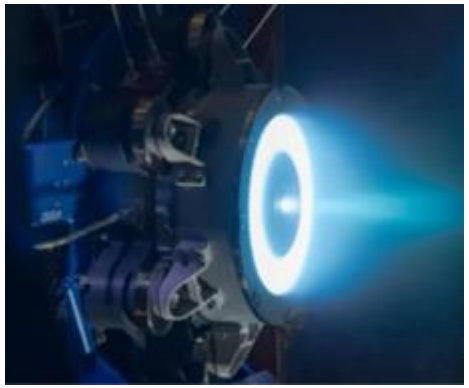
Qualification Progress and Mission-Enabling Capabilities of the 12-kW Hall-Effect, Advanced Electric Propulsion System (AEPS) Thruster



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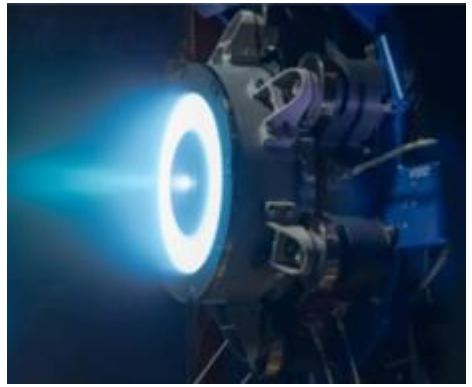

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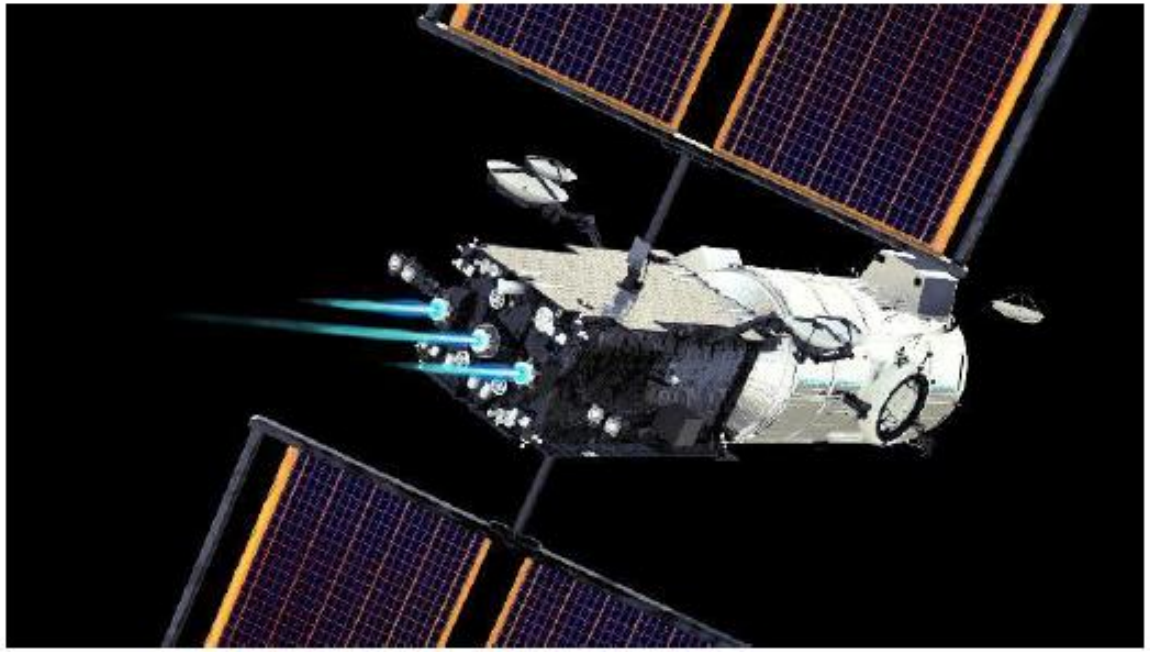
Solar Electric Propulsion (SEP) Project Overview



Project Description	Key Information
The Solar Electric Propulsion (SEP) project is developing and qualifying an advanced 12 kW Electric Propulsion (EP) thruster to the Power and Propulsion Element (PPE) requirements, which are applicable to human/robotic exploration and commercial spaceflight missions. SEP technology development includes a 12 kW magnetically shielded Hall-effect thruster.	Project Phase: D Milestone Dates: Qualification System Acceptance Review (QSAR) #1: July 2026 QSAR#2 NLT Q4 FY 2027

SEP Project Objectives

SEP has met most of its high-level objectives

- **Develop** and manufacture high-power (12 kW) next generation electric propulsion thruster
- **Mature** manufacturing processes
- **Reduce** interface and plasma interaction **uncertainty**
- **Develop** the interface between the mission user and the thruster provider

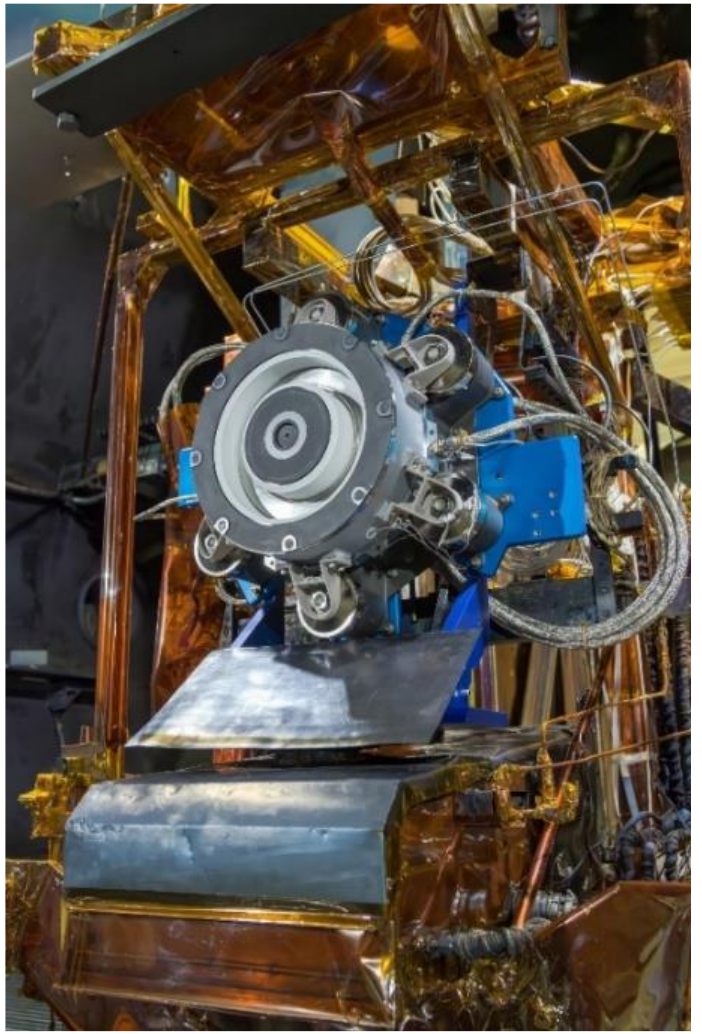
Two high-level objectives are ongoing

- **Complete qualification** of 12 kW Advanced Electric Propulsion System (AEPS) thruster
- **Publish and distribute** predictions, lessons learned, and other information **for assessment, understanding, and infusion**

AEPS Thruster Overview

- **The 12-kW AEPS thruster is based on the NASA-developed Hall Effect Rocket with Magnetic Shielding (HERMeS)**
  - **Aerojet Rocketdyne (AR)** utilized the HERMeS design while making modifications to improve manufacturability, structural robustness, cycle life capability, and ease of spacecraft integration
- **Thruster envelope of 210 mm height x 530 mm diameter with 53 kg maximum mass**
- **Three harnesses provide discharge power, auxiliary power for cathode and magnet components, and power for thermal components (magnet heaters and temperature sensors)**
- **Throttle-able from 300 V, 6 kW to 600 V, 12 kW**

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

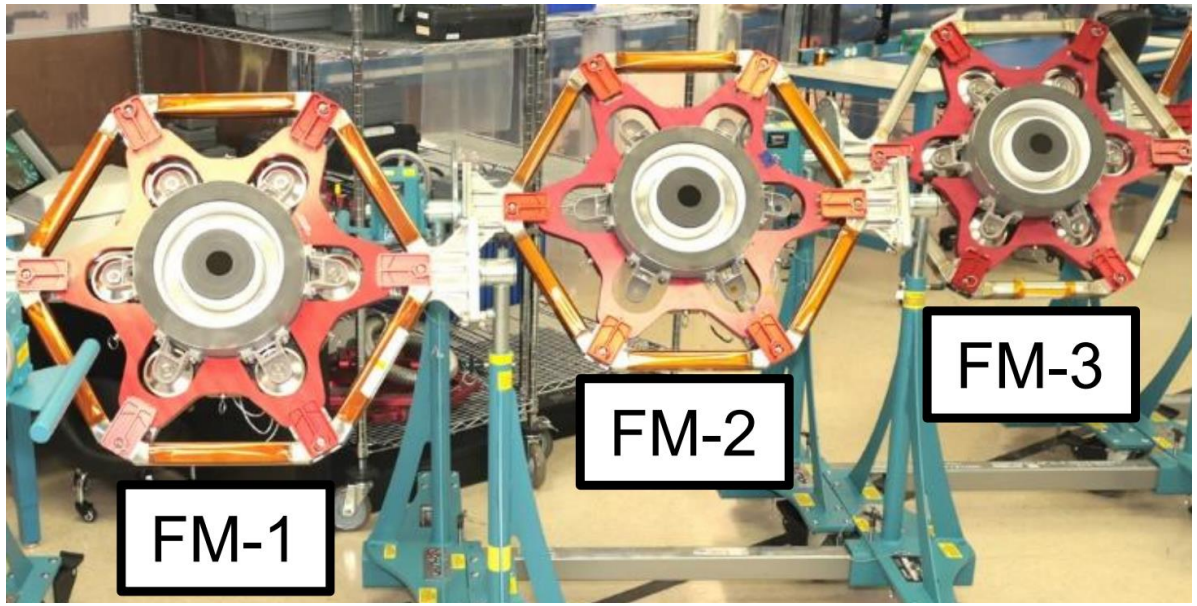


AEPS QM-1 installed within Vacuum Facility 5 (VF-5) at NASA Glenn Research Center (GRC)

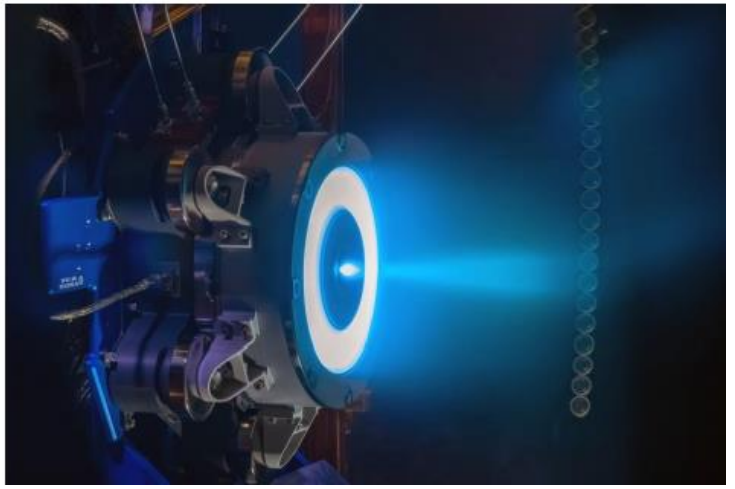
Flight Thruster Status

AR completed fabrication, acceptance tested, and delivered to NASA all three flight thrusters (FM-1, -2, and -3) in 2025.

- AR acceptance testing: random/sine vibration testing, thermal cycling, and performance characterization
- NASA shipped the FMs to Intuitive Machines (ex Maxar/Lanteris) for integration on the PPE spacecraft as delivered
- Delivery was on schedule despite several challenges including a US government shutdown

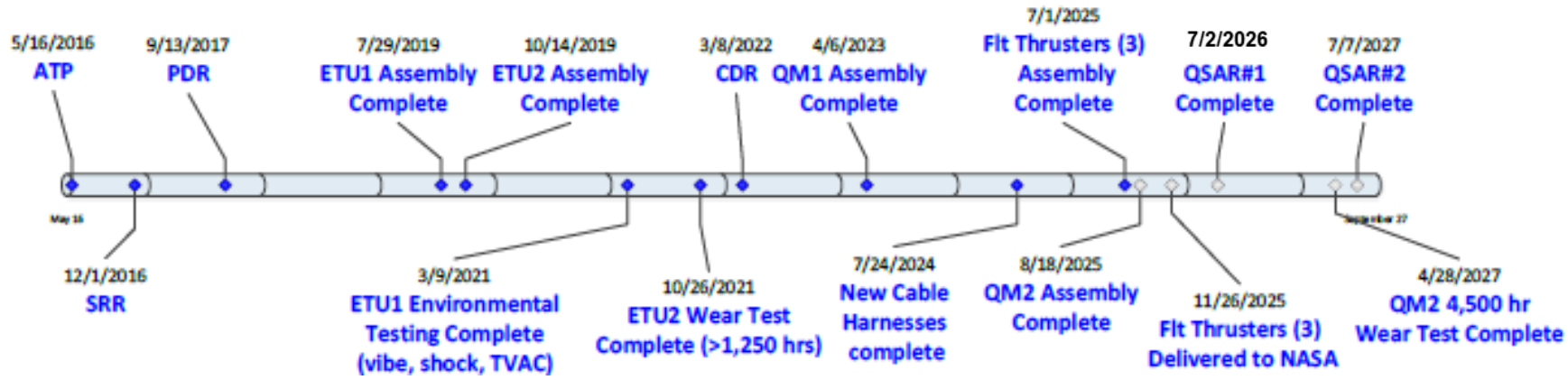


Three flight model thrusters at Aerojet Rocketdyne



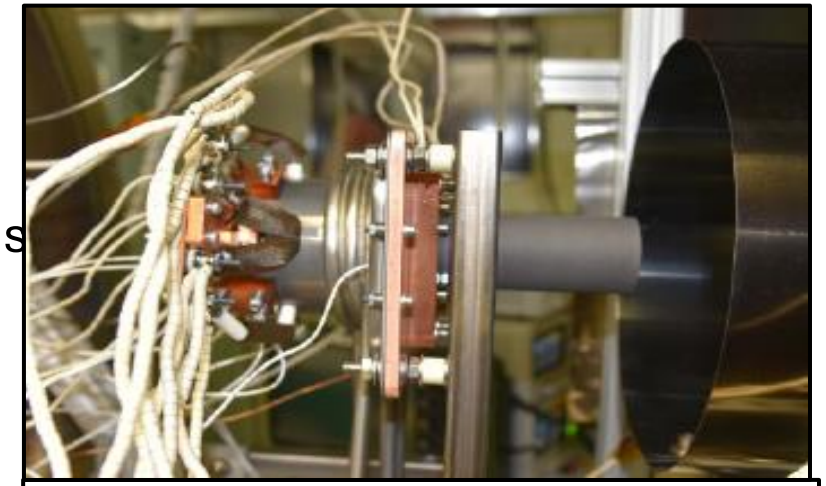
QM-1 operating in VF-5 at NASA GRC

Qualification Status



AEPS qualification consists of multiple parallel efforts

- Thruster environmental qualification (complete at QSAR#1)
- Thruster life qualification (begins Fall 2026)
- Component qualification testing (30-100% complete to 2550 cycles
  - Verification of thermomechanical cyclic requirements
  - Includes ignition testing of a Qualification Cathode

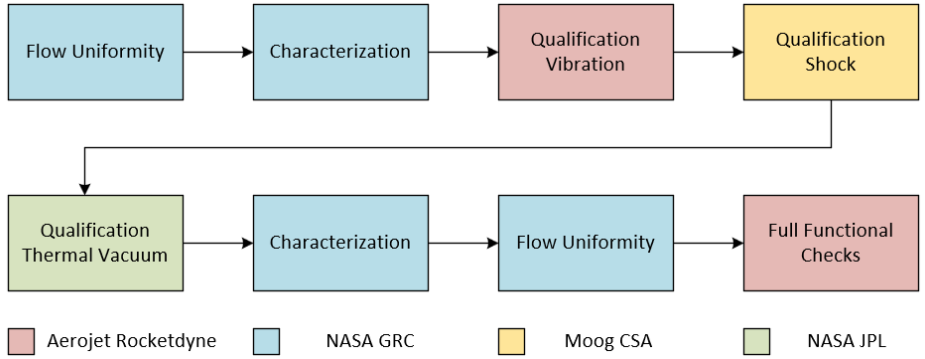


Qualification cathode TVAC Setup at JPL

Qualification Status

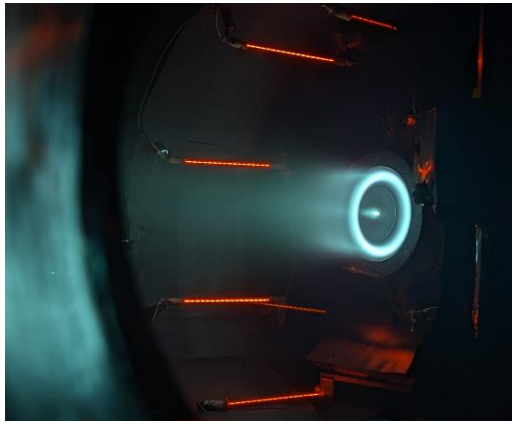
QM-1: Thruster Environmental Qualification

- Completed pre-environmental performance characterization and flow uniformity testing at NASA GRC in 2024
- Completed qualification vibration testing at Aerojet Rocketdyne in 2024
- Completed qualification shock testing at Moog CSA in 2024
- Completed thermal-vacuum cycle testing at NASA JPL in early 2026
- Completed post-environmental performance characterization, flow uniformity testing, and full functional checks at NASA GRC in 2026



Flow of the AEPS environmental qualification testing. QM-1 is now at the end of its qualification test procedure sequence.

Final documentation underway



QM-1 Thruster in TVAC in Owen's chamber at JPL.

QM-1 Thruster undergoing lateral shock test.

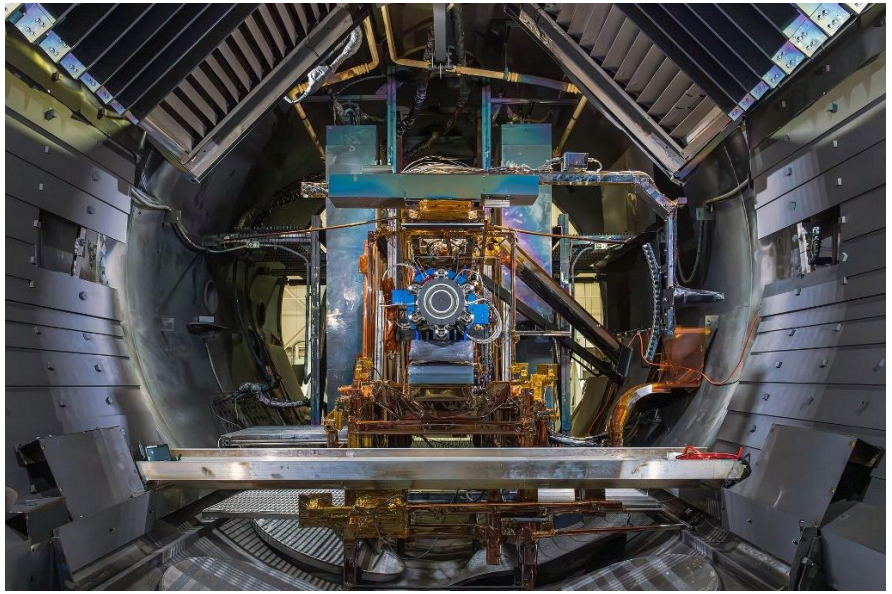
Qualification Status

QM-2: Thruster Life Qualification

- Successfully completed thruster acceptance performance and vibration testing in early 2026.
- Enters life qualification testing in Fall 2026
  - AEPS thruster designed to process 1770 kg of Xe plus 50% margin across its throttle range
    - 23,000 h at 12 kW
    - Required throughput for qualification is tied to mission-enabling need (plus margin)

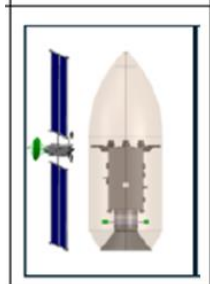
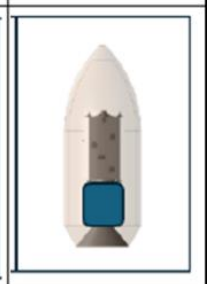
- GRC's VF-5 is being readied for a multi-year test:
  - Upgraded xenon feed system
  - Upgraded liquid nitrogen feed system
  - Upgraded plasma diagnostics
  - Upgraded visual access
  - New, in-situ wear measurement capability
  - Improved xenon recovery process

  Upgrades will increase schedule efficiency and decrease overall cost.

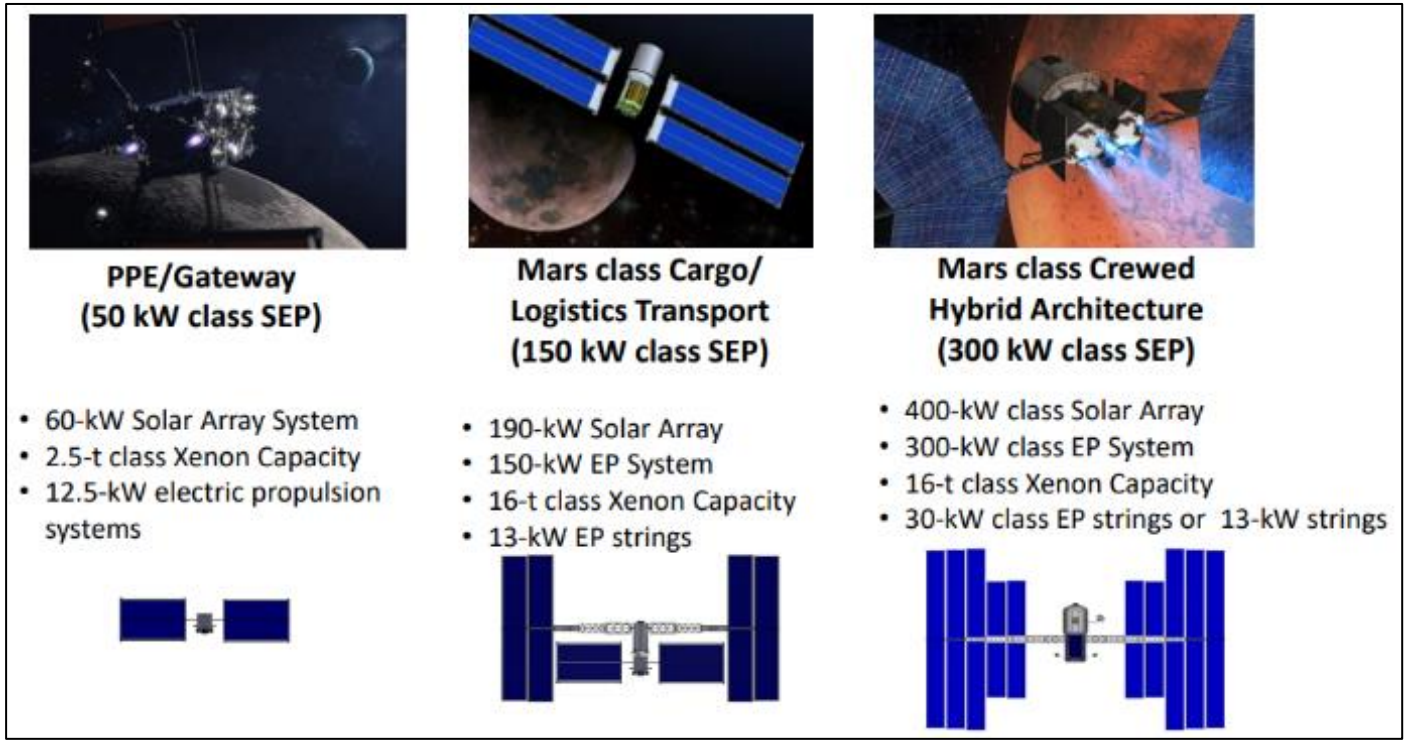


AEPS thruster in VF-5 at NASA GRC

Extensibility

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

Several options have been identified to incorporate AEPS-PPE for Mars exploration



AEPS-enabled missions include 50-300 kW class missions: significantly simplifying mission planning and spacecraft development

Lessons Learned

SEP along with Aerojet Rocketdyne is beginning to share lessons learned during AEPS development and testing (3 of many discussed in the paper)

- **Schedule (and schedule management) is foundation of trust within the project**
  - Collaboration to ensure communication between teams and team members at all levels
  - Delegated responsibility for execution including schedule management
  - Transparency in schedule variance
  - Multi-directional visibility in insight and oversight
- **Criticality scoring may improve effective risk mitigation**

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

- **Requirement definition and management should be tailored**
  - Expectations from pre-flight design were hard-wired into requirements (CDR)
  - Requirement modifications post-qualification build proved very expensive
  - Early identification of requirement relationships might have allowed for quick and inexpensive changes

Summary/Closing Remarks

- **On-time delivery of 3 Flight Models to Intuitive Machines for integration with PPE spacecraft**
- **Qualification testing of QM-1 and QM-2 thrusters:**
  - QM-1 environmental testing completed in mid-April
    - Performance unaffected by environmental qualification testing
  - QM-2 wear testing scheduled to begin in September 2026.
- **AEPS thruster enables a broad range of missions**
- **Several lessons learned over the course of the SEP project are being shared prior to the conclusion of the SEP project (2029)**
  - Mutual transparency and open, structured communication has proven critical to effective schedule and cost management