QUALIFICATION PROGRESS AND MISSION-ENABLING CAPABILITIES OF THE 12-KW HALL-EFFECT, ADVANCED ELECTRIC PROPULSION SYSTEM (AEPS) THRUSTER

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ABSTRACT:

An update of the 12 kW Advanced Electric Propulsion System (AEPS) qualification and flight thruster status is provided. Three flight thrusters completed acceptance testing in 2025 and have been delivered to NASA. Environmental qualification is complete and preparations are under way for long-duration life-demonstration testing. A brief overview of three of SEP's programmatic lessons learned are discussed: risk management, contract oversight, and requirement definition. In addition, the extensibility of the AEPS thruster to enable a variety of NASA missions is presented.

1. INTRODUCTION

As described in [1] the National Aeronautics and Space Administration (NASA) continues to evolve the human exploration approach for beyond low-Earth orbit in collaboration with international, academic, and industry partners. In support of the effort, NASA's Space Technology Mission Directorate (STMD) initiated a project to advance the state of the art for Hall-Effect Thrusters (HET) technology. The resulting Solar-Electric Propulsion (SEP) Project has developed a 12 kW Advanced Electric Propulsion System (AEPS) Hall-effect thruster. A detailed history of the project can be found in [1]. SEP and Aerojet Rocketdyne (AR) are approaching the closeout of the AEPS contract which is expected in mid to late-2027. Fig. 1 provides a timeline of the project's major contract milestones.

This paper provides an update of the flight and qualification thruster status including acceptance and qualification testing. Flight thruster status is followed by qualification status and how these are tied to SEP's high-level objects. The project has met all of its high-level objectives except qualification of the thruster which remains an on-going activity. A brief review of AEPS-enabled missions is given following illustrating the importance of those objectives. The paper concludes with short summaries of three lessons learned over the course of the project. These include schedule management, risk management, and requirement definition

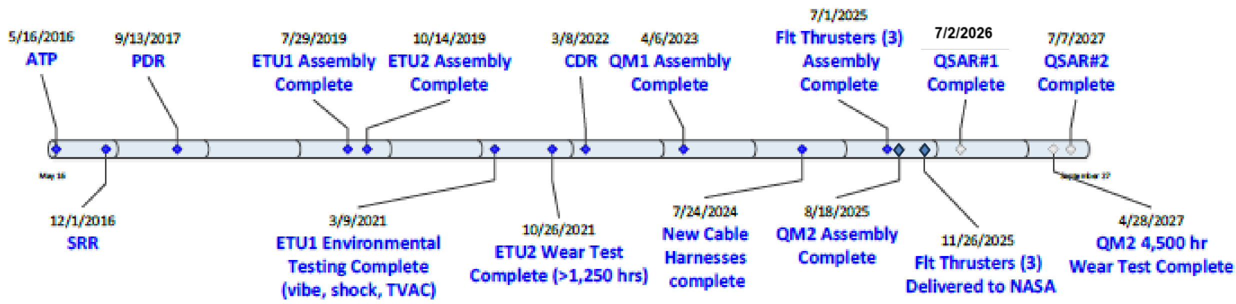


Figure 1. AEPS Project Milestones

Table 1. AEPS thruster design requirements and increase with respect to state of the art (SOTA)

12-kW HET developed for 50-kW class system		
Power	12-13 kW	3x SOTA
Xe throughput	1770 kg + 50% margin	7x SOTA (10x with margin)
Isp capability	>2600 s at 600 V	1.5x SOTA

2. FLIGHT THRUSTER STATUS

Aerojet Rocketdyne completed assembly of three flight thrusters and acceptance tested them at AR in Redmond, WA as well as in VF-5 at NASA Glenn Research Center (GRC) in 2025. Fig. 2 shows the Flight Model 1 (FM-1) unit installed in the vacuum chamber. This chamber provides the best simulation of the space environment for the performance and wear characterization of EP devices in the US. In the mid-to-late 2010's, a collaboration between NASA, the Air Force Research Laboratory (AFRL), US academia, and US industry led to a standardized practice for maximizing Test Like You Fly (TLYF) ground testing of EP devices.[2,3] Best practices for TLYF have been implemented for all of the SEP-AEPS testing at GRC and at the NASA Jet Propulsion Laboratory (JPL). VF-5 has demonstrated that it accurately captures known differences in HET operation in other ground facilities and in space.[4] Therefore, it is expected that differences in AEPS performance measured during acceptance and qualification testing and performance measured in-flight will be small. It is also expected that anomalies will not be masked during the ground test and manifest in flight.

The AR-NASA team successfully demonstrated concurrent processing of multiple flight thrusters, performing functional testing of one flight thruster while hot-firing another unit. The parallel processing resulted in significant schedule savings and enabled the delivery of all three thrusters to NASA on or ahead of schedule. Additional detail on the acceptance testing is presented in [5,6] Table 1 provides the top-level requirements for the AEPS thruster. Table 2 provides the average thrust and specific impulse measured during FM thruster acceptance testing. Note that the thrusters meet or exceed the Isp requirement given in Table 1 across the 9-12 kW throttling range. NASA provided the thrusters to Intuitive Machines (formerly Lantaris) for integration on the PPE spacecraft within a week of each delivery to NASA.

Table 2: Average thrust and specific impulse values measured during FM acceptance testing.

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

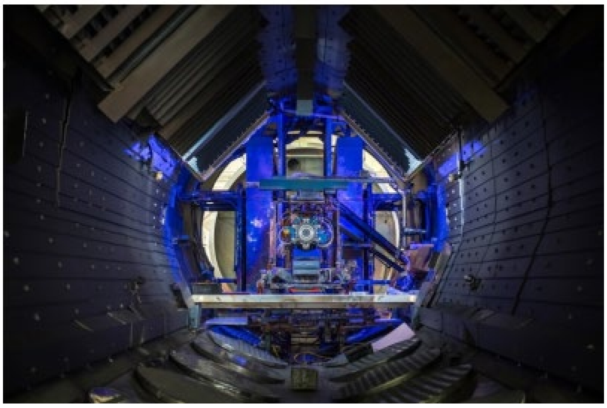


Figure 2. AEPS FM-1 installed in VF-5 at NASA GRC. Note the two large He cryo- surfaces behind the thruster (center), the distributed He cryo-surfaces at the top of the photo, and the graphite panelling to mitigate back-sputtered material.

A rendering of the AEPS thrusters propelling the PPE spacecraft is shown in Fig. 3

In addition to the concurrent processing of multiple thrusters in test, another key contribution to the completion of the flight thrusters was the collaboration in mitigating risks associated with an updated thruster harness. In 2023, PPE reevaluated the thruster-gimbal mechanical interface and the radiation environment expected during the orbit raising of the co-manifested vehicle (CMV) for Gateway. As a result, the requirements for the thruster harnesses were updated and the decision was made by PPE to replace them. The SEP and AR teams collaboratively iterated a new design to provide a thermally compliant, radiation tolerant, and more flexible harness. The joint redesign effort successfully minimized the delay caused by the requirement change.

3. QUALIFICATION STATUS

AEPS thruster qualification activities are divided between two qualification model thrusters: Qualification Model One (QM-1) is primarily dedicated to verifying design compliance to AEPS environmental requirements while QM-2 is primarily

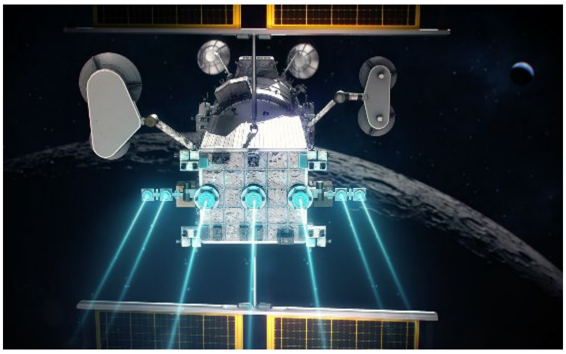


Figure 3. Artistic rendering of three AEPS thrusters (center) shown on the PPE spacecraft. Credit NASA

dedicated to verifying AEPS lifetime requirements through a long duration wear test. The division of labor between the thrusters was retained because QM-2 includes all the updates made to the flight thrusters following requirement changes, especially with respect to the thruster harnesses noted above.

3.1. Environmental Qualification

Fig. 4 shows the QM-1 qualification test procedure sequence. QM1 completed acceptance testing in 2023 as well as qualification hot fire characterization in GRC's VF-5. Fig. 5 shows the thruster mounted to a thrust stand. The thruster is in the same configuration as shown in Fig. 2. Fig. 6 is a photograph of QM-1 operating at high-vacuum. Note that the weak plume extending only a short distance downstream of the exit plane is indicative of the low background pressure. This low-pressure operation is critical to measurement of performance, stability and erosion that is representative of in-space operation.

Mechanical environmental testing consisted of vibration testing at AR in Redmond, WA and mechanical shock testing at Moog CSA in Mountain View, CA. This testing was successfully completed in 2024.[5]

QM-1 entered thermal-vacuum (TVAC) cycle testing in 2025 in JPL's Owens Chamber shown in Fig. 7. Thermal cycling included worst-case hot and cold exposure for the thruster if operated between 0.8 and 1.5 AU: corresponding to a Venus gravity assist and operation at Mars. This legacy requirement predated PPE and more than enveloped the PPE-Gateway need which was roughly 1 AU throughout its life. However, the extremes were maintained to qualify AEPS for extensible missions. TVAC testing was completed in early 2026.

Post-environmental testing in GRC's VF-5 began in February 2026 and was completed in April, 2026. The performance measured during post-environmental testing was consistent with that measured in the pre-environmental test. This verified that the thruster still meets performance requirements following exposure to qualification level environments. QM-1 has been returned to AR and is undergoing detailed post-test inspections

Details of the qualification testing were previously presented at the 38th International Electric Propulsion Conference [7]. The status and results to-date of AR-led AEPS qualification tests and status and results of NASA-led independent testing are summarized in that paper. Full reporting of the environmental qualification data and trends will follow their documentation at the Qualification System Acceptance Review One (QSAR-1) scheduled for July 2026.

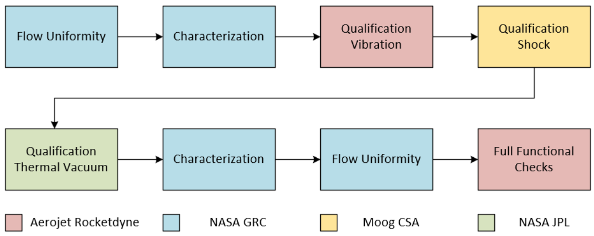


Figure 4. Flow of the AEPS environmental qualification testing. QM-1 is now at the end of its qualification test procedure sequence. [5]

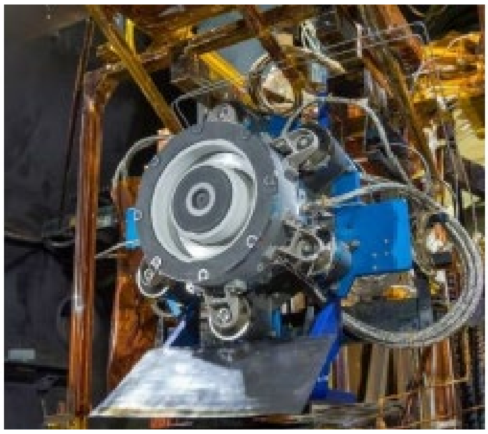


Figure 5. The QM-1 thruster in VF-5 at NASA GRC Electric Propulsion and Power Laboratory.

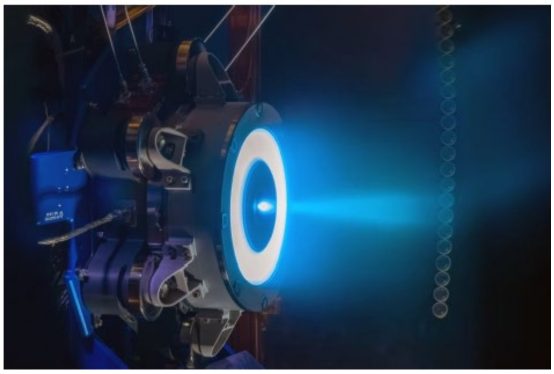


Figure 6. QM-1 operating in VF-5 at NASA GRC

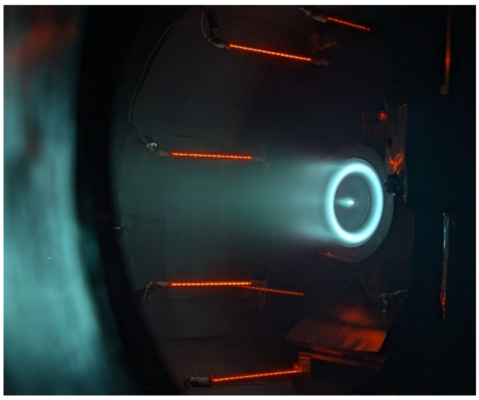


Figure 7. AEPS QM-1 Thruster in TVAC at JPL.

3.2. Component Qualification

Several components in the AEPS thruster are susceptible to thermomechanical cyclic failure. SEP-AEPS component qualification verifies the overall cycle-life requirement through component-level qualification tests. This allows multiples (typically 3) of the same component to be subjected to qualification cycles tailored to the environments each component would see during thermal cycling of the thruster. This supplants cycling and instrumenting multiple thrusters and prevents under or over test compromises likely required in a ground test configuration. The components will complete thermal and operational life cycles as part of the life verification.

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 cathode heater, inner and outer magnets, magnet heater, heater transition tube, and resistive temperature detector were selected to complete component-level cycle testing. All components are undergoing testing to 150% of 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 will complete testing before QSAR-2 scheduled for mid-2027.

The component tests are being run in the Component Test Facility at NASA JPL. The facility can accommodate multiple component tests in parallel. The tests utilize periodic electrical functional testing to assess the component performance. 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.

The project also fabricated a flight-like cathode assembly (the qualification cathode). It was subjected 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, post-mechanical characterization, and qualification thermal vacuum testing. At the time of this writing, it has completed roughly 25% of its ignition cycling requirement.

NASA has completed other risk reduction testing including EMI characterization testing, JPL-led near-field plume measurements leading to validation of significantly improved thruster life-models, and testing at GRC to investigate cathode performance after extended atmospheric exposure. The extended cathode testing is approaching 33% of its total test duration which will be a significant risk reduction for a number of missions. GRC and AR are also performing several material characterization tests to inform future designs and component life models.

3.3. Thruster Life Qualification

The second qualification thruster, QM-2, completed final assembly near the end of 2025 and completed acceptance testing in GRC's VF-5 in February 2026. Its performance was in-family with the three flight thrusters (see Table 2) and QM-1.

Because QM-1 was completed before the change in harness design, the NASA and AR teams agreed that QM-2 (which is identical to the flight thrusters) should be subjected to a delta-qualification vibration test at Aerojet Rocketdyne to verify the new harness connections and other (slight) design modifications will still survive launch. The delta-qualification vibration test was successfully completed in March, 2026.

A delta-shock test was deemed unnecessary because none of the changes made to the flight design were considered sensitive to shock loads. QM-1 is thermally conservative with respect to QM-2. The risk of not performing a delta-TVAC was deemed to be acceptably low by the project and PPE.

The QM-2 thruster will enter wear testing in GRC's VF-5 in the fall of 2026 following pre-test characterization identical to the pre-environmental characterization of QM-1. The wear testing is delayed until the fall to accommodate an upgrade to the xenon feed system (XFS) that will mitigate the risk of contamination of the AEPS cathode over the years of planned wear testing. Several other facility and diagnostic upgrades will be implemented concurrently. The testing is planned to continue through September 2029.

3.4. SEP Project Objective Status

With the delivery and acceptance of the flight thrusters and the completion of environmental qualification, SEP has met all of its programmatic objectives except life-qualification of the 12 kW thruster. These objectives [8] and their status are

1) **Develop, manufacture, and qualify a high-power (12 kW) next generation EP thruster for space flight system integration.** Five flight-like thrusters have been manufactured. Three have been delivered for integration on the PPE spacecraft and QM-1 has completed environmental qualification. Component qualification is on-going and is expected to complete no later than spring, 2027.

2) **Mature manufacturing processes to enable a commercially available high-power EP thruster for space vehicle integration.** AR is ready to provide AEPS flight thrusters without further development costs and can leverage SEP-AEPS qualification.

3) **Complete qualification of 12 kW Advanced Electric Propulsion System (AEPS) thruster to include qualification wear-testing to at least 100% of the PPE mission-based, per-thruster xenon throughput requirement.** Life qualification testing will begin in the fall of 2026. However, QM-2 is expected to satisfy the throughput requirement given the very limited erosion and negligible performance degradation measured over thousands of hours of development thruster testing and modelling. [9,10]

4) **Reduce interface and plasma interaction uncertainty to improve probability of demonstration mission success, enable private-sector infusion, and enhance future exploration application of the SEP technologies**. The Plasma Diagnostics Package (PDP) which SEP was providing for the PPE spacecraft would have provided extremely valuable correlation between flight and ground test plume data. However, it was cancelled in 2022 as a mass savings for the PPE spacecraft. SEP has met this objective through significant improvements in plume diagnostics and numerical modelling. Data are being shared with the JANUS Space Technology Research Institute (STRI) led by Georgia Institute of Technology.[11] This NASA-Academia collaboration and the NASA-AR collaboration have greatly reduced the uncertainty in test-like-you-fly (TLYF) plasma interactions of EP devices.

5) **Publish and distribute electric propulsion thruster life qualification, plasma plume model predictions, and other information to allow for US private sector assessment, understanding, and infusion of the electric propulsion systems**. Several AEPS papers have been included in conference and journal publications over the past 10 years and continue to be submitted.

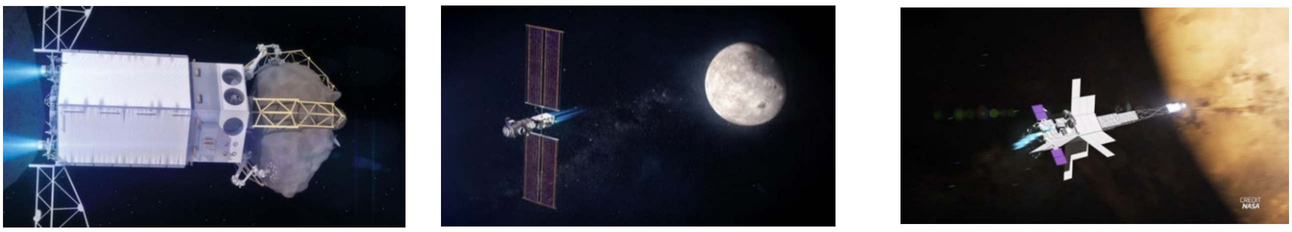
6) **Develop the interface between the mission user (PPE) and the AEPS contractor to ensure electric propulsion requirements, capabilities, and qualification meet the mission needs**. Detailed requirement and interface documentation has been developed and AR can leverage this collaboration and their ongoing expertise in EP thruster integration to facilitate future AEPS integration. Detailed acceptance test reports have been generated and approved by NASA.

4. AEPS-ENABLED MISSIONS

Through both ground testing and numerical modelling, the qualification of AEPS is laying the foundation for both solar-powered and nuclear-powered electric propulsion (SEP and NEP). AEPS thrusters were designed to be incorporated into 10 to 100 kW-class spacecraft. But, in addition, the development and. qualification of AEPS is fundamental to the maturation and integration of both lower and higher-power HET systems.

The history and highlights of the AEPS development program through early qualification testing is provided in [11]. However, Fig. 8 captures the impact the SEP-AEPS project has had on NASA's space architecture imagination: (a) a mission rendezvousing with an asteroid, capturing a piece of it, and returning that piece to cis-lunar orbit for human interaction, (b) a lunar space station enabling sustained human operations and exploration at multiple landing sites, and (c) a combined solar and nuclear-powered mission to Mars with deployable payload and a possible extended mission to the outer planets. While AEPS thrusters enabled these missions, the overarching objective remained the same: demonstrate deep-space exploration capabilities needed for human missions to Mars and beyond.[12]

AEPS-PPE has been considered enabling for a number of SEP missions to Mars. Fig. 9 shows four



a. The Asteroid Redirect Vehicle with AEPS

b. Two elements of Gateway: AEPS-PPE and HALO

c. Conceptual NEP spacecraft with AEPS-PPE

Figure 8. Renderings of three transformative missions enabled by AEPS thrusters. Credits: NASA

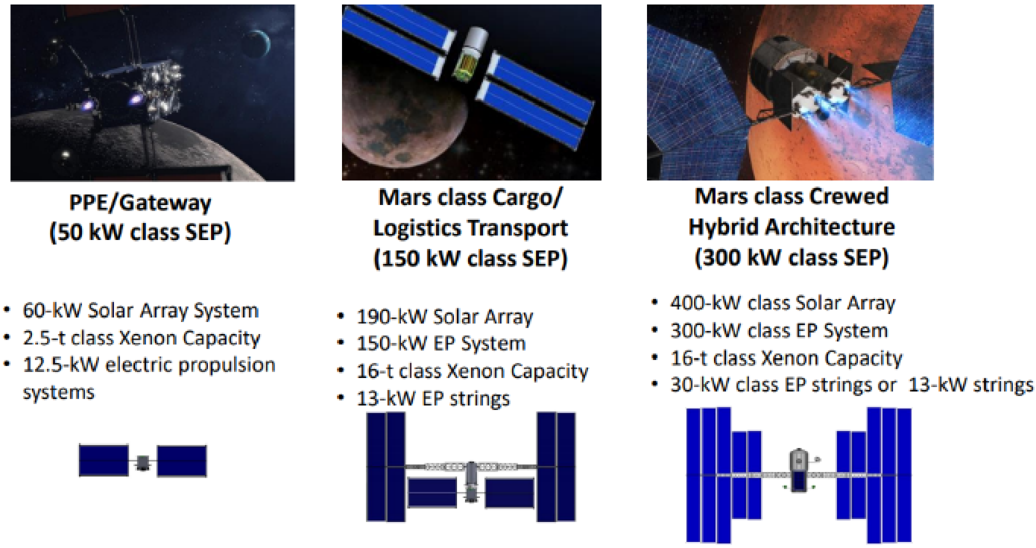


Figure 10. SEP system extensibility building upon the PPE bus spacecraft. [13]

mechanical and throughput requirements currently governing the AEPS qualification campaign encompass all of these missions. The campaign includes thermal cycling to the maximum (lowest) cold temperatures expected at 1.5 AU and repeated ignitions at these temperatures.

AEPS is also enabling for a number of near-term NEP missions. Consistent with earlier studies using solar power, NEP architectures requiring EP powers up to 300 kW can be accomplished through the clustering of 12 kW thrusters.[13,14]. A notional progression of AEPS-powered spacecraft is shown in Fig. 10. Cluster testing with both Xe and Kr propellant is being conducted with AEPS laboratory model thrusters as risk-mitigation for NASA's NEP technology maturation project.[14].

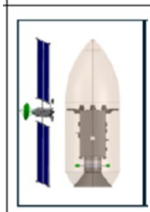
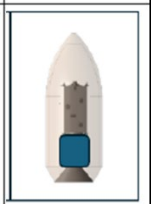
Case 1	Case 2	Case 3	Case 4
Launch to escape, spiral to Mars SOI, spiral down to ASO	Launch to escape, spiral to Mars SOI, spiral down to 5 SOL, support ~5t payload for ~ 5yrs	Launch to escape, spiral to Mars SOI, spiral down to ASO (visit Deimos on the way): deploy ~4 smallsats at ASO or Deimos (carry 2.5t)	Launch to escape, spiral to Mars SOI, spiral down to LMO, support ~2t radarsat payload for ~ 5yrs
633 Days	980 Days	795 Days	1,078 Days
~300 kg	~4t	~ 2.5t	2t
			
~ 1 kW	~ 15 kW	~ 1kW	Up to 10 kW

*Figure 9. PPE-to-Mars design reference cases.[**Error! Bookmark not defined.**]*

5. LESSONS LEARNED

In partial fulfilment of its 5th high-level objective given in Section 3.4 above, SEP along with Aerojet Rocketdyne is sharing lessons learned. Many more will be shared following the closeout of the AEPS contract in 2027 and SEP project closeout in 2029.

5.1. Schedule Management

One of the primary lessons learned over the course of the SEP project is that schedules are the foundation of trust throughout layers of the project. A. credible schedule entails not only budgeting of time with margin, but also a schedule control plan that ensures schedule management at all levels.[15] A non-credible schedule, whether real or perceived, consistently led to mistrust. SEP and AR have collaborated to build trust not only with respect to contract execution but within the execution of specific tasks.

Several actions that have helped SEP improve schedule management.

- The NASA and AR teams have collaborated to ensure communication between teams and team members at all levels.
- Responsibility for the execution (including scheduling) of specific tasks is delegated to and managed by task leads
- Transparency in schedule variance reporting has significantly improved at both the AEPS contract and team levels.
- Permanent on-site AR test engineers at GRC which yielded faster anomaly response and smoother qualification planning and execution,
- Structured communication between AR and NASA test teams resulted in improved test readiness reviews.
- Proactive contractor-identified changes that saved time in flight deliveries

Since 2025, the schedule has been resilient under stress. Localized slips did not result in delays to delivery of key hardware. This resilience also indicated cost and schedule trades maintained the project's technical rigor to achieve the mission's priorities.

5.2. Risk Management

SEP risk management has successfully mitigated all of its red risks and is currently carrying only a handful of yellow risks. However, in retrospect, failure of the project to use NASA's best practices in risk characterization prevented SEP from being proactive in mitigating significant schedule and cost delays. The NASA Risk Management Handbook recommends criticality analysis of risks which explicitly scores a risk's uncertainty and timeframe. [16] Three examples are discussed below to illustrate the impact of using criticality scoring.

NASA has adopted a best practice of qualifying EP thruster life by 100% test with 50% margin by analysis.[17] At the start of the SEP project, there was a risk of insufficient validation of the numerical model used to establish the margin. In scoring this risk as red, SEP disproportionately gave it high priority and visibility within SEP's programmatic reporting.

The first row in Table 3 shows that the criticality scoring is significantly less than the boarded likelihood and consequence (LxC) score. The uncertainty score incorporates a combination of detectability and TLYF uncertainty factors, yielding a score of 3. The far-term timeframe of the risk is based on a year-long effort needed before the projected end of wear testing, 4-5 years after CDR. The net result is a 1x2 criticality score. The work could have been rephased after qualification testing when its criticality increased as it became a mid/near-term need.

Mitigation of SEP's risk associated with delays in cathode fabrication did not receive adequate resources in a timely fashion. The risk was scored and tracked as a mid-level risk that might, in itself, add marginal cost and delay. However, if it continued to do so, it would directly impact several upcoming milestones. The risk was eventually mitigated after realizing some of these impacts.

For this discussion, the uncertainty in the risk of cathode fabrication delay is scored as yellow strictly on the basis of its cross-cutting consequences which could (and eventually did) generate cascading delays in flight and qualification hardware assembly and testing. As seen in the second row of Table 3, the criticality score is much higher in this case, promoting the risk to a red: 5x3. Applying additional resources earlier towards mitigating this risk would have potentially saved significant costs and furthered the commercialization of the AEPS thruster.

The majority of SEP's risks do not have as large a discrepancy between their LxC scoring and their criticality scoring. For example, the independent assessment of the impact of atmospheric exposure on cathode life is tied to an associated risk. As shown in the third row in Table3, the impact of a high uncertainty due to propagation potential and far-term timeframe is a complexity score of 2x4. That is very similar to the LxC score of 2x5. This suggests that this risk is being appropriately addressed by SEP. The criticality scoring process would not upend the risk management, but it would clearly identify the priority of risks for the project to mitigate.

5.3. Requirement Definition

As noted in [1], AR was contracted by NASA to design and build the AEPS engineering model thrusters. These were subjected to extensive performance and wear testing. Expectations for the performance of qualification and flight model thrusters were based on those of the engineering models. However, in many cases, targets became requirements which did not include sufficient margin for design changes. This led to several non-conformances during qualification that had no direct connection to mission need. Even though neither thruster operation nor capability was impacted, the process required to document and waive these non-conformances added significant inefficiency to the execution of the qualification and acceptance testing. In hindsight, better approaches to requirement definition and modification were needed.

6. CONCLUSION

The SEP-AEPS Project has delivered three flight thrusters for integration onto the PPE spacecraft. The QM-1 thruster has completed environmental qualification. The thrusters meet or exceed their performance requirements and are under their

Table 3. Criticality ranking for three SEP risks.

Risk (scored at CDR/KDP-D)	LxC	Uncertainty	Timeframe	Criticality
Unvalidated modelling of erosion mechanisms	2x5	3: Yellow	Far-term	1x2
Cathode Delays and Technical Issues	3x3	3: Yellow	Near-term	5x3
Cathode Exposure Duration	2x5	4: Red	Far-term	2x4

mass limit. Component qualification is ongoing, including ignition cycling of a qualification cathode. All component qualification testing being conducted at NASA JPL will complete by the QSAR-2 review expected to occur in mid-2027. Long-duration wear testing of the QM-2 thruster will begin in the fall of 2026 and likely continue into 2029. The qualification campaign will not only qualify AEPS for its first use on PPE, but for subsequent uses on future PPE-like spacecraft, high-power commercial spacecraft, and/or very-high-power NASA exploration spacecraft.

The SEP Project has met all of its objectives except the qualification of the AEPS thruster, which is ongoing. These include design, fabrication, and delivery of the 12 kW flight thrusters and mitigation of TLYF risks to spacecraft integration. SEP has encouraged regular publication of technical and programmatic status and achievements. This is now extended to the sharing of lessons learned. In particular, lessons learned in risk management, schedule management, and requirement definition may have immediate value to other projects.

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7. ACKNOWLEDGEMENTS

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