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

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Abstract: NASA is charged with landing the first American woman and next American man on the South Pole of the Moon by 2024. To meet this challenge, NASA's Gateway will develop and deploy critical infrastructure required for operations on the lunar surface and that enables a sustained presence on and around the moon. NASA's Power and Propulsion Element (PPE), the first planned element of NASA's cis-lunar Gateway, leverages prior and ongoing NASA and U.S. industry investments in high-power, long-life solar electric propulsion technology investments. NASA awarded a PPE contract to Maxar Technologies to demonstrate a 2,500 kg xenon capacity, 50 kW-class SEP spacecraft that meets Gateway's needs, aligns with industry's heritage spacecraft buses, and allows extensibility for NASA's Mars exploration goals. Maxar's PPE concept design, is based on their high heritage, modular, and highly reliable 1300-series bus architecture. The electric propulsion system features two 13 kW Advanced Electric Propulsion (AEPS) strings from Aerojet Rocketdyne and a Maxar-developed system comprised of four Busek 6 kW Hall-effect thrusters mounted in pairs on large range of motion mechanisms pointing arms with four 6 kW-class, Maxar-built PPUs derived from Geostationary Earth Orbit (GEO) heritage. NASA is continuing to develop the 13 kW AEPS system through a contract with Aerojet Rocketdyne. In addition to the flight demonstration of an advanced electric propulsion system on PPE, a government-furnished plasma diagnostics package is planned to assess on-orbit performance characteristics and vehicle interactions. The paper will present overviews of NASA's Gateway and the PPE Project, the Maxar ion propulsion subsystem, the status of the two electric propulsion system developments, and the implementation of the plasma diagnostics package on the Maxar PPE spacecraft. The project is currently heading into the System Requirements Review, with the propulsion build scheduled for 2021, and launch in 2022.

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Nomenclature

ΔV	=	Velocity Delta
AEPS	=	Advanced Electric Propulsion System
BAA	=	Broad Agency Announcement
BHT	=	Busek Hall Thruster
DSM	=	Dual Axis Solar Electric Propulsion Module
EDU	=	Engineering Development Unit
ELO	=	Elliptical Lunar Orbit
EOL	=	End of Life
EOR	=	Electric Orbit Raising
ETU	=	Engineering Test Unit
GEO	=	Geostationary Earth Orbit
GFE	=	Government Furnished Equipment
GRC	=	Glenn Research Center
GSM	=	Gimbaled Solar Electric Propulsion Module
GTO	=	Geostationary Transfer Orbit
HEOMD	=	Human Exploration and Operations Mission Directorate
HET	=	Hall Effect Thruster
IPS	=	Ion Propulsion System
Isp	=	Specific Impulse
MEP	=	Main Electronics Package
NRHO	=	Near Rectilinear Halo Orbit
NSSK	=	North/South Station-Keeping
PDP	=	Plasma Diagnostics Package
PFCV	=	Proportional Flow Control Valve
PPE	=	Power and Propulsion Element
PPU	=	Power Processing Unit
RSGS	=	Robotic Servicing of Geosynchronous Satellites
S/C	=	Spacecraft
SEP	=	Solar Electric Propulsion
SPT	=	Stationary Plasma Thruster
SRR	=	System Requirements Review
SSM	=	Subsystem Manager
TASU	=	Thruster Auxiliary Support Unit
TPA	=	Thruster Probe Assembly
XFC	=	Xenon Flow controller
ZVS	=	Zero Voltage Switching Trays

I. Introduction

STUDIES performed for NASA's Human Exploration and Operations Mission Directorate (HEOMD) and Science Mission Directorate have demonstrated that a 40 kW-class solar electric propulsion (SEP) capability can be enabling for both near term and future architectures and science missions.[1] For missions beyond low Earth orbit, spacecraft size and mass can be dominated by onboard chemical propulsion systems and propellants that may constitute more than 50 percent of spacecraft mass. Since 2012 NASA has been developing a 13 kW Hall thruster electric propulsion string that can serve as the building block for a 50 kW-class SEP capability. A high-power, 40 kW-class Hall thruster propulsion system provides significant capability and represents, along with flexible blanket solar array technology, a readily scalable technology with a clear path to much higher power systems. NASA's Gateway will leverage the benefits of high-power SEP capability provided by the Power and Propulsion Element, the first element of the Gateway.

To support NASA's Moon to Mars exploration objectives, NASA will need a highly reliable spacecraft bus for PPE capable of supporting the high-power, high-throughput, and high-propellant capacity SEP capability. Prior and ongoing NASA and U.S. industry investments in high-power, high-throughput SEP technology and leveraged high-reliability heritage spacecraft permit targeting PPE launch in 2022 as a partnership addressing both commercial and

NASA needs. For NASA, PPE enables the start of Gateway and crewed lunar surface operations by 2024 followed by a sustainable presence in lunar orbit for expanded surface operations and extensibility for Mars exploration beyond.

Maxar identified that the use of flight proven commercial hardware and processes would result in a cost effective firm-fixed price for PPE.[2] Maxar's long and successful history with SEP in Geostationary Earth Orbit (GEO) was a driving factor in their proposal. To date, Maxar has launched 38 Geostationary Earth Orbit (GEO) communication spacecraft with Hall-effect thrusters with two of those operational satellites recently surpassing their 12-year contracted lifespan. The SEP-equipped Maxar fleet has accumulated over 100,000 hours of on-orbit firing time.[3] This system has grown from one strictly for on-orbit North/South Station-keeping (NSSK), to one capable of providing all propulsion needs for the spacecraft, from initial electric orbit raising (EOR) through end of life (EOL) deorbit. The Maxar subsystem has evolved from 1.5 kW class thrusters fired one at a time, to the current day 4.5 kW class thrusters which can be fired in groups of four for 18 kW operation.[4, 5] The thrusters are mounted on two-axis gimbals capable of positioning for both multi-thruster electric orbit raising and single-thruster station-keeping.

PPE will utilize 60 kW arrays, two large xenon tanks, and a combined 49 kW electric propulsion system spread over six thrusters and six power processing units. Four 6 kW Hall thrusters will be provided by Busek mounted on Maxar's traditional Dual-Axis SEP Modules (DSMs) and two 12.5kW Hall thrusters by Aerojet mounted on smaller range of motion two-axis gimbals.[6, 7] The xenon feed system provides up to 2500 kg of xenon at launch and can be refuelable while in-orbit around the moon. The six Hall Thrusters, in addition to 20 hydrazine monopropellant chemical thrusters are designed to supply all propulsion needs for the entire cis-lunar gateway. A top-level propellant budget for the mission is shown in Table 1.

Table 1. PPE Xenon propellant budget assuming a 50% margin on ΔV for both EOR maneuvers.

	ΔV (m/s)	ΔV x1.5 (m/s)	Isp (sec)	Xenon Used (kg)	Xenon Remaining (kg)	S/C Mass (kg)
Separation					2500	7000
GTO -> ELO	3100	4665	2600	1170	1330	5830
ELO -> NRHO	230	344	2600	78	1252	5752
Xenon Dispersion / Leak (5%)				125	1127	
Xenon Hold-up				25	1102	
Xenon for Gateway Station-keeping				1102		
With 2000kg Refueling				3102		
Total System Throughput				4475		

II. NASA Exploration and the Power and Propulsion Element Overview

A. The Artemis Program and NASA's Gateway

On December 11, 2017 the National Space Policy of the United States was updated by the President and directed NASA to "Lead an innovative and sustainable program of exploration with commercial and international partners to enable human expansion across the solar system and to bring back to Earth new knowledge and opportunities. Beginning with missions beyond low-Earth orbit, 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." [8] In keeping with this new Space Policy Directive, NASA is charged with landing the first American woman and next American man on the South Pole of the Moon by 2024, followed by a sustained presence on and around the Moon by 2028. The Artemis Program created to meet this challenge is divided into two Phases: Phase I is focused on the missions and systems required to achieve landing humans on the surface of the moon in 2024 and Phase II will establish a sustainable long-term presence on the lunar surface. The Artemis Program Phase I is depicted in Fig. 1.

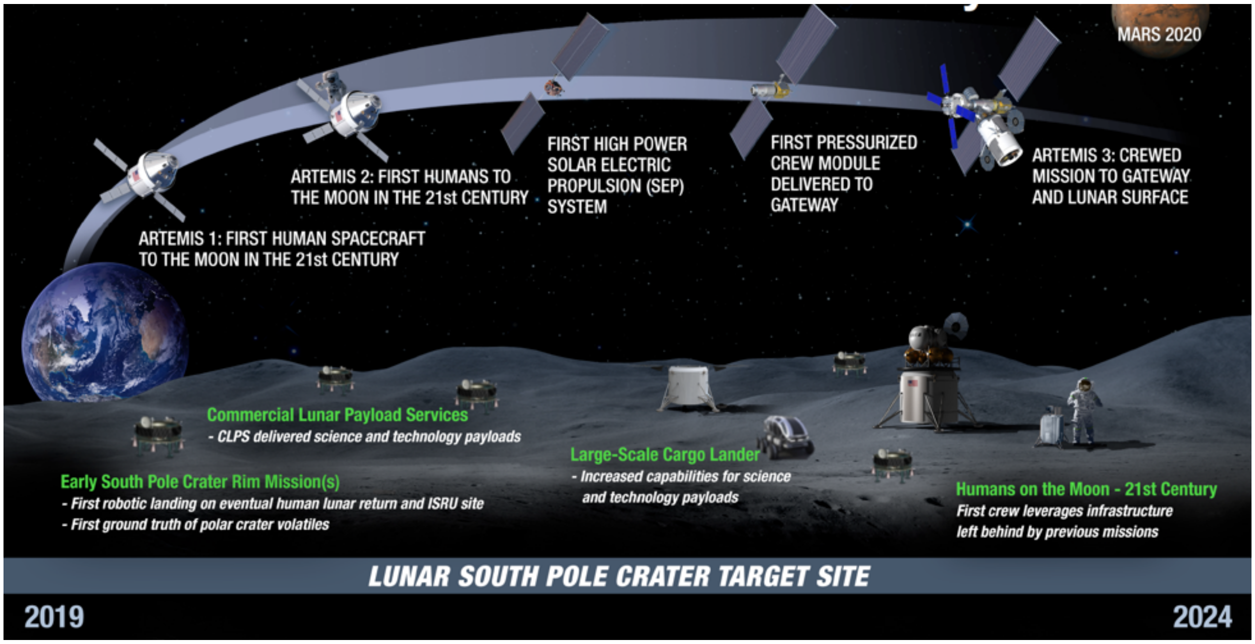

Figure 1. Artemis Program Phase 1 Illustration.

As a core element of the Artemis Program, NASA's Gateway, illustrated in Fig. 2, will develop and deploy critical infrastructure required for operations on the lunar surface and that enables a sustained presence on and around the moon. The cis-lunar Gateway:

- 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

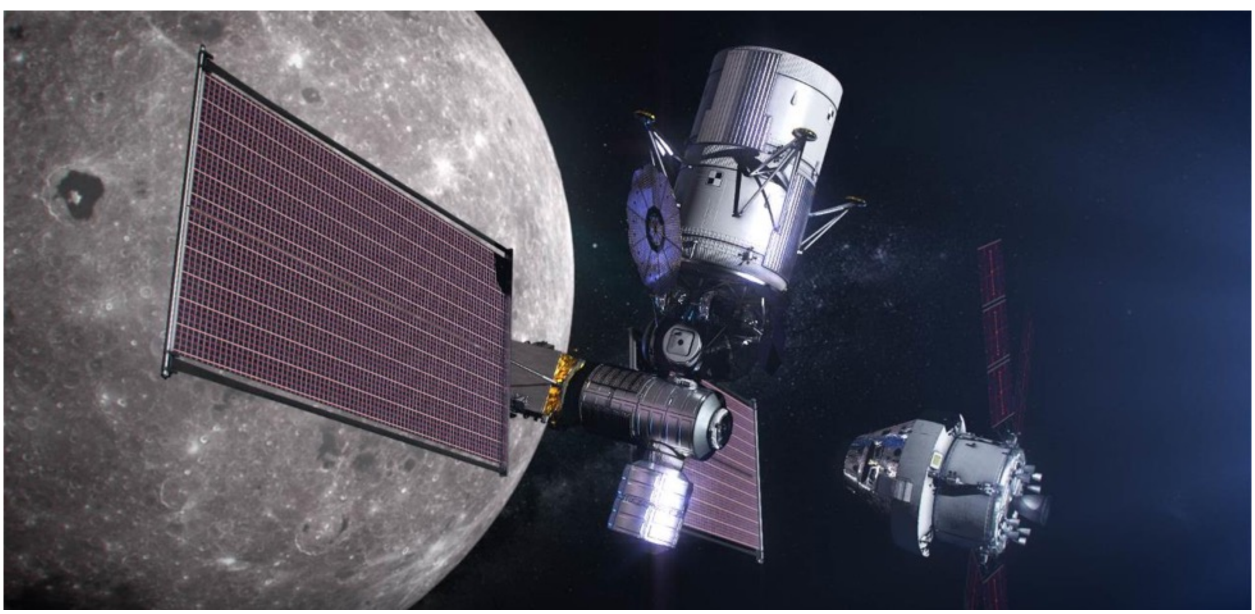

Figure 2. Phase I Gateway illustration including the Power and Propulsion Element (PPE), Habitation and Logistics Outpost (HALO), Human Lunar Lander, and crewed Orion vehicle.

B. Power and Propulsion Element (PPE)

The first element of NASA's Gateway will be the Power and Propulsion Element (PPE) that leverages prior and ongoing NASA and U.S. industry investments in high-power, long-life solar electric propulsion technology investments. In a Broad Agency Announcement (BAA) released on September 6, 2018, NASA specified only its unique requirements allowing the partner the opportunity to complete the requirement set suiting their specific interests.[9] To support NASA's Moon to Mars exploration objectives NASA will need a highly reliable spacecraft bus, which NASA recognized the satellite industry could provide having several decades-long historical record of spacecraft on-orbit performance. On May 24, 2019, NASA awarded a PPE contract to Maxar Technologies to demonstrate 50 kW-class SEP spacecraft that meets Gateway's needs, aligns with industry's heritage spacecraft buses, and allows extensibility for NASA's Mars exploration goals.[10] The PPE partner, Maxar, will own and operate PPE through design, development, launch, and a spaceflight demonstration period to last up to one year. At the conclusion of the demonstration, Maxar will deliver the PPE in a southern lunar Near-Rectilinear Halo Orbit (NRHO) where NASA would have the option to acquire the PPE for use as the first element of Gateway.

Maxar's PPE concept design, illustrated in Fig. 3, is based directly on the high heritage, modular 1300-series bus architecture. PPE is a high power 60 kW class spacecraft equipped with a large 50 kW class SEP system, advanced communications and avionics capabilities, as well as a multitude of interfaces to support Gateway functions. To date Maxar has flown 38 satellites equipped with electric propulsion, including multiple long duration Electric Orbit Raising (EOR) missions to Geostationary orbit, and accumulating more than 100,000 hours of Hall-effect thruster on orbit firing time. PPE, although a significant evolution in capability for Maxar spacecraft, represents a manageable technological step, building on decades of investment in high power systems and electric propulsion at Maxar.[2]

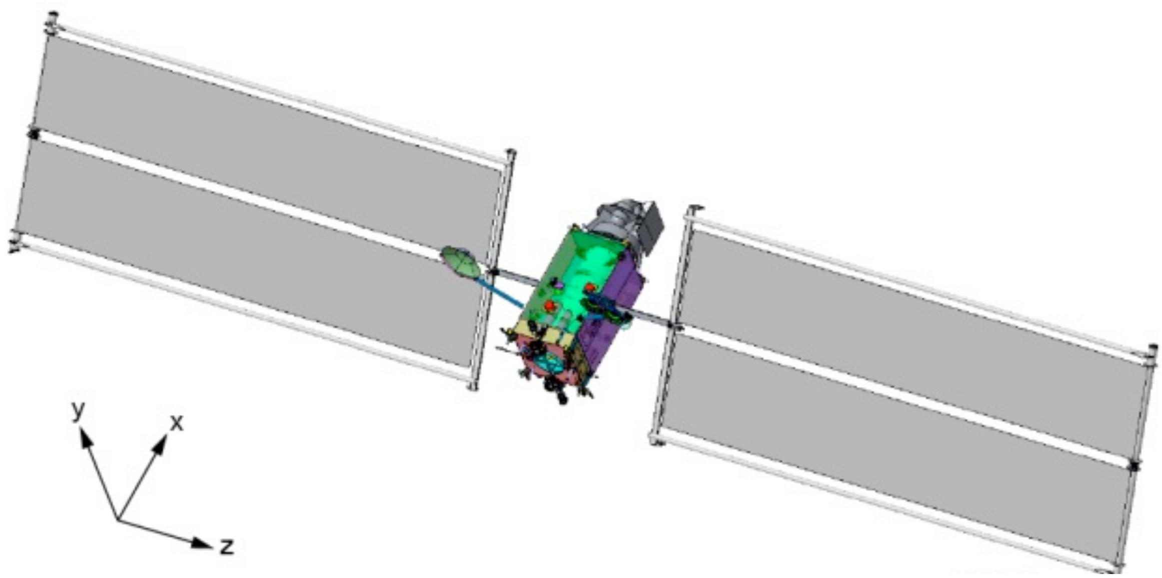

Figure 3. Maxar PPE Design Concept.

In the context of the Gateway, PPE will provide several critical functions including power transfer and storage, high thrust chemical and low thrust electric propulsion, attitude control, communications, and data relay services. PPE will provide regulated 100 V power to the Gateway under nominal conditions from the arrays while in sunlight, and in the shade via Lithium-Ion batteries. A high thrust chemical propulsion system will provide for attitude control and translational ΔV for specific maneuvers which may not be suitable for execution with long duration SEP burns. A high efficiency SEP system will provide the primary source of ΔV capability for initial orbit raising and insertion as well as midlife orbit transfers of the entire Gateway stack. An expanded set of reaction wheels combined with a standard sensor suite will provide for attitude control throughout all mission phases. PPE will provide X-band telemetry and command to Earth, high rate Ka-band to Earth ground stations, Ka-band lunar communications link, and an S-band link for visiting vehicle operations. Mission processors implemented on PPE will connect to Gateway via time-triggered ethernet link and will provide relay functionality between Gateway, visiting vehicles, the moon, and Earth.

The PPE demonstration mission is based on the set of NASA PPE objectives as well as a set of Maxar commercial objectives which have been chosen to further our capabilities in the areas of communications, transport, and satellite servicing. These objectives include:

1. Demonstrate Next-Generation Commercial Communications Capabilities
   - 1A: Demonstrate lunar lander communications relay services at the moon
   - 1B: Demonstrate high-power SEP capabilities for commercial communications satellites
2. Demonstrate Next-Generation Commercial Space Transportation Capabilities
   - 2A: Demonstrate high-power SEP-enabled cargo transfer
   - 2B: Demonstrate heavy-lift launch vehicle capability
3. Demonstrate Next-Generation Commercial Satellite Servicing Capabilities
   - 3A: Demonstrate detailed spacecraft inspection capability
   - 3B: Demonstrate xenon transfer capability

The PPE concept demonstration mission depicted in Fig. 4, begins in 2022 with a launch on a heavy lift launch vehicle placing PPE in a highly elliptical transfer orbit. After separation from the launch vehicle PPE will perform a series of bus equipment checkouts as well as a xenon transfer demonstration. PPE will then begin a period of long duration autonomous EOR utilizing the SEP system to transfer to an intermediate drop off orbit for the lunar rideshare payload, then continuing on to the target Near Rectilinear Halo Orbit (NRHO). While in the NRHO, PPE will perform a series of tests to validate PPE for use in the Gateway, demonstrate a lunar communications relay with the rideshare payload, and will perform a set of detailed spacecraft inspections.[11]

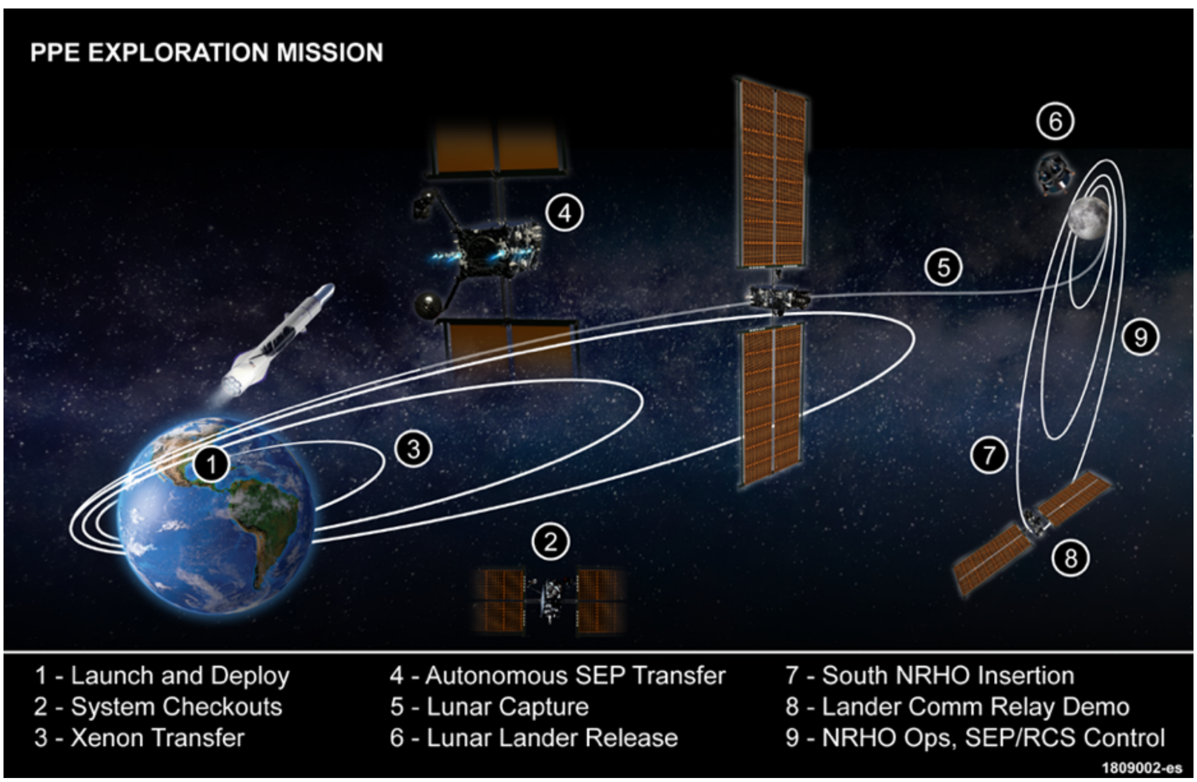

Figure 4. Maxar PPE Concept Demonstration Mission Overview.

III. Maxar Ion Propulsion Subsystem

A. Overview of Maxar PPE Ion Propulsion Subsystem

Maxar's PPE spacecraft draws heavily on the heritage 1300-series spacecraft bus and subsystems to convey reliability and lower program risk. Although a significant evolution in terms of capability for Maxar spacecraft, PPE is not a high-risk "leap," rather, it is a manageable technological "step," building on Maxar's consistent and long-term investments in deploying cutting-edge SEP architectures and systems.[2]

The electric propulsion system features two 12.5 kW AEPS strings from Aerojet Rocketdyne which include the 12.5 kW thruster, associated PPU and XFC. Each of these thrusters is mounted on a gimbal with range of motion sufficient to support Gateway configurations over life. Complementing the two AEPS systems is a Maxar-developed system comprised of four Busek 6 kW Hall-effect thrusters mounted in pairs on large range of motion pointing arms, supported by four 6 kW class PPUs, as well as four XFC's. The 6 kW system is based on an existing Maxar-Busek development project for a 5 kW advanced Hall-effect thruster and leverages a NASA Tipping Point project to uprate this thruster system to increased power, thrust, and specific impulse.

The baseline subsystem schematic, shown in Fig. 5, includes two 825L Xenon tanks, refueling ports, a bang-bang pressure regulation system, the thrusters and flow controllers, positioning gimbals, and power processing units.

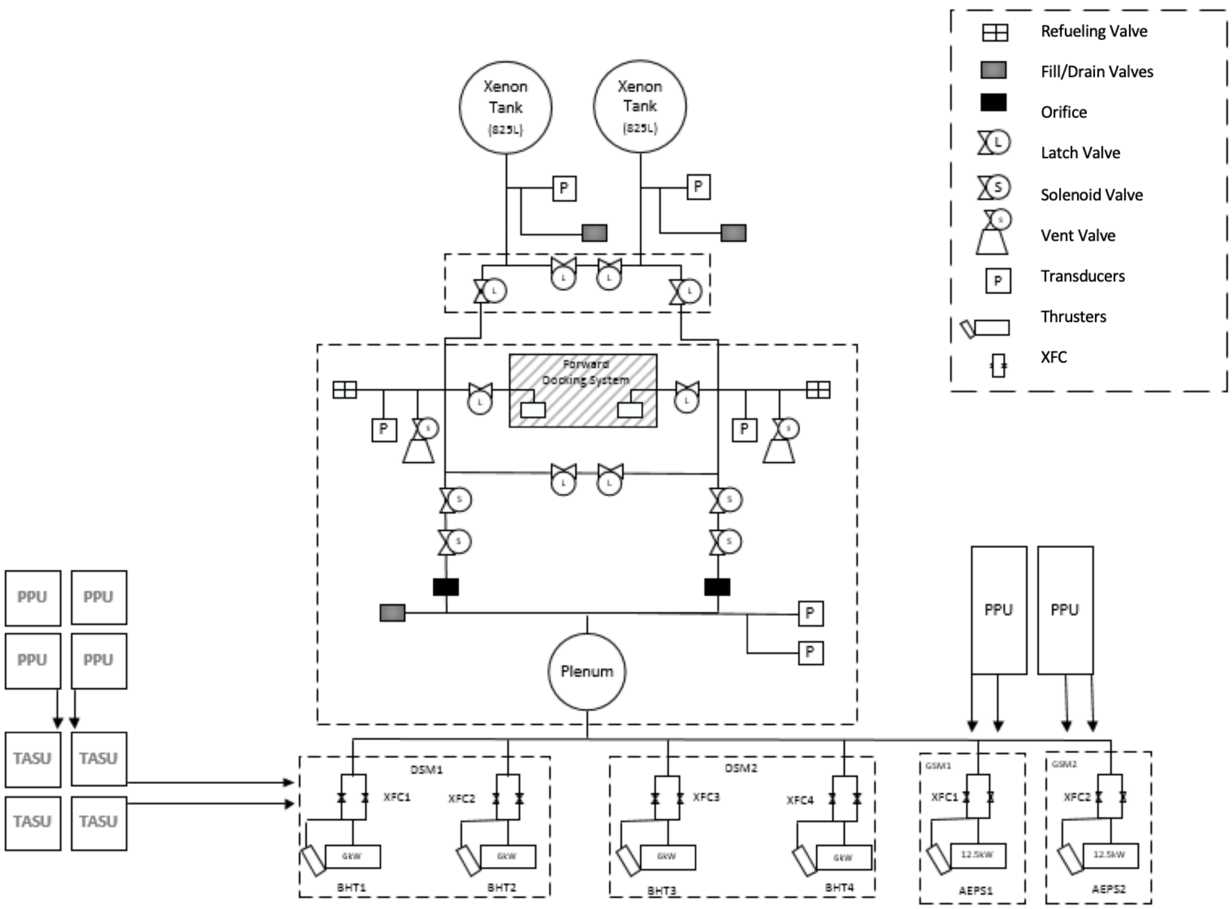

Figure 5. Maxar proposal baseline PPE electric propulsion subsystem block diagram.

Dual 825 L xenon tanks will be housed within the spacecraft in the same manner that the heritage Maxar bipropellant tanks are on GEO communication satellites. As shown in Fig. 6, a 1650 L xenon tank volume allows for the storage of the required 2500 kg. The tanks are isolated by latch valves to prevent tank leakage from being a single-point failure. Strict limits on the temperature gradient across and between the tanks will be maintained to minimize propellant accounting uncertainty and increase thruster flow rate and specific impulse estimates.

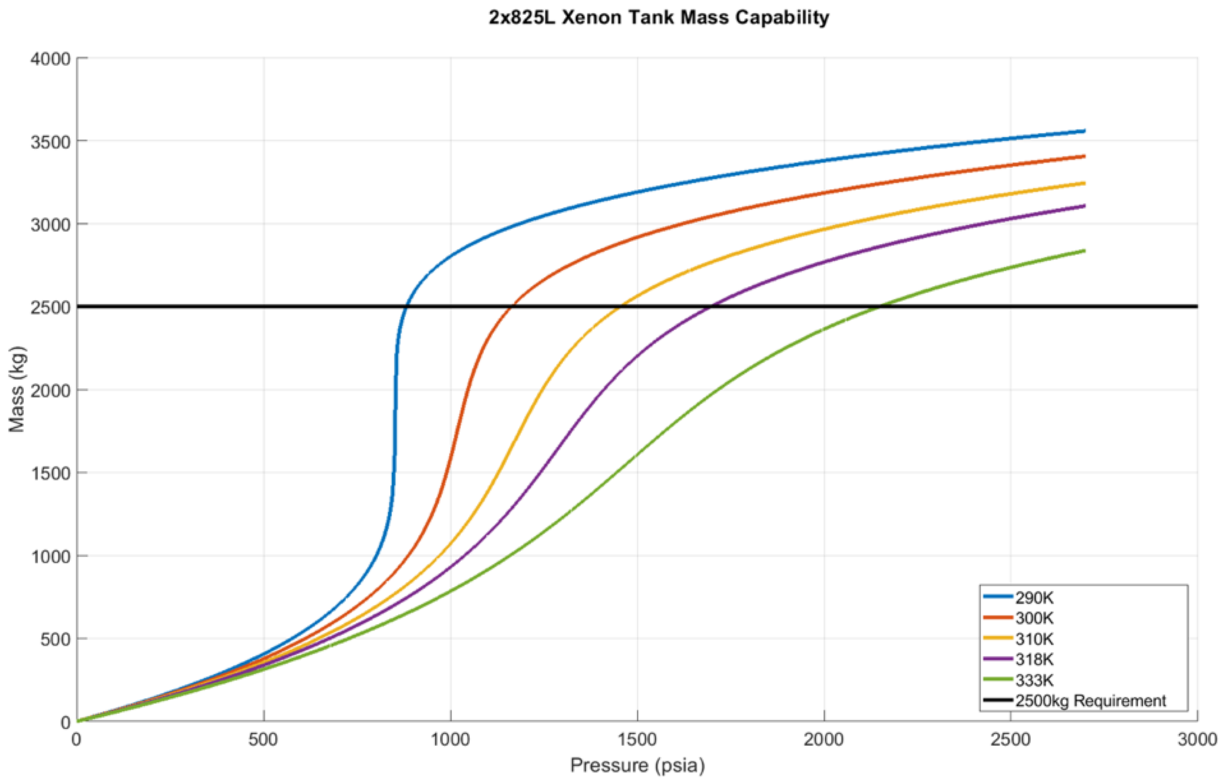

Figure 6. 1650 L Xenon tank capacity.

The spacecraft is required to be refueled on-orbit and two separate means will be included to allow for this operation. NASA will be providing a government furnished docking system which interfaces with the next module in the Gateway. This interface will have two hydrazine ports and two xenon ports. All four are required to be vented to vacuum pressures prior to actuation. The aft of the spacecraft will include docking berths and refuelable valves to allow a Restore-L or Robotic Servicing of Geosynchronous Satellites (RSGS) type spacecraft to refuel PPE with both hydrazine and xenon.[12, 13] Recent efforts across the industry, and by NASA Goddard Space Flight Center in particular, have resulted in more efficient, feasible, and low-cost refueling technologies being available for this purpose.[14]

During the proposal phase it was believed that the 6 kW and 12.5 kW thruster strings may require different operating pressures over the life of the mission. As such a single-fault tolerant bang-bang pressure regulation system was baselined. Since then, recent work has shown that a fixed inlet pressure to the xenon flow controllers of both types of electric propulsion strings will be an acceptable pressure for operating all thrusters at all power levels, leading to a trade study between the baselined bang-bang pressure regulation system and a mechanical regulator system with split downstream manifolds to reduce regulator flowrates as shown in Fig. 7. Mechanical regulators have flown on all Maxar geostationary spacecraft. At the time of the writing of this paper, the trade study remains open.

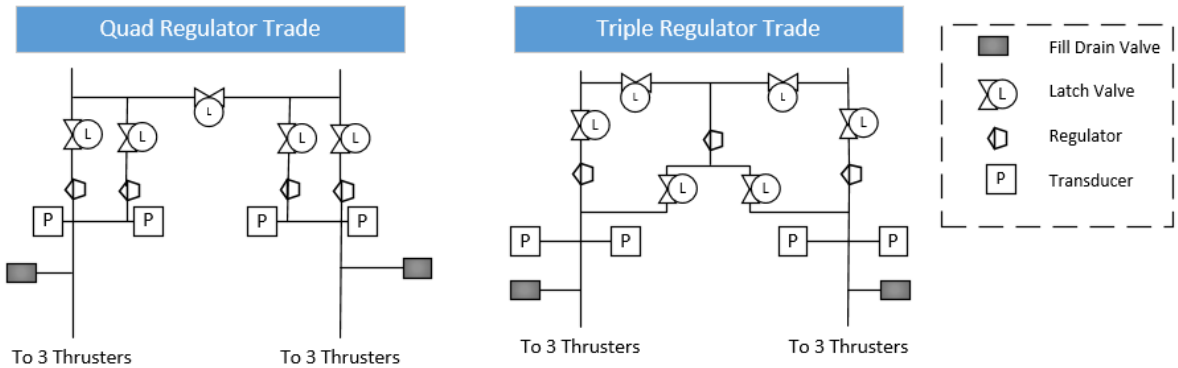

Figure 7. Mechanical pressure regulation systems with split downstream manifolds under consideration.

The thruster performance is a high point of interest for this mission. On-orbit pressure-volume-temperature mass flow rate estimates, coupled with thrust measurements via orbit determination, will lead to improved pressure corrections for vacuum chamber measurements.[15] Preliminary assumptions for the AEPS and BHT-6000 thrust and specific impulse are shown in Fig. 8. These will continue to be evaluated over the course of the development effort as the thrusters enter qualification and acceptance testing.

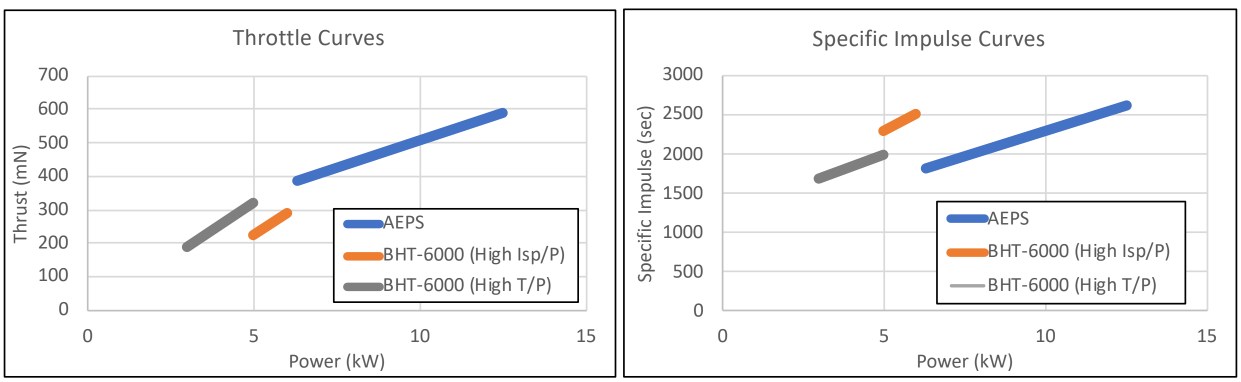

Figure 8. Preliminary EP thruster performance estimates.

Using the above preliminary thruster performance curves, baseline estimates can be calculated for five EOR thruster configurations (Table 2), all of which operate the thrusters at their maximum specific impulse condition. The thrust varies from 580 mN (12 kW) up to 2.34 N (49 kW), while the flow rate varies from 2 kg/day up to 8 kg/day. The specific impulse is expected to be above 2500 sec for all configurations. Operating at 49 kW, an EOR of 3.1 km/sec deltaV would require 800 kg of Xenon and last 100 days. Efforts are on-going to reduce the required delta-V by optimizing the trajectory.

Table 2. Subsystem performance preliminary estimates for five 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

1. AEPS Implementation

Each 12.5 kW AEPS thruster will be mounted on a gimbaled solar electric propulsion module (GSM). These gimbals will have a 20 degree half-angle cone range of motion, allowing for both orbit raising and station-keeping maneuver capability. The gimbal, its motors, and hold-downs are based on heritage Maxar concepts. The AEPS Xenon Flow Controller has a maximum XFC-to-thruster distance of 10 m and will be placed inside the spacecraft to simplify the gimbal design and minimize thermal variations.

The expected throughput through the AEPS thrusters, wide plume dispersion angles, and the increased ion energy associated with operating at 600 V, have resulted in plume effects on the spacecraft being a high risk. As such the solar arrays have been placed on 2 m booms in an attempt to remove them from the bulk of the plume and the thruster gimbals will be extended from the deck to further increase the distance between the thruster exit plane and spacecraft surfaces, as shown in Fig 9. As the plume is known to have particles which exit at angles exceeding 90 degrees, Maxar and NASA Glenn Research Center (GRC) will be conducting sputtering tests of the materials on the ROSA array at 600 V energy levels to determine the expected level of array degradation over the course of the mission.[16]

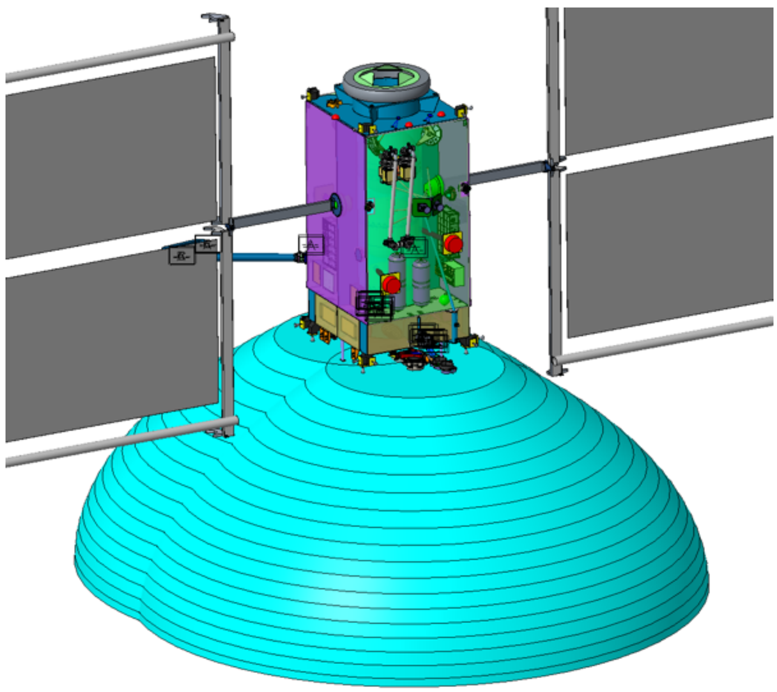

Figure 9. AEPS thruster plume stay-out zone.

2. 6 kW EP Strings

Maxar has a long history of dual-axis solar electric propulsion positioning modules (DSM), shown in Fig. 10.[4] This module was originally designed and flown in 2006 for the SPT-100 Hall thruster, increased in size for the larger SPT-140 Hall thruster, and will now be modified further for the BHT-6000 Hall thruster. The module has over 100 degrees of rotation in both axes, allowing for both orbit raising and station-keeping operations. The modules include two thrusters, their respective XFCs, hold-downs, thermal hardware, and the two motors, each with potentiometers for position knowledge.

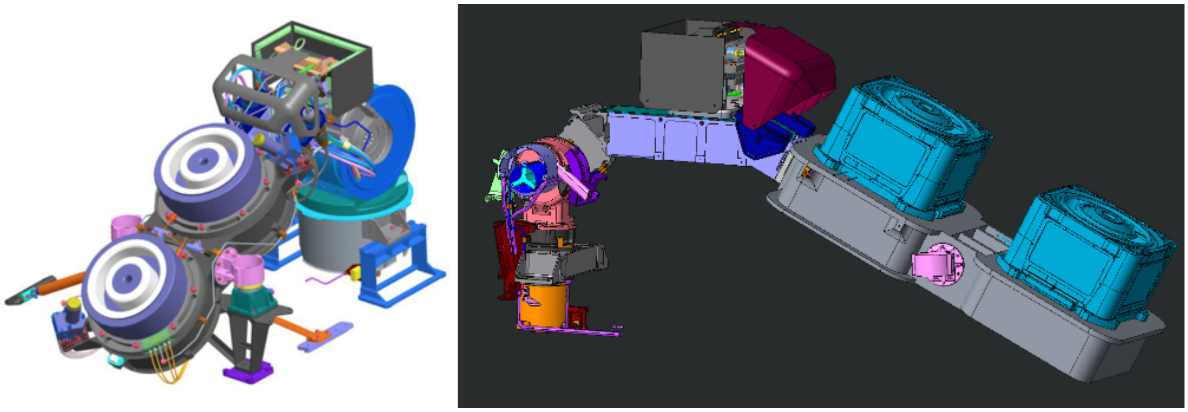

Figure 10. DSM-140 (left) and a preliminary model of the DSM-6000 for PPE (right).

Maxar utilized Xenon Flow Control (XFC) units, based around the Moog proportional flow control valve (PFCV), are qualified up to 23 mg/sec flow rates, high enough to support the BHT-6000 thruster.[17] The Moog PFCVs have a long history, are fast reacting, and operate at currents between 70-140 mA.[18] The XFC has an upstream solenoid valve, PFCV, and orifices for the anode and cathode. Maxar mounts the XFC on the DSM to minimize pneumatic length between the PFCV and thrusters. The PPU controls both the solenoid and PFCV valves.

B. Overview of the Advanced Electric Propulsion System (AEPS) Contract

The NASA in-house development of the 12.5 kW Hall Effect Rocket with Magnetic Shielding (HERMeS) thruster system, led by the NASA GRC and the Jet Propulsion Laboratory (JPL), began with maturation of the high-power Hall thruster and power processing unit (PPU) to provide the long lifetimes and high specific impulse needed for NASA human and robotic exploration campaigns.[19, 20] Three Technology Development Units (TDU) thrusters and breadboard power processing units were developed under this effort and completed a comprehensive test campaign including extended life and environmental testing at GRC and JPL.[21] The technology development work transitioned to Aerojet Rocketdyne via a competitive procurement selection for the Advanced Electric Propulsion System (AEPS) contract in May 2016. The AEPS contract is a cost-plus, fixed fee contract that includes the development, qualification, and delivery of two 12.5 kW electric propulsion strings qualified for flight. The AEPS EP string consists of the Hall thruster, power processing unit (including digital control and interface functionality), xenon flow controller (XFC), and associated intra-string harnesses. Management of the contract is being led by the NASA GRC. NASA continues to support the AEPS development leveraging in-house expertise, plasma modeling capability, and world-class test facilities. NASA also executes mission risk reduction activities to support the AEPS development and mission application.[22]

Aerojet Rocketdyne recently completed the fabrication of the first Engineering Test Unit (ETU) thruster, shown in Fig. 11, and is completing fabrication a second ETU thruster. The ETU-1 thruster will undergo acceptance testing followed by qualification level environmental testing at JPL's Owens chamber. ETU-2 will undergo extensive performance, stability, and plume characterization testing in NASA GRC's Vacuum Facility-5 chamber before extended wear testing prior the AEPS Critical Design Review (CDR). Fabrication of the ETU and Engineering Development Unit (EDU) PPUs are currently in-progress. The ETU PPU will be used to assess the thermal characteristics of the PPU and then integrated into a 1,000-hour string-level wear test of the ETU-2 HCT, ETU PPU, and EDU XFC. The EDU PPU will undergo full qualification-level environmental and performance characterization prior to integration into a string-level thermal vacuum characterization. Finally, two EDU XFCs will undergo full qualification-level environmental and performance characterization prior to integration in string-level test campaigns. The results of the ETU and EDU component and string-level test campaigns will be used to provide final design improvements for the AEPS qualification/flight design. The AEPS contract is expected to complete its Critical Design Review (CDR) next year. Additional details regarding the AEPS contract can be found in References 23 and 24.

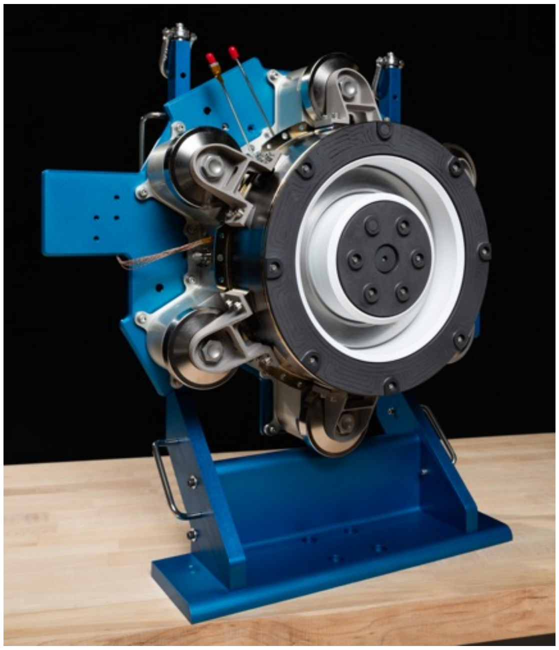
Figure 11. AEPS ETU-1 thruster.

C. Overview of the 6 kW Electric Propulsion System Development

Busek is developing a 5 kW Hall Thruster (BHT-5000) which can operate up to 600 V. Dual mode operation at 300 V (high thrust/power) and 600 V (high Isp/power) will give spacecraft improved propellant usage and time of flight capability. At the writing of this paper, the BHT-5000, shown in Fig. 12, is partway through its qualification life test. Through a NASA Tipping Point Project, Maxar and Busek will be using the majority of the same thruster hardware to run at 6 kW, creating the BHT-6000 thruster. This project will determine the level of modifications to the 5 kW hardware necessary to operate at 6 kW.

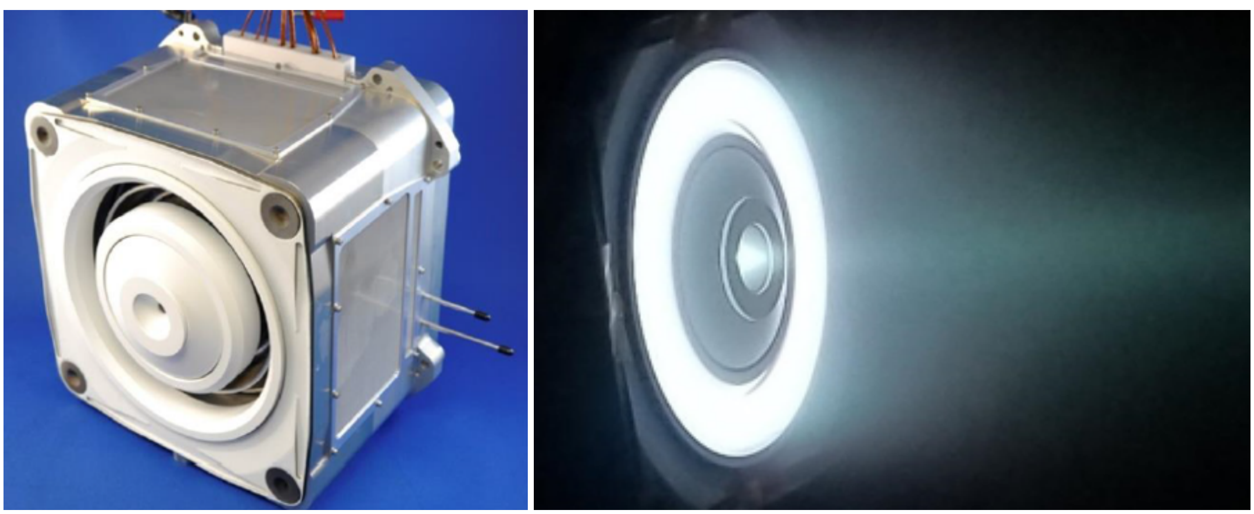
Figure 12. BHT-5000 thruster

The 6 kW power processing units (PPUs) are an extension of the 4.5kW SPT-140 PPUs.[25] These units are based on 300 V, 5 A Zero-Voltage Switching (ZVS) trays. The PPU-140 utilizes three of these trays, while the 6 kW PPU will utilize four. Relays to place the trays in parallel or series will be used to operate at 600 V. The heritage Maxar filter units will continue to be used for the 6 kW system. Placed between the PPUs and thrusters, the thruster auxiliary support units (TASUs) effectively damp out the high frequency oscillations generated from the Hall thruster discharge.

IV. Plasma Diagnostics Package

A. GFE PDP Implementation Overview

A flight plasma diagnostics package (PDP) is being developed by NASA GRC that will be delivered to Maxar as Government Furnished Equipment (GFE) for inclusion on the PPE. It will provide the data needed to validate models of high-power SEP operation and spacecraft plasma interactions, design tools that are critical for enabling high-power SEP spacecraft to support future human and robotic missions to Mars. The PDP will provide flight plasma spacecraft interaction data that cannot be accurately assessed by ground test plasma measurements.

The PDP consist of a Thruster Probe Assembly (TPA), Main Electronic Package (MEP), and associated harnesses. The TPA, shown in Fig. 13, has ten sensors with three sets of duplicate sensors at different angular positions facing an AEPS thruster and two sets facing away from the AEPS thruster.[22] The MEP serves as the avionics for the TPA data collection and communication link to the PPE spacecraft.

Once NASA successfully completes an integrated functional system test of the PDP, the PDP flight hardware will be delivered to Maxar for integration into the PPE spacecraft. Joint PPE and PDP concepts of operation and interfaces control documents will be worked on by NASA and Maxar. Once operational on PPE, PDP data will provide NASA and Maxar invaluable plasma plume characteristics of high-power SEP in a space environment.

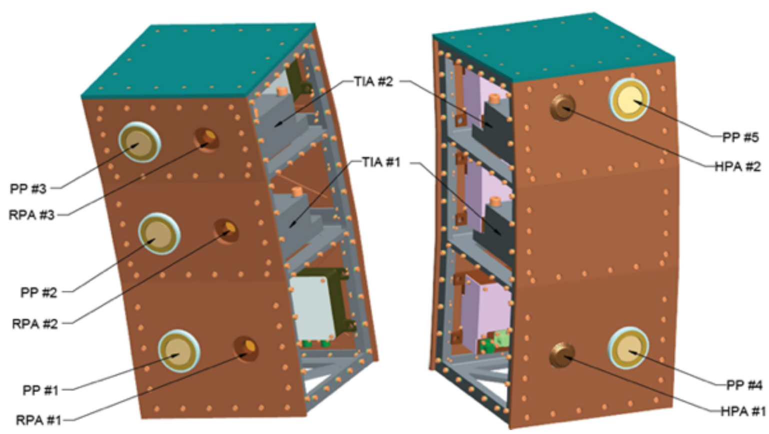

Figure 13. Concept of the PDP Thruster Probe Assembly (TPA).

The PPE spacecraft is required to fly a plasma diagnostics probe at a distance of 1 m from the AEPS thruster. As shown in Fig. 14, the probe will be mounted on the -X deck along with the thrusters, with line of sight to the thruster, while remaining out of the monopropellant thruster field of view and away from the berthing posts, refueling valves, and launch vehicle adapter. NASA is providing the probe and interface electronics unit.

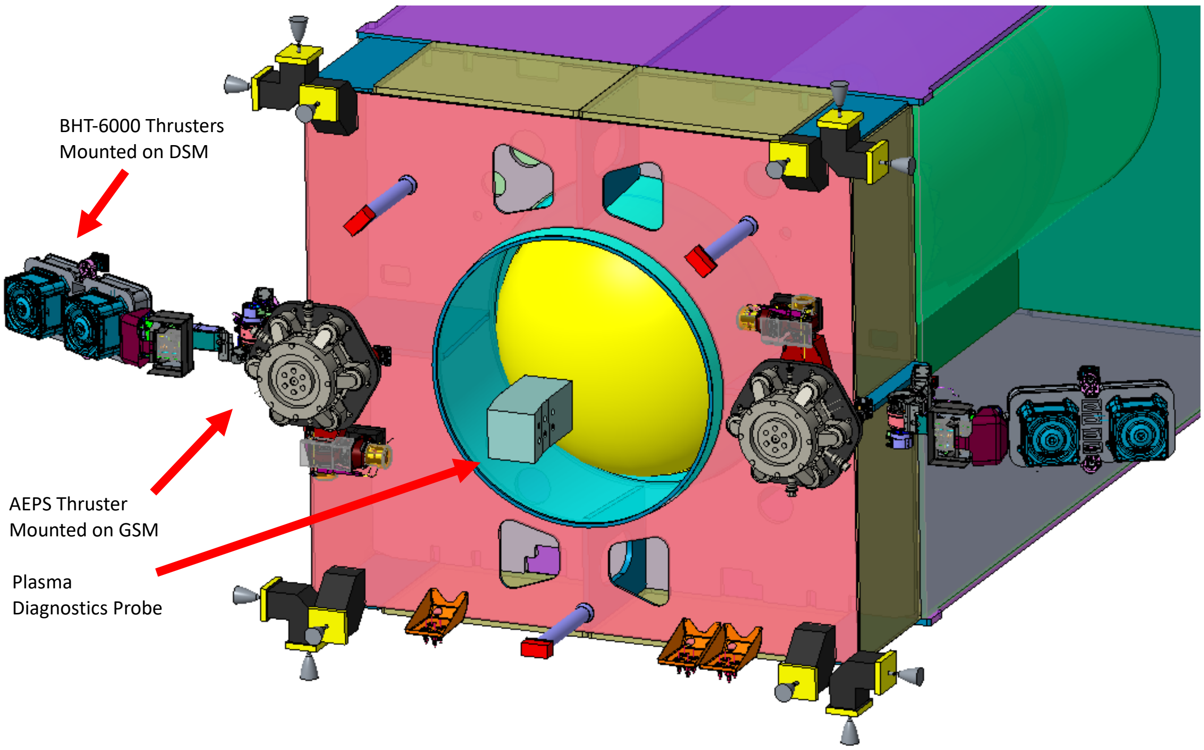

Figure 14. View of the propulsion deck on the PPE spacecraft showing the DSMs, AEPS gimbals, and PDP location to view an AEPS thruster.

V. Conclusion

To meet the Artemis challenge, NASA's Gateway will develop and deploy critical infrastructure required for operations on the lunar surface and that enables a sustained presence on and around the moon. NASA has reaffirmed its commitment to the development and application of high power solar electric propulsion as a key element of future human exploration plans. As the first element of the cislunar Gateway, NASA's Power and Propulsion Element (PPE) will provide orbit control and maneuvering and electrical power in addition to communications with Earth, visiting vehicles and lunar systems, and external research payload accommodations. The PPE contract was recently awarded to Maxar Technologies to demonstrate a 2,500 kg xenon capacity, 50 kW-class SEP spacecraft. Maxar's PPE concept design is based directly on their high heritage, modular, highly reliable 1300-series bus architecture. The electric propulsion system features two 13 kW Advanced Electric Propulsion (AEPS) strings from Aerojet Rocketdyne and a Maxar-developed system comprised of four Busek 6 kW Hall-effect thrusters mounted in pairs on large range of motion mechanisms. Development tests of the AEPS and 6 kW electric propulsion hardware are ongoing. PPE is well on its way to launch in 2022, returning to the Moon to stay and onward to Mars.

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