Advanced Electric Propulsion System (AEPS) 12kW Hall Current Thruster Program Overview

IEPC-2025-128

Presented at the 39th International Electric Propulsion Conference
Imperial College London • London, United Kingdom
14-19 September 2025

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Abstract: Aerojet Rocketdyne (AR) Inc., an L3 Harris Technologies Company, in collaboration with NASA, has developed a 12-kW Hall Current Thruster in support of the NASA Gateway mission to establish a permanent human presence in lunar orbit. AR has completed all development phases of the program, including full development and integration testing of the Engineering Model hardware, Critical Design Review, and ground test equipment validation. Qualification testing to support verification of the environmental and life requirements of the AEPS design has commenced and is expected to complete in 2027. Testing is conducted on two thruster units, a stand-alone cathode, and critical components including magnet heaters, temperature sensors, cathode heaters, and magnetic coils. This paper will present an overview of the AEPS program, thruster capabilities, flight design, and preliminary results from thruster and component qualification testing.

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I. Motivation and Background

AEROJET Rocketdyne Inc., an L3Harris Technologies Company, in collaboration with NASA, has developed a 12 kW Hall Current Thruster in support of the NASA Gateway mission to establish a permanent human presence in lunar orbit and to land the next American astronauts on the South Pole of the Moon. The Gateway is a preliminary step towards an expansion of in-space infrastructure that will facilitate NASA's exploration goals of extending human presence to Mars and beyond.

The first two elements of Gateway will be launched as a co-manifested system. The Power and Propulsion Element (PPE) and Habitation and Logistics Outpost (HALO) will launch together and use a high-power Solar Electric Propulsion (SEP) system to transfer to a lunar orbit. The PPE includes the 12-kW Advanced Electric Propulsion System (AEPS) developed by Aerojet Rocketdyne (AR) and a Maxar-developed 6-kW Hall thruster system.

The AEPS program has completed the development testing of a high power, solar-electric propulsion Hall Current thruster design that will be used on the NASA Power & Propulsion Element of the Gateway space station. Development testing was performed on two Engineering Test Unit thrusters and multiple critical components. Production of the three flight thrusters is nearing completion and the program is performing parallel qualification tests at the component and thruster levels.

II. AEPS Program Overview

The AEPS program was awarded to AR in May of 2016 with the goal of developing a 12.5kW Hall Thruster System, including the Hall Current Thruster (HCT), Power Processor Unit (PPU) and Xenon Flow Controller (XFC). During execution of the development program, the scope of the program was restructured to support the Gateway PPE mission, as detailed in Ref. [1]. Current scope includes the development, qualification, and delivery of three flight 12kW Hall Current Thrusters.

Figure 1: Flight Model 1 at Final Assembly Closeout

The program has progressed significantly through the various development, qualification and flight manufacturing phases from 2016, as shown in Figure 2 below.

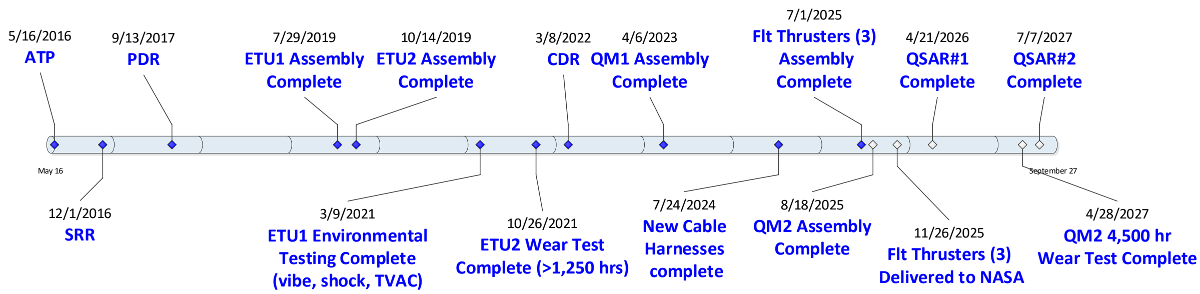

Figure 2: AEPS Program Milestones

The first qualification thruster, designated QM1, completed acceptance testing in 2023 and qualification level hot fire, vibration, and mechanical shock testing in 2024 and is currently undergoing TVAC cycle testing at NASA Jet Propulsion Laboratory's (JPL) Owens test facility. The second qualification thruster, designated QM2, is completing final assembly and will be used to support the planned 4,500-hour wear test starting in 2026.

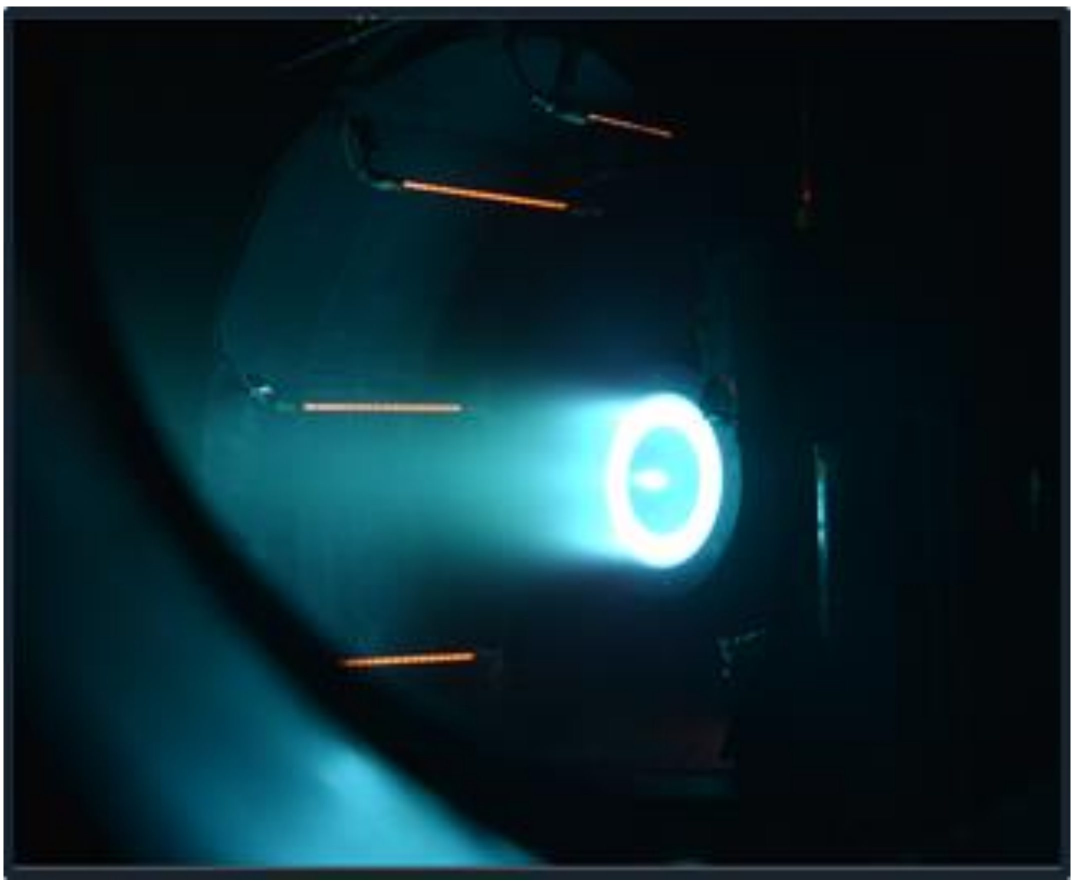
Figure 3: AEPS QM1 Thruster in TVAC testing at JPL's Owens Chamber

All three Flight thrusters are now fully assembled, with FM1 having successfully completed acceptance testing and delivery. FM2 has completed acceptance testing and is in the documentation review process in support of delivery. The FM3 thruster is in the final stages of acceptance testing and will be delivered in the fall of 2025.

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Figure 4: AEPS Qualification and Flight Thrusters at Aerojet Rocketdyne, Redmond WA prior to acceptance testing of Flight 1

This paper summarizes the status of the AEPS program, including discussion of flight and qualification hardware testing performed with the thruster and subassemblies.

III. Thruster Design

The AEPS Hall Current Thruster has three fundamental subassemblies that work together to achieve the Hall current working mechanism: the anode assembly, magnetic circuit assembly and cathode assembly. The magnetic circuit generates a magnetic field that captures electrons produced by the cathode assembly. The anode flows a neutral gas into the insulating discharge channel of the magnetic circuit, where the gas is ionized by the captured electrons. The ions accelerate into space through the electric field produced by an electrically biased anode assembly and a negatively charged cathode assembly, producing thrust.

The thruster is designed to be directly mounted to the spacecraft with a mounting structure interface. The thruster body is isolated from the spacecraft mechanical and electrical interfaces by six shock isolators. This enables the thruster to be affixed to the spacecraft without a structural adapter. The spatial envelope of the thruster is 210mm in height by 530mm in diameter, with a maximum mass of 53kg.

Three harness assemblies interface to spacecraft power and are rated to withstand high radiation and electromagnetic environments such that they can be routed along the exterior spacecraft surface without additional shielding. The Discharge Cable Assembly provides 300-600V, 10-20A power to the anode, depending on desired operating setpoint. The Auxiliary Cable Assembly provides 50-100V, 2-5A of power to the cathode and magnet components. Two propellant line interfaces are used to deliver xenon to the spacecraft, one for the anode and one for the cathode.

The AEPS thruster is the highest power Hall thruster in production, providing around 600mN of thrust and a specific impulse of approximately 2800s at a 12kW operating point. This is a high performance device for low thrust, high efficiency electric propulsion technology, offering the benefit of higher relative thrust with a more efficient propellant utilization. The AEPS thruster is a throttle-able technology from 300V, 6kW to 600V, 12kW to suit different mission profile and spacecraft design needs.

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IV. Acceptance Testing Approach

Acceptance testing of all AEPS flight thrusters includes vibration testing, thermal vacuum cycling, and reference firings, with inspections and functional tests between each test phase. After production of an AEPS flight thruster completes, AR test personnel subject the flight thruster to acceptance-level random and sinusoidal vibration environments at the AR vibration test facility in Redmond, WA. AR and NASA technical teams review the results of the vibration test, identifying resonant frequencies and other mechanical behavior. Upon approval of the results, AR performs functional checks and prepares the flight thruster for transport to Glenn Research Center (GRC) for the remainder of Acceptance testing.

At Glenn Research Center, AR personnel conduct extensive functional testing of the thruster's electrical interfaces and magnetic field to baseline thruster health post-shipment. After install of the flight thruster in the Vacuum Facility 5 (VF-5) chamber, AR repeats a limited suite of functional testing within the chamber, followed by chamber evacuation, cathode conditioning, and thruster conditioning. Thermal vacuum cycling involves one thermal cycle that subjects the flight thruster to both minimum non-operating temperatures and the maximum steady-state temperature achievable without external heating. First, the thruster ignites at the minimum non-operating temperature, and the thruster remains on until the maximum temperature is achieved. Then, after a shutdown and a twenty-minute "off" period, the thruster ignites again until the maximum temperature is achieved again. Finally, the thruster is shut down and allowed to cool to ambient chamber temperatures.

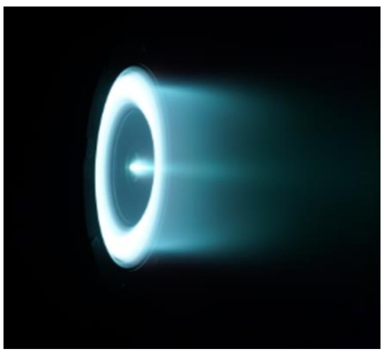

Figure 5: An AEPS Flight Thruster during acceptance testing at NASA GRC

Following the thermal cycle, reference firing of the flight thruster progresses through a set four operating conditions: 600 V/9 kW, 600 V/10 kW, 600 V/11 kW, and 600 V/12 kW. This set is conducted in one continuous hot-fire sequence, one condition after the other with no more than twenty minutes between conditions, to ensure similarities in the thermal baseline across conditions. The AR test team conducts one set of reference firings once per day over three days; each day includes a two-and-a-half-hour warm-up prior to firing to ensure thermal equilibrium. Each set collects thruster electrical telemetry including steady-state and transient events. The VF-5 thrust stand also provides thrust data during these conditions.

At the conclusion of hot-fire testing, the AR and NASA technical teams review flight thruster anode and cathode discharge behavior (current and voltage), thrust values, specific impulse, and thruster efficiency for compliance to contractual specifications and repeatability. VF-5 environmental data, including chamber pressure and temperature, are also evaluated for specification compliance. Following a successful review, the flight thruster proceeds to final inspection, preparation for spacecraft integration, and delivery.

Table 1: Thrust and specific impulse values measured during acceptance testing, averaged from QM1, FM1, and FM2 results

Parameter	9kW	10kW	11 kW	12 kW
Avg. Thrust (mN)	445	493	541	588
Avg. Specific Impulse (s)	2602	2659	2703	2740

The AEPS program is on track to deliver all flight shipsets in 2025. At the time of writing, the first flight thruster, FM1, has completed Acceptance Testing and has been formally delivered to NASA for integration into the PPE spacecraft. This delivery included a review of the build and test data, verification status, and integration documentation.

The second flight thruster, FM2, has successfully completed all acceptance testing and is awaiting paperwork closeout. The third flight thruster, FM3, has completed vibration testing at the AR Redmond facility and has shipped to Glenn Research Center for hot-fire testing. As a part of the test and delivery process, the team was able to successfully demonstrate concurrent processing of multiple flight thrusters, performing functional testing of one flight thruster while hotfiring another unit. The parallel processing resulted in significant schedule savings for hardware delivery. Additional detail on the acceptance testing is presented in Ref. [3], which is also being presented at this conference.


Figure 6: The Flight 1 Thruster following ATP hotfire testing

V. Qualification Approach

The AEPS program leverages parallel qualification tests to verify the system is compliant to the mission requirements. The test articles include two qualification thrusters and a series of subassemblies and components. Testing at multiple stages of thruster assembly enables collection of more data for statistical analysis in a more cost-effective manner.

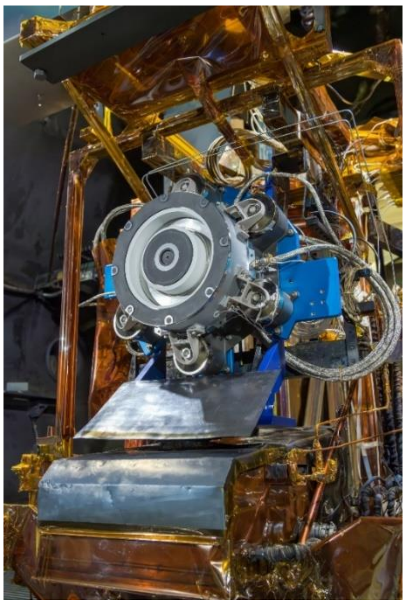
Figure 7: The QM1 Thruster installed in VF-5 at NASA GRC

The first AEPS thruster produced by Aerojet Rocketdyne that incorporated the lessons learned from the Engineering Technology Unit testing was the Qualification Model 1 (QM1) thruster shown in Figure 7. QM1 was the first thruster to undergo the rigors of the flight acceptance test procedure, the results of which were published in Ref. [1]. Following acceptance testing, QM1 proceeded directly into the Environmental Qualification test sequence in 2023. This test exposes the thruster to qualification-level dynamic environments, including vibration and shock, as well as thermal cycle testing. Performance is characterized by an expanded hot fire characterization sequence intended to quantify any changes that may result from exposure to the qualification environments. Testing is performed at a variety of facilities including Aerojet Rocketdyne, NASA GRC, NASA JPL, and a commercial shock test supplier.

Aerojet Rocketdyne has also fabricated a qualification cathode, three sets of qualification magnetic coils, and sets of cathode heaters, resistive temperature sensors, and magnet survival heaters. The cathode has completed an environmental test campaign that included characterization and qualification-level vibration, shock, and thermal vacuum testing. Earlier this year the cathode began the final phase of its qualification which is a life cycle test. The additional fabricated components are in the process of thermal and electrical life cycling.

The last test article in fabrication is the Qualification Model 2 (QM2) thruster. This thruster will be acceptance tested before undergoing qualification-level vibration testing followed by a 23,000 hour life test. The life test will be initially led by AR with NASA support for the first segment, after which the test responsibility will be transferred to NASA.

VI. Status of AEPS Qualification Testing

A. QM1 Environmental Qualification

The QM1 qualification test program (QTP) is intended to verify the AEPS thruster design compliance to AEPS environmental requirements, whereas QM2 will be primarily dedicated to verify compliance to AEPS thruster life requirements. QM2 will also undergo a qualification-level vibration test prior to life testing. Following the close out activities of QM1 in Redmond, Washington, QM1 entered Qualification Test in October 2023 beginning with Anode Flow Uniformity Testing. The QM1 environmental QTP sequence is summarized in Figure 8. At the time of writing, QM1 has entered Qualification Thermal Vacuum testing, with the following sections detailing the results of the completed environmental QTP phases.

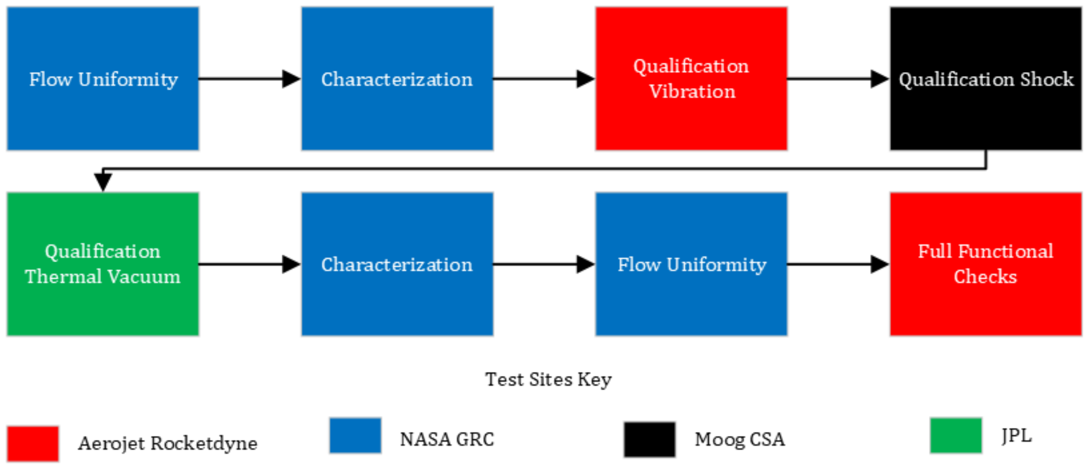

Figure 8: QM1 Qualification Test Procedure sequence

1. *QM1 Thruster Acceptance Testing*

Following build, QM1 was subjected to the ATP sequence shown in Figure 9. The acceptance test sequence is identical to the sequence described in the Acceptance Testing Approach section of this paper, except the thruster was returned to AR in Redmond, WA for functional checks and final inspections.

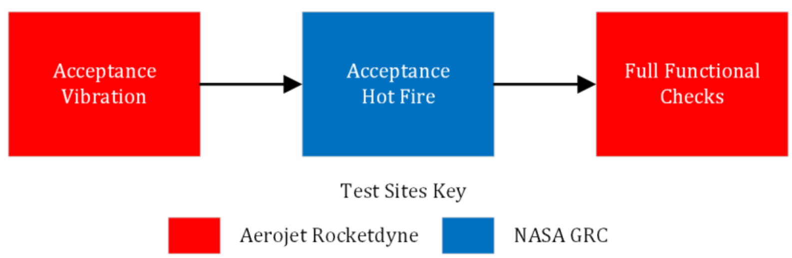

Figure 9: QM1 Thruster Acceptance Test sequence

The thruster underwent acceptance vibration to screen for build defects and validate thruster performance. After acceptance vibration, QM1 underwent hot fire testing in VF-5 at NASA GRC. As with the flight units, the hot fire test evaluated the thruster performance across the four nominal operating conditions and demonstrated an acceptance thermal cycle, including activation of the survival heaters and a hot restart. An image of this first operation of QM1 is shown in Figure 10.

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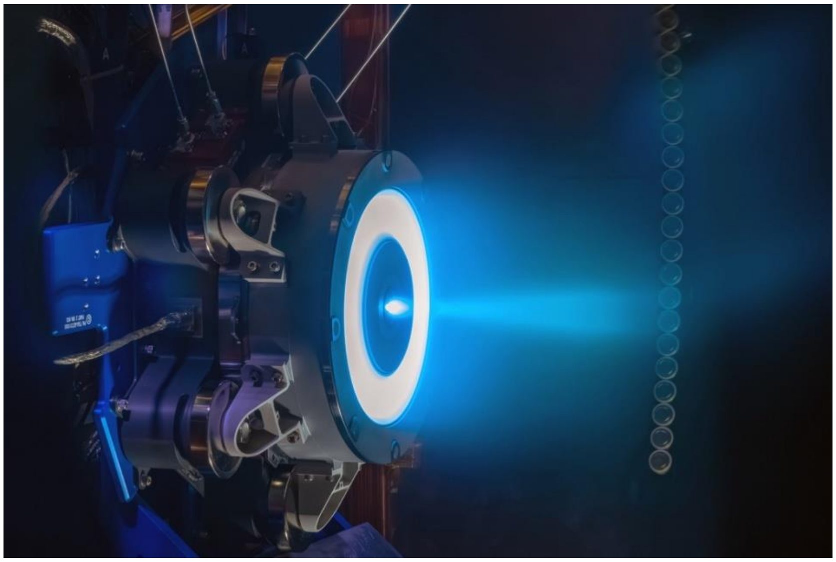

Figure 10: QM1 operating during ATP inside the VF-5 vacuum chamber at NASA GRC

Following acceptance hot fire, QM1 returned to AR in Redmond, Washington for functional tests, detailed visual inspections, and magnetic field mapping. Collected data confirmed QM1 was compliant to the build and performance requirements and was suitable for use in the Environmental Qualification test campaign.

2. Pre-Environmental Characterization Testing

Bookending Qualification testing is the Anode Flow Uniformity test, performed prior to any qualification hot-fire characterization and again after the thruster has undergone vibration, shock, thermal vacuum cycling, and two rounds of hot-fire characterization. The test aims to provide azimuthal flow uniformity at the thruster assembly level; these uniformity data later contribute to confirming compliance of the qualification thrusters to the flow uniformity requirements. One parameter of interest is the worst-case uniformity result, that is, the largest variation of local pressure to the average pressure measured at a particular location.

The flow uniformity tool installed over the thruster face measures gas flow via a pressure probe every 5° ± 2°, intervals from -40° ± 2° to 310° ± 2°, dwells for at least five seconds at each location, and repeats at least once to take into account hysteresis. The pressure probe is positioned equidistant between the discharge chamber walls and at the axial midpoint between the anode surface and the thruster exit plane. In addition to probe position and pressure measurements, the data acquisition system also gathers mass flow rate at the feed line, the feed line pressure, and the chamber pressure. Results of the testing are shown in Figure 11 at two xenon flow rates. QM1 demonstrated an azimuthal variation in pressure of <3% at the maximum operational flow rate, which corresponds to the 12 kW operating point.

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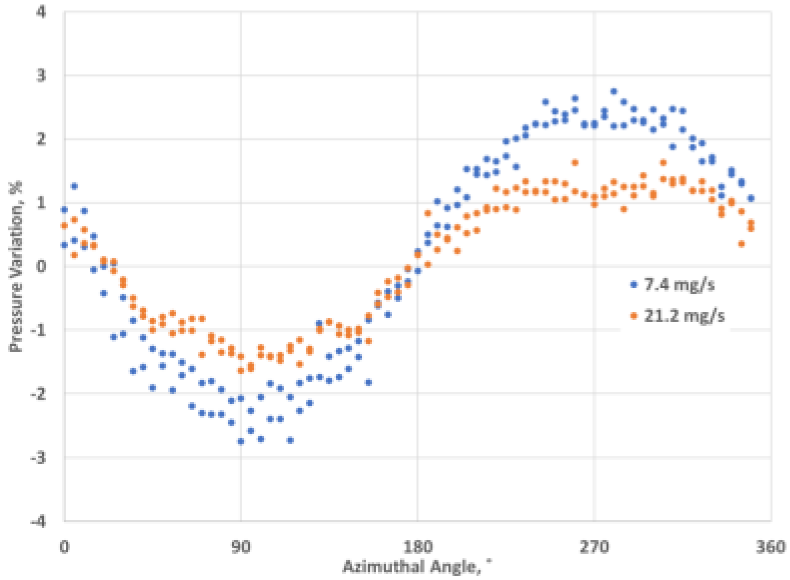

Figure 11: Normalized pressure variation with azimuthal location in the QM1 discharge channel at 7.4 and 21.2 mg/s xenon flow rate

Following QM1 anode flow uniformity testing in VF-5 at NASA GRC, a second hot-fire test sequence was performed prior to QM1 exposure to qualification level mechanical and thermal environments. Whereas QM1 ATP hot-fire sequence is intended to screen for build defects and validate performance against requirements, the goal of the QM1 QTP sequence is to perform a detailed characterization of thruster performance, stability, and plume properties across the full range of expected PPE throttle conditions. These pre-environmental characterization tests established a baseline for QM1 behavior, which can be compared to a similar post-environmental characterization sequence. QM1 is shown installed in VF-5 in the background of Figure 12 prior to the start of the Pre-environmental Characterization Test.

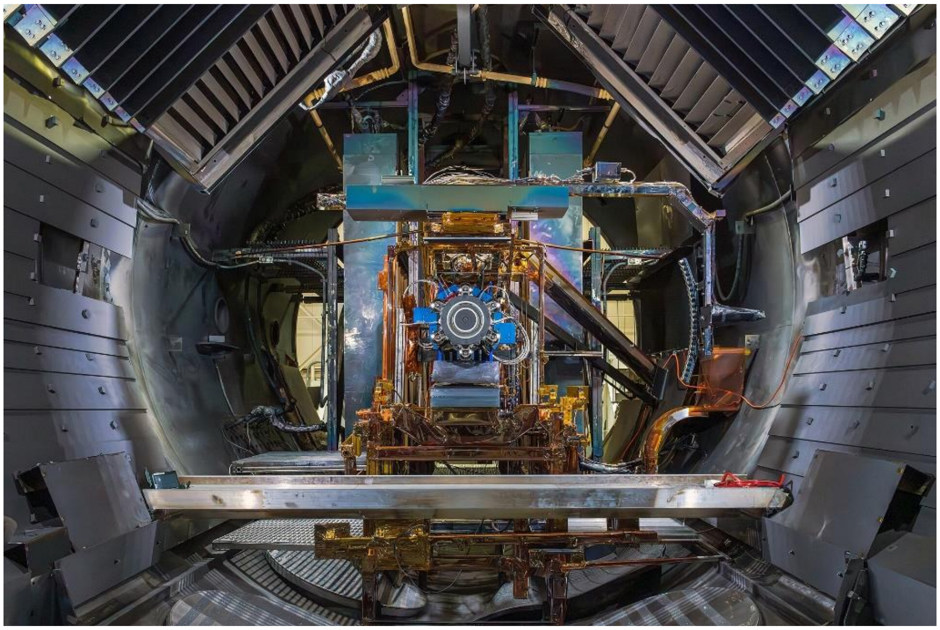
Figure 12: QM1 installed in VF-5

Using the same process as QM1 and Flight ATP reference firings, the performance of QM1 was evaluated for a second time at the four nominal operating conditions (600 V/9 kW, 600 V/10 kW, 600 V/11 kW, and 600 V/12 kW). Following performance evaluation, QM1 was operated at the same 4 nominal conditions to collect additional baseline plume mapping and thrust vector data, which will be compared to an identical suite of plume measurements and thrust vector data following exposure to qualification environments. Plume mapping was performed using a Faraday probe, a retarding potential analyzer (RPA), a Langmuir probe, and an ExB probe (or Wien probe), the operation of which is detailed in Ref. [6]. Subsequent QM1 thrust vector measurements were performed using a Thrust Vector Diagnostic, further detailed in Ref [2]. Example data from thrust vector mapping is shown in Figure 13, with "Theta" indicating the azimuthal angle in the horizontal plan and "Phi" indicating the polar angle in the vertical plane.

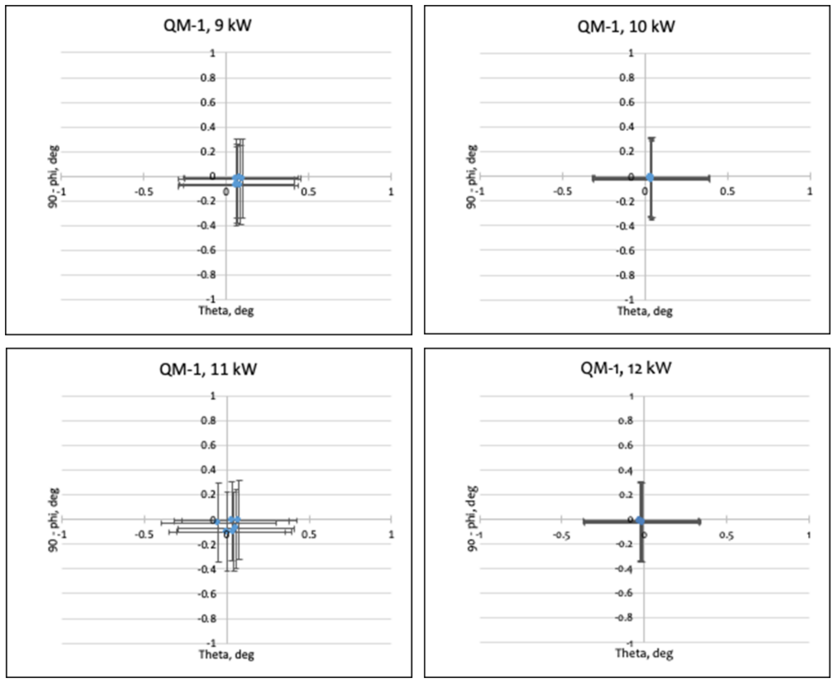

Figure 13: Measurements of QM1 thrust vector acquired during Pre-Environmental Characterization Testing

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3. Mechanical Environment Testing

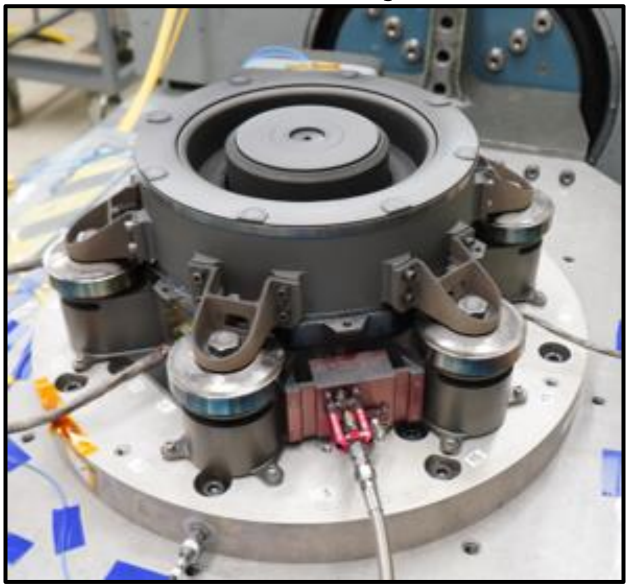

Figure 14: QM1 undergoing qualification-level vibration testing at AR in Redmond, WA

The QM1 QTP Mechanical Environment Testing, consisting of qualification-level vibration and shock testing, is intended to verify the AEPS thruster design against mechanical environment requirements. Following pre-environmental characterization, QM1 returned to AR's Redmond, Washington site for qualification-level vibration. During QM1 QTP vibration, QM1 was exposed to random and sinusoidal vibration environments, with low-level sine sweeps before and after each of these qualification-level tests to screen for any changes in thruster response to mechanical environments. The collected spectrums show that QM1 has a resonant frequency that exceeds the minimum requirement. Electrical health checks and visual inspections were performed prior to and following qualification-level vibration testing, which verified no changes to QM1 electrical health or physical characteristics occurred from the qualification-level vibration environment. A photo of QM1 during acceptance vibration testing is shown in Figure 14.

Following qualification-level vibration, QM1 underwent qualification shock testing at Moog CSA. A qualification shock environment was applied to QM1 at each axis, and test data demonstrates that QM1 was exposed to the appropriate qualification level shock spectrum. An image of the QM1 thruster in the shock test configuration is shown in Figure 15. Electrical health checks and detailed visual inspections were performed before, after, and in between each applied shock to verify that no changes to QM1 electrical health or physical characteristics were incurred from the shock environment. After application of all shocks, a rotation of QM1 yielded no indication of any loose components or debris following exposure to shock environments. QM1 Mechanical Environment testing was completed in May 2024, successfully exposing QM1 to qualification level vibration and shock environments.

Figure 15: QM1 during shock testing at Moog, CSA in Mountain View, CA

4. Thermal Vacuum Testing

The QM1 QTP Thermal Vacuum Testing verifies the AEPS thruster design against thermal environmental requirements. This test sequence consists of a series of thermal vacuum cycles, with health functional checks performed prior to, between, and following thermal cycles. A set of reference firings are performed prior to all thermal vacuum cycles at the four nominal conditions (600 V/9 kW, 600 V/10 kW, 600 V/11 kW, and 600 V/12 kW) to compare any changes in electrical telemetry following exposure to qualification thermal environments. Due to the

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thermal environments within the thermal vacuum test affecting thrust measurement equipment, performance data is not collected during these reference firings. QM1 will then proceed through thermal cycles with active heating and cooling to induce greater temperature extremes. Following completion of thermal vacuum cycles, QM1 will re-perform reference firings before returning to VF-5 at NASA GRC for full post-environmental characterization. As of the time of writing, QM1 has completed pre-thermal vacuum reference firings and is currently progressing through qualification-level thermal cycles.

B. Cathode Qualification Testing

Of the components and subassemblies in the AEPS thruster, the cathode was identified as one of the most critical. As a part of program risk reduction, qualification testing was planned to include a stand-alone cathode test to verify design compliance. The cathode qualification test sequence is shown in Figure 16. The planning mirrors the QM1 thruster environmental qualification with the addition of life cycle testing. After fabrication and preliminary characterization, the cathode is subjected to dynamic environments including qualification-level vibration and shock testing. After an additional characterization, the cathode undergoes thermal vacuum cycling followed by life cycling to verify the design is robust to cyclic fatigue failure modes. At the time of publication, the cathode has completed all environmental testing and has entered into the life cycle test.

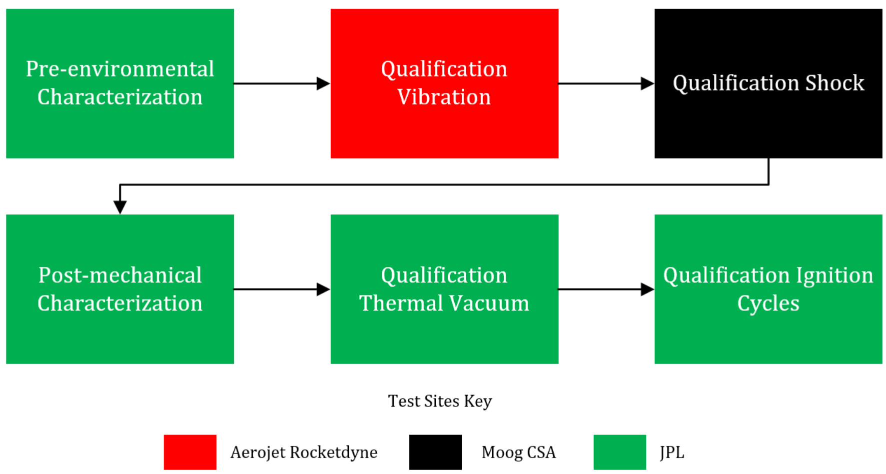

Figure 16: Cathode Qualification test sequence

1. *Pre-Environmental Characterization Testing*

An initial hot-fire characterization of the qualification cathode was performed at the Jet Propulsion Laboratory Cathode Test Facility in December 2023. The test established a baseline for cathode performance across a range of operating parameters prior to beginning the qualification sequence. The characterization testing included an expanded range of operating setpoints compared to the thruster acceptance test procedure. The hot-fire testing included a conditioning sequence, ignition sequence, and a performance assessment across the thruster throttling points. Telemetry collected includes high-speed voltage and current during ignition as well as low-speed voltage, current, and thermal traces for steady-state operation. These preliminary data are compared to the performance after dynamic testing to identify trends and verify the design is robust to the expected environments.

The preliminary characterization also exercised the cathode through plume mode and keeper mode characterization. For plume mode, the cathode was ignited and run at the 600V/12 kW thruster set point, after which the flow was decreased until a plume mode transition was observed. The plume mode behavior manifests as a transition in telemetry to a more unstable operating regime with respect to peak-to-peak oscillations and discharge voltage, as well as a divergence in the cathode plume. At the beginning of qualification testing, the plume mode transition occurred once the mass flow rate was reduced to 25% of the nominal mass flow. The keeper mode characteristic testing ignited the cathode across a range of mass flow rates and heater currents to identify if any combinations resulted in an unsuccessful ignition. The cathode ignited for all ignition combinations in the test plan and demonstrated a robustness across the thruster operational envelope.

2. Mechanical Environmental Testing

Following performance characterization of the cathode at the JPL Cathode Test Facility, the qualification cathode was returned to AR Redmond, Washington for qualification-level vibration testing. The cathode underwent qualification-level mechanical loads while installed in a thruster mass simulator to replicate the expected loading of the flight environment. The cathode was subjected to the same loading tests as the QM1 qualification environmental testing. An image of the cathode vibration test configuration is shown in Figure 17. Response telemetry indicated the cathode met all requirements for the vibration test.

After successfully completing vibration testing, the cathode was sent to Moog CSA in Mountain View, California for qualification-level shock testing. This test also used a thruster mass simulator to replicate the expected loading of the cathode in flight. The cathode received two each shock hits in three axes during the test. Response telemetry from attached accelerometers indicated that the cathode was exposed to the appropriate environments and the testing met all requirements for qualification.

Electrical functional test data was collected throughout testing including continuity, isolation resistance, dimensional inspections, and visual inspections to assess whether the cathode changes upon exposure to dynamic environments. All collected data indicate that the cathode is robust to the dynamic environments and sufficient for the expected loading the thruster will receive during launch.

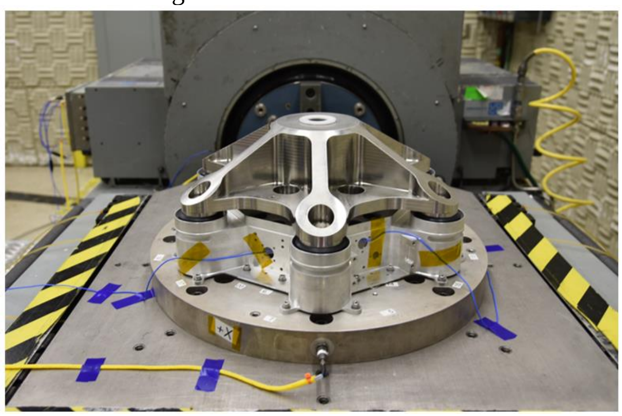

Figure 17: Cathode Qualification Vibration Test setup

3. Thermal Vacuum and Life Cycle Testing

Following the dynamic testing, the cathode was returned to the JPL Cathode Test Facility to begin the thermal vacuum cycle and life cycle testing. The thermal vacuum cycle cycles the assembly to expected worst-case hot and cold conditions and monitors electrical telemetry and thermal telemetry from multiple nodes to characterize performance. The cathode ignited successfully during this test, indicating the assembly continued to function after qualification-level dynamic loads. Data collected throughout the TVAC cycles indicated the cathode performed nominally within the expected thruster thermal environments.

The cathode began life cycle testing in 2025. Per the test plan, it will complete 1.5 times the expected life cycles with electrical functional characterization testing periodically to evaluate trends in cathode performance.

C. Component Qualification Testing

The AEPS program is supplementing the thruster- and cathode-level qualification testing with qualification of multiple critical components. The components being qualified include the inner and outer magnetic coils, magnet heaters, temperature sensors, and cathode heaters. Each component is tested in a fixture designed to thermally cycle the components through the worst-case thermal environments while monitoring the electrical and thermal telemetry of the units. The components undergo TVAC cycling followed by ignition cycling testing.

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Component tests are being run in the Component Test Facility at NASA JPL. The facility can accommodate multiple component tests in parallel. The component qualification test sequence is defined in Figure 18. The tests utilize periodic electrical functional and visual inspections to assess the component performance throughout testing. Life cycle testing is performed in predefined blocks. After each block, data are reviewed and trends are assessed to verify nominal performance. Testing began with the magnetic coils in September 2022. At the time of writing, all component tests had started.

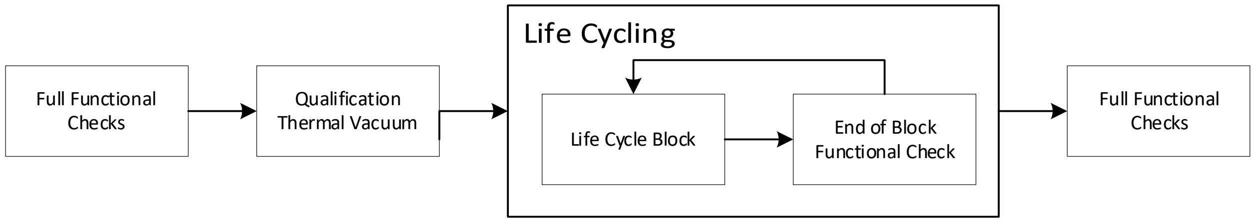

Figure 18: Qualification Test Procedure for components

VII.Conclusion

The Advanced Electric Propulsion System contract has successfully delivered the first of three flight thrusters and is well underway in thruster, cathode, and component-level qualification testing. The first application of the AEPS system will be as the primary propulsion element for the Lunar Gateway space station. The remaining flight shipsets will be delivered in 2025 and the Environmental Qualification of the QM1 thruster will complete in late 2025. AR will continue additional qualification efforts including the life cycling of the qualification cathode and critical subassemblies and components, as well as the thruster wear testing of the Qualification Model 2 thruster, which is set to begin in 2026. This year, Maxar will begin integration of the flight thrusters into the Power and Propulsion Element to support the co-manifested launch with HALO in support of the Artemis 4 mission.

VIII. Notice of Copyrighted Information

Acknowledgments

The authors would like to thank the tireless work of the AR traveling GRC test team, Abbey Mattingly, Nick Simon, Michael Dai, Brett Biggs, Ethan Horstman, and Nick Branch. Likewise, the authors give thanks to the AR traveling JPL test team, Cheong Chan, Megan Clements, Hoang Dao, Sam Reagan, Josh McCabe, Greg Simon, Arlette Molina, Min Xu, Chris Ajalat, and Nathan Jordan.

The AEPS contract is managed by the Solar Electric Propulsion (SEP) project at NASA GRC under the Technology Demonstration Missions program as a part of NASA's Space Technology Mission Directorate. Aerojet Rocketdyne is funded under contract # NNC16CA21C.

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