Development and Qualification Status of the Electric Propulsion Systems for the NASA PPE Mission and Gateway Program

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Space Policy Directive 1: To the Moon, then Mars

- Lead an innovative and sustainable program of exploration with commercial and international partners
- The United States will lead the return of humans to the Moon for long-term exploration and utilization, followed by human missions to Mars and other destinations

The Artemis Program

Artemis is the twin sister of Apollo and goddess of the Moon in Greek mythology. Now, she personifies our path to the Moon as the name of NASA’s program to return astronauts to the lunar surface by 2024.

Gateway Core Element of Artemis

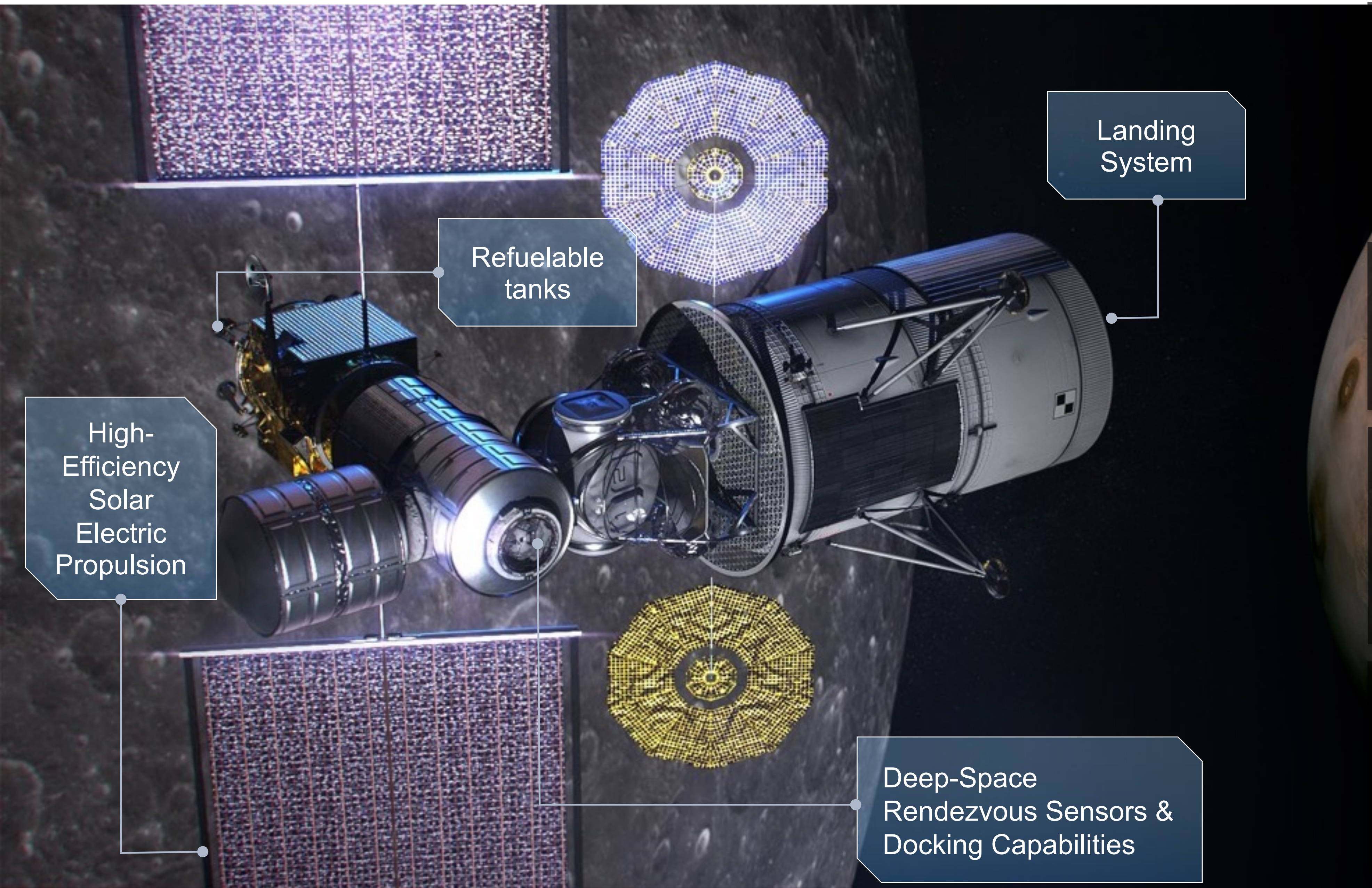
Gateway provides critical infrastructure required for operations on the lunar surface and that enables a sustained presence on and around the moon.

- Enables human crewed missions to cislunar space including capabilities that enable surface missions
- Provides aggregation point for the 2024 human mission to the lunar south sole
- Establishes a strategic presence around the moon adding resilience and robustness in the lunar architecture
- Demonstrates technologies that are enabling to lunar missions and that feed forward to Mars, and
- Provides a building block for future expanded capabilities on and around the Moon

Gateway is divided into two phases

- Phase 1 – Initial capability focused on support for human lunar surface operation
- Phase 2 – Sustaining capability for long-term lunar presence

Gateway Phase 1 Configuration



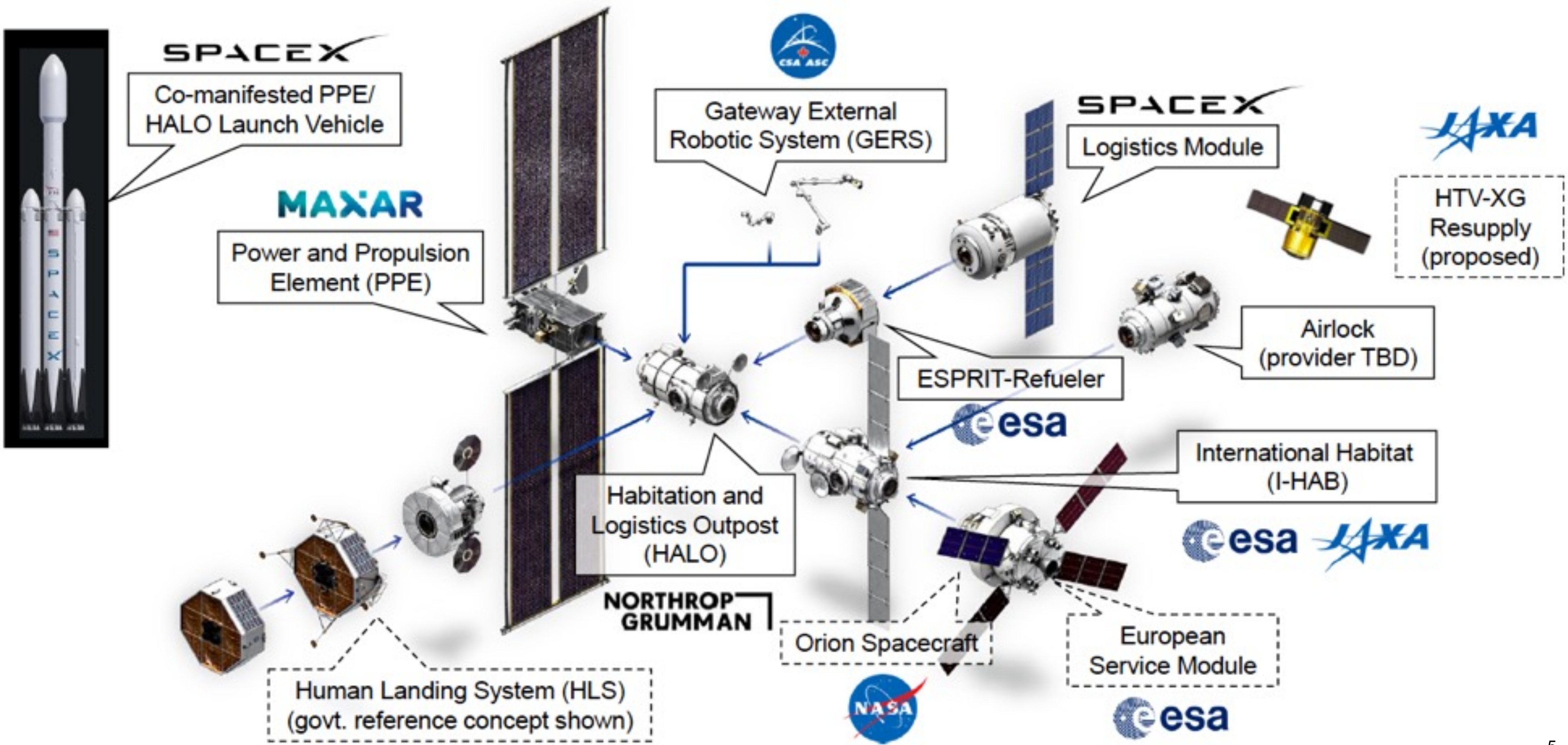
IN-SPACE POWER & PROPULSION:
- High-efficiency, long-life SEP extensible to Mars cargo missions
- Power enhancements feed forward to deep-space habitats and transit vehicles

LANDING SYSTEM DEPLOYMENT:
- Aggregation, automated docking, and deployment of Human Landing System from an orbiting platform

OPERATIONS:
- Extended operations in lunar orbit in preparation for missions farther into deep space
- High-efficiency propulsion demonstration for deep-space trajectory and navigation techniques

TRANSPORTATION & OPERATIONS:
- Common rendezvous sensors and docking systems for deep space
- Transfers and maneuvers in low-gravity regimes

Gateway Buildup and Configurations



Approach for Power and Propulsion Element

- PPE contract awarded to Maxar on May 24, 2019
  - Public-private partnership leveraging U.S. industry capabilities
  - Systems Requirement Review completed in Sept. 2019

NASA Demo Objectives

- Demonstrate in relevant space environment:
  - 50-kW class solar array and electric propulsion
  - Deployment and successful long-term, deep-space operation of high-power next-generation SEP system
  - High-data throughput uplink / downlink Comm system
  - PPE insertion into a crew-accessible Near Rectilinear Halo Orbit (NRHO)
- Obtain design, development, and flight demonstration data to determine acceptability of the Gateway PPE
- Observe and characterize performance of integrated end-to-end high-power SEP system

Maxar Demo Objectives

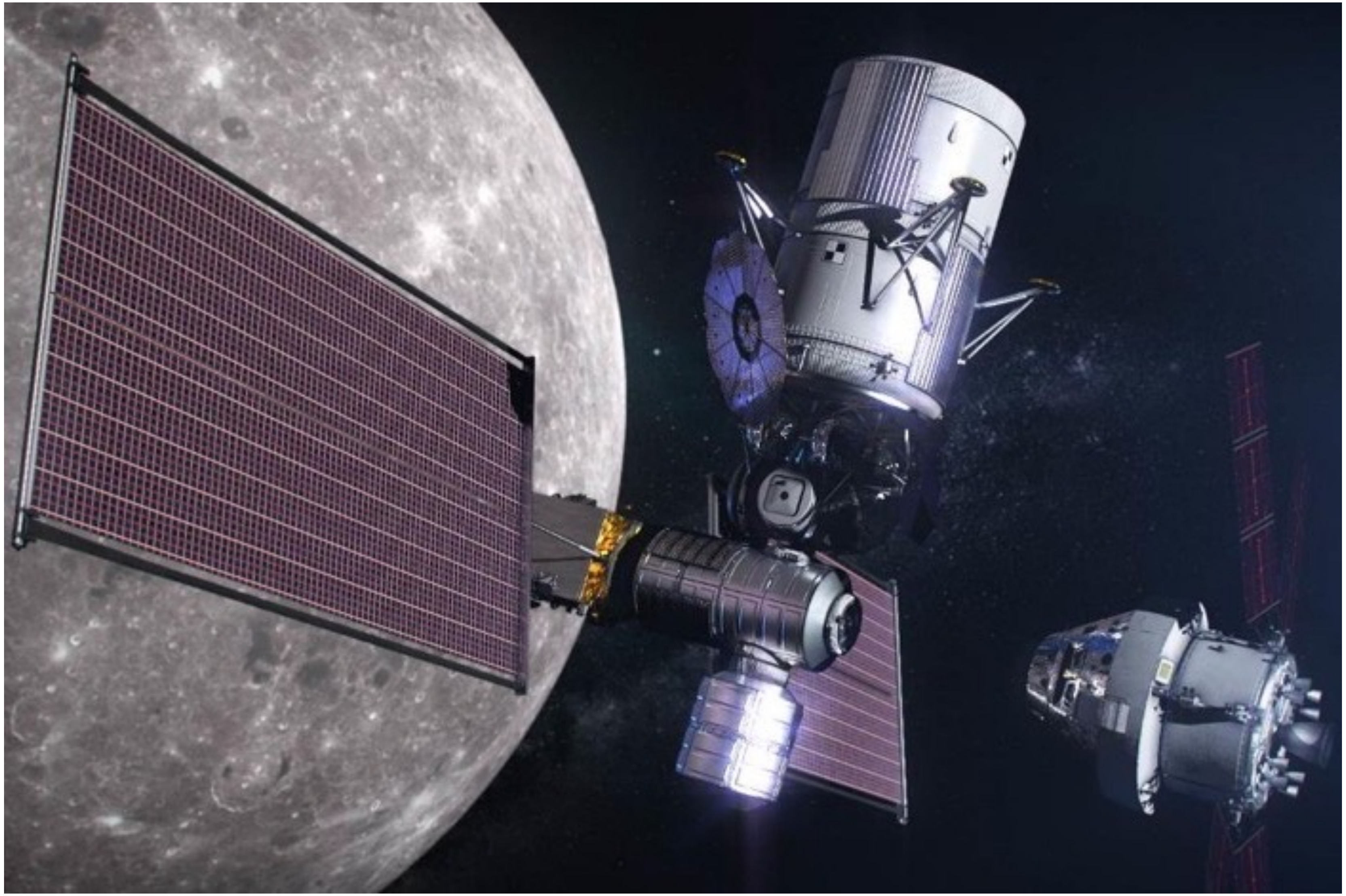
- Demonstrate Next-Generation Commercial Communications Capabilities
  - Demonstrate lunar lander communications relay services at the moon
  - Demonstrate high-power SEP capabilities for commercial communications satellites
- Demonstrate Next-Generation Commercial Space Transportation Capabilities
  - Demonstrate high-power SEP-enabled cargo transfer
  - Demonstrate heavy-lift launch vehicle capability
- Demonstrate Next-Generation Commercial Satellite Servicing Capabilities
  - Demonstrate detailed spacecraft inspection capability
  - Demonstrate xenon transfer capability

Co-Manifested Launch Decision

- In May 2020, NASA directed a Gateway significant change effecting the first two element of Gateway:
  - Power and Propulsion Element (PPE)
  - Habitation and Logistics Outpost (HALO)

- Instead of separately launching the two elements with on-orbit rendezvous, the decision was made to integrate the two spacecraft on the ground and launch as a Co-Manifested Vehicle (CMV)
  - Decision significantly impacted PPE design and implementation requiring a delta-SRR and delaying completion of PDR
  - CMV mass and launch apogee relative to PPE alone requires double the electric propulsion total impulse to deliver to Near-Rectilinear Halo Orbit (NRHO)
    - Increased xenon storage capacity to 2770 kg
    - Increase from 2 to 3 Advanced Electric Propulsion System (AEPS) thrusters

Gateway Phase 1 Status



Gateway Power and Propulsion Element

- Co-Manifested Vehicle (CMV) scheduled to launch in late 2024
  - Power and Propulsion Element (PPE) provided by Maxar Technologies
    - Preliminary Design Complete (CDR planned in 2023)
  - Habitation and Logistics Outpost (HALO) provided by Northrop Grumman
    - Preliminary Design Complete (CDR planned for fall 2022)
- Human Lander System awarded to SpaceX in April 2021
  - Second award planned in 2023
- Logistics Element
  - First award to SpaceX in March 2020

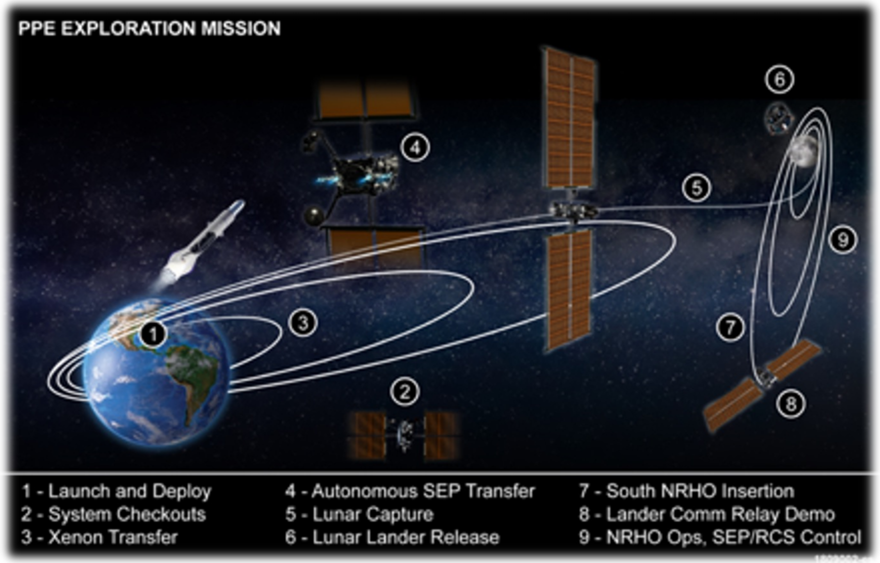
PPE Spacecraft Overview (Post CMV Change)

Leverage heritage reliability, proven development approach, and the scalable 1300-class platform as the basis for a PPE

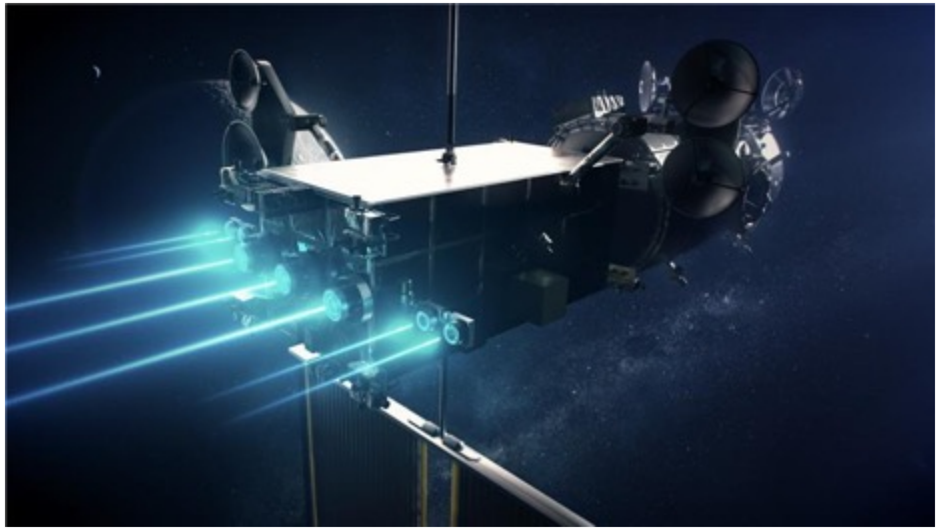
- **Power** – 60 kW+ provided by Roll Out Solar Array (ROSA) and Maxar's 1300 commercial power subsystem
- **Propulsion** – Combined 60 kW of EP spread over 7 EP strings that leverage NASA development of 12 kW Electric Propulsion (EP), and internal Maxar advanced 6 kW EP development, with Maxar expertise in system accommodation of EP elements
- **Communications** – Ka-band relay from Lunar vicinity to Earth, accommodations for future optical communications payloads
- **Guidance Navigation and Control** – Utilize proven approaches for station keeping, momentum management, and autonomous low thrust electric orbit transfer

PPE preliminary design completed in Nov. 2021

- PPE spacecraft critical design review in 2023



PPE Mission – launch through NRHO insertion


Maxar PPE Design Concept

PPE Ion Propulsion Subsystem

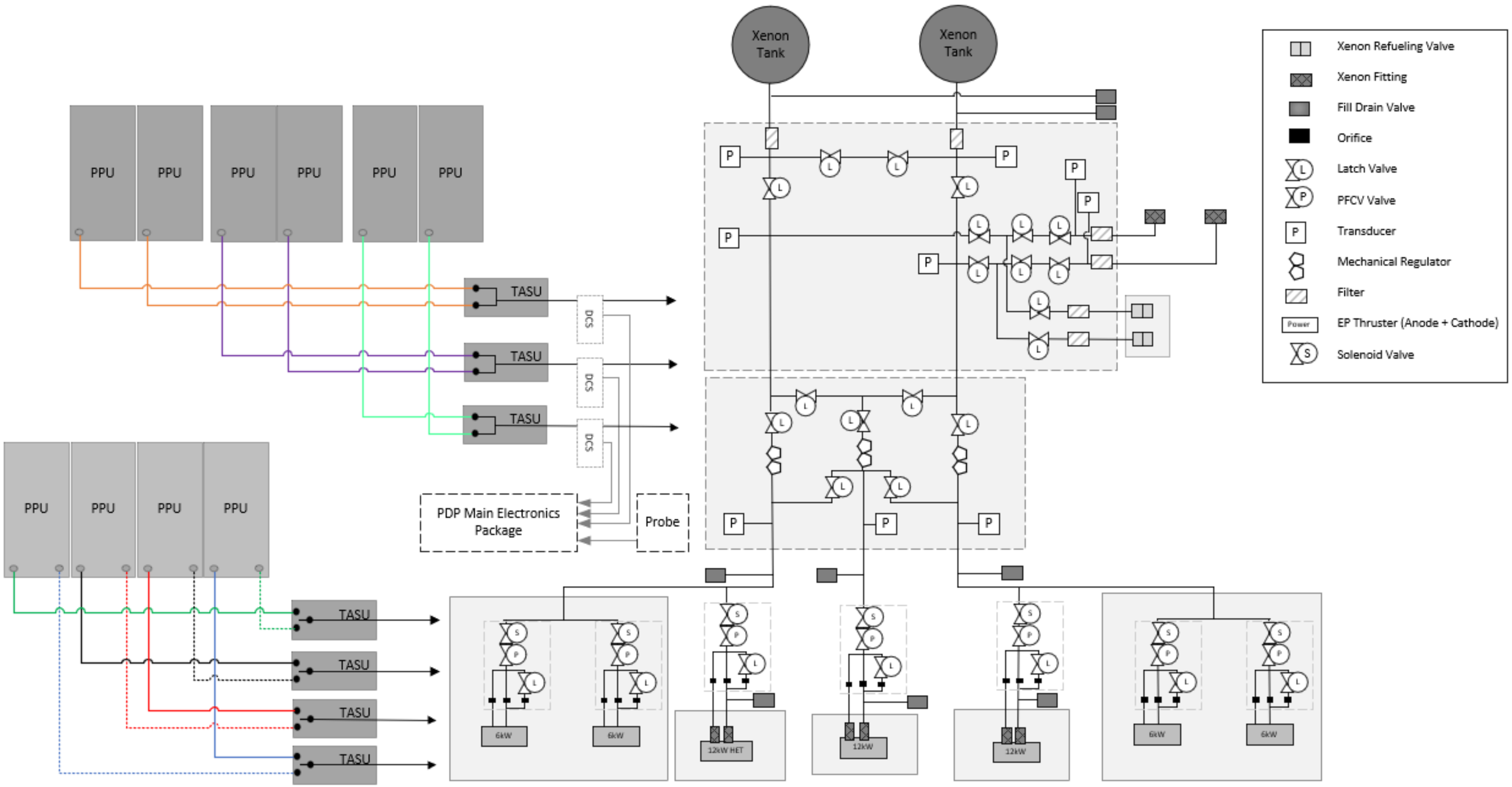
Leverage Maxar SEP expertise having manufactured and flown 41 satellites equipped with 164 Hall thrusters and accumulated more than 180,000 hours of on-orbit firing time

- **Three 12 kW EP Strings – AEPS Hall Thruster provided by Aerojet Rocketdyne, 12kW PPU provided by Maxar**
  - AEPS thruster provided as GFE under the AEPS Contract
- **Four 6 kW EP String – BHT-6000 Hall Thruster provided by Busek, 6 kW PPU provided by Maxar**
  - Developed through Maxar-Busek internal investment and NASA Tipping Point Contract
- **Two 825 L Xenon Tanks – Provided by NuSpace**
  - Capability to store 2770 kg xenon
- **On-Orbit Propellant Refueling** – refueling interfaces for xenon and bi-propellant
  - Government-furnished NASA Docking System with 2 sets of xenon and bi-propellant ports mounted on the HALO spacecraft that is part of the co-manifested vehicle

	Electric Propulsion	Chemical Propulsion
Post-Launch		
Detumble		X
First Rev Activities		X
EOR		
Primary Propulsion	X	
Momentum Management	(during maneuvers)	
Lunar Capture	X	(if needed)
Lunar Operations		
Orbit Transfers, Deorbit	X	
Orbit Maintenance	X	
Momentum Management	(during maneuvers)	X (if high moment of inertia or faster slews)
NRHO Re-orientation		
Off-Nominal Scenarios		
Spacecraft Safing		X
Momentum Dumping		X

PPE Mission Ion Propulsion System Functional Uses

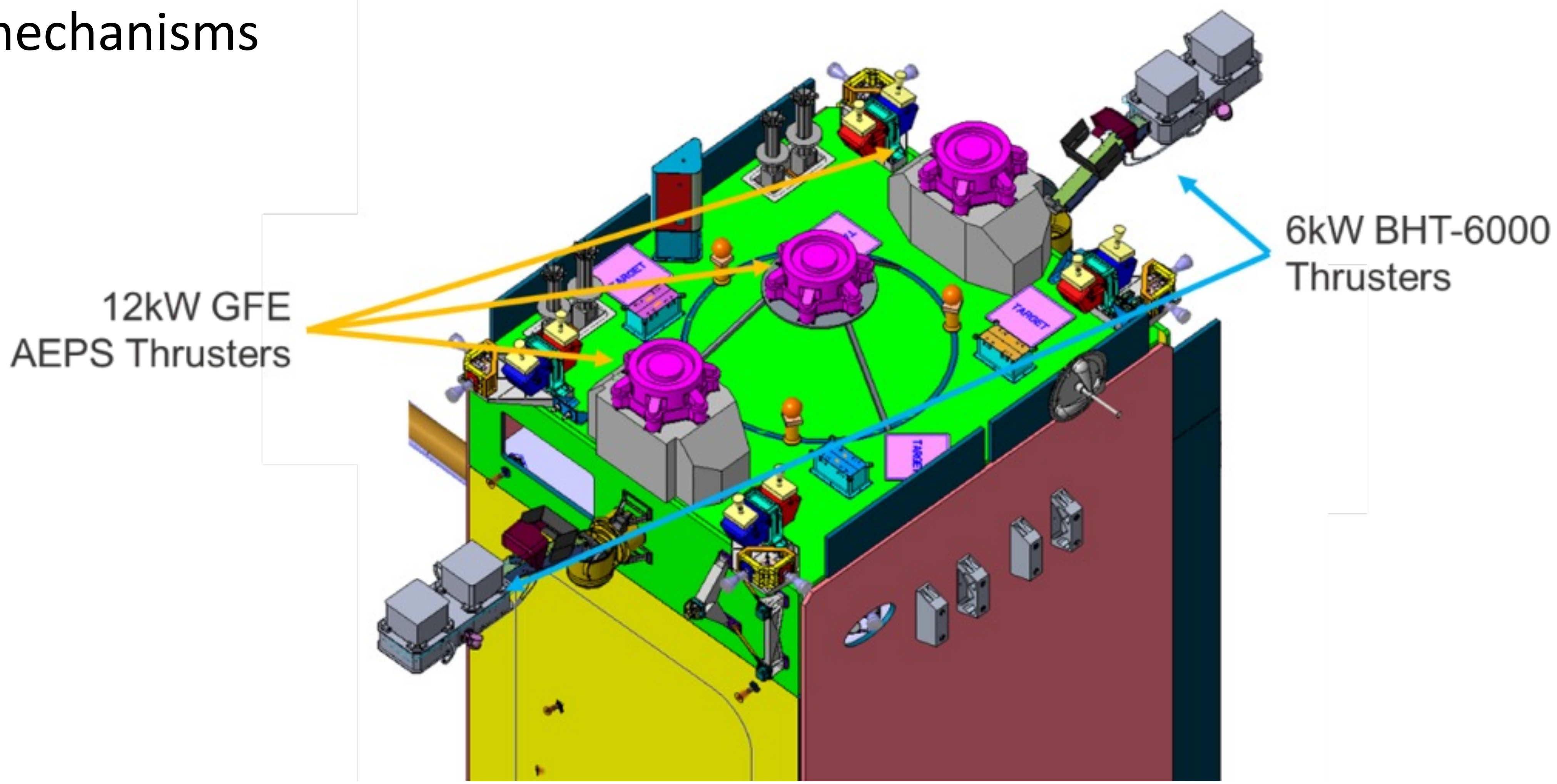
PPE Ion Propulsion Subsystem



PPE electric propulsion subsystem block diagram

PPE Electric Propulsion Thruster Locations

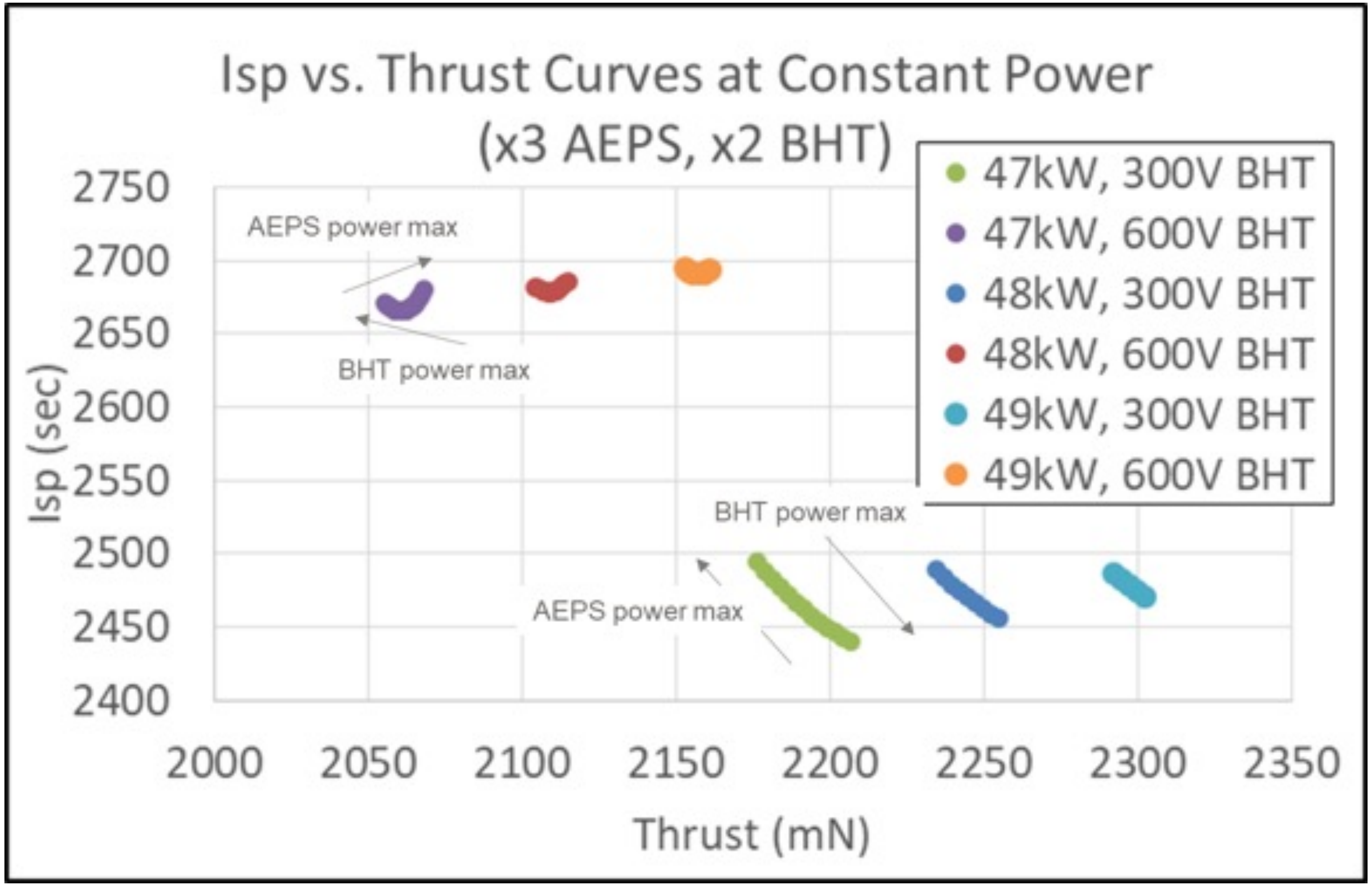
- Two gimballed and one hard-mounted AEPS thrusters
- BHT-6000 thruster pairs mounted on large range-of-motion gimbal mechanisms



PPE Spacecraft Preliminary Design - Aft Deck

PPE IPS Capability and Performance

- PPE IPS Capabilities
  - 60 kW combined thruster discharge power capability (subject to spacecraft power and thermal constraints)
  - Greater than 150 MN-s flight-allowable electric propulsion total impulse capability
  - Dissimilar redundancy and single fault tolerance to loss of a single EP string
  - Variable power, thrust, and specific impulse capability

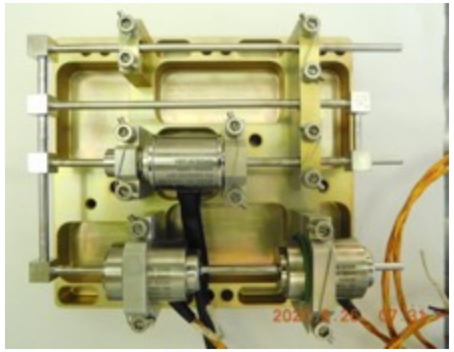


Subsystem Preliminary Performance Estimates for CMV Lunar Transit

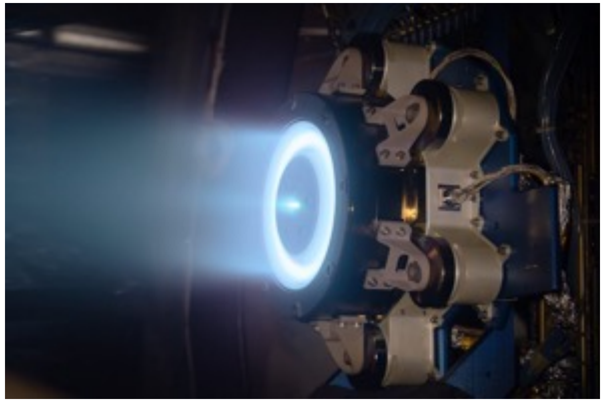
12 kW EP Strings

12 kW EP string operates at 600 V over 9 – 12 kW discharge power

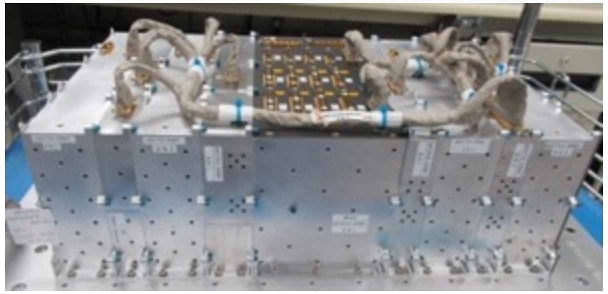
- **Aerojet AEPS Thruster**
  - Provided as GFE under AEPS contract
  - Completed CDR and into Qualification and Flight thruster production
- **Maxar 12 kW PPUs**
  - Comprised of two 6 kW PPU’s with anode outputs tied in parallel
  - Controls XFC solenoid and PFCV valves
  - Completed PDR with CDR planned in late 2022
- **Maxar 12 kW Thruster Auxiliary Switching Unit (TASU)**
  - Combines the 6kW PPU outputs to power AEPS thruster
  - Contains power electronics output filter
  - Completed PDR with CDR planned in late 2022
- **Moog XFC**
  - Qualified up to 23 mg/s flow rates and will be flown on Psyche spacecraft
  - Flight units in production
- **Ruag dual-axis thruster gimbal**
  - Provides +/-30 degree pointing range
  - Completed CDR with flight units in production



Moog XFC

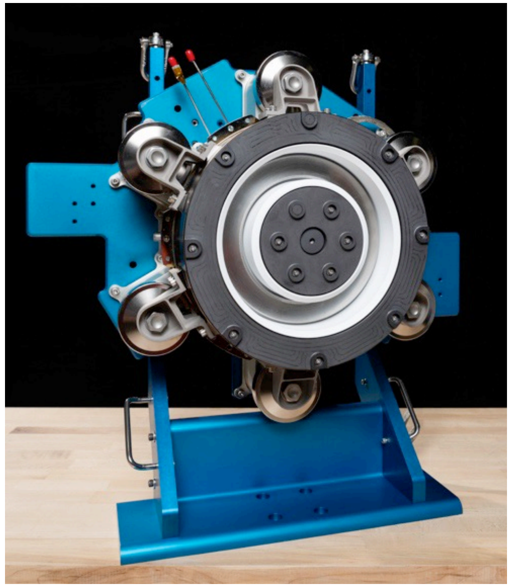


Aerojet 12kW AEPS Thruster



Maxar 12kW PPU

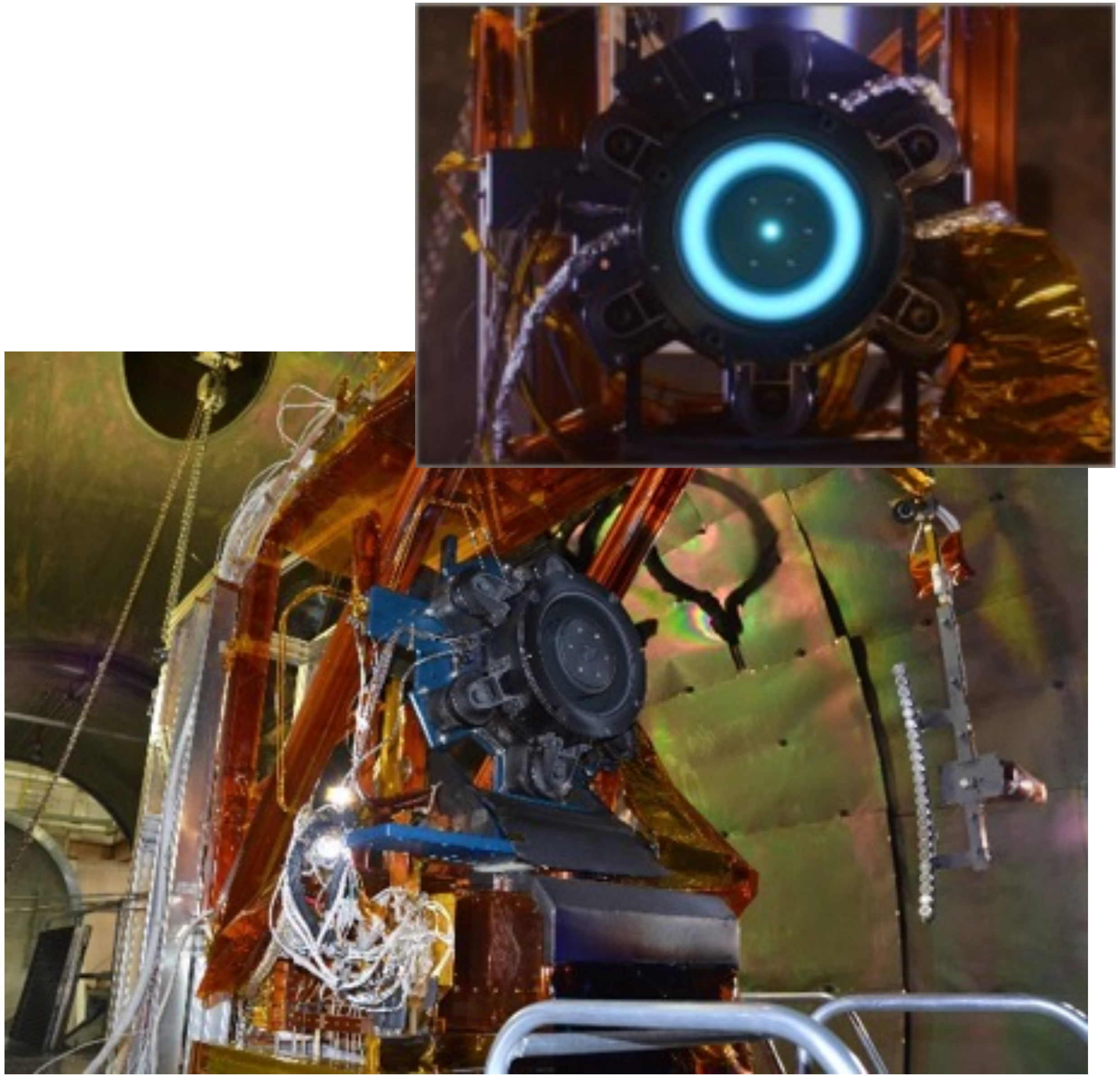
Maxar 12kW TASU



Aerojet 12kW AEPS Thruster

12 kW EP String Integrated Testing

- 12kW EP string integrated testing at NASA GRC
  - Ensure compatibility of 12kW EP string hardware, especially critical since primary component original designs not specifically intended to operate together
  - Verified the functionality of PPE's electric propulsion hardware working together in both nominal and off-nominal conditions
  - Showed that the 12kW thruster performs the same with the PPU/TASU as on lab supplies allowing the team to confidently move towards component and spacecraft CDRs
  - A 12kW Phase 2 test is planned for late 2022

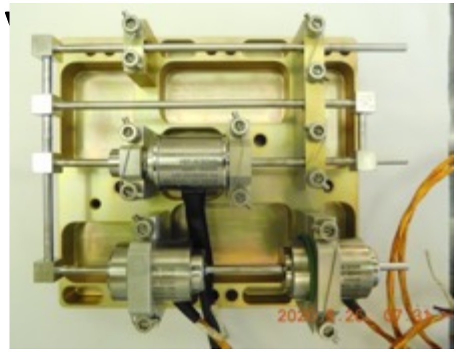


AEPS ETU-2 Thruster in NASA GRC VF-6 during 12kW Integrated String Testing.

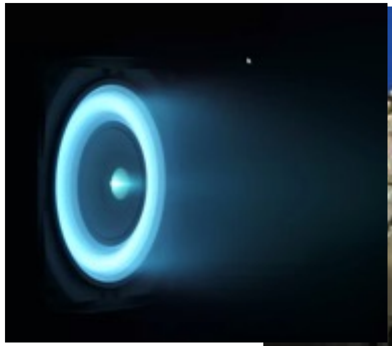
6 kW EP Strings

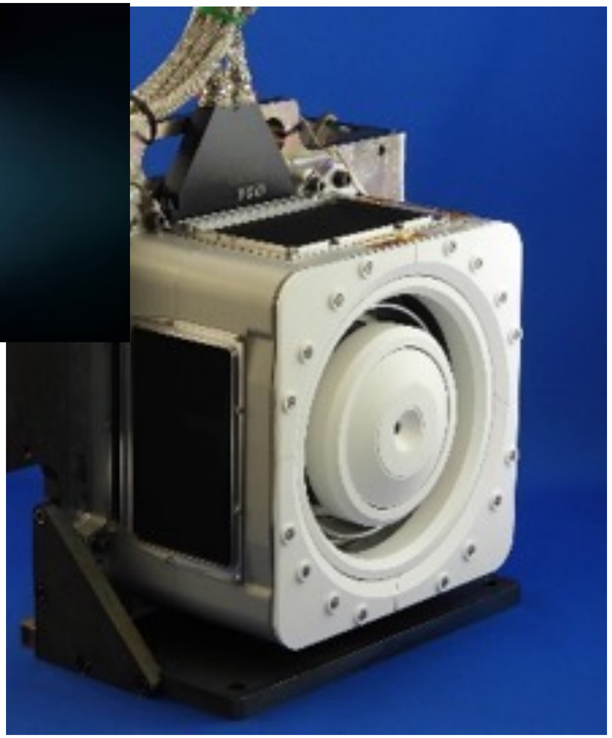
Dual-mode 6 kW EP string operates at 300 thrust/power) and 600 V (high Isp/power)

- **Busek BHT-6000 Thruster**
  - BHT-6000 is a modification of the BHT-5000 thruster
  - NASA Tipping Point contract upgraded thruster power , thrust, and specific impulse
  - Completed CDR and into Qualification
- **Maxar 6 kW PPUs**
  - An extension of the 4.5 kW SPT-140 PPUs based on 300 V, 5 A Zero-Voltage Switching (ZVS) trays
  - Includes relays to place the 4 discharge trays in parallel or series
  - Controls XFC solenoid and PFCV valves
  - Completed CDR and into Qualification hardware build
- **Moog XFC**
  - Qualified up to 23 mg/s flow rates and will be flown on Psyche spacecraft
  - Mounts on DSM to minimize line length to thruster
  - Flight units in production
- **Maxar Dual-axis SEP Module (DSM) Thruster**
  - Provides 100 degree rotation in both axes for 6 kW EP string pairs
  - Modified version of the DSM flown with pairs of SPT-140 thrusters
  - Targeting CDR in late 2022

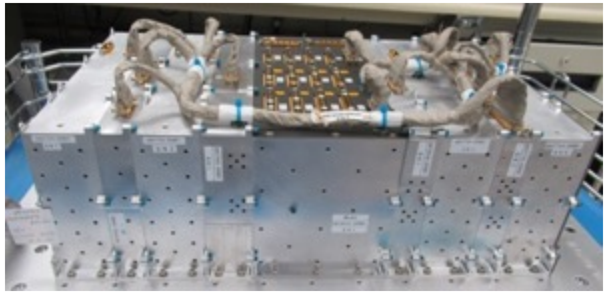


Moog XFC



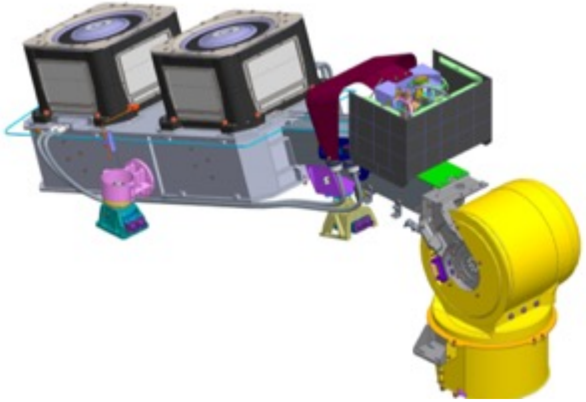


BHT-6000 Thruster Operating at 6 kW, 600 V



Maxar 12kW PPU

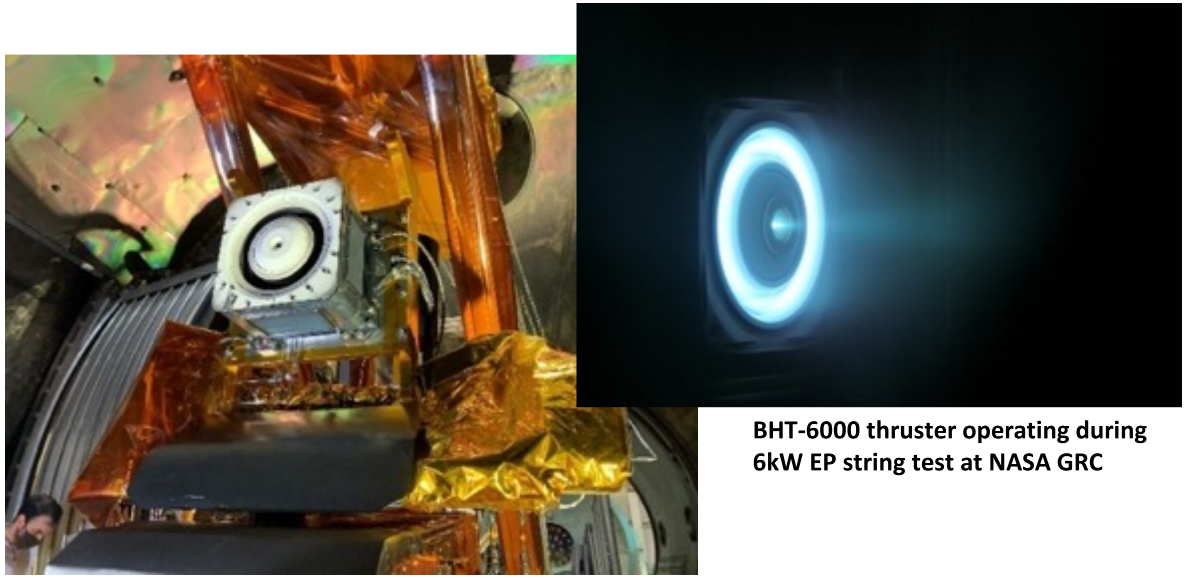
Maxar 12kW TASU



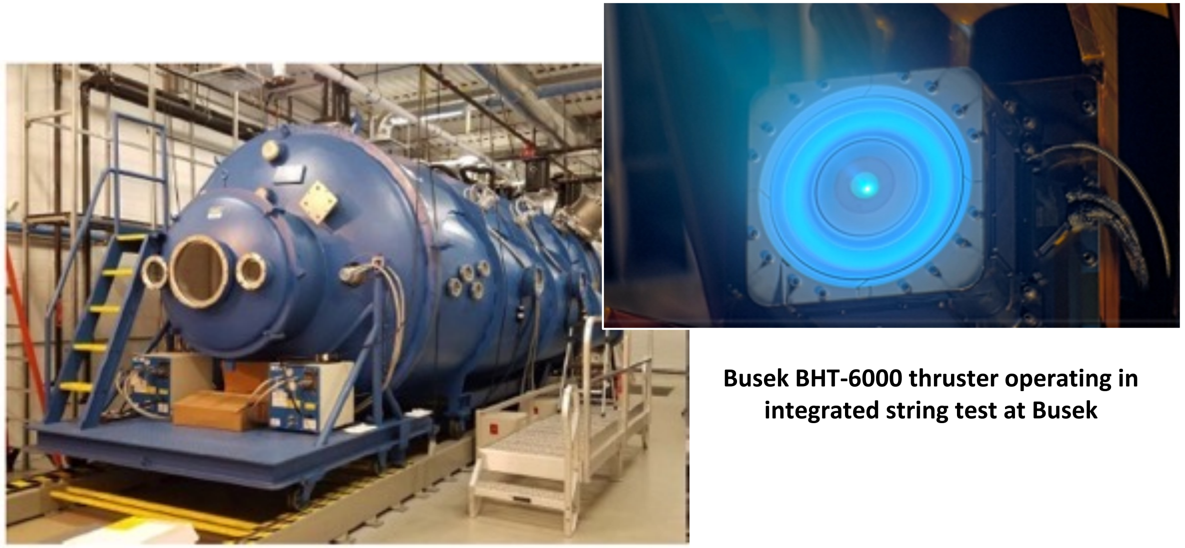
Preliminary DSM-6000

6 kW EP Integrated Testing

- Multiple 6kW EP string integrated tests have been conducted at Busek and one at NASA GRC
  - Verified the functionality of PPE’s 6kW electric propulsion hardware working together in both nominal and off-nominal conditions
  - Demonstrated the ability to operate in dual 300V and 600V modes
  - Validate string operation in stressed conditions
  - Validate responses in fault conditions
  - Characterize the integrated string (e.g., inrush current, control logic and stability, etc.).
  - An additional 6kW integrated string test with the final flight-like configuration hardware is planned in 2022.



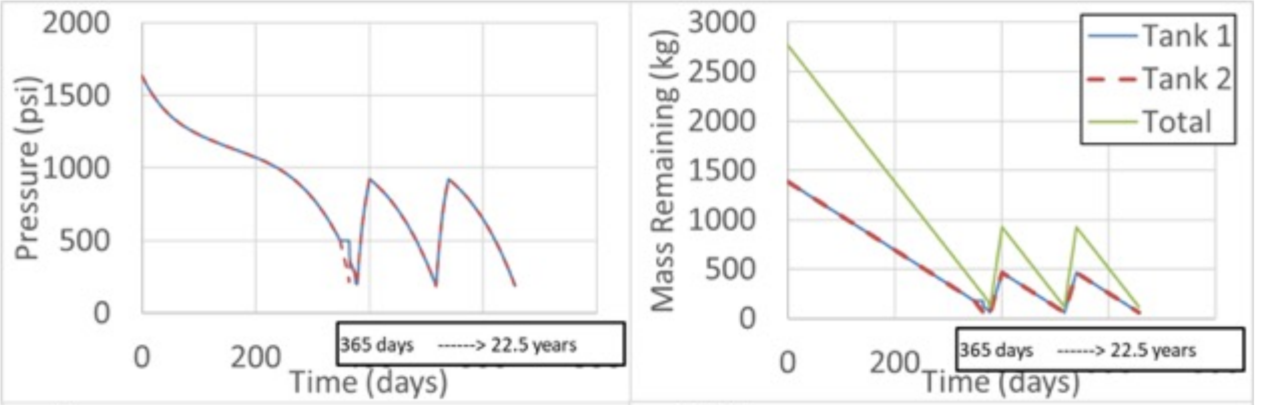
BHT-6000 thruster operating during 6kW EP string test at NASA GRC

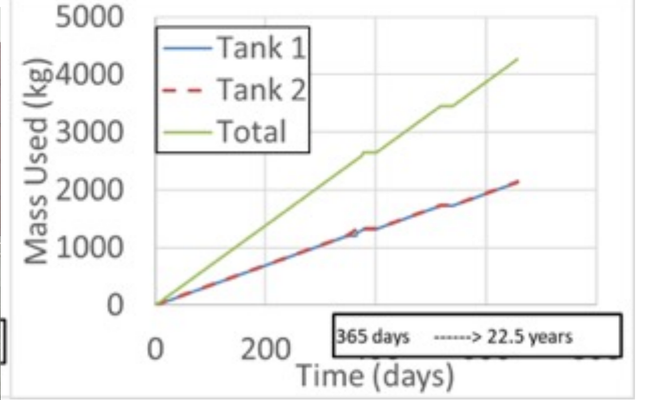


Busek BHT-6000 thruster operating in integrated string test at Busek

Xenon Storage and Refueling Capabilities

- PPE xenon storage increased to 2770 kg of xenon after co-manifested direction change
  - Approximately 2500 kg used for CMV lunar transit
- To meet program need for Gateway stack to perform two cis-lunar transfers requires PPE xenon refueling
  - Preliminary analysis assumed two 800 kg xenon transfers (max 2,000 kg xenon refueling total)
    - ESA-provided ESPRIT Refueling Module (ERM) will provide first transfer of 800 kg
    - TBD visiting vehicle additional refueling through ERM via second fluid transfer docking interface on ERM



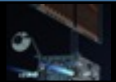


Xenon usage and remaining profiles during PPE mission

NuSpace 825 L COPV

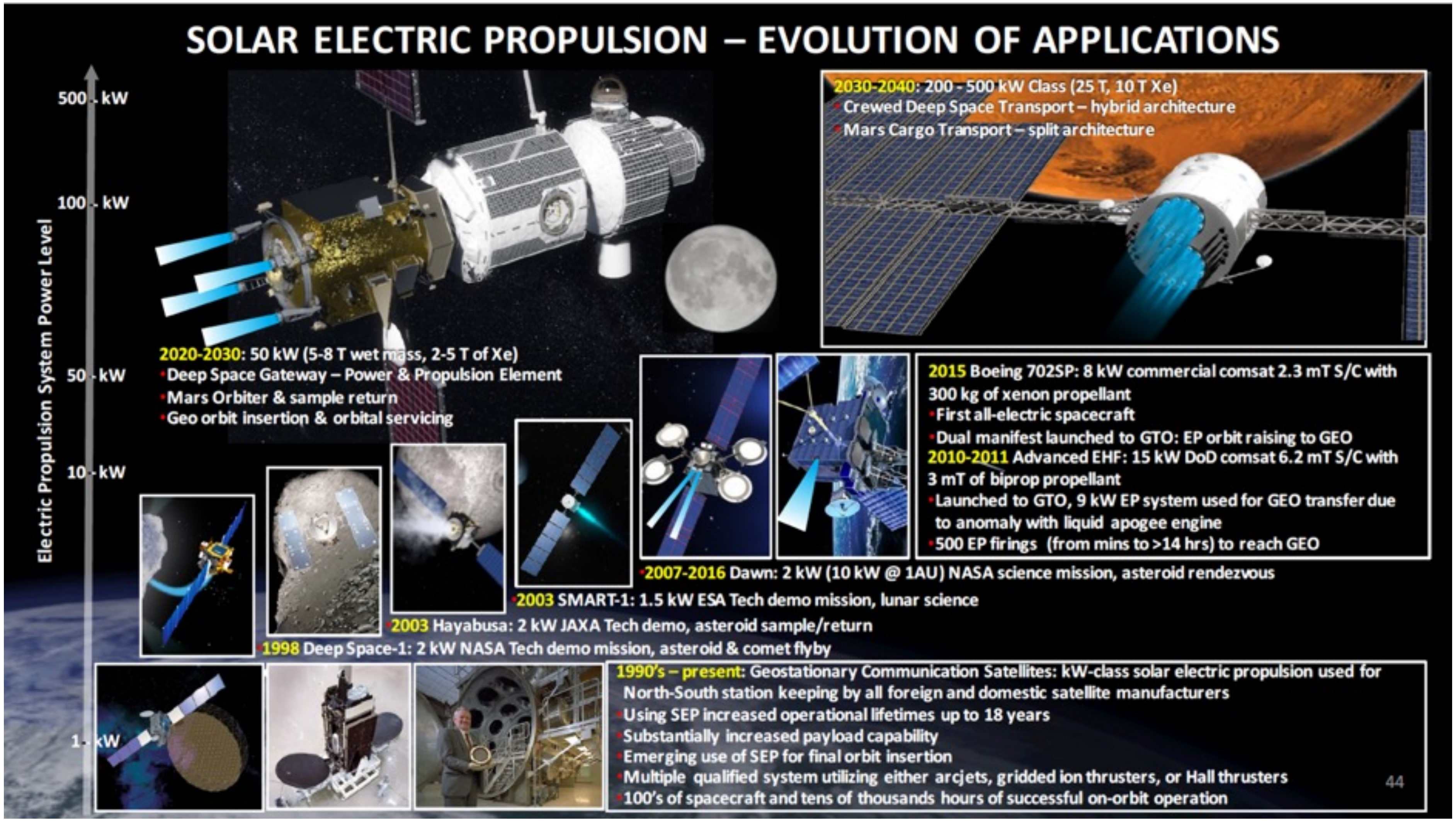
Conclusions

- NASA is embarking on a new and exciting era of human exploration to the Moon and its vicinity in the Artemis program
  - NASA is developing the lunar Gateway, an orbiting platform in Near Rectilinear Halo Orbit (NRHO) about the Moon to support initial human landing on the moon and sustained lunar operations
- A significant change to a co-manifested launch of the first two Gateway modules (PPE and HALO) in 2024 and the transfer of this large payload to cislunar orbit will mark a significant milestone in electric propulsion
  - The co-manifest change was a significant impact to PPE resulting in roughly doubling the required EP capability for the lunar transit to NRHO that required an increase in xenon storage capability and the addition of a 3rd AEPS thruster (resulting in 7 EP thrusters on PPE)
- PPE provides unparalleled electric propulsion capability (60 kW and >150 MN-s) and the spacecraft has completed its preliminary design
  - Planned PPE spacecraft CDR in 2023
- The majority of the PPE IPS components have completed CDR and are well into qualification and flight productions efforts including both the 12kW AEPS and 6kW BHT-6000 thrusters.
- Multiple integrated EP string tests have been completed and additional integration tests are planned to ensure successful demonstration and operation on PPE in support of the Artemis program




WE GO

Evolution of Electric Propulsion



NASA Human Exploration Strategic Principles

STRATEGIC PRINCIPLES FOR SUSTAINABLE EXPLORATION

- **FISCAL REALISM**
  Implementable in the near-term with the buying power of current budgets and in the longer term with budgets commensurate with economic growth;

- **SCIENTIFIC EXPLORATION**
  Exploration enables science and science enables exploration; leveraging scientific expertise for human exploration of the solar system.

- **TECHNOLOGY PULL AND PUSH**
  Application of high TRL technologies for near term missions, while focusing sustained investments on technologies and capabilities to address the challenges of future missions;

- **GRADUAL BUILD UP OF CAPABILITY**
  Near-term mission opportunities with a defined cadence of compelling and integrated human and robotic missions, providing for an incremental buildup of capabilities for more complex missions over time;

- **ECONOMIC OPPORTUNITY**
  Opportunities for U.S. commercial business to further enhance their experience and business base;

- **ARCHITECTURE OPENNESS AND RESILIENCE**
  Resilient architecture featuring multi-use, evolvable space infrastructure, minimizing unique developments, with each mission leaving something behind to support subsequent missions;

- **GLOBAL COLLABORATION AND LEADERSHIP**
  Substantial new international and commercial partnerships, leveraging current International Space Station partnerships and building new cooperative ventures for exploration; and

- **CONTINUITY OF HUMAN SPACEFLIGHT**
  Uninterrupted expansion of human presence into the solar system by establishing a regular cadence of crewed missions to cis-lunar space during ISS lifetime.

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