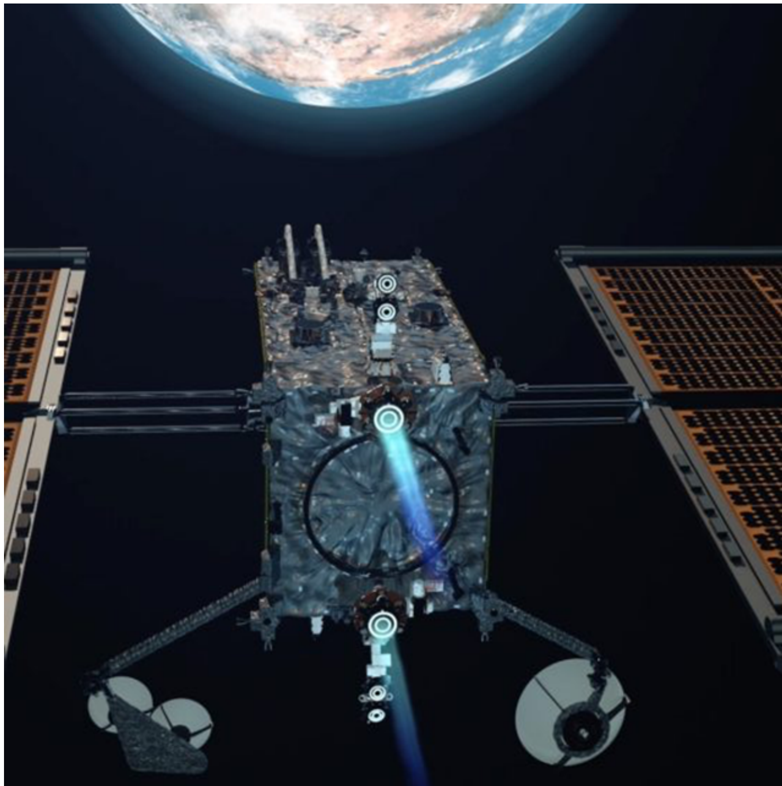

The Application of Advanced Electric Propulsion on the NASA Power and Propulsion Element (PPE)

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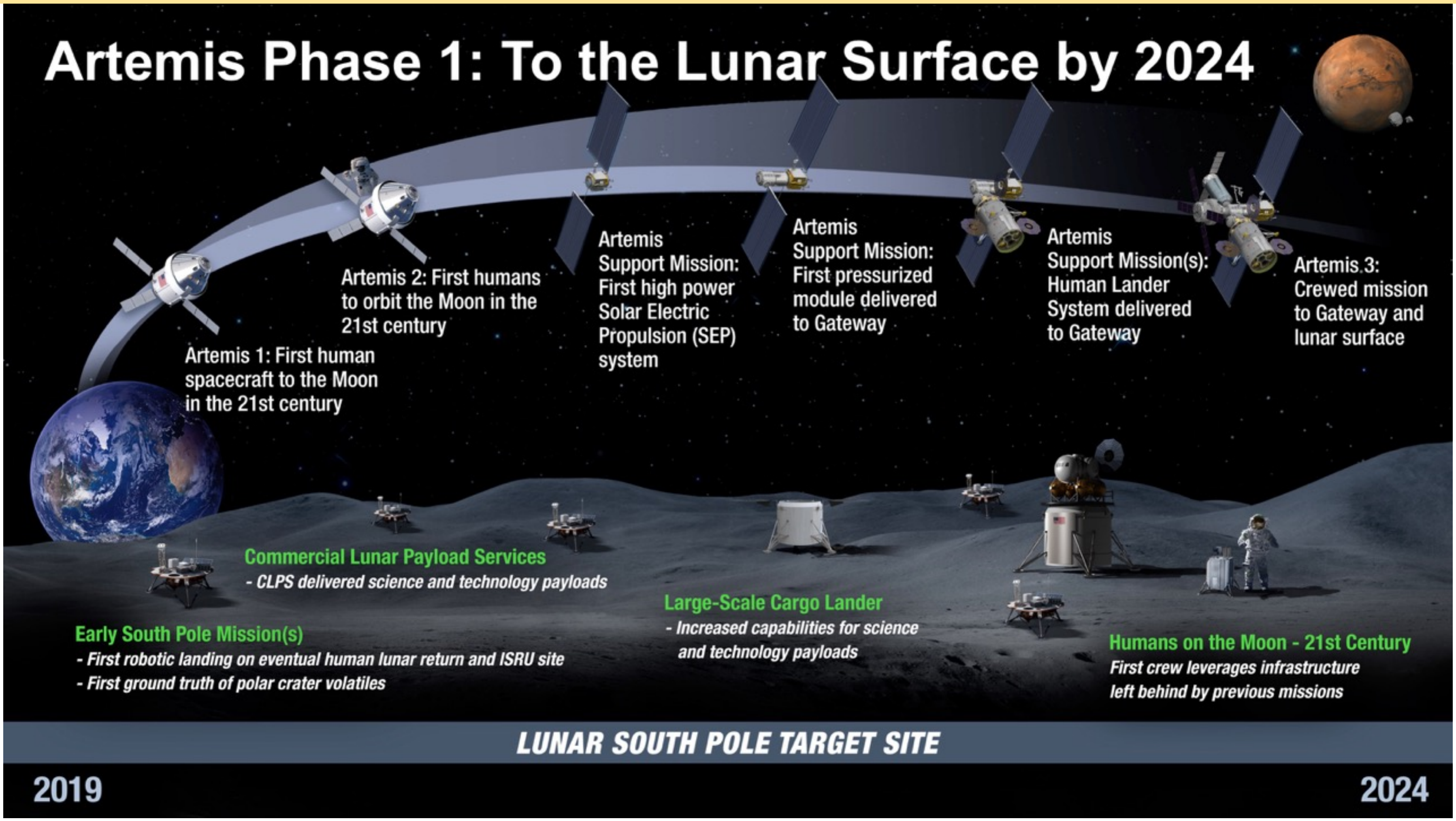
Space Policy Directive 1: To the Moon, then Mars

- 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

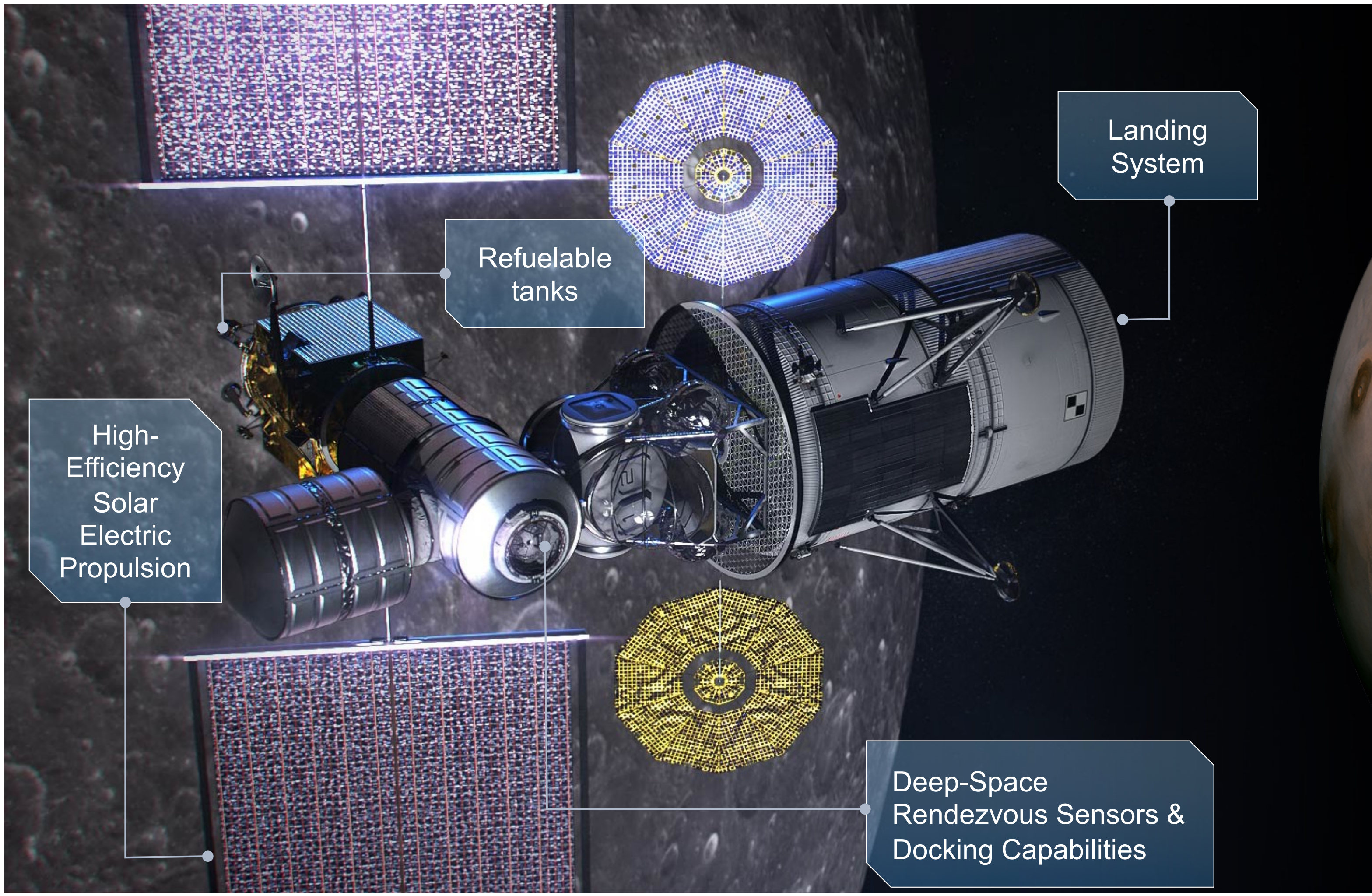
The Artemis Program

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.

The Artemis Program



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

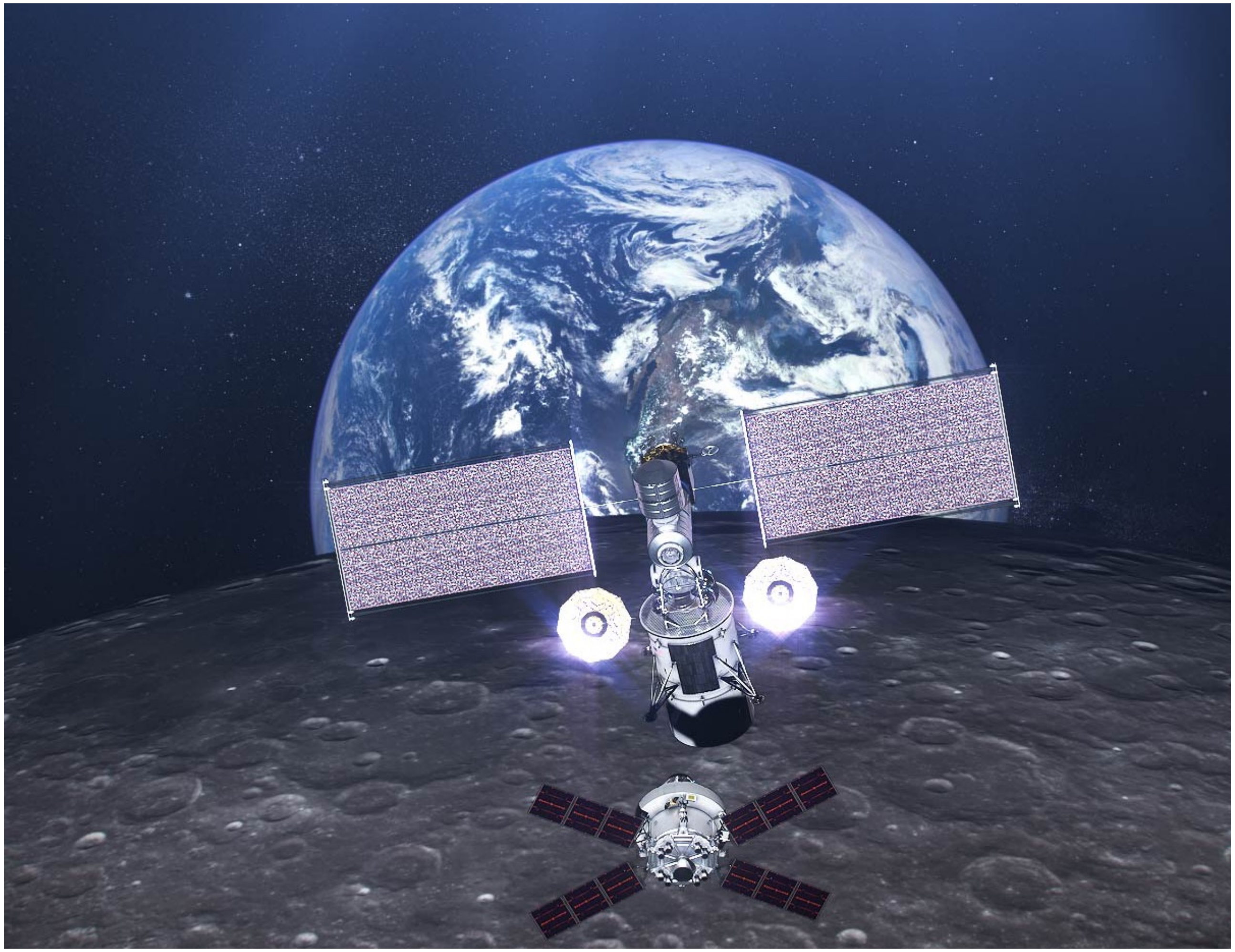
OPERATIONS:

- 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 Phase 1



Gateway Power and Propulsion Element

Gateway Phase 1 Status

- Power and Propulsion Element (PPE)
  - Based on a commercial satellite bus
  - Recently awarded to Maxar Technologies
  - Scheduled to launch in 2022
- Habitation and Logistics Outpost (HALO)
  - Recently awarded to Northrop Grumman
  - Scheduled to launch in late 2023
- Logistics Element
  - Being modeled after ISS Commercial Resupply Services
  - Scheduled to launch in 2024, just ahead of Orion crewed flight, Artemis 3

Approach for Power and Propulsion Element

- NASA and its PPE partner Maxar began upon contract award May 24, 2019
  - Public-private partnership leveraging U.S. industry capabilities
  - Target launch date December 2022, followed by Maxar-owned demonstration up to 1 year
  - Includes contract option to acquire residual asset (PPE) for NASA use, after demonstration completion

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

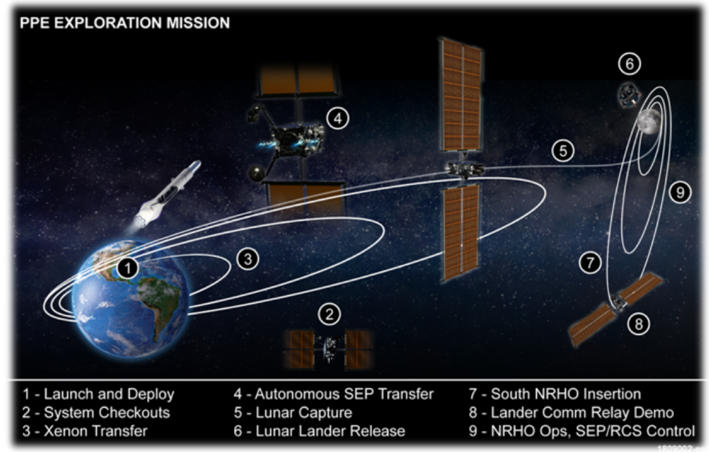
Maxar Demo Objectives

- 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

Summary of Maxar's PPE approach

Leverage heritage reliability, proven development approach, and the scalable 1300-class platform as the basis for a PPE demonstration mission culminating with delivery of PPE to NASA in the target NRHO

- **Power** – 60 kW+ provided by Roll Out Solar Array (ROSA) and Maxar's 1300 commercial power subsystem
- **Propulsion** – Combined 49 kW of EP spread over 6 EP strings that leverage NASA development of 12.5 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
- **Payload Transfer** – 1000 kg for lunar lander or science instruments



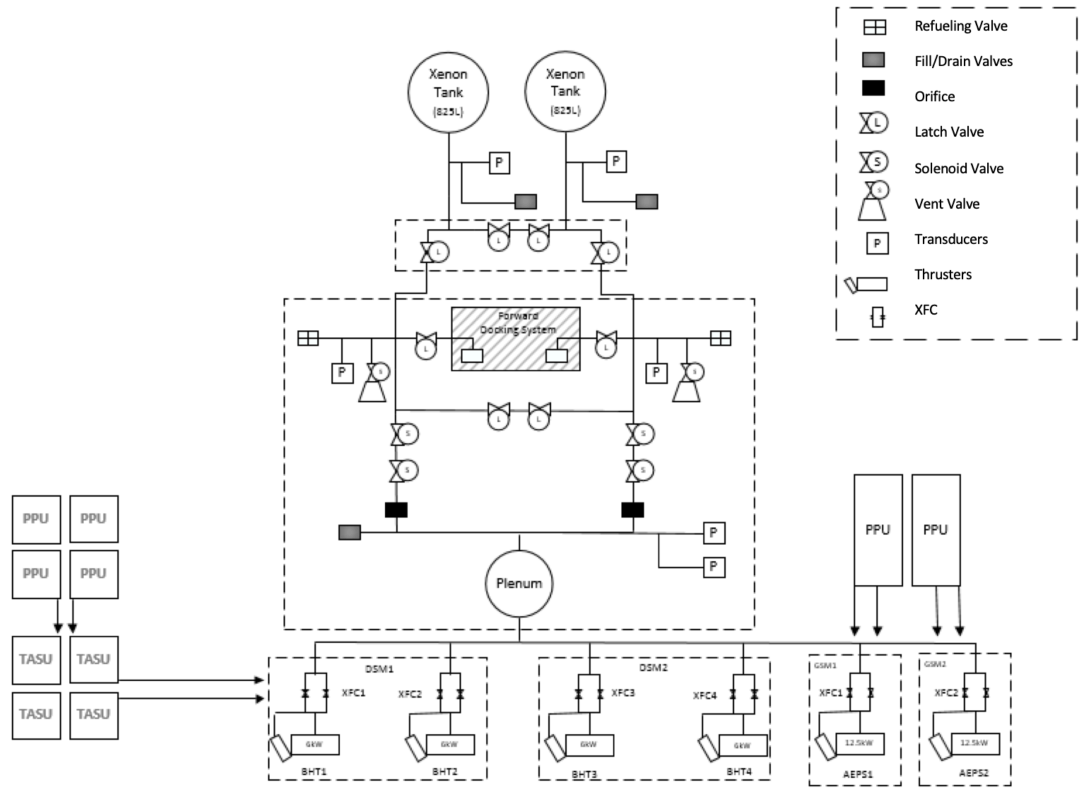
Maxar PPE Concept Demonstration Mission Overview

Maxar PPE Design Concept

PPE Ion Propulsion Subsystem

Leverage Maxar SEP expertise having manufactured and flown 38 satellites equipped with 152 Hall thrusters and accumulated more than 100,000 hours of on-orbit firing time

- **Two 12.5 kW AEPS EP Strings** – Provided by Aerojet Rocketdyne
  - Under development through the AEPS Contract
- **Four 6 kW EP String – BHT-6000 Hall Thruster provided by Busek, 6 kW PPU provided by Maxar**
  - Under development through Maxar-Busek internal investment and NASA Tipping Point Contract
- **Two 825 L Xenon Tanks – Provided by Keystone**
  - Capability to store 2500 kg xenon at pressures below 2000 psi and temperatures below 55 C
- **On-Orbit Propellant Refueling** – Two dissimilar refueling interfaces for xenon and hydrazine
  - Government-furnished NASA Docking System with 2 xenon and 2 hydrazine ports interfaces with next module in the Gateway
  - Commercial docking berths and refueling valves based on Restore-L or Robotic Servicing of Geosynchronous Satellites (RSGS) type refueling

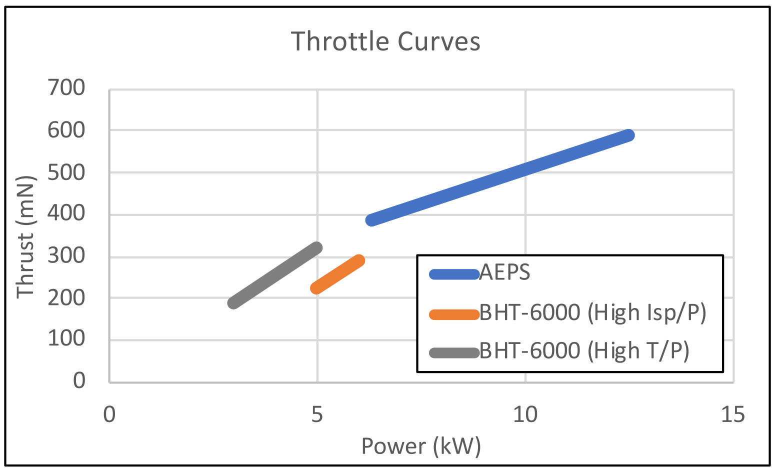


Maxar proposal baseline PPE electric propulsion subsystem block diagram

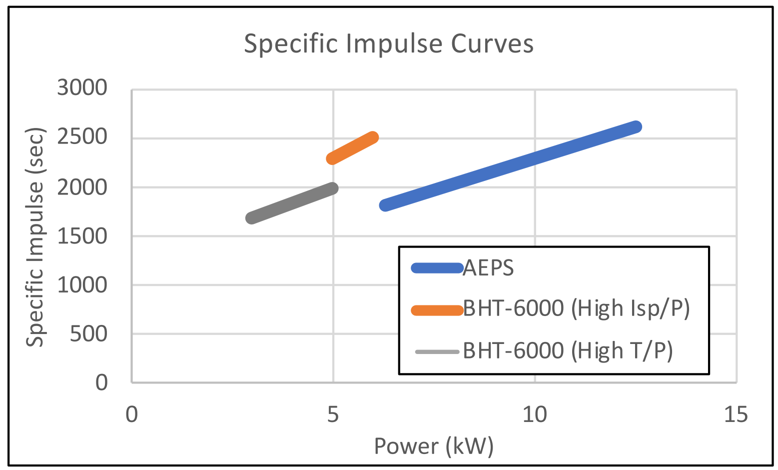
PPE Ion Propulsion Subsystem Performance

- Subsystem Preliminary Performance Estimates for 5 Electric-Orbit Raise (EOR) Configurations

Configuration	Thruster Power (kW)	Thrust (N)	Flow Rate (mg/sec)	Mass Used / Day (kg)	Specific Impulse (sec)
x2 AEPS	25	1.18	46	4.0	2620
x2 BHT-6000	12	0.58	24	2.0	2505
x4 BHT-6000	24	1.16	47	4.1	2505
x1 AEPS, x2 BHT-6000	24.5	1.17	47	4.0	2560
x2 AEPS, x4 BHT-6000	49	2.34	93	8.0	2560



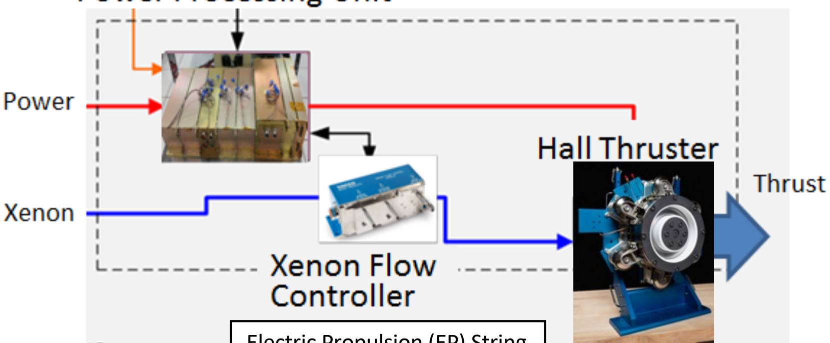
Preliminary AEPS and 6 kW EP Strings Performance Assumptions



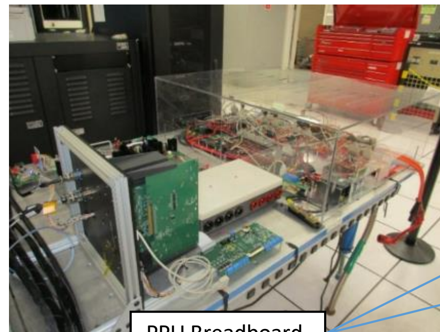
Preliminary AEPS and 6 kW EP Strings Performance Assumptions

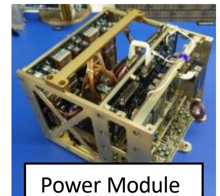
Advanced Electric Propulsion System (AEPS)

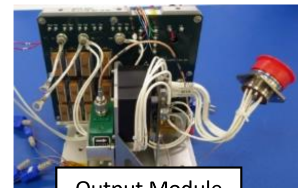
Advanced Electric Propulsion Systems contract competitively awarded to Aerojet-Rocketdyne in May 2016

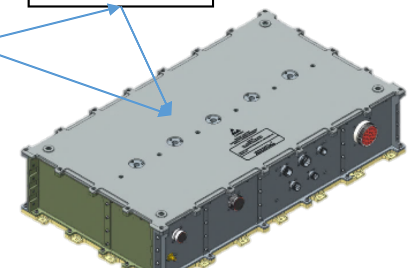


Electric Propulsion (EP) String

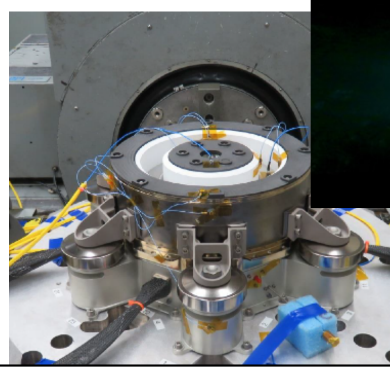

PPU Breadboard

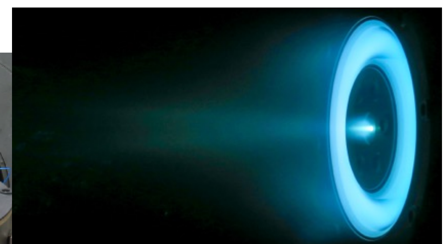

Power Module


Output Module

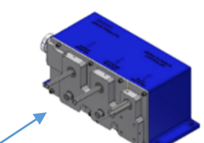

AEPS PPU


Special Test Equipment


AEPS ETU-1 thruster on AR vibe test stand


AEPS ETU-1 thruster hot-fire


EDU#2 and EDU#1 XFC

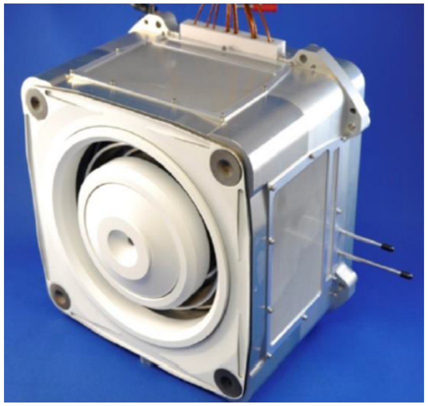

AEPS XFC

Aerojet Rocketdyne is completing engineering model (EM) hardware fabrication, beginning EM testing, and is on the path to an AEPS system CDR in summer 2020

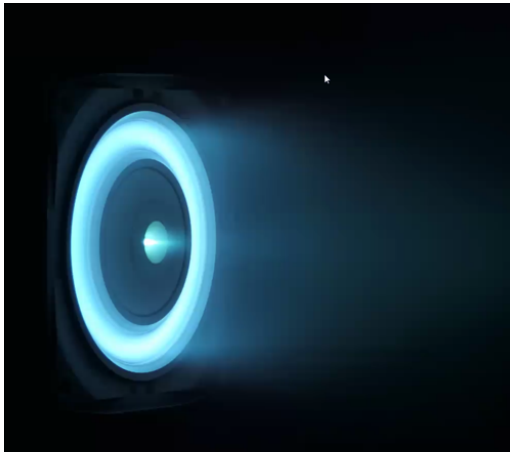
6 kW EP Strings

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

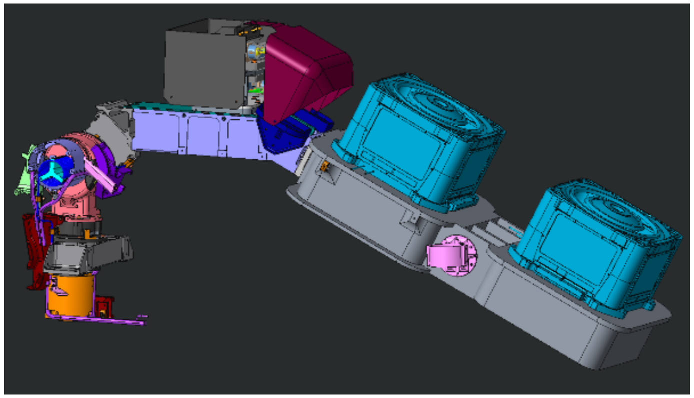
- **Busek BHT-6000 Thruster**
  - BHT-6000 is an extension of the BHT-5000 thruster currently in it life qualification test
  - NASA Tipping Point contract initiated to complete thruster development
- **Maxar 6 kW PPUs**
  - An extension of the 4.5 kW SPT-140 PPUs based on 300 V, 5 A Zero-Voltage Switching (ZVS) trays
  - Utilizes a 4th discharge tray to operate a 6 kW
  - Includes relays to place the trays in parallel or series
  - Controls XFC solenoid and PFCV valves
- **Moog XFC**
  - Qualified up to 23 mg/s flow rates
  - To be flown on Psyche spacecraft
  - Mounts on DSM to minimize line length to thruster
- **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



Busek BHT-5000 Thruster

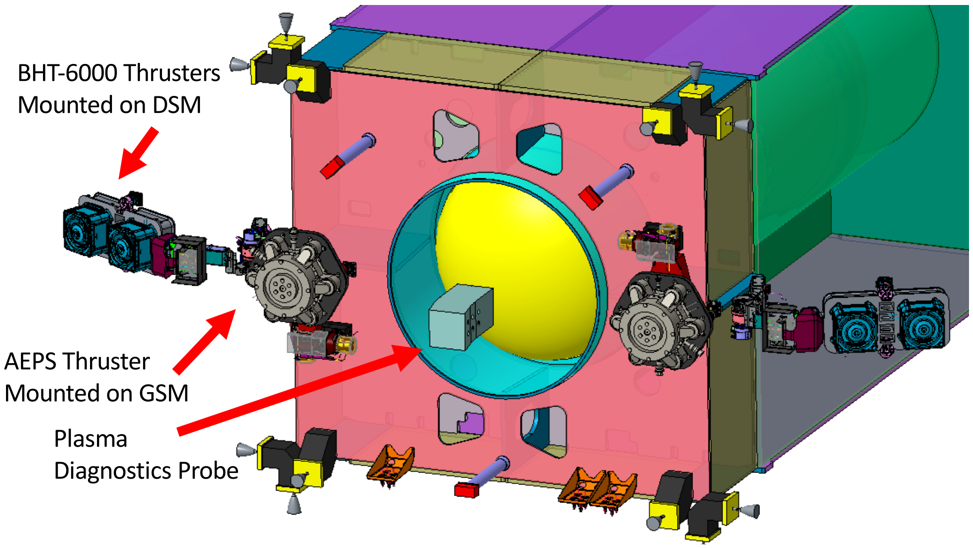


BHT-5000 Thruster Operating at 5 kW, 600 V

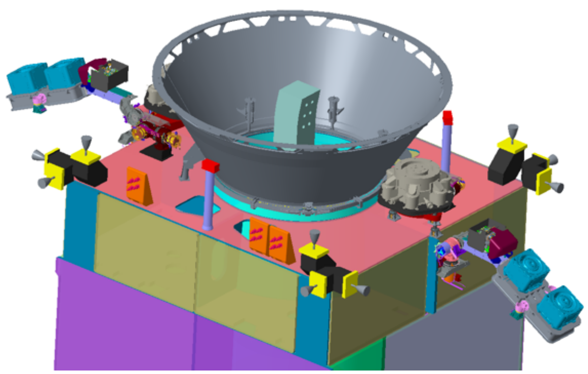


Preliminary DSM-6000

GFE Plasma Diagnostics Package (PDP)

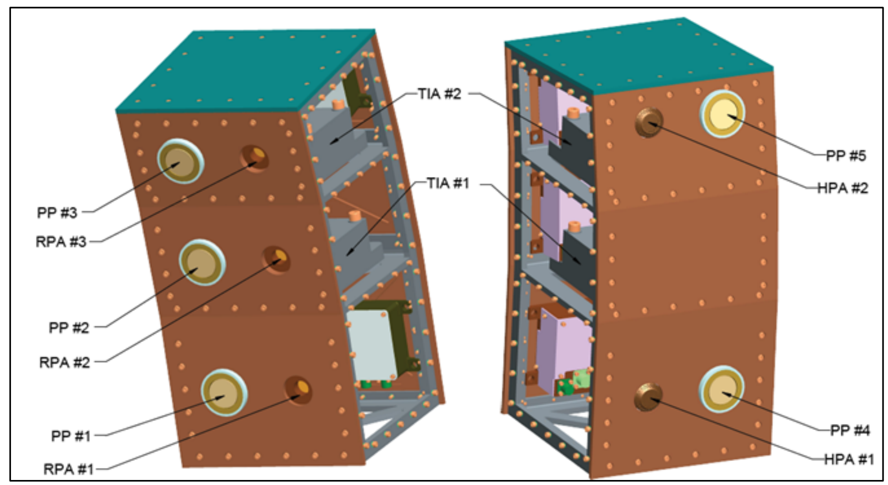


Government-Furnished Plasma Diagnostics Package (PDP) placement relative to EP thrusters



PDP centered inside launch vehicle adapter

Probe types	Measured Plume Characteristic
Discharge Current Sensor (from PPE)	Discharge current waveforms (oscillations)
PP (Planar Probe – total 5 in TPA)	Time-resolved ion flux, electron temperature, plasma potential
HS – RPA (High-Speed Retarding Potential analyzer – total 3 in TPA)	Ion energy distribution, Time-resolved/energy-filtered ion characteristics
HPA (Hemispherical Potential Analyzer - total 2 in TPA)	Ion energy distribution



Government-Furnished Plasma Diagnostics Package (PDP)

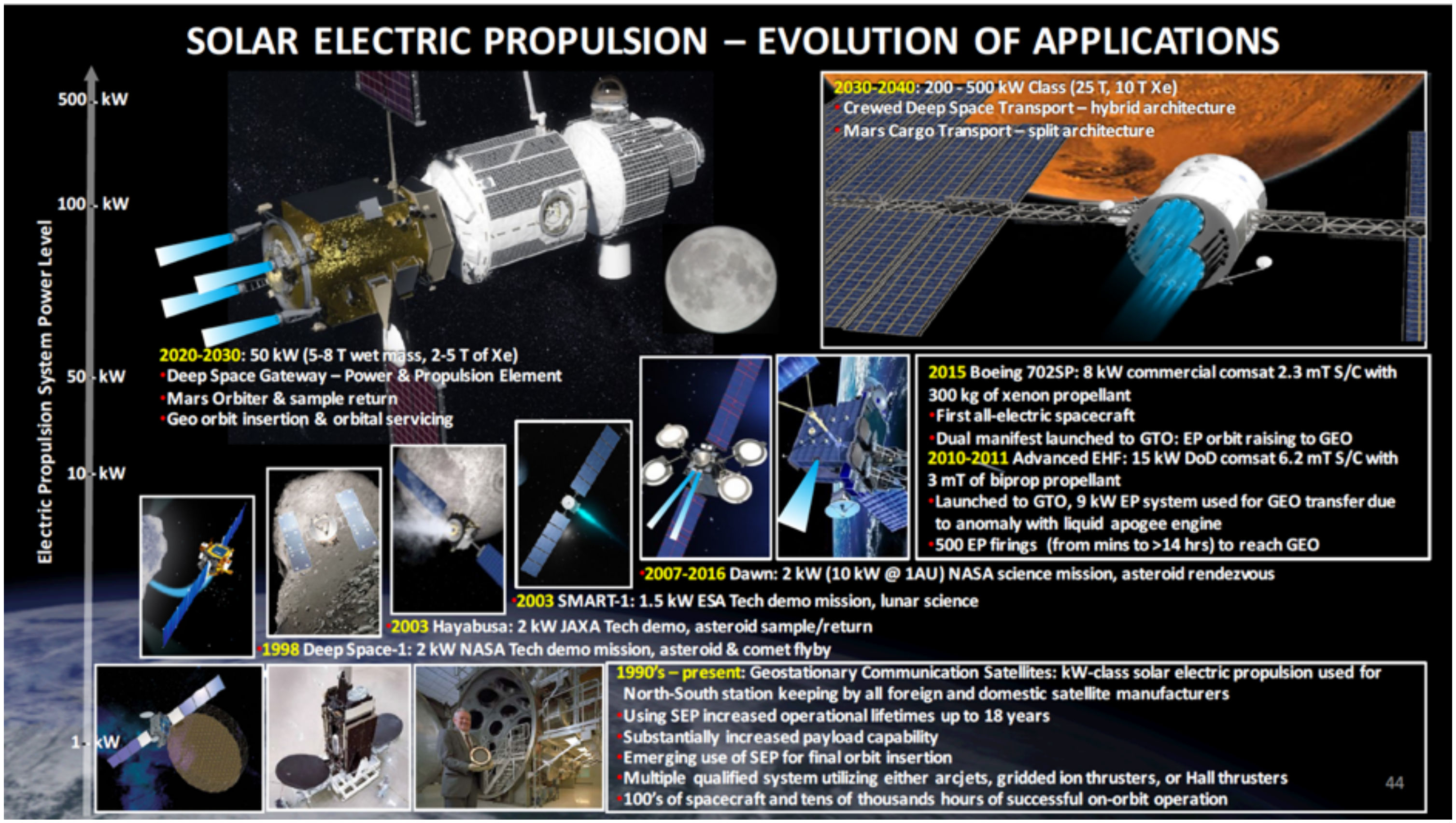
Conclusions

- To meet the ambitious SP1 mandate, NASA is implementing Phase 1 of the Gateway and has (or will shortly) awarded contracts for the defined elements including the Maxar award for PPE in May 2019
- Maxar's PPE Demonstration meets the combined NASA and Maxar objectives, including (but not limited to):
  - Two advanced, high-performance electric propulsion strings
  - High xenon propellant storage and refueling capability
  - Implements a GFE Plasma Diagnostics Package to characterize on-orbit EP system behavior and interactions with the spacecraft
- The AEPS and 6 kW EP systems are in advanced development and are on a path for qualification to meet the planned 2022 PPE launch


WE GO

NASA

Evolution of Electric Propulsion



NASA Human Exploration Strategic Principles

STRATEGIC PRINCIPLES FOR SUSTAINABLE EXPLORATION

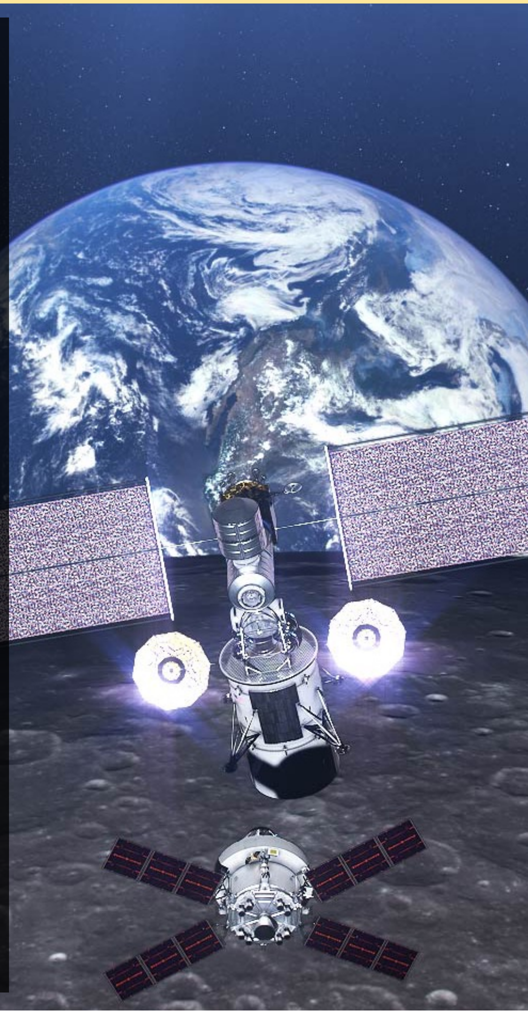
- **FISCAL REALISM**
  Implementable in the near-term with the buying power of current budgets and in the longer term with budgets commensurate with economic growth;
- **SCIENTIFIC EXPLORATION**
  Exploration enables science and science enables exploration; leveraging scientific expertise for human exploration 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.

5

Gateway Phase 1

Gateway Benefits

- Supports the acceleration of landing Americans on the surface of the Moon in 2024, while preserving the ability to evolve for a longer-term human presence
  - Provides power, propulsion, and communication for surface landing systems
  - Port for landing system vehicle aggregation, checkout, & crew safe haven
  - Provides a temporary home for crew who remain in orbit during surface expedition
  - Accessible for many rockets on the market
  - Provides access to the entire lunar surface
- Enables reusability and sustainability
  - Early Utilization opportunities are being protected for simple payloads
  - Serves as a reusable command module and port for logistics delivery and landing system aggregation
- Is a stepping stone to Mars exploration
  - Allows for deep space systems testing



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Gateway Power and Propulsion Element