Technology Demonstration Mission
Solar Electric Propulsion
Annual Review – March 5, 2024

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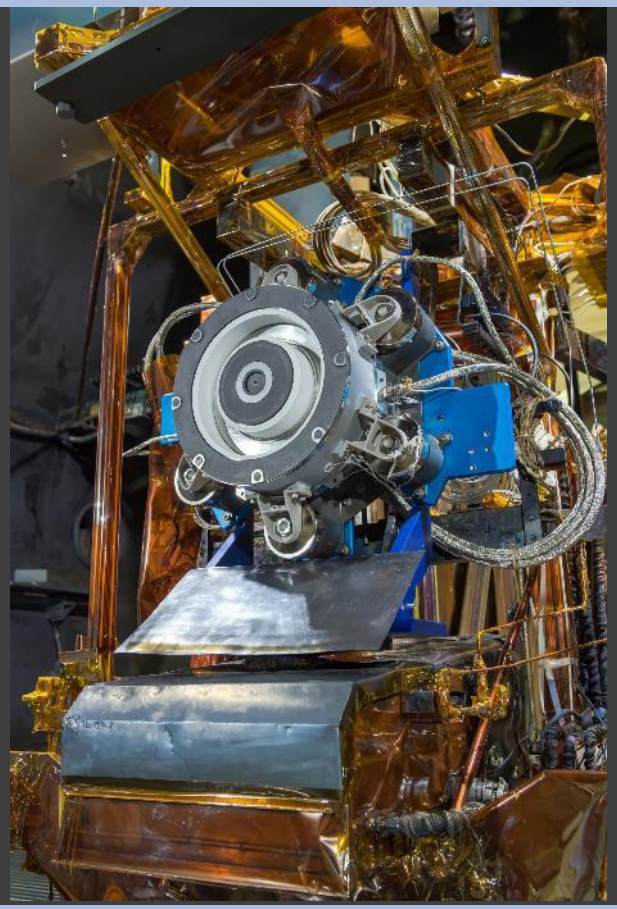
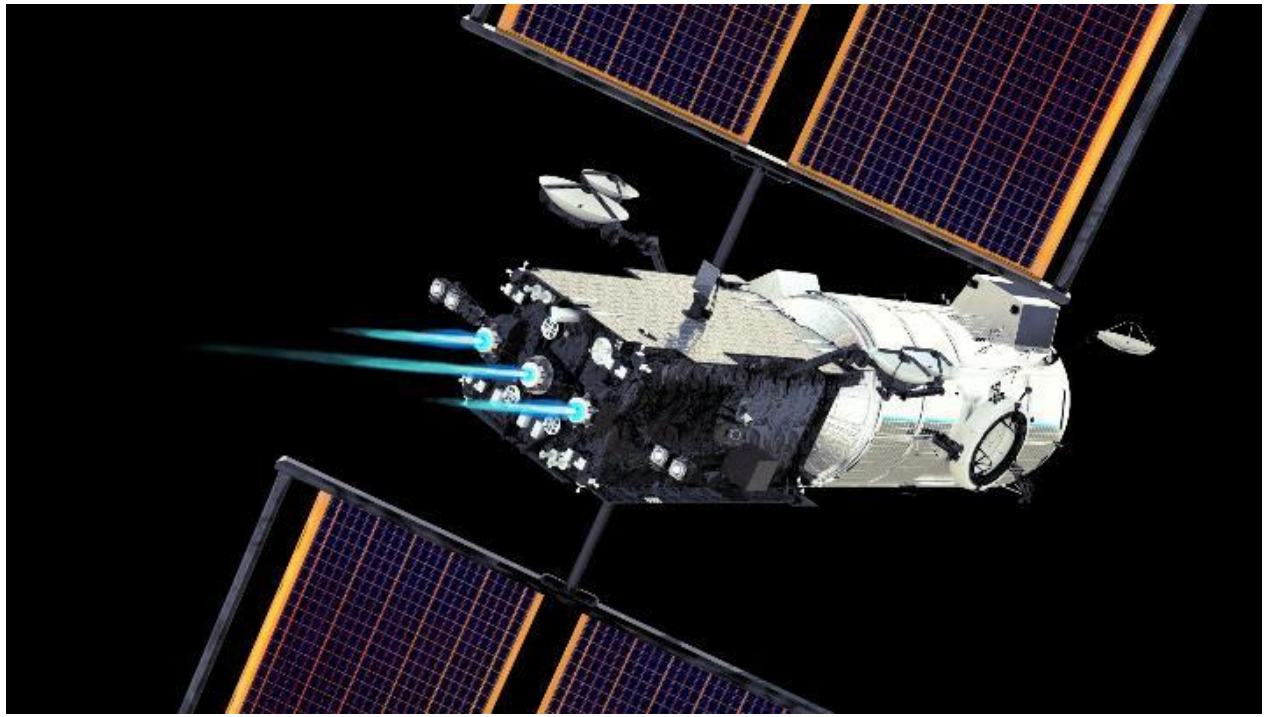
NASA Glenn Research Center

March 5th, 2024

NASA Technology Demonstration Missions (TDM)



SEP Project Overview



Project Description	Key Information	Elements
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 thruster.	Project Phase: D Milestone Dates: QSAR#1: Q1 FY2025 QSAR#2: Q4 FY2026 QM2 Wear Test: Q4 FY2028	Electric Propulsion Thruster ** The SEP Project includes Qualification of Hardware; The PPE flight hardware is separate **

SEP Project

The SEP Project includes the following activities

- **Develop, manufacture, and qualify high-power (12 kW) next generation electric propulsion thruster for space flight system integration**
- **Mature manufacturing processes** to enable a commercially available high-power (12 kW) electric propulsion thruster for space vehicle integration
- **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 (expected to be 23,000 hours)
- **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
- **Publish and distribute** electric propulsion thruster life qualification, plasma plume model predictions, and interface information to allow for US private sector assessment, understanding, and infusion of the electric propulsion system
- **Develop the interface between the mission user (PPE) and electric propulsion contractor (Aerojet Rocketdyne)** to ensure electric propulsion requirements, capabilities, and qualification meet the mission needs

SEP Governance

Power & Propulsion Element (PPE) and the Exploration Systems Development Mission Directorate (ESDMD) have defined roles in the governance of SEP

- Space Technology Mission Directorate (STMD)/Technology Demonstrations Missions (TDM) manages and provides governance of the SEP Technology Objectives and development and qualification of the AEPS Thruster
- ESDMD/PPE is responsible for the identification and control of the NASA AEPS Thruster requirements
- TDM and PPE maintain control boards required for making changes to the objectives and requirements within the SEP Project
- SEP project is responsible for implementation of the NASA AEPS Thruster requirements and contractor oversight
- PPE provides the technical requirements for the AEPS contract
  - Changes to the requirements documentation needs approval from PPE
  - For PPE driven requirement changes to the AEPS contract, PPE is responsible for the associated development and qualification cost
- SEP and PPE hold joint Review Boards and Control Boards for changes or items that could have technical, cost or schedule impacts to PPE
  - SEP project is responsible for changes that affect qualification as determined by SEP control board
  - The joint boards to reduce time and increase integrated review efficiency
  - The joint boards are jointly chaired by the TAs for Engineering and SMA and SEP and PPE Project Managers

SEP KDP-D Overview

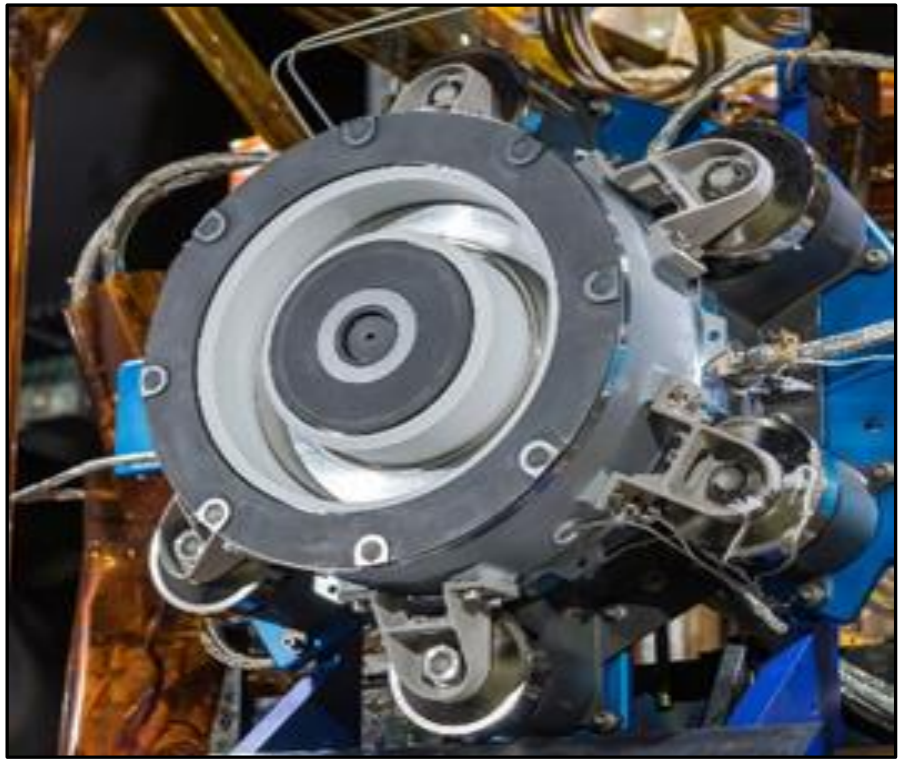
Solar Electric Propulsion (SEP) Key Decision Point D (KDP-D) was held on May 9, 2023

- The Goal of KDP-D was to evaluate the SEP project capability to qualify and deliver to PPE the required Advanced Electric Propulsion System (AEPS) within the defined project constraints and to evaluate the ability of the production plans to meet PPE's operational support requirements
  - Standing Review Board address SEP progress since CDR, planned uses of the Qualification Model (QM)-1 and QM-2, and readiness of the project to conduct acceptance and environmental qualification testing on QM-1
  - STMD Chief Engineer presented project technical assessment
  - TDM Program Office presented program office observations and assessment
    - JCL Analysis presented showed that the project will remain within ABC, but to update MA to reflect incurred costs during development
  - All three presentations recommended that the project move into Phase D activities
  - ESDMD and SMA were also polled and neither had a major concern
- STMD AA, Jim Reuter, approved SEP to move into Phase D activities

AEPS Production Overview

AR has continued to make strong progress on the production of qualification and flight thrusters

- Qualification Module (QM)-1 is undergoing qualification testing
- QM-1 and Flight Module (FM)-1 cathodes are complete
- FM-1 thruster sub-assembly is complete
- FM-2 thruster sub-assembly is nearing completion
- FM-3 thruster sub-assembly is in work
- QM-2 magnetic circuit and anode assemblies in work



QM-1 in Vacuum Facility (VF)-5

SEP in the News

NASA, Aerojet Rocketdyne Put Gateway Thruster System to the Test – NASA

https://www.nasa.gov/centers-and-facilities/glenn/nasa-aerojet-rocketdyne-put-gateway-thruster-system-to-the-test/

"Led by NASA's Technology Demonstration Missions program, the Advanced Electric Propulsion System (AEPS), built by Aerojet Rocketdyne, provides 12 kilowatts of propulsive power – over two times more powerful than current state-of-the-art in-space electric propulsion systems."

True Blue: High-Power Propulsion for Gateway – NASA

https://www.nasa.gov/image-article/true-blue-high-power-propulsion-for-gateway/

"The blue hue of the Advanced Electric Propulsion System (AEPS) is seen inside a vacuum chamber at NASA's Glenn Research Center in Cleveland during recent thruster qualification testing. This 12-kilowatt Hall thruster is the most powerful electric propulsion thruster in production, and it will be critical to future science and exploration missions at the Moon and beyond."

"The Solar Electric Propulsion project is led at NASA Glenn and managed by NASA's Technology Demonstration Missions program under the agency's Space Technology Mission Directorate."

Technology Development Advancements

PPE-SEP Integration

NASA SEP & PPE teams have been working integration of the AEPS thruster onto the PPE spacecraft

- Rev B of the ICD-371379 was signed by all parties 15-Feb-2023
- Joint ICD content is being updated by NASA, AR, and Maxar in preparation for Spacecraft CDR in March 2024
- Data transfers are occurring at regular intervals to aid integration
  - AEPS has delivered simplified thermal model, System Safety Hazard Analysis, and FMEA/CIL
- Weekly NASA, AR, and Maxar technical integration meetings are held to work key issues for coordination of AEPS thruster onto the PPE spacecraft
  - Integrated AEPS-Gimbal thermal modeling results were presented
- Successfully completed 12 kW ElectroMagnetic Interference (EMI) characterization testing with Maxar PPU & AEPS ETU-2 thruster
  - Testing was performed at The Aerospace Corporation (TAC) EP-3 Facility
  - Radiated emission data acquisition started on 26-Sept-2023 and was completed on 17-Oct-2023
    - All planned tests were completed
    - Obtained additional data at 9, 10 & 11 kW, varying magnetic field settings, and during thruster starts
    - Radiated emission data reduction activities are ongoing and the final test report is due March 2024
- 12 kW Maxar Power Processing Unit (PPU) & Xenon Flow Controller (XFC) integration testing with AEPS ETU-2 thruster occurred in May-June 2023
  - 2nd phase of integrated testing performed with post-CDR PPU and Thruster Auxiliary Support Unit (TASU)
  - Test focused on fault handling and off-nominal operation, as well as characterization of high-voltage transients
  - All test objectives successfully met
  - 3rd phase of integrated testing expected to occur fall 2024

Thruster Qualification Testing

QM-1 Acceptance Testing (ATP) was successfully completed

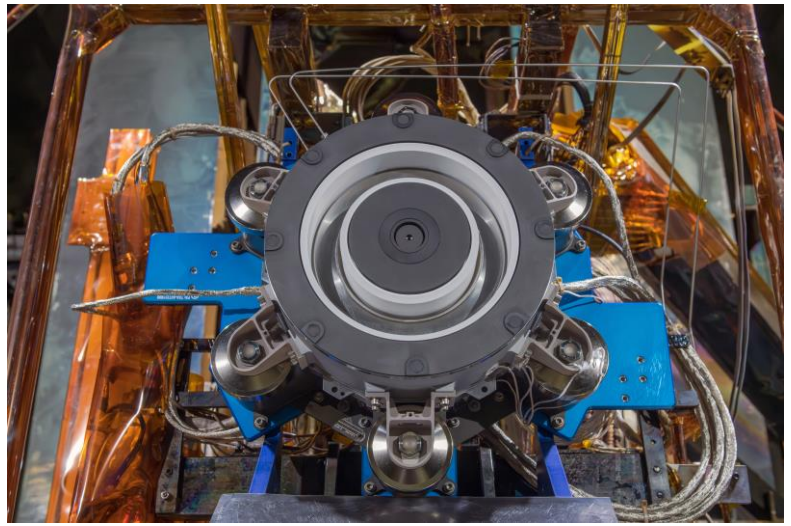
- Initial thruster ignition occurred on 6-Jul-2023
- Testing successfully completed on 12-July-2023, including thermal cycle and performance measurements
- QM-1 ATP successfully closed

QM-1 Flow Uniformity Test was successfully completed

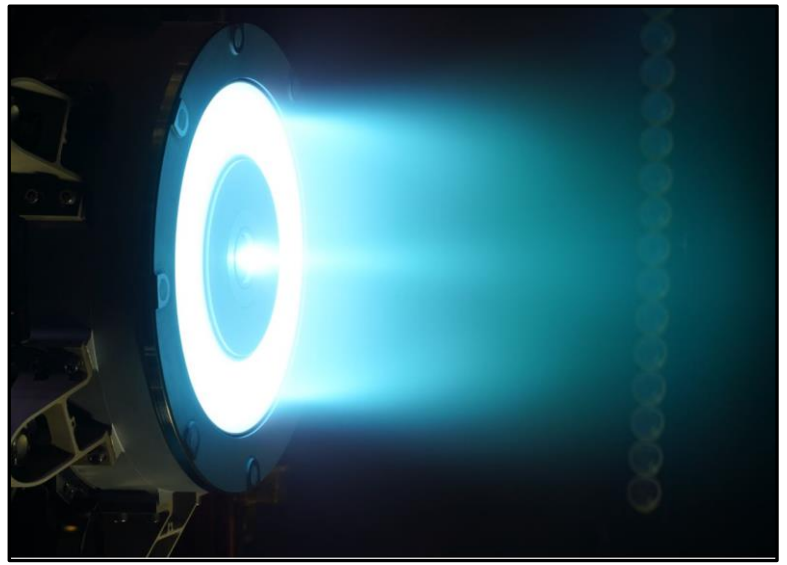
- First test in qualification test campaign is to verify azimuthal flow uniformity prior to hot-fire
- Testing successfully completed on 5-Dec-2023

QM-1 pre-environmental characterization hot-fire test

- Test to characterize thruster performance prior to exposure to mechanical and thermal environments
- Test initiated in Vacuum Facility (VF)-5 in Jan 2024
- Reference firing condition performance data collection completed on 5-Feb-2024
- Test was put on hold to investigate low specific impulse at 9 kW which slightly fell below requirement
  - Outage is minor and acceptable to PPE
  - Investigation initiated to determine root cause and assess risk of continuing test
  - Joint AR/NASA board to determine an interim NC disposition that will allow continuation of pre-environmental characterization test has been scheduled for 29-Feb

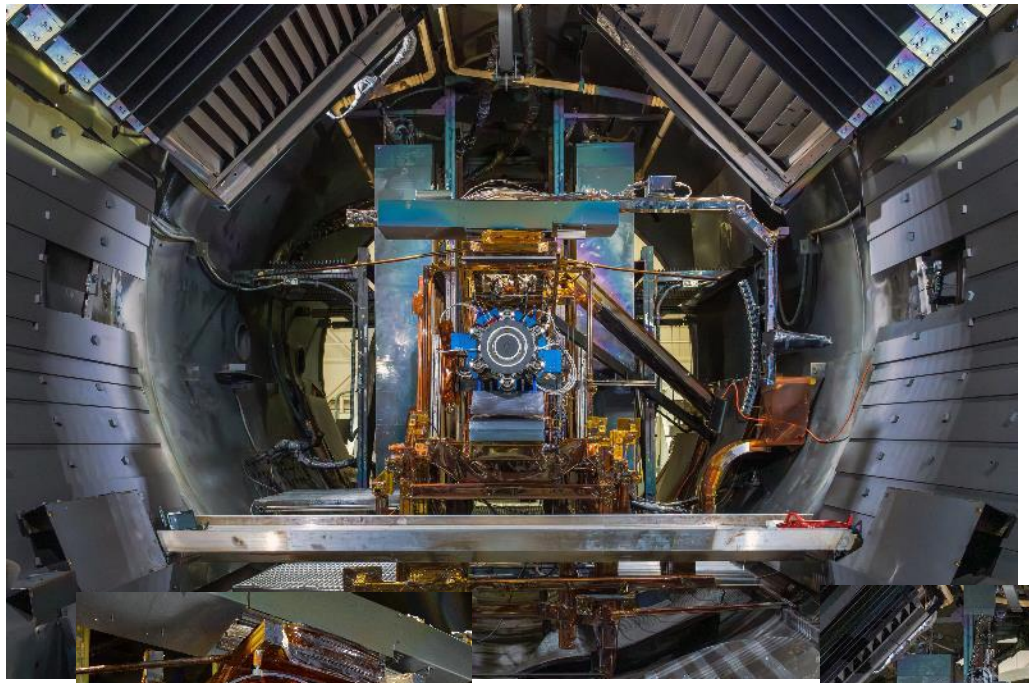


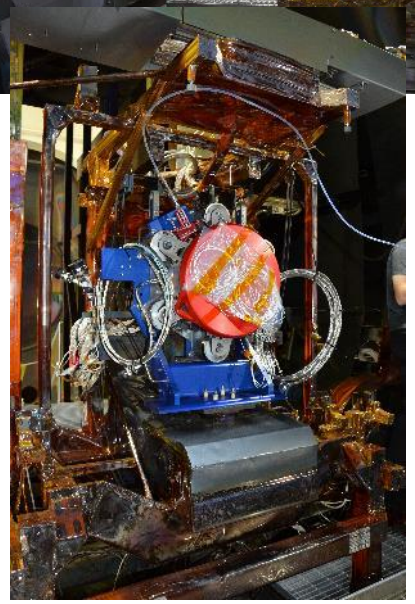
QM-1 installed on thrust stand within VF-5 at GRC

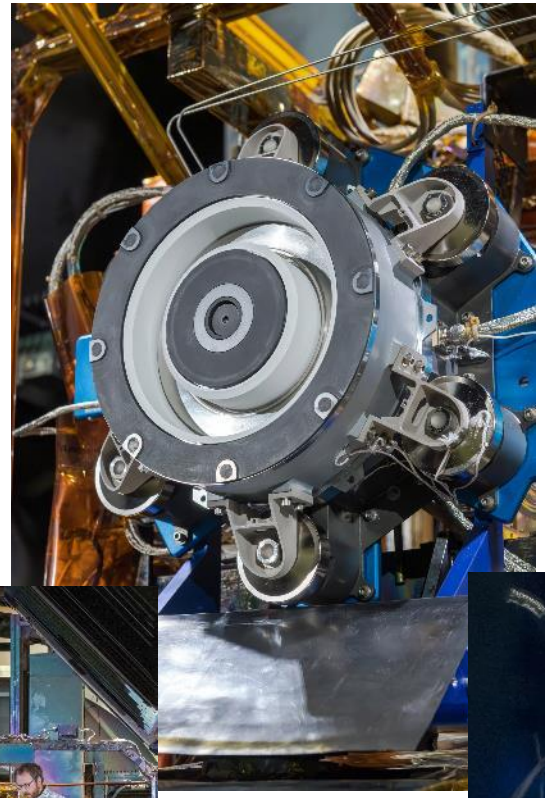


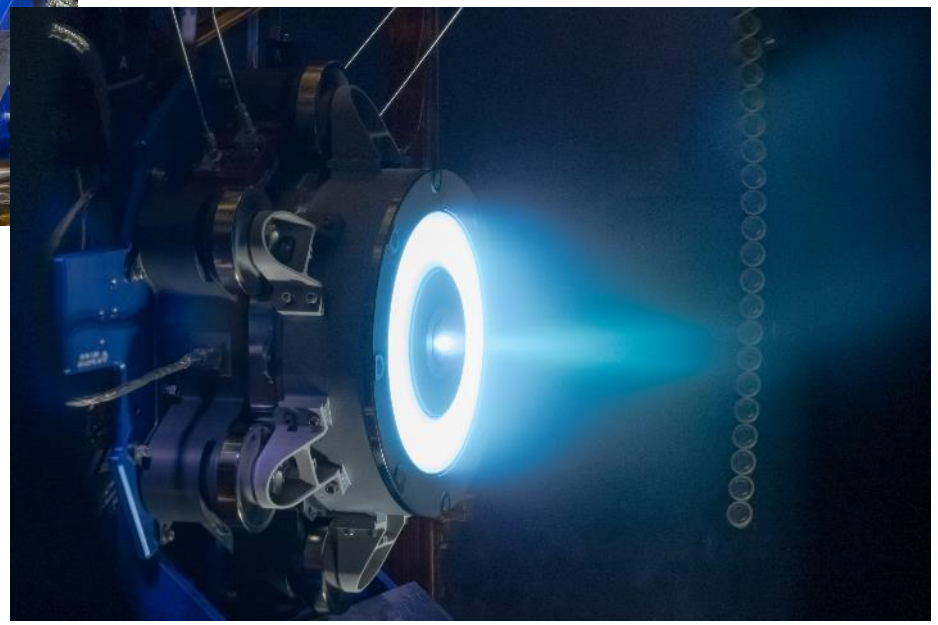
QM-1 ATP hot-fire within VF-5 at GRC

QM-1 Testing









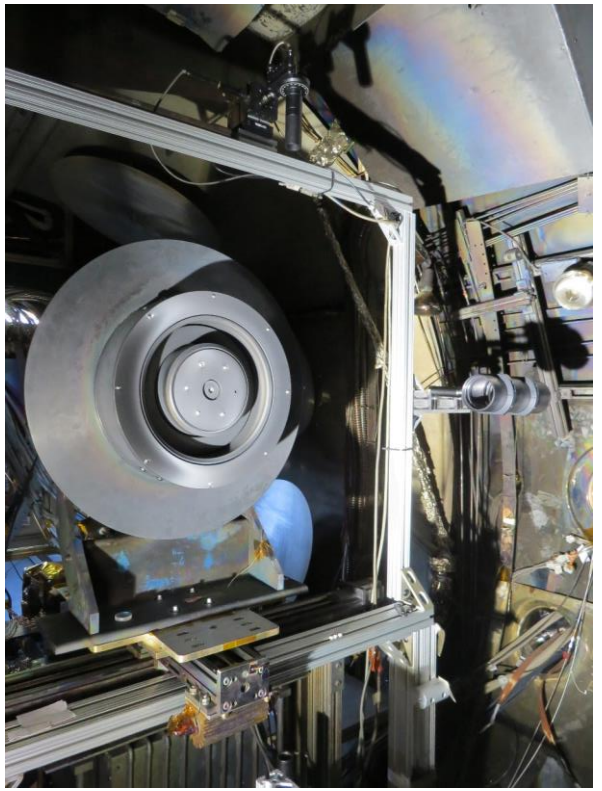
JPL Risk Reduction Testing

Risk reduction testing being performed at JPL on Technology Demonstration Unit (TDU)-2

- Goal of testing is to validate key physical mechanisms contributing to pole cover erosion in Hall2De simulations

Laser-Induced Fluorescence (LIF) Risk Reduction Test

- Successfully measured time-averaged azimuthal ion velocity distributions at near pole and main beam locations, as well as time-averaged r-z ion velocity distributions in the outer beam edge and side plume regions
- Measured ion temperatures near the poles are consistent with those previously assumed in the plasma models and are sufficient to explain the observed erosion patterns on the pole covers
- Similarly, data collected near the channel exit at the nominal operating point of 600 V are consistent with values in the models that yield the observed erosion
- The measurements verify that the numerical model of the known erosion mechanisms can be used to extend life qualification by 50% beyond test
    - It is also verified as a tool to assess off-nominal operation of the thruster over the course of its service life



In-chamber configuration for azimuthal LIF measurements at JPL

Test data obtained to-date is consistent with the wear model being used to verify thruster lifetime

- Testing continues to provide confidence in the thruster model
- Model provides extrapolation of ground test to in-space operation and verification of 1.5x margin to lifetime that will be demonstrated by QM-2 life test

Component Qualification Testing

Inner/outer magnet coils component qualification testing

- Life cycle testing was initiated on 2-Dec-2022 at JPL
- Expected completion date in September 2025
- Current cycle count is ~900-1000 cycles

Magnet survival heaters and temperature sensors (thermal components) qualification testing

- Magnet heaters life cycle testing was initiated on 23-Mar-2023 at JPL
  - Current cycle count on magnet heater is ~2230 cycles
- Temperature sensor life cycle testing was initiated on 14-Feb-2023 at JPL
  - Low insulation resistance anomaly observed during TVAC, which paused life cycling while investigation occurred
  - Anomaly investigation resulted in corrective action to perform vacuum bakeout of components prior to installation on thrusters
  - Life cycling testing of qualification units resumed after being subjected to prescribed vacuum bakeout – current cycle count ~ 360 cycles

Component Test Facility with all fixtures installed at JPL

Cathode qualification testing

- Successfully completed pre-environmental hot-fire on 11-Dec-2023
- Successfully completed vibration testing on 15-Jan-2024
- Successfully completed shock testing on 1-Feb-2024
- Successfully completed post-mechanical inspection
- TRR for TVAC/life cycling at JPL scheduled for 29-Feb-2024

Other Technical Accomplishments

Requirements Verification

- NASA has approved 18 of the 123 Verification Closure Notices (VCNs)
  - 3 VCNs have been transferred from SEP to PPE
  - Verification closure of 12 NASA parent requirements

Qualification and Flight Test Preparations

- Completed compliance reviews to NASA-STD-5005D on both AR- and NASA-provided Ground Support Equipment (GSE)
- NASA completed review of the AR's GSE compliance documents to NASA-STD-5005D and conditionally approved the use on QM-1
  - Full approval is contingent on receipt of hazard analyses
    - NASA and AR have reached an agreement on hazard analysis content
    - AR has grouped the 33 hazards into 5 subsets
  - AR plans to provide the first subset in March 2024

SEP Technical Issues and Risks

Issues

- **Cathode low cycle fatigue (LCF) on cathode heater termination joint**
  - Closed by AR after additional modeling and risk reduction testing on EDU-1 development cathode
  - NASA assessing options to reduce risk inherent with AR's approach with respect to variation in materials properties
    - Team is developing options to either mechanically or thermally cycle multiple representative wire samples to better characterize low cycle fatigue life and mitigate risk
    - Plan to take to ERB/PCB for project consideration in March 2024

Risks

- **Top risk <u>was</u> the "Use of Harness Wire Outside Rated Temperature Range" (SEP-167)**
  - Associated with use of GORE harness wire at temperatures in excess of 200 C
  - Closed after risk was determined to be too high and project decided to execute contingency by switching to alternative wire (see next slide)

- **Top risk <u>is</u> the "Impact of High-Voltage Transients on AEPS Thruster" (SEP-162)**
  - Significant progress made in understanding magnitudes of transients with SEP testing on development thrusters in 2023
  - AR actively working on risk to thruster components based on test data and electrical model to estimate magnitudes at various locations – results expected in March/April 2024
  - Data also shared during integration meetings with PPE/Maxar, with plan for Maxar to implement mitigations to protect spacecraft components from these transient magnitudes

Harness Re-design Summary

Technical integration meetings revealed an incompatibility between the original AEPS harness and PPE gimbals

- Design option chosen in March 2023 replaced the harness wire with new wire that meets bend radius, radiation hardness, and electrical performance, but not wire temperature
  - Additional analysis and testing was planned to verify the temperature rating of the wire to higher temperature
- New wire was currently available through transfer between projects
  - Receiving inspection of wire at AR noted contamination of the silver plating
  - Subsequent deliveries of the noted a similar contamination which delayed the building of new harnesses
- Initial wire-level testing at higher temperatures for 2000 hours indicated increased risk of failures
  - Passed Dielectric Withstanding Voltage (DWV) testing
  - Observed significant degradation of insulation resistance as well as cracking and lifting of outer (non-insulating) jacket
  - Results indicated high risk of failing to up-screen wire to required 10,000-hour test at high temperature

Alternative wire (M22759) was investigated by NASA in parallel

- M22759 wire was initially not chosen due to long lead procurement time (>9 months)
- Sufficient stock of wire to build all necessary harnesses for AEPS was procured and eventually received by NASA in January 2024
- Testing and analysis conducted to address potential concerns associated with operation at lower temperatures and radiation/deep charging tolerance
  - Additional testing/analysis planned, but preliminary results are favorable

Joint PPE/SEP Control Board on 2-Feb-2024 concurred on switching AEPS harness wire to M22759

- Schedule critical paths for either wire had similar programmatic impacts, while using M22759 wire had significantly less technical risk

AR has completed harness design with M22759 wire and proceeding into drawing release and harness fabrication

SEP Programmatic Issues and Risks

Issues

- **Non-Conformances (NCs) related to hardware build, assembly, and test**
  - Large number of NCs on the first build of the thruster has caused negative cost and schedule variances
  - Lessons learned from the NCs has improved the build and assembly of the flight thrusters
  - Lessons learned from QM-1 testing has informed updated test plans and procedures
- **Consistent cost overruns during initial production and test**
  - CPI cumulative is 0.93 since CDR
  - Program Office planning has ensured project budgeted reserves protect against this cost threat

Risks

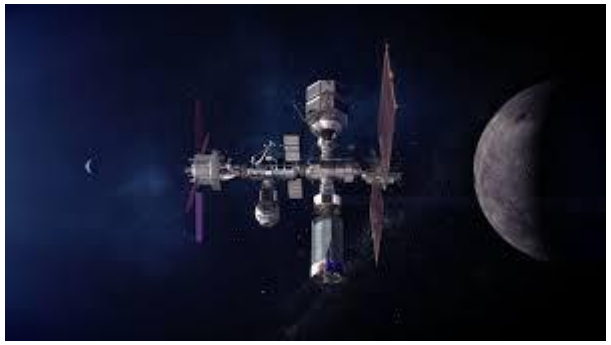
- **Requirements changes driven by PPE updates**
  - Updated requirements have delayed thruster delivery dates
  - PPE and SEP project and technical teams increased communication to understand and address any ongoing issues
- **Thruster life qualification from 1x to 1.5x by analysis requires a validated numerical model**
  - Project continues to apply resources to mitigate the risk such as testing to improve model

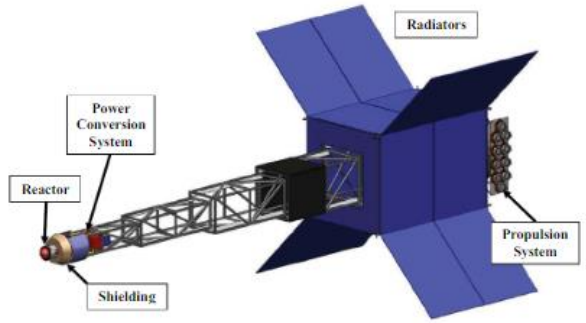
SEP/AEPS Infusion

Gateway/PPE is the first and requirement-defining user for the AEPS thruster

NASA and Aerojet are actively seeking additional users and identifying future mission applications

- **Aerojet-Rocketdyne is actively promoting AEPS for commercial use**
  - "AEPS will significantly advance the nation's commercial space capabilities" (https://www.rocket.com/space/space-power-propulsion/solar-electric-propulsion)
  - AR continues to invest internal resources to develop a commercial package, confident of commercial and other-government users
- **NASA and AR are continuing to promote AEPS at different forums**
  - International Electric Propulsion Conference, AR has submitted the abstract, "*AEPS 12 kW Hall Current Thruster Program Status and Future Plans*"
  - International Conference On Space Propulsion, NASA has submitted the abstract, "*Summary of NASA Progress on the Development and Qualification of a 12-kW Hall-Effect, Solar Electric Propulsion Thruster*"
  - International Astronautical Congress, NASA has submitted the abstract, "*NASA Progress on the Development and Qualification of a 12-kW Hall-Effect, Solar Electric Propulsion Thruster*"
- **AEPS was called out as 1 of 2 viable technologies for a potential Nuclear Electric Propulsion Demonstration Mission (NASA's 2022 Prometheus and Constellation Workshop)**
  - 10 kW NEP could enable a class of outer solar system missions not otherwise possible and could significantly enhance a range of other deep-space mission concepts; John Casani, 2020, http://hdl.handle.net/2014/47277





300 kW NEP demonstrator
Bragg-Sitton, 2011

SEP 1-Year Look Ahead

- Qualification Model (QM)-1 Vibration Testing Complete – April 2024
- QM-1 Shock Testing Complete – May 2024
- QM-1 TVAC Testing Complete – August 2024
- Flight Module (FM)-1 Acceptance Testing Begins – August 2024
- FM-2 Acceptance Testing Begins – September 2024
- QM-1 Testing Complete – November 2024
- FM-3 Acceptance Testing Begins – November 2024
- Qualification Subsystem Acceptance Review (QSAR) #1– January 2025
- QM-2 Assembly Complete – January 2025
- FM-1 Delivered to NASA – February 2025
- QM-2 Acceptance Hot Fire Testing – February 2025
- FM-2 Delivered to NASA – April 2025
- FM-3 Delivered to NASA – June 2025

SEP Summary

The AEPS thrusters will meet PPE mission needs

- Hardware exceeds minimum PPE requirements for performance, life, thermal and structural margins

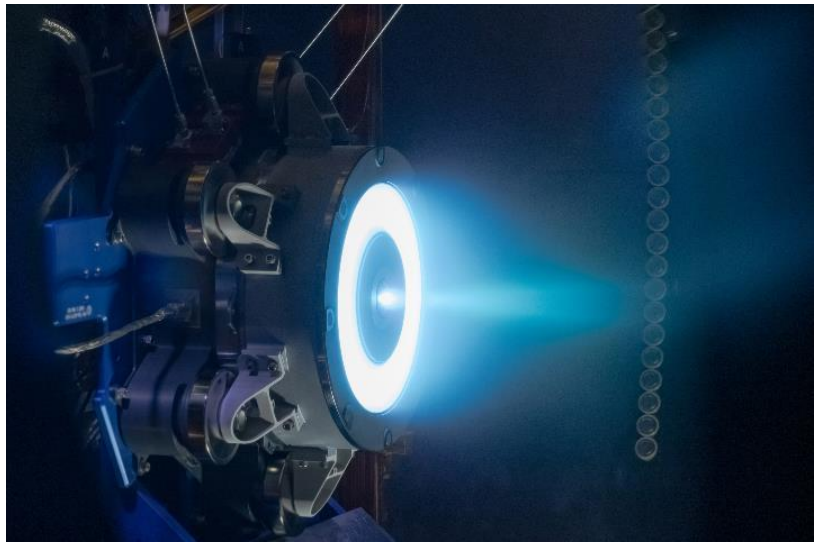
Thruster qualification testing is continuing

Component qualification testing is ongoing at JPL

Thruster production is proceeding well

Aerojet Rocketdyne leadership continues strong working relationship

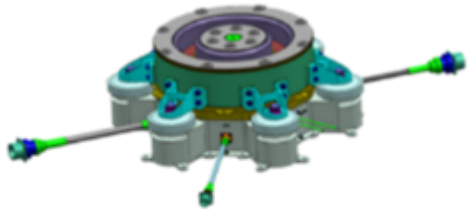
Acceptance testing of the first flight thruster will begin in Fall 2024



BACKUP CHARTS

SEP Overview

Solar Electric Propulsion (SEP)



Develop and qualify an advanced 12 kW class EP thruster applicable to exploration & commercial spaceflight: Mature manufacturing processes to enable a commercially available high-power next generation electric propulsion thruster for space vehicle integration

- AEPS Contract (Aerojet Rocketdyne)
  - Hall Current Thruster
- In-House (GRC/JPL)
  - In-line Testing & Modeling
  - Contract Oversight
  - Independent Design Assessment

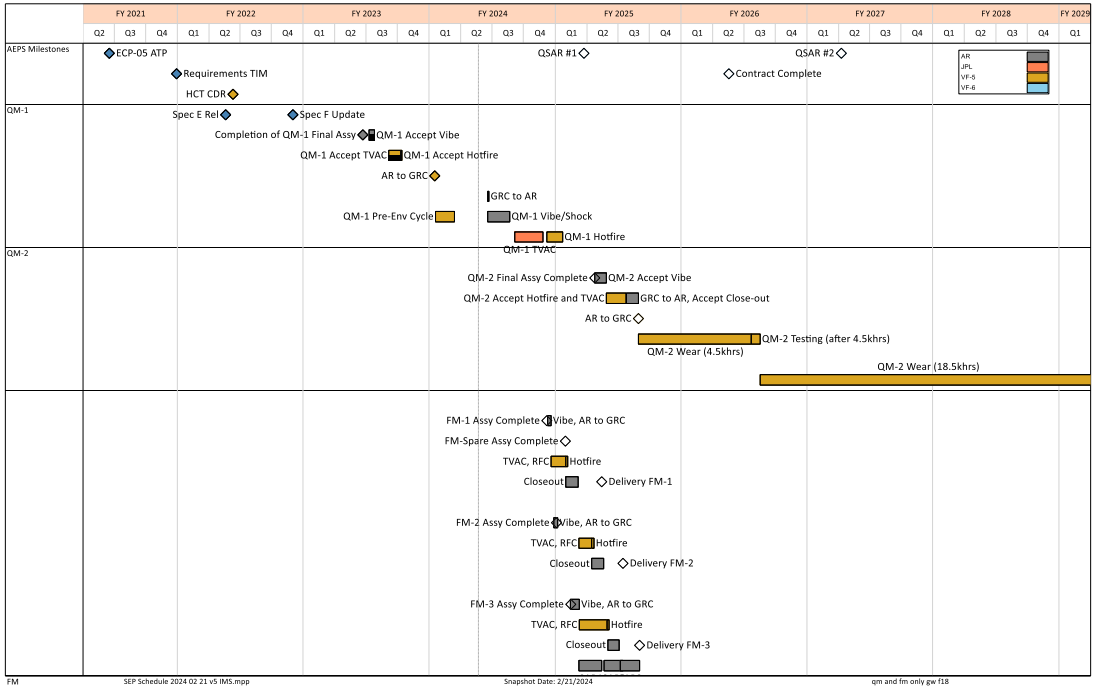
Advanced Electric Propulsion System (AEPS) Contract Status

AEPS Contract

- Cost Plus Fixed Fee contract plus Performance Incentive Fee (schedule & technical), awarded May 2016
- Original Contract for AEPS String Development with Option to deliver qualification and flight strings
- March 2021: ECP-05 Awarded for two (2) qualification thrusters only
- December 2021: ECP-06 awarded for fabrication of three (3) flight thrusters with ESDMD funding
- September 2022: ECP-07 awarded for updated requirements from PPE
- February 2023: ECP-08 awarded for the descope of the DCSU
- March 2023: ECP-09 awarded to modify design to meet PPE environments
- February 2024: ECP-10 RFP released to resolve technical issues on harness wire and update the qualification plan

CLIN	Scope of Effort under CLIN	Status
CLIN 1	Development w/ Hardware for EP String (HCT, PPU & XFC)	Close-out in Oct 2020
CLIN 2	Long Lead Material Items for Qual & Flight	Closed – all materials received
CLIN 3	Option – Qualification and Space Flight hardware delivery	Removed
CLIN 4	Capital Assets (no assets identified)	N/A – not proposed
CLIN 5	Performance Incentive Fees	Not earned; Removed
CLIN 6	Qualification effort of EP String	PPU/XFC descoped in Jan 2021, Thruster activities transferred to CLIN 7 in ECP-05
CLIN 7	Thruster-only development and qualification effort	ECP-05 Awarded in March 2021
CLIN 8	Thruster-only flight hardware delivery & acceptance testing	ECP-06 RFP released May 2021, awarded Dec 2022
CLIN 9	Flight Long Lead Material Initial Fabrication activities	Unsolicited Proposal to begin early Fab work (Jul 2021) - Closed

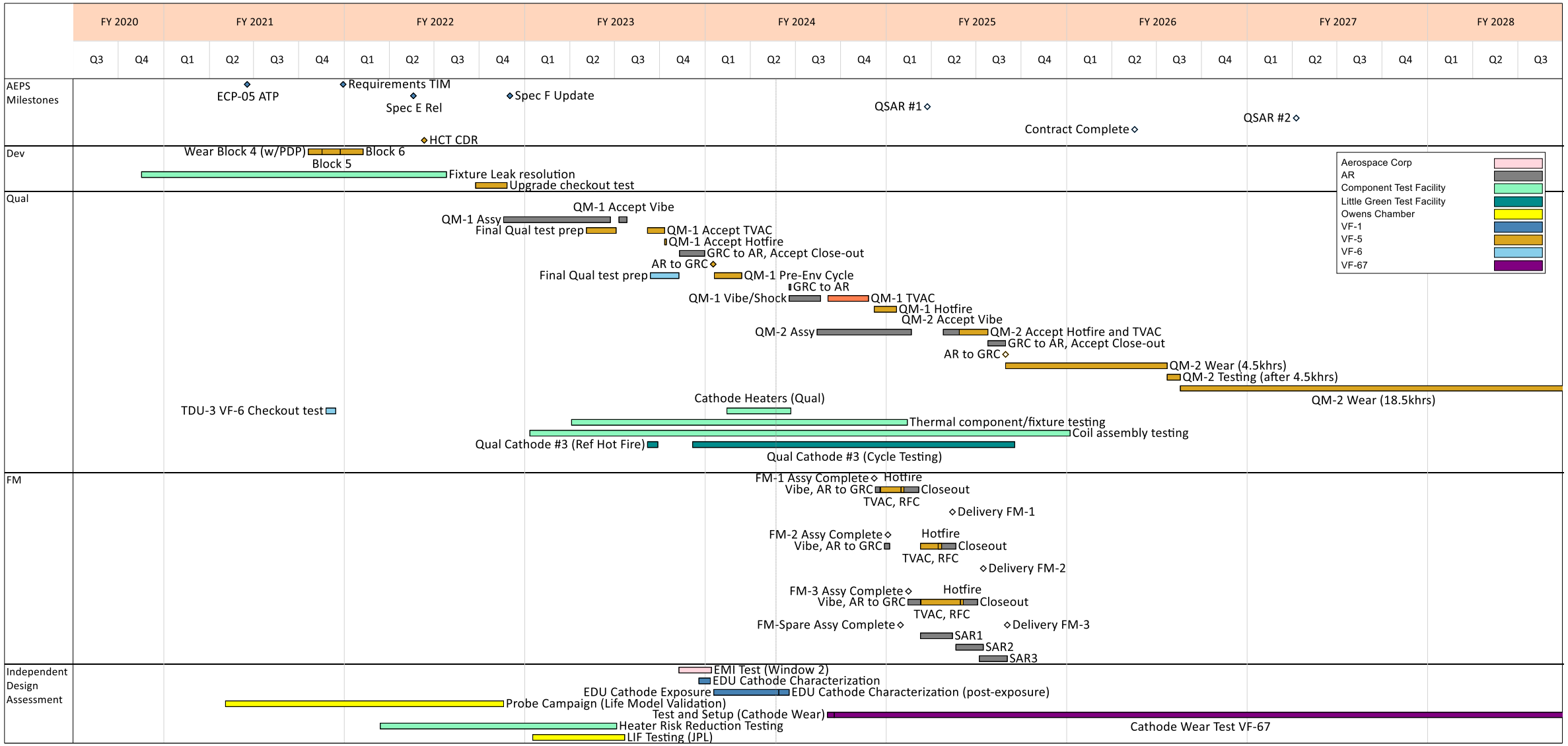
AEPS Key Milestones



CLIN 7 (Qualification Dev & Test) Major Milestones	ECP-07 Baseline	Jan Month End IMS*	Schedule Margin (Working Days)
QM-1 Final Assy Complete	04/07/2023	04/06/2023	Complete
QM-2 Final Assy Complete	06/03/2024	1/24/2025	40
Qualification System Acceptance Review (QSAR) #1	10/07/2024	1/24/25	
4500 Hour Wear Test Complete	11/03/2025	5/18/26	0
QSAR #2	02/04/2026	9/4/26	22
CLIN 7 Complete	02/16/2026	9/4/26	0
18500 Hour Wear Test Complete (SEP)	Q4 FY2028	Q4 FY2029	0

CLIN 8 (PPE Flight Thruster Build) Major Milestones	ECP-07 Baseline	Jan Month End IMS*	Schedule Margin (Working Days)
FM-1 Thruster Assembly Complete	09/05/2023	9/6/24	0
FM-1 Delivery	01/30/2024	2/12/25	1
FM-2 Thruster Assembly Complete	12/06/2023	9/26/24	54
FM-2 Delivery	04/29/2024	4/17/25	1
FM-3 Thruster Assembly Complete	03/13/2024	11/13/24	55
FM-3 Delivery	07/30/2024	6/2/25	1

SEP-AEPS Integrated Schedule

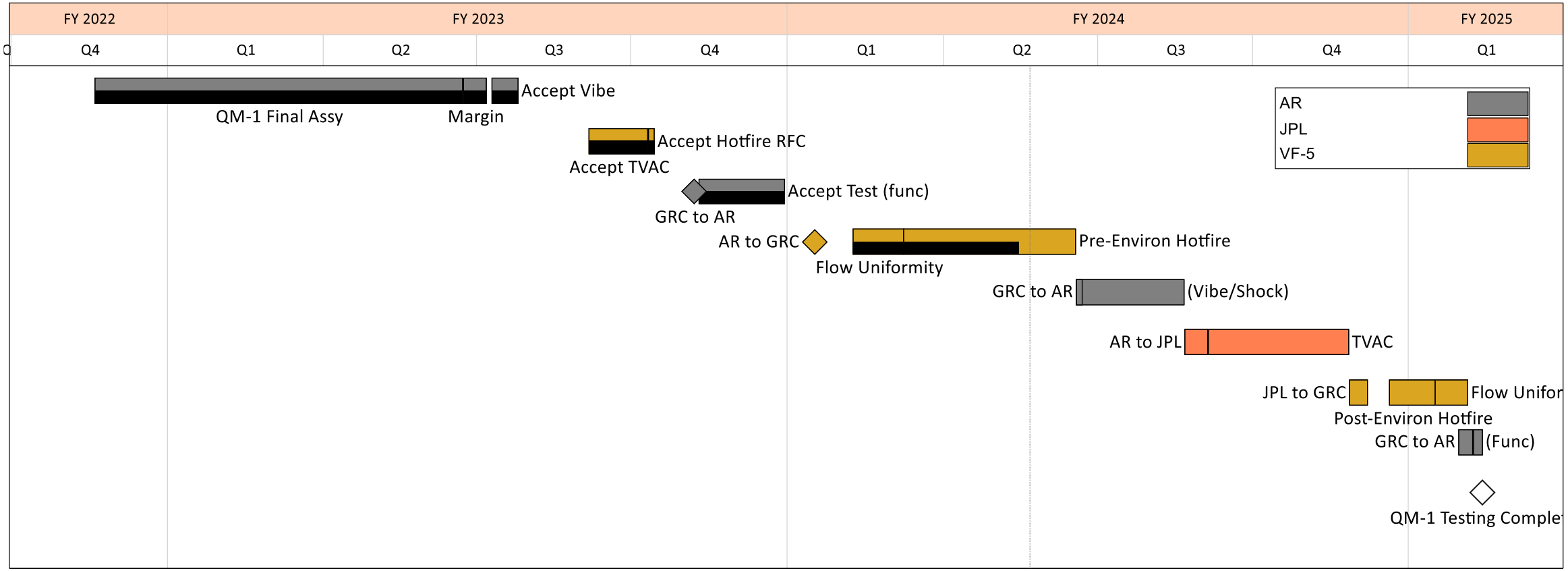


SEP Schedule 2024 02 21 v5 IMS.mpp

Snapshot Date: 2/21/2024

lifecycle7 F4 GW simple

QM-1 Testing Schedule



SEP Schedule 2024 02 21 v5 IMS.mpp

Snapshot Date: 2/21/2024

QM1 testing f9

Technical Issue – Harness Requirement Change

SEP Thrusters were designed with a harness that meets SEP requirements, but it was determined that Beyond Gravity's heritage gimbal design could not accommodate the SEP harness without substantial impacts (19 to 24-month PPE schedule impact)

- PPE/SEP/AR/MAXAR teams evaluated possible options based on four critical factors: bend radius, radiation hardness, temperature rating, and electrical performance