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

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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 and establishing sustainable lunar exploration by the end of the decade. 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 provide a 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 three 12 kW Advanced Electric Propulsion (AEPS) thrusters from Aerojet Rocketdyne and four BHT-6000 thrusters from Busek. Maxar-provided power electronics and xenon flow controllers from Moog are utilized in both the 12kW and 6kW electric propulsion strings on the spacecraft. The paper will present overviews of NASA's Gateway and the PPE Project, status of the development and qualification activities for the two electric propulsion system, and the planned implementation of PPE electric propulsion system as keystone of NASA's Gateway. The PPE spacecraft is currently heading into the Critical Design Review, with the qualification and flight electric propulsion hardware fabrication already initiated and significant progress being made toward planned qualifications in support of the planned PPE spacecraft co-manifest launch in 2024.

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Nomenclature

ΔV	=	Velocity Delta
AEPS	=	Advanced Electric Propulsion System
BAA	=	Broad Agency Announcement
CDR	=	Critical Design Review
CMV	=	Co-Manifested Vehicle
DSM	=	Dual Axis Solar Electric Propulsion Module
EOL	=	End of Life
EOR	=	Electric Orbit Raising
ETU	=	Engineering Test Unit
GEO	=	Geostationary Earth Orbit
GFE	=	Government Furnished Equipment
GRC	=	Glenn Research Center
HALO	=	Habitation and Logistic Outpost
HEOMD	=	Human Exploration and Operations Mission Directorate
IPS	=	Ion Propulsion System
NRHO	=	Near Rectilinear Halo Orbit
NSSK	=	North/South Station-Keeping
PDR	=	Preliminary Design Review
PPE	=	Power and Propulsion Element
PPU	=	Power Processing Unit
SEP	=	Solar Electric Propulsion
SRR	=	System Requirements Review
SSM	=	Subsystem Manager
VF	=	Vacuum Facility
XFC	=	Xenon Flow controller

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.[1,2] 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.[3-5] The high-power Hall thruster system, along with flexible blanket solar array technology, provides 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 (PPE), 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. A NASA and commercial partnership with Maxar was formed to leverage NASA and U.S. industry investments in high-power, high-throughput SEP technology on a high-reliability, heritage, commercial spacecraft platform that can address both commercial and NASA needs. For NASA, PPE enables the start of Gateway and crewed lunar surface operations followed by a sustainable presence in lunar orbit for expanded surface operations and extensibility for Mars exploration beyond.

To date, Maxar has launched 41 Geostationary Earth Orbit (GEO) communication spacecraft with a total of 164 electric propulsion Hall-effect thrusters. The SEP-equipped Maxar fleet has accumulated over 180,000 hours of on-orbit firing time.[6] This system has grown from one strictly for on-orbit North/South Station-keeping (NSSK), to being capable of providing all propulsion needs for the spacecraft, from initial electric orbit raising (EOR) through end of life (EOL) deorbit. The Maxar commercial electric propulsion subsystems have 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.[7, 8] 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 48 kW electric propulsion system spread over seven thrusters and ten power processing units. Four 6 kW Hall thrusters will be provided by Busek, mounted on a modification of Maxar's traditional Dual-Axis SEP Modules (DSMs), and three 12 kW Hall thrusters provided by Aerojet that are mounted on smaller range of motion two-axis gimbals built by Ruag.[9, 10] The xenon feed system provides up to 2770 kg of xenon at launch and can be refuelable while in-orbit around the moon. The seven Hall thrusters, in addition to 24 bipropellant chemical thrusters are designed to supply all propulsion needs for the entire cis-lunar Gateway.

The paper will present overviews of NASA's Gateway and the PPE Project, status of the development and qualification activities for the two electric propulsion strings, and the planned implementation of PPE electric propulsion system, including significant changes made since baseline design and implementation described in Ref. 11 to a co-manifested launch, as keystone of NASA's Gateway. The PPE spacecraft is currently heading into the Critical Design Review in early 2023, with the qualification and flight electric propulsion hardware fabrication already initiated and significant progress being made toward component qualifications in support of the planned PPE spacecraft co-manifest launch in 2024.

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." [12] 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.

As a core element of the Artemis Program, NASA's Gateway, illustrated in Fig. 1, will develop and deploy critical infrastructure required for operations on the lunar surface and that enables a sustained presence on and around the moon.[13] 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

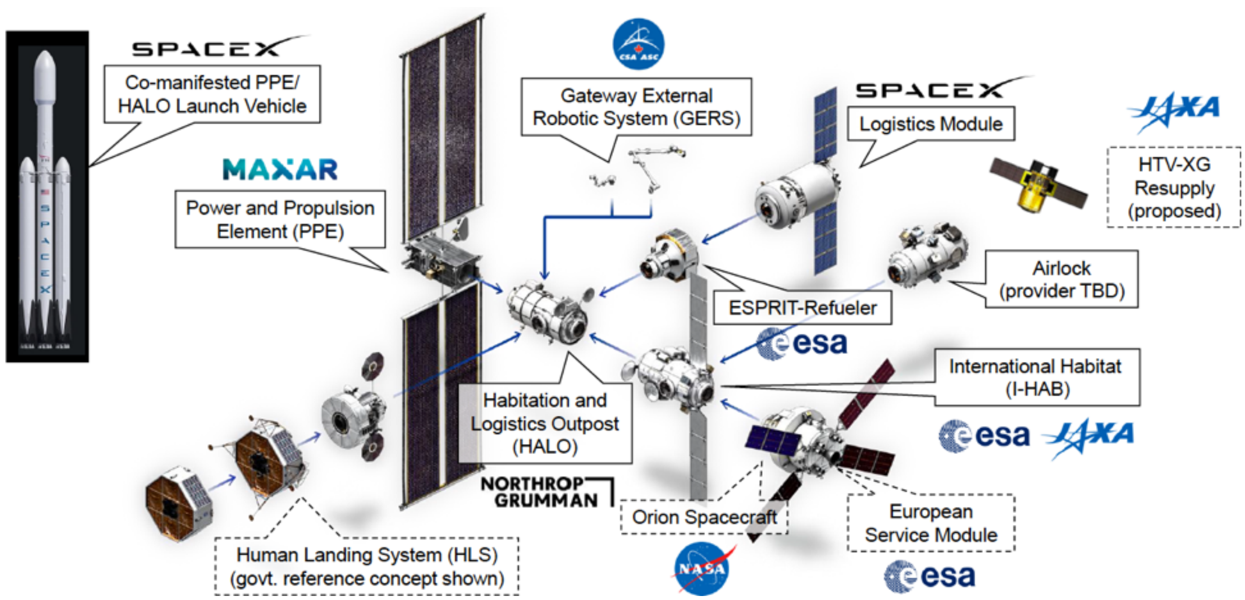

Figure 1. Gateway integrated spacecraft to support the Artemis Program.

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. Phase I of Gateway, see Fig. 2, consists of the PPE, a Habitation and Logistics Outpost (HALO), the Human Lunar Lander, and the crewed Orion vehicle. The integrated PPE and HALO elements provide the basic Gateway power, propulsion, and crewed support needs supporting the initial human operations on the lunar surface and sustained presence beyond.

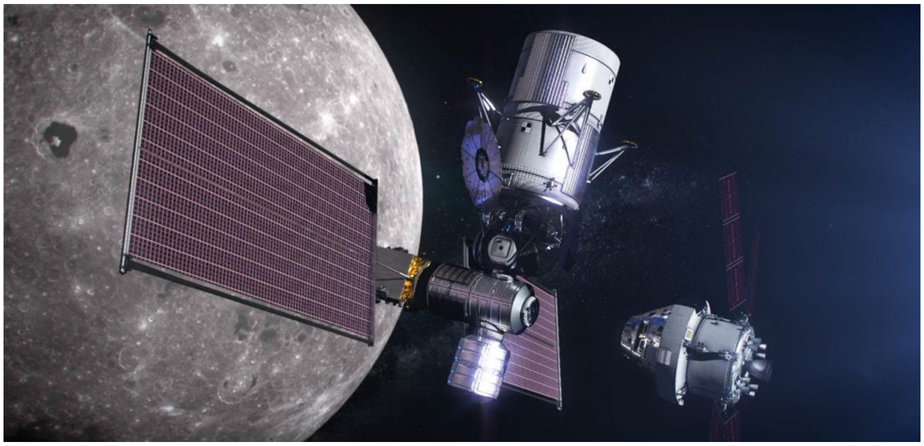

Figure 2. Phase I Gateway illustration including the Power and Propulsion Element (PPE), Habitation and Logistics Outpost (HALO), Human Lunar Lander, and crewed Orion vehicle.

B. Power and Propulsion Element (PPE)

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.[14] 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.[15] 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] In September 2019, Maxar successfully completed the PPE System Requirements Review (SRR).

In May 2020, NASA directed a significant change to the plan for launching the initial elements of the Artemis program. Instead of launching the first two modules, PPE and HALO, separately and docking them in lunar orbit as originally planned, the decision was made to integrate them on the ground and perform a co-manifested vehicle (CMV) launch on a single launch vehicle to eliminate the cost of the second launch vehicle and the risk of the on-orbit docking. The resultant significant contractual and technical changes to the PPE for the co-manifest launch required a delta SRR reflecting the roughly doubling of the required electric propulsion total impulse to be provided by PPE during co-manifest electric orbit raise due to increased co-manifest vehicle mass and reduced launch apogee, as well as many other significant changes to the PPE spacecraft and mission.

To provide the increased electric propulsion capability associated with the co-manifested launch change, the biggest changes to the PPE electric propulsion system were an increase in the xenon storage capacity and an increase from two to three 12kW thrusters, see Fig. 3. The 12kW Advanced Electric Propulsion System (AEPS) thrusters will be fabricated by Aerojet Rocketdyne and provided by NASA to Maxar as government-furnished equipment (GFE). The rest of the 12kW EP string hardware consists of the Maxar-provided power electronics and Maxar-subcontracted xenon flow controllers provided by Moog. The PPE spacecraft Preliminary Design Review (PDR), including the updates for the co-manifested launch change, was successfully completed in November 2021 with a planned PPE spacecraft Critical Design Review (CDR) scheduled for early 2023.

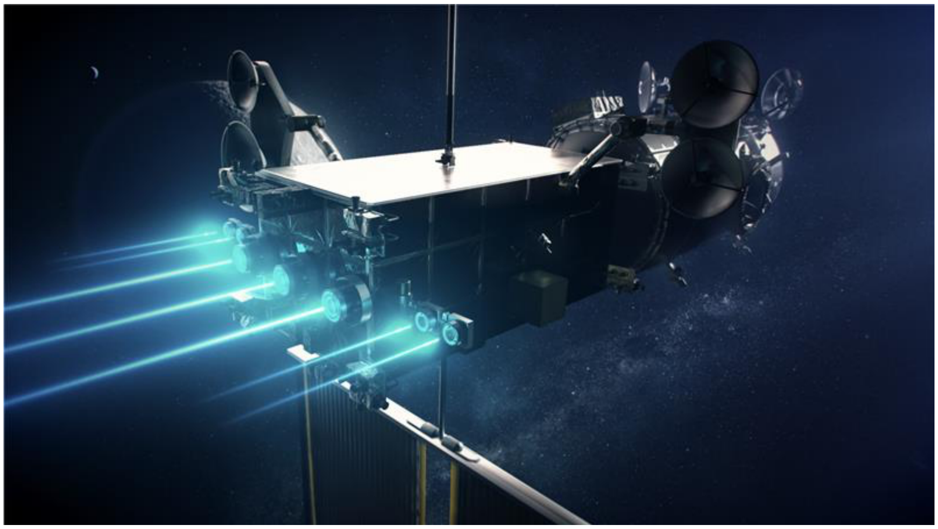

Figure 3. Rendering of PPE spacecraft showing seven high-power EP thrusters operating.

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 (functional uses defined in Table 1), attitude control, communications, and data relay services. PPE will provide regulated 120 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. The high efficiency SEP system will provide the primary source of ΔV capability for initial CMV orbit raising and insertion into the Near-Rectilinear Halo Orbit (NRHO), for the integrated Gateway stack orbit maintenance maneuvers, for the midlife orbit transfer of the entire Gateway stack, and for the end-of-life Gateway disposal. 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.

Table 1. PPE Propulsion Systems Functional Uses.

	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

The PPE mission depicted in Fig. 4, begins in 2024 with a launch on a Falcon Heavy launch vehicle placing CMV in a highly elliptical transfer orbit. After separation from the launch vehicle PPE will perform a series of bus equipment checkouts and immediately start raising perigee out of the atmosphere and the low altitude LEO environment rapidly being occupied by small sat constellations. PPE will then begin a period of long duration autonomous EOR utilizing the SEP system to move through the radiation belts and transfer to the target NRHO around the moon.

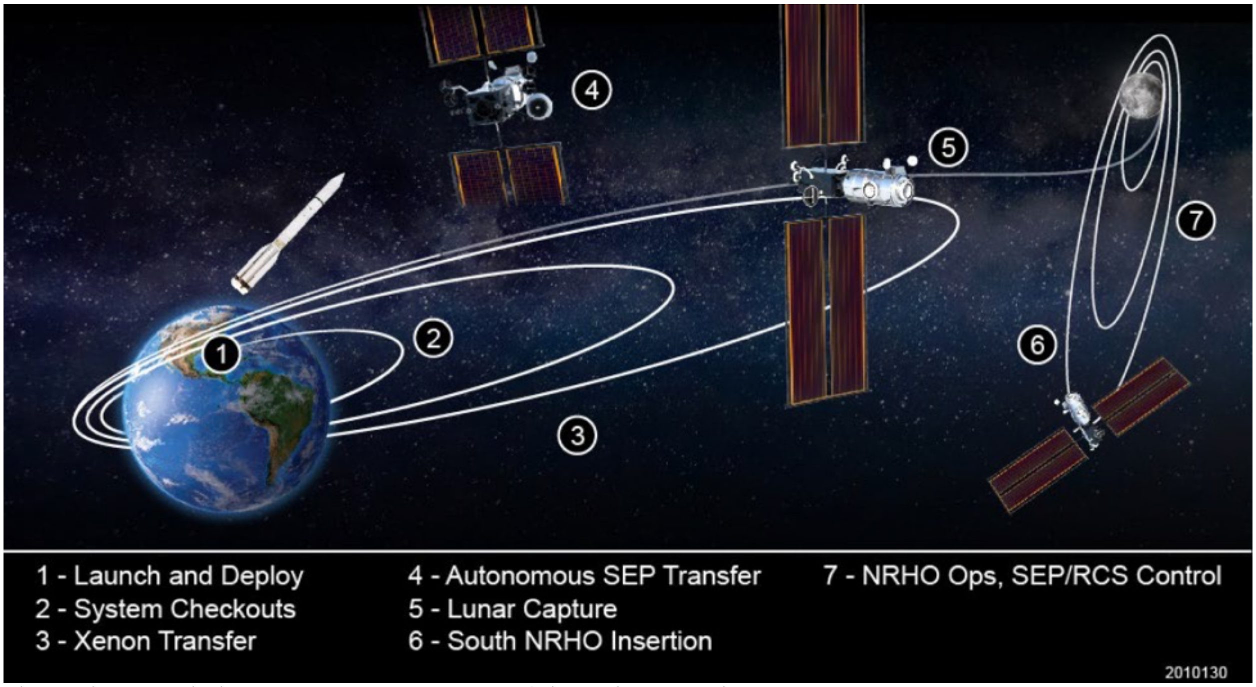

Figure 4. PPE mission – launch through NRHO insertion overview.

III. PPE Ion Propulsion Subsystem

The PPE spacecraft including the ion propulsion subsystem is at a preliminary design level. The preliminary layout of electric propulsion thrusters mounted on the aft deck of the PPE spacecraft is shown in Fig. 5 (hard-mounted structure for center AEPS thruster not shown). Integrated analysis such as electric propulsion plasma plume interactions have been matured to a preliminary level.[16] The advancement of the PPE design can be seen in Fig. 5 when compared to the similar figure Ref. 11 for the PPE IPS preliminary design before the co-manifested launch change.

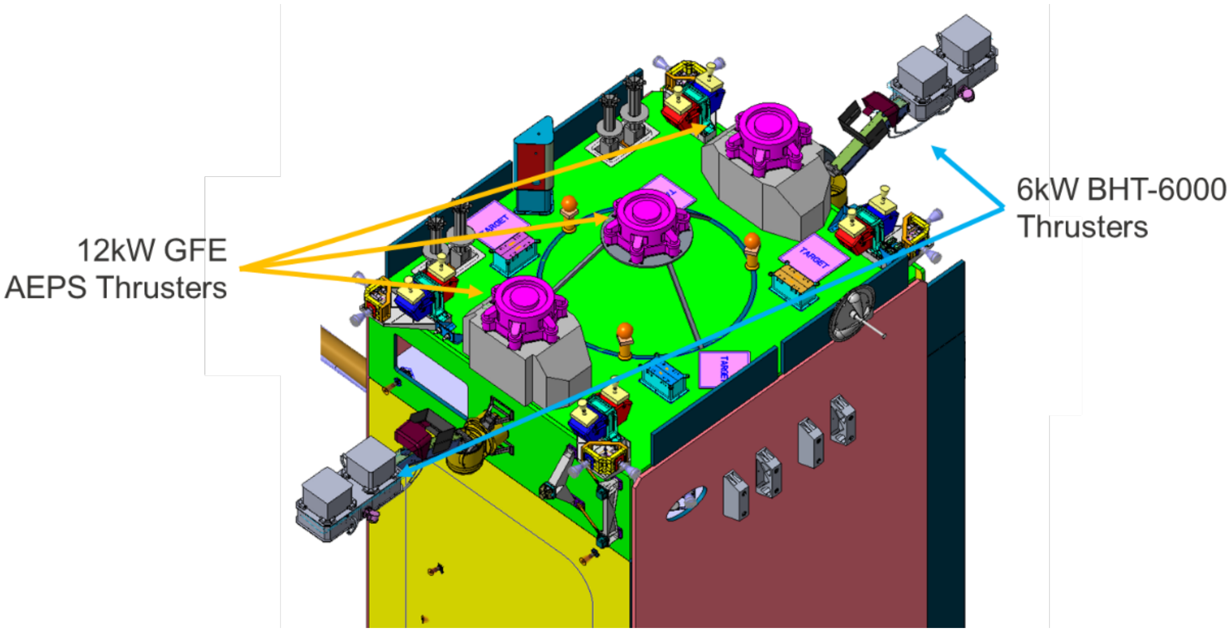

Figure 5. PPE preliminary spacecraft aft layout showing electric propulsion thrusters.

A. Maxar PPE Ion Propulsion Subsystem Design Overview and Status

Maxar's PPE spacecraft draws heavily on the heritage 1300-series spacecraft bus and subsystems to leverage established reliability and lower program risk. Numerous Maxar components which have flown successfully on GEO spacecraft since 2004 will also fly on PPE. Many of these components have undergone minor design iterations based on on-orbit lesson's learned.[17] 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] 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. The spacecraft is required to be refueled on-orbit for both bi-prop and xenon propellants, which is needed to support the program 15 year orbit maintenance in the NRHO and cis-lunar transfers since the CMV lunar transit consumes a significant portion of the xenon loaded at launch. A refuelable Gateway platform also provides significant long-term flexibility and the on-orbit refueling experience feeds forward into future exploration architectures. This will be the first on-orbit transfer of Xenon propellant in an electric propulsion spacecraft.

The electric propulsion system features three 12 kW AEPS thrusters from Aerojet Rocketdyne powered by Maxar power electronics and xenon flow controller from Moog. Two of the three AEPS thrusters are mounted on a RUAG gimbal with range of motion sufficient to support the wide variation in Gateway configurations over life. Complementing the 12kW EP strings are four Busek 6 kW Hall-effect thrusters mounted in pairs on large range of motion pointing arms, supported by four 6 kW class power processing units (PPUs), as well as four Moog xenon flow controllers (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.[18]

As previously discussed, the most significant changes in the PPE IPS simplified schematic, shown in Fig. 6, resultant from the co-manifested launch decision are the increase in xenon propellant capability (addition of a second 825 L xenon tank) and the addition of the third AEPS thruster in order to meet more demanding electric propulsion mission needs. See Ref. 11 for details on the PPE IPS preliminary design before the co-manifested launch change.

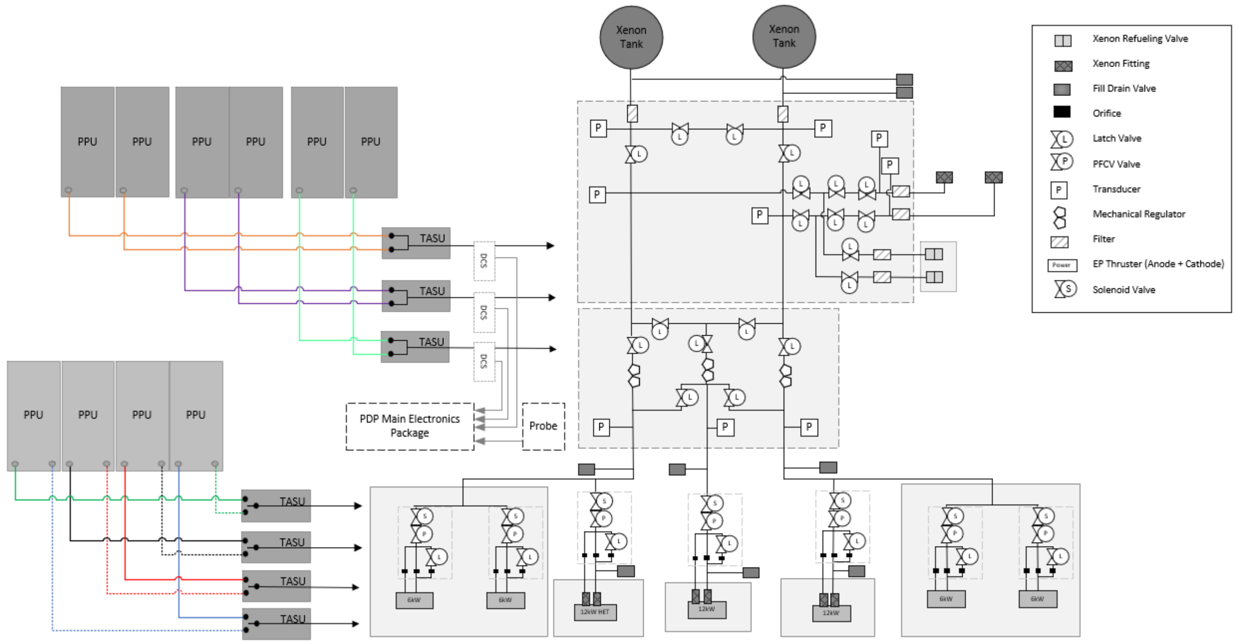

Figure 6. Maxar PPE Ion Propulsion System (IPS) Simplified Schematic.

B. PPE IPS Performance Capability

The individual electric propulsion thrusters/strings can be combined to provide an unparalleled and dynamic integrated spacecraft electric propulsion system capability. The PPE IPS can provide 60 kW of electric propulsion power, but spacecraft power and thermal restrictions apply. For CMV lunar transit, the preliminary mission operations consists of three AEPS thrusters and two BHT-6000 thruster pairs operating for the majority of the approximately one year CMV lunar transit. For various constant solar array powers, the two different throttleable thrusters can provide a range of specific impulse and thrust combinations (see Fig. 7). The combination of the seven electric propulsion thrusters also provides a significant total impulse capability that exceeds 150 MN-s.

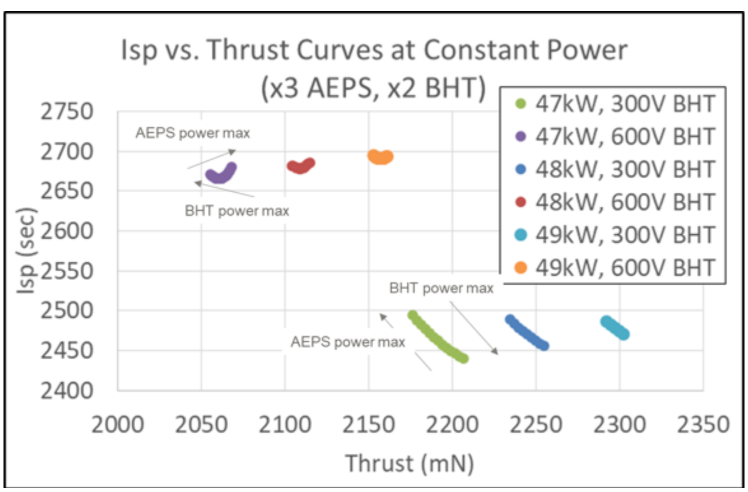

Figure 7. PPE IPS constant power performance curves during nominal CMV lunar transit operations. Note: AEPS thrusters are operating at 600 V over discharge power levels between 9 – 12 kW.

Based on swirl torque calculations the PPE IPS system can generate upwards of 15mN-m of torque when operated at 48kW.[19] The team plans to wire the AEPS and BHT thruster magnetic fields in opposite directions as a mitigation to cancel out the swirl torques to the extent possible. This should result in 5mN-m of torque during 48kW EOR operation with both sets of thrusters, and upwards of 10mN-m of torque during 20-30kW AEPS-only operation during Gateway cis-lunar orbit transfers.

IV. PPE Ion Propulsion Subsystem Component Status

The PPE spacecraft completed PDR in November 2021, but all PPE IPS components are well past PDR and the majority past CDR with some already into flight unit production. The following sections provide an overview of the current status of the PPE IPS components with references to corresponding papers for additional details.

A. 12kW EP String Development/Qualification Status and Implementation

The three 12kW PPE EP strings each consist of the AEPS thruster, the 12kW power electronics, the xenon flow controller, and the gimbal mechanism (2 of 3 AEPS thrusters are gimbaled and one is hard mounted).

1. *AEPS Thruster*
   The 12kW Aerojet thruster is being developed and provided by Aerojet through the NASA Advanced Electric Propulsion System (AEPS) contract. As part of the AEPS contract, Aerojet built two Engineering Test Unit (ETU) Hall thrusters (see Fig. 8) based on the NASA HERMeS magnetically shielded Hall thruster and conducted a series of tests to validate the design. One series of tests focused on environments and functional testing, while the other series was primarily focused on long duration wear test blocks to characterize erosion rates.[20, 21] The Aerojet 12kW AEPS thruster is being qualified and flight units produced under the AEPS contract and will be provided to PPE as GFE. The AEPS thruster has completed CDR and production has begun on the two qualification units and 3 flight thrusters. For additional details see references 3 – 5, 10, 20, and 21.

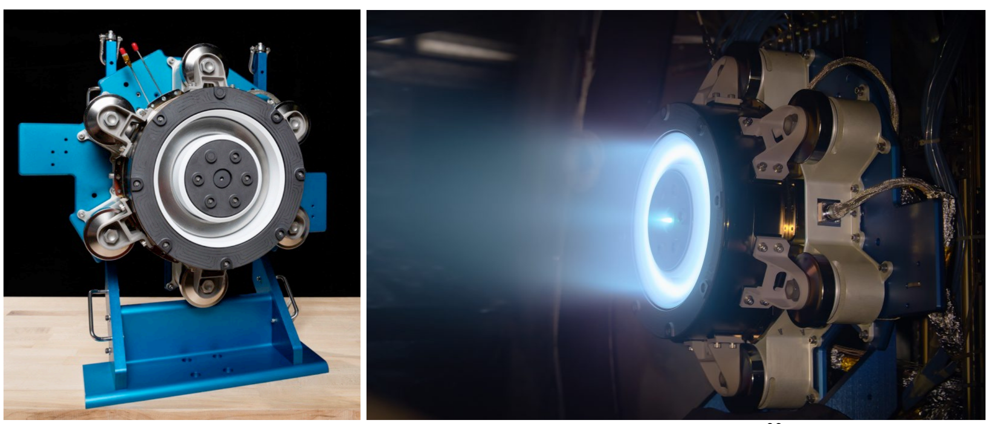

Figure 8. Aerojet-fabricated AEPS ETU thruster.[22]

2. *12kW Power Electronics*
   The Maxar 12kW power processing unit (PPU) and 12kW thruster auxiliary support unit (TASU) are based on heritage Maxar designs[23] and have completed one subsystem end-to-end hot fire test campaign[24], with additional development testing planned in the coming months. The 12kW PPU is comprised of two 6kW PPUs with their anodes tied in parallel. Each 6kW PPU is comprised of 9 individual trays, all of which will begin their qualification builds in 2022. The 6kW PPU and TASU units have passed CDR with a 12kW application CDR planned for late 2022. The TASU includes the output filter and, for the 6kW TASU, includes the cross-strapping functionality. The 6kW TASU qualification unit is in production.

3. *Ruag GSM*
   The Ruag Gimbaled Solar electric propulsion Module (GSM) is based on heritage principles[25] has completed CDR and the two flight builds are progressing. This gimbal will be the largest electric propulsion module ever built to hold the 12kW AEPS thruster and will have a pointing range of +/-30deg to allow for use over the

widely varying gateway configurations. The team has completed harness, pneumatic, and a gimbal only shock test. A combined gimbal+thruster shock test is planned to occur in late 2022.

4. *XFC*
The Moog 12kW Xenon Flow Controller will have an orifice modification to the variant qualified for the Psyche program and will be capable of providing up to 23mg/sec of Xenon at two anode/cathode flow split ratios of based on the position of the latch valve.[26] All three flight XFCs are in production.

5. *12kW EP Integrated String*
String level tests are necessary to ensure compatibility of separately developed electric propulsion hardware. This is ever more important for the 12kW string on PPE as primary components of the string (the XFC and PPU) are modifications of hardware not originally designed to operate at 12kW. As such, string level testing is a necessary step to not only validate the current design, but also to help define requirements elsewhere in the subsystem and on the spacecraft. The 12kW Phase 1 test was conducted at NASA GRC in vacuum facility 6 (VF-6) from Dec. 2021 – April. 2022 (see Fig. 9 for test images).[27] The 12kW integrated string test followed previous Maxar electric propulsion string test plans.[29]

The 12kW Phase 1 test was highly successful in that it (1) verified the functionality of PPE's electric propulsion hardware working together in both nominal and off-nominal conditions and (2) 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.[27] A 12kW Phase 2 test is planned for late 2022.

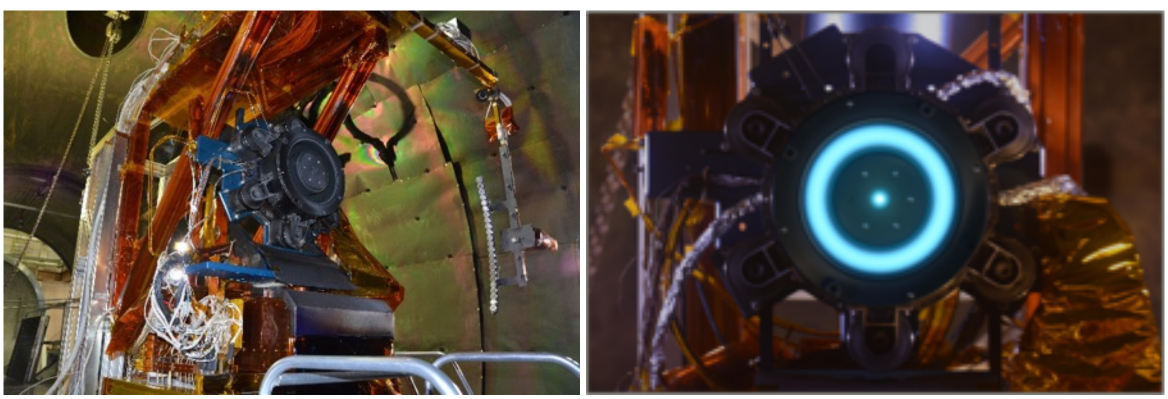

Figure 9. The 12kW string has been tested at NASA Glenn Research Center (GRC) in VF-6.

B. 6kW EP String Development/Qualification Status and Implementation

The four 6kW PPE EP strings each consist of the BHT-6000 thruster, the 6kW power electronics, the xenon flow controller, and the gimbal mechanism (each gimbal has two thrusters mounted on it). The 6kW EP string hardware is shown in Fig. 10. Additional information on the 6kW electric propulsion system can be found in reference 18.

1. *BHT-6000 Thruster*
The 6 kW EP thruster 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.[18, 28] The Busek designed 6kW Hall thruster has completed CDR and is well into its qualification phase. On-going efforts to better characterize this thruster are planned: future subsystem end to end hot fire testing, a low-pressure plume and stability characterization test at NASA Glenn Research Center (GRC).

2. *6kW Power Electronics*
   The Maxar 6kW power processing unit (PPU) and 6kW thruster auxiliary support unit (TASU) have completed two subsystem end-to-end hot fire tests, with additional development testing planned in the coming months.[24] The PPU is comprised of 9 individual trays, all of which will begin their qualification builds in 2022.

3. *Modified DSM*
   The 6kW DAPM-actuated Solar electric propulsion Module (DSM-6000) is a modification of Maxar's DSM-100 and DSM-140 variants which have been in operation on GEO spacecraft for almost two decades.[6] Maxar's DSM design holds two thrusters and two XFCs, allowing for a simplified interface to the spacecraft to reduce volume and mass. The DSM has a rotation range exceeding 90deg allowing for both electric orbit raising operation (thrust vector pointed forward along PPE axis) as lunar stationkeeping (thrust vector varies to point at gateway center of mass for different configurations). The module is targeting a CDR in late 2022.

4. *XFC*
   The Moog designed 6kW Xenon Flow Controller is identical to that qualified for the Psyche program and is capable of providing up to 23mg/sec of Xenon at two different anode/cathode flow split ratio's based on the position of the latch valve.[26] The Psyche spacecraft launch in late 2022 will show the XFC can be successfully operated on-orbit from the Maxar PPU power supply and control algorithm. All four flight XFCs are in production.

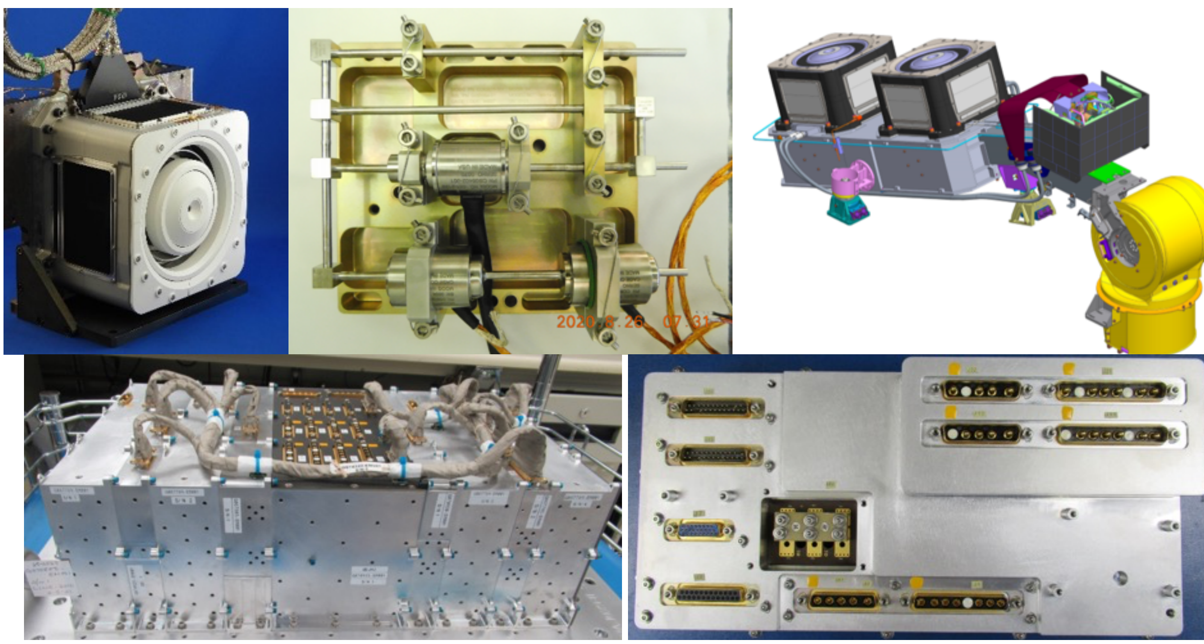

Figure 10. 6kW string hardware: BHT-6000 thruster (top left), 6kW XFC (top middle), 6kW DSM (top right), 6kW PPU (bottom left), and 6kW TASU (bottom right).

5. *6kW EP Integrated String*

The 6kW EP string has completed integrated string tests in both Busek[18] and NASA facilities, see Fig. 11, following the test plan of previous Maxar electric propulsion string level testing.[29] The 6kW EP string integrated tests 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, and 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.

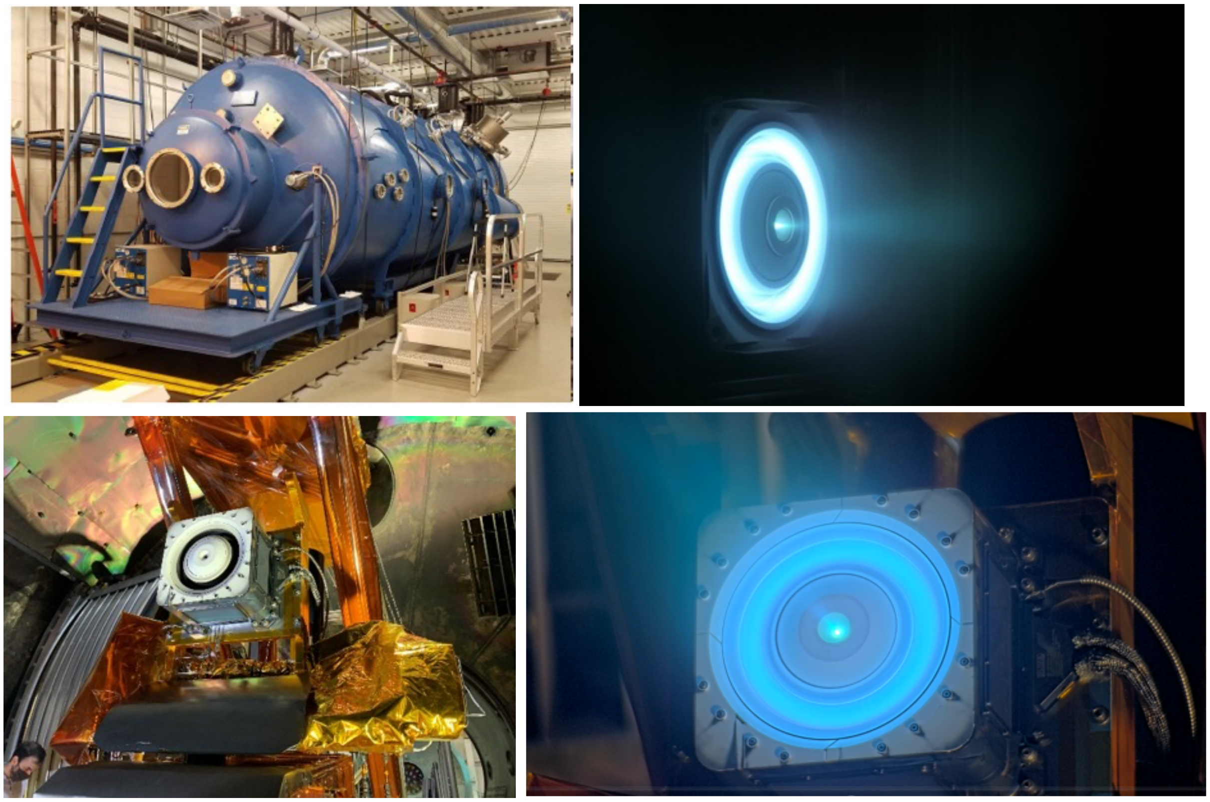

Figure 11. The 6kW string has been tested in both Busek facilities (top) and NASA GRC facilities (lower).

C. Xenon COPV

The 12kW and 6kW strings share common 825L xenon tanks, refueling manifolds, as well as Maxar-heritage regulation and isolation components. The NuSpace 825L xenon tank, see Fig. 11, is a modification of a heritage COPV design and has passed CDR and have progressed into production of the two flight units.[30] The 825L xenon tanks are launched fully loaded containing 2770 kg of xenon at a pressure that is less than 2000 psi. The tank pressures over the Gateway mission profile are included in Fig. 13 and reflects two 800 kg xenon refueling events during the 15 year mission.

Figure 12. NuSpace 825L COPV tank.

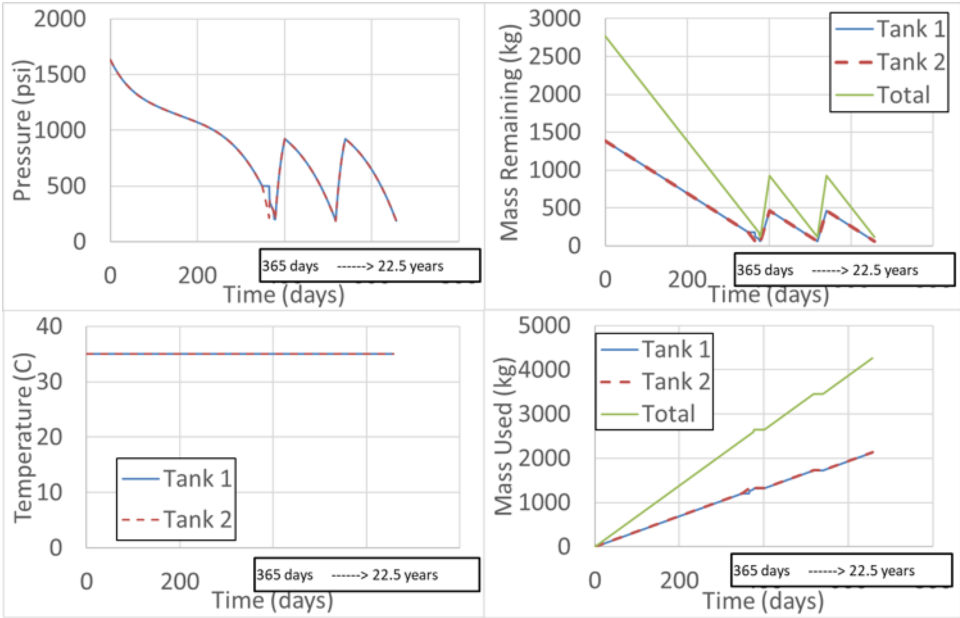

Figure 13. PDR analysis of Xenon tank pressure profiles over the mission duration assuming a 2500 kg EOR, followed by lunar orbit maintance, orbit transfers, and two 800 kg refueling events. This profile uses just over 4000 kg of propellant and applies 105 MNs of total impulse to the Gateway.

V. Conclusion

NASA is embarking on a new and exciting era of human exploration to the Moon and its vicinity. Under the Artemis program, NASA is developing the lunar Gateway, an orbiting platform in Near Rectilinear Halo Orbit (NRHO) about the Moon. The launch of the two Gateway modules (PPE and HALO) and the transfer of this large payload to cislunar orbit will mark a significant milestone in electric propulsion, as it will demonstrate the ability of SEP to transfer very large payloads over great distances. This establishes the precedent that could lead to cargo transfers from the Earth to the Moon or even to Mars using SEP. In 2024 the initial elements of the Gateway will be launched and then transferred from a high Earth orbit to the NRHO via the use of electric propulsion that is contained within the PPE spacecraft. PPE has completed its preliminary design with a planned CDR in early 2023. All PPE IPS components are well past PDR and the majority past CDR with some already into qualification and flight unit production. Multiple integrated EP string tests have been completed and additional integration tests are planned to ensure successful demonstration and operation of this unparalleled EP capability on PPE in support of the Artemis program.

References

[1]Smith, B. K., Nazario, M. L., and Cunningham, C. C., "Solar Electric Propulsion Vehicle Demonstration to Support Future Space Exploration Missions," Space Propulsion 2012, Bordeaux, France, May 7-10, 2012.

[2]Lord, P. W., Tilley, S., Goebel, D. M., and Snyder, J. S., "Third Generation Commercial Solar Electric Propulsion: A Foundation for Space Exploration Missions," 2018 IEEE Aerospace Conference, Big Sky, MT, March 2018.

[3]Herman, et. al., "The Ion Propulsion System for the Solar Electric Propulsion Technology Demonstration Mission," IEPC-2015-008, 34th International Electric Propulsion Conference, Kobe, Japan, July 4 – 10, 2015.

[4]Hofer, et. al., "Completing the Development of the 12.5 kW Hall Effect Rocket with Magnetic Shielding (HERMeS)," IEPC-2019-193, 36th International Electric Propulsion Conference, Vienna, Austria, Sept. 15 – 20, 2019.

[5]Peterson, et. al, "Overview of NASA's Solar Electric Propulsion Project," IEPC-2019-836, 36th International Electric Propulsion Conference, Vienna, Austria, Sept. 15 – 20, 2019.

[6]Johnson, I., G. Santiago, J. Li, and J. Baldwin, "100,000 hrs of on-orbit electric propulsion and Maxar's first electric orbit raising," to be presented at the 2020 AIAA SciTech Forum, Orlando, FL, Jan. 6-10, 2020.

[7]Johnson, I. K., Kay, E., Lee, T., Bae, R., and Feher, N., "New Avenues for Research and Development of Electric Propulsion Thrusters at SSL," IEPC-2017-400, 35th International Electric Propulsion Conference, Atlanta, GA, October 2017.

[8]Delgado, J. J., Baldwin, J. A., Corey, R. L., "Space Systems Loral Electric Propulsion Subsystem: 10 Years of On-Orbit Operation," IEPC-2015-04, 30th International Electric Propulsion Conference, Kobe, Hyogo, Japan, July 4 - 10, 2015.

[9]Hruby, V., "Overview of Busek EP Thrusters," IEPC-2019-926, 36th International Electric Propulsion Conference, Vienna, Austria, Sept. 15 – 20, 2019.

[10]Jackson, et. al., "13kW Advanced Electric Propulsion Flight System Development and Qualification IEPC-2019-692," 36th International Electric Propulsion Conference, Vienna, Austria, Sept. 15 – 20, 2019.

[11]Herman, et. al., "The Application of Advanced Electric Propulsion on the NASA Power and Propulsion Element (PPE)," IEPC-2019-651, 36th International Electric Propulsion Conference, Vienna, Austria, Sept. 15 – 20, 2019.

[12]https://www.whitehouse.gov/presidential-actions/presidential-memorandum-reinvigorating-americas-human-space-exploration-program/

[13]Lueders, K. and Free, J., "NASA Space Operations Mission Directorate and Exploration Systems Development Mission Directorate Status Report," Presented at Human Explorations and Operations Committee of the NASA Advisory Council, Jan. 18-19, 2022.

[14]https://www.fbo.gov/index?s=opportunity&mode=form&id=98f5fc528dd2a2b9b2c525a2973f2a4e&tab=core&_cview=1

[15]https://www.nasa.gov/press-release/nasa-awards-artemis-contract-for-lunar-gateway-power-propulsion

[16]Corey, et. al., "Lunar Gateway Power and Propulsion Element (PPE): Electric Thruster Plume Analysis," IEPC-2022-466, 37th International Electric Propulsion Conference, Boston, MA, June 19 - 23, 2022.

[17]Lord, P., et. al. "Beyond TRL 9: Achieving the Dream of Better, Faster, Cheaper Through Matured TRL 10 Commercial Technologies", 2019 IEEE Aerospace Conference, 2019.

[18]Lenguito, et. al., "MAXAR Electric Propulsion String Development: 6kW 300/600V Dual Mode at a Tipping Point," IEPC-2022-407 37th International Electric Propulsion Conference, Boston, MA, June 19 - 23, 2022.

[19]Snyder, et. al., "Electric Propulsion for the Psyche Mission: Development Activities and Status," AIAA-2020-3607, AIAA Propulsion and Energy 2020 Forum, New Orleans, LA, Aug. 24 – 28, 2020.

[20]Boyce, et. al., "Development of 12 kW Hall Thrusters for NASA Lunar Gateway and Power and Propulsion Element," Paper 438 presented at the Space Propulsion 2020 Conference, Estoril, Portugal, May 9 – 13, 2022.

[21]Frieman, et. al., "Extended Wear Testing of the 12.5-kW Advanced Electric Propulsion System Engineering Test Unit Hall Thruster," IEPC-2022-XXX, 37th International Electric Propulsion Conference, Boston, MA, June 19 - 23, 2022.

[22] https://blogs.nasa.gov/artemis/2022/06/02/gateways-propulsion-system-testing-throttles-up/

[23]Tomescu, B., et. al. "High Efficiency, Versatile Power Processing Units for Hall-Effect Plasma Thrusters", 2018 AIAA Joint Propulsion Conference, AIAA 2018-4642, 2018.

[24]Nelson, et. al., "Development of 6 kW and 12 kW Power Processing Unit Platforms for the Power and Propulsion Element Spacecraft," IEPC-2022-551, 37th International Electric Propulsion Conference, Boston, MA, June 19 - 23, 2022.

[25]https://www.ruag.com/system/files/2016-12/EPPM.pdf

[26]Lengito, et. al., "Versatile Xenon Flow Controller for Extended Hall Effect Thruster Power Range," IEPC-2019-303, 36th International Electric Propulsion Conference, Vienna, Austria, Sept. 15 – 20, 2019.

[27]Johnson, et. al., "PPE Electric Propulsion Advancing to CDR: 12kW String," IEPC-2022-467, 37th International Electric Propulsion Conference, Boston, MA, June 19 - 23, 2022.

[28]Mullins, et. al., "Development of a 5kW Class Thruster," IEPC-2019-492, 36th International Electric Propulsion Conference, Vienna, Austria, Sept. 15 – 20, 2019.

[29]Kerl, T., et. al. "Maxar Electric Propulsion Development for Deep Space", 2020 AIAA Propulsion and Engergy Forum, AIAA 2020-3605, 2020.

[30]https://keyengco.com/wp-content/uploads/2020/02/Data-Sheet-1140000.pdf