qualification & flight hardware all supplied by L3 Harris Aerojet Rocketdyne (AR). Development of the 12-kW Hall thruster electric propulsion system began with maturation of the Hall Effect Rocket with Magnetic Shielding (HERMeS) Technology Demonstration Units (TDUs). The technology development was then transitioned to AR via the AEPS contract, which built and tested two Engineering Test Unit (ETU) thrusters and multiple critical components. The project transitioned to the production of the three flight thrusters and entered qualification testing at the component and thruster levels.

**Keywords:** Electric propulsion, Gateway, PPE, AEPS

**Acronyms/Abbreviations**

AA	Associate Administrator
AEPS	Advanced Electric Propulsion System
AR	Aerojet-Rocketdyne
ARRM	Asteroid Redirect Robotic Mission
BAA	Broad Agency Announcement
CDR	Critical Design Review
CMV	Co-manifested vehicle
CSA	Canadian Space Agency
EMI	Electro-Magnetic Interference
EP	Electric Propulsion
EPPL	Electric Propulsion and Power Laboratory at NASA GRC
ESA	European Space Agency
ESDMD	Exploration Systems Development Mission Directorate

ETU	Engineering Test Unit
GRC	NASA Glenn Research Center
HALO	Habitation and Logistics Outpost
HCT	Hall Current Thruster
HEOMD	Human Exploration and Operations Mission Directorate
HERMeS	Hall Effect Rocket with Magnetic Shielding
JAXA	Japan Aerospace Exploration Agency
JPL	NASA Jet Propulsion Laboratory
KDP	Key Decision Point
MBRSC	Mohammed Bin Rashid Space Center
NASA	National Aeronautics and Space Administration
NextSTEP	Next Space Technologies for Exploration Partnerships

PDR	Preliminary Design Review
PPE	Power and Propulsion Element
PPU	Power Processing Unit
PRR	Production Readiness Review
QM	Qualification Model
QSAR	Qualification Subsystem Acceptance Reviews
SAR	System Acceptance Reviews
SEP	Solar Electric Propulsion Project
SRR	System Requirement Reviews
STMD	Space Technology Mission Directorate
TDM	Technology Demonstration Missions
TDU	Technology Demonstration Unit
TRL	Technology Readiness Level
VF-5	GRC Vacuum Facility 5
XFC	Xenon Flow Controller

## 1. History

Advancements by NASA in magnetically shielded Hall-effect thrusters have been occurring over the past decade between the collaboration of GRC and JPL. Through funding from the STMD Game Changing Development Program in 2014, the SEP project began the development of a magnetically shielded thruster, the Hall Effect Rocket with Magnetic Shielding (HERMeS). This technology was originally pursued as the propulsion system for the Asteroid Redirect and Robotic Mission (ARRM). The project developed and fabricated three high-fidelity laboratory thrusters (TRL-4), the Technology Demonstration Units (TDUs).

TDU-2 was used at the JPL test facility for environmental testing, while TDUs-1 and -3 (Figure 1) were used by GRC test facilities for life performance and wear testing. A major life-limiting factor on magnetically shielded Hall-effect thrusters was the erosion of the pole coatings. To mitigate this issue, graphite pole covers were incorporated onto TDU-3 and a series of long and short wear tests, 1700 hours and 250 hours respectively, were conducted over several different operating conditions [1]. Data indicated that maximum erosion occurred at the throttled condition of 300V, 20A and that an engineering solution for this erosion provided significant margin for operation at higher powers. TDU-2 underwent vibration testing consistent with a Delta-IV Heavy launch and a thermal vacuum cycle test (TVAC) consistent with the expected ARRM mission [2]. Both tests were successful and validated the design. In addition to magnetic shielding, a particular innovation incorporated into the TDU design was operation with the thruster chassis tied to cathode potential.



*Fig. 1 12.5 kW HERMeS Technology Development Unit-3 (TDU-3)*

The unique electrical configuration was motivated by facility interaction studies and a refinement of the test-like-you-fly approximation to spacecraft integration [3]. In addition to reducing the difference between operation in space and during ground tests, the configuration increased the performance of the thrusters by ~5% compared to a floating thruster body configuration. The fundamental work provided the backbone of NASA's use of this type of propulsion system for the ARRM mission.

ARRM was a multi-Center, multi-Directorate, Agency high priority mission. The mission was developed from the 2010 NASA Authorization Act on the use of cis-lunar space to advance human space exploration. ARRM was aligned with the Global Exploration Roadmap and the interests of NASA international partners to include missions in the lunar vicinity. One of the mission objectives was to demonstrate a high power solar electric propulsion system which enabled a capability for future deep-space human exploration and included applicability to the public and private sector space requirements [4,5].

After releasing the initial Next Space Technologies for Exploration Partnerships (NextSTEP) Broad Agency Announcement (BAA) in 2014, NASA released a follow-on BAA (NextSTEP-2) in April of 2016 seeking proposals for uses for an advanced solar electric propulsion vehicle capability [6]. NASA made the decision to realign the SEP project to support Gateway and future Moon to Mars objectives. In May of 2016, the AEPS contract was awarded to AR with the goal of developing a 12.5kW Hall Thruster System, including the Hall Current Thruster (HCT), Power Processing Unit (PPU) and Xenon Flow Controller (XFC) based on the technology demonstrated with the HERMeS testing. NASA chose the SEP project to manage the AEPS contract with AR. In 2018, NASA

released a BAA for the final version of the Power and Propulsion Element (PPE), the first element of the Gateway Program, that will utilize the 50kW solar electric propulsion system to maintain the Gateway's position as well as move it between lunar orbits as needed [7]. The BAA was in support of Space Policy Directive 1 that will return NASA to the moon with commercial and international partners as part of an overall agency Exploration Campaign [8]. From this competition, Maxar Technologies was selected to build the PPE in May of 2019. The 12-kW thrusters will provide the primary propulsion for the Gateway element, PPE, from Low Earth Orbit to a Near Rectilinear Halo Orbit around the Moon. The Gateway lunar station was established and will play a key role in NASA's Artemis Program which utilizes collaboration with the Canadian Space Agency (CSA), the European Space Agency (ESA), Mohammed Bin Rashid Space Center (MBRSC), and the Japan Aerospace Exploration Agency (JAXA).

After the contract was awarded to Maxar Technologies, NASA made the decision to descope the PPU and XFC from the AR contract and utilize the Maxar Technologies contract for the PPU and XFC. Maxar has commercial experience with electric propulsion thrusters and previously built at PPU rated for 6kW. Therefore, the decision was made to change the AEPS thruster to operate at 12kW instead of 12.5kW. The AEPS contract was modified to execute this scope while taking advantage of lessons learned from the TDU and ETU (AR development thrusters) testing campaigns.

In May 2020, the Associate Administrator (AA) for the Human Exploration and Operations Mission Directorate (HEOMD) directed a launch change for PPE and the Habitat and Logistics Outpost (HALO), the second Gateway element. The HEOMD AA decided to launch a co-manifested vehicle (CMV) to eliminate the cost of a second launch vehicle and the risk of an on-orbit docking [9]. The initial PPE EP system was designed to include two (2) hard mounted AEPS thrusters. The addition of the HALO module required a third AEPS thruster with the two (2) outboard thrusters requiring gimbal capability for added control stability. The project will build five (5) AEPS thruster, two (2) qualification thrusters and three (3) flight thrusters (Figure 2).



*Fig. 2. AEPS qualification and flight thrusters at Aerojet Rocketdyne in Redmond, WA*

STMD invested and continues to invest significant resource to support thruster development and verification of numerical models to complement the qualification of AEPS and facilitate the development of future, higher-power thrusters. Supported by data collected during the AEPS ETU program, the plasma code's capability to predict thruster erosion and radial flux of high-energy ions has been demonstrated [10]. The code has been verified as extensible to other operating conditions through a series of laser and physical probe characterization of the near-field plume. The modelling has shown the capability satisfies STMD's goal of qualifying AEPS operating life with 23,000 hours of test with a 50% margin demonstrated by analysis through numerical models. In addition, the numerical models have demonstrated the ability to predict the impacts of off-nominal operation and are supporting a sensitivity analysis of the AEPS design [11].

## 2. AEPS Project Overview

With the different iterations of the AEPS thruster, NASA created a unique project structure to support the needs across the Agency. STMD holds Level I project management authority for SEP and the STMD Technology Demonstration Missions (TDM) Program Office provide direction and oversight of SEP. The Exploration Systems Development Mission Directorate (ESDMD), the new NASA directorate overseeing Gateway, is responsible for the identification and control of the AEPS thruster requirements and risk management, while the SEP project is responsible for implementation of the AEPS thruster requirements and contractor oversight. Gateway through PPE is the owner of the AEPS technical requirements, and any changes must be approved by PPE. STMD manages and provides governance of the SEP Technology Objectives and development and qualification of the AEPS Thruster. To help implement this unique project structure, team members are 'dual-hatted' between the PPE and SEP teams to ensure active and consistent communication between the projects.

NASA's Glenn Research Center (GRC) maintains project management authority. The SEP Project Manager, located at GRC, is responsible for overall management of the technical, safety, cost, and schedule requirements of the project. SEP's principal stakeholders are STMD, ESDMD, and the GRC, while the electric propulsion technical community, the commercial space industry, and the public are also stakeholders.

From the overall governing of the project within NASA, the AEPS project was structured to follow standard NASA procedural requirements that include appropriate key decision points and formal reviews. The list of this milestones for the SEP project is listed below.

- Key Decision Point (KDP)-A – Completed March 2015
- System Requirement Reviews (SRR) – Completed May 2016
- KDP-B – Completed July 2016
- Preliminary Design Review (PDR) – Completed September 2017
- KDP-C – Completed February 2020
- Critical Design Review (CDR) – Completed March 2022
- Production Readiness Review (PRR) – Completed April 2022
- KDP-D – Completed May 2023
- Qualification Subsystem Acceptance Reviews (QSAR) – Expected to complete in 2025 and 2027.
- System Acceptance Reviews (SAR) – Expected to complete for all flight thrusters in 2025.

The project has progressed through the development, qualification, and flight manufacturing phases from 2016 through early 2024. Through the testing of HERMeS and ETUs, there has been over 8,000 hours of development testing on the 12-kW Hall-effect thruster design. The testing occurred at the GRC Vacuum Facility 5 (VF-5) and GRC Vacuum Facility 6 (VF-6), which is part of the NASA Electric Propulsion and Power Laboratory (EPPL, Figure 3) and the JPL Owens Chamber.



Fig. 3. VF-5 at the NASA GRC Electric Propulsion and Power Laboratory (EPPL)

The test campaign successfully reduced the overall risk of the AEPS project going into CDR. After the successful completion of CDR in March of 2022, AR has completed the assembly of the first qualification thruster, QM-1 (Figure 4). The AEPS project was now able to transition to acceptance and qualification testing of the QM-1 thruster.

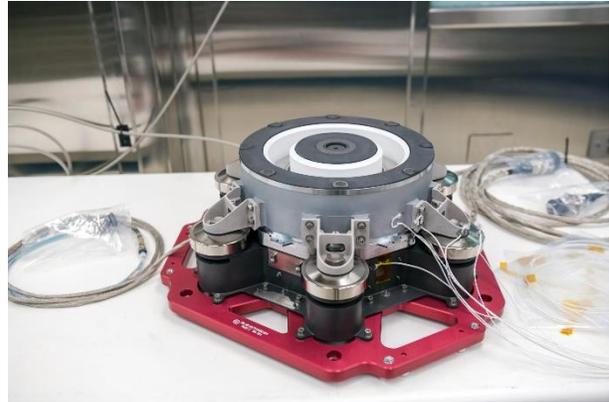


Fig. 4. AEPS QM-1 in the GRC clean room prior to pre-characterization testing

### 3. AEPS Qualification Testing

AEPS thruster qualification activities are divided between two qualification model thrusters where QM-1 is primarily dedicated to verifying design compliance to AEPS environmental requirements while QM-2 is primarily dedicated to verifying AEPS lifetime requirements through a long duration wear test.

Following completion of the QM-1 assembly, the thruster was subjected to Acceptance Test Procedures (ATP) that included vibration testing, hot-fire testing, and a detailed set of functional tests, dimensional inspections, and mass measurements.

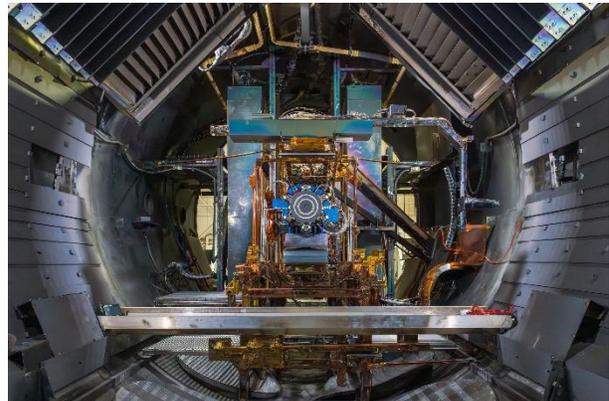
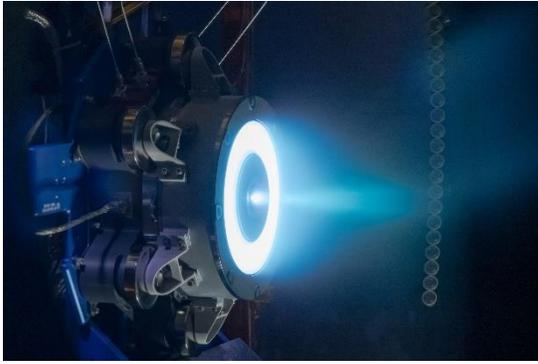


Fig. 5. AEPS QM-1 installed at VF-5 at NASA GRC prior to pre-characterization testing.

The ATP close out activities confirmed that the QM-1 thruster still met all design requirements after acceptance vibration and hot fire testing and was therefore cleared to begin its qualification test campaign. The acceptance test matured the thruster Technology Readiness Level (TRL) 6 [12]. An image of this first operation of QM-1 is shown in Figure 6.



*Fig. 6. QM-1 operating inside VF-5 at NASA GRC during ATP.*

Following the completion of the ATP testing and measurements, the QM-1 thruster began the qualification test campaign in October of 2023. The thruster has completed pre-environmental characterization including flow uniformity and hot-fire testing, qualification vibration testing, and qualification shock testing. At the time of this writing, QM-1 is preparing for qualification thermal vacuum testing. The qualification test plan also includes post-environmental characterization testing to ensure the thruster still meets requirements after exposure to environments.

AEPS component qualification focuses on components that are susceptible to cyclic failure modes to verify design compliance through component-level qualification tests. The components will complete thermal and operational life cycles as part of the life verification. The qualification cathode will also be subject to mechanical environmental testing to verify the design to AEPS structural requirements. The qualification cathode has completed pre-environmental characterization, qualification vibration testing, qualification shock testing, and post-mechanical characterization. At the time of this writing, the cathode is preparing for qualification thermal vacuum testing.

Components were selected for qualification testing based on their margin to the expected thermal environments and the consequence of the component's failure during flight. The project also fabricated a qualification cathode that has completed qualification vibration and shock testing and is being prepared for thermal vacuum and life-cycle testing. The cathode heater, inner and outer magnets, magnet heaters, heater transition tubes, and resistive temperature detectors were selected to complete component-level cycle testing. All components will be tested 150% the thruster life cycle requirement. Once the components have completed the life cycle testing, each component will be uninstalled, visually examined, and undergo a functional checkout. At the time of this writing, all components have begun their testing, and all are expected to complete testing in 2025. NASA also completed other risk reduction testing

to include EMI characterization testing with a Maxar provided PPU and XFC, JPL testing to support life-modelling activities, and GRC testing to investigate cathode performance after extended atmospheric exposure.

Details of the qualification testing were previously presented at the 38th International Electric Propulsion Conference [13]. The status and results to-date of AR-led AEPS qualification tests and status and results of NASA-led independent testing are summarized in the paper.

#### 4. Summary

NASA awarded the AEPS contract in 2016 with the goal of developing and qualifying a 12 kW Hall-effect thruster for NASA and commercial applications, with its first intended use on the Power and Propulsion Element as part of NASA's Gateway lunar space station. The thruster design successfully passed CDR in 2022. Qualification testing and flight hardware fabrication began and continue to proceed. The QM-1 qualification thruster has successfully undergone pre-environmental characterization testing, qualification vibration and shock testing, with TVAC testing expected to occur in 2024. Additional qualification testing of components such as the cathode, magnet coils, and thermal components are continuing to demonstrate design robustness of these critical thruster elements. In its insight/oversight role, NASA has also conducted numerous risk reduction tests in support of AR's qualification campaign and the PPE mission. Flight hardware fabrication and testing is expected to be completed by 2025, at which point the hardware will be delivered to Maxar for integration and use on the PPE spacecraft.

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