Application of Solar Electric Propulsion to the Low Thrust Lunar Transit of the Gateway Power and Propulsion Element

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I. Motivation and Background

NASA has committed to returning to the moon, landing the first woman and the next man on its surface. To support a sustained lunar presence, NASA will assemble an orbital platform in a quasi-stable orbit near the moon known as a Near Rectilinear Halo Orbit (NRHO) [1]. This platform, known as Gateway, will support long duration exploration missions targeting the lunar south pole. An architecture simplification implemented in 2020 combined the first two elements of the Gateway together onto a single commercial launch vehicle (CLV). When launched, the Power and Propulsion Element (PPE) and the Habitation and Logistics Outpost (HALO) will form the initial capability of NASA's Gateway [2]. The PPE, with its high-power Solar Electric Propulsion (SEP) system, will propel the combined vehicle from an elliptical Earth parking orbit to the target NRHO [3]. A transit of such a large mass, delivered to the moon from a single launch vehicle, is only made possible using the highly efficient SEP system [4]. Delivering the same mass via more traditional chemical propulsion systems would require major modifications to the mission architecture, significantly more propellant mass, and could necessitate the use of a more powerful launch vehicle. This paper describes the design of the nominal low-thrust transit by which Gateway will be delivered to the NRHO utilizing the PPE SEP system. Additionally, this paper captures how the unique capabilities of the PPE electric propulsion system have guided the design of the trajectory and how mission requirements have, in turn, impacted the maturation of the SEP system.

II. Approach

The PPE is outfitted with a 50-kW class solar electric propulsion system being developed in partnership with Maxar Space and managed by NASA's Glenn Research Center (GRC). The PPE Ion Propulsion System (IPS) is comprised of 7 individual hall effect thrusters (HETs) of two different designs. Three Advanced Electric Propulsion System (AEPS) thrusters, originally developed at NASA GRC and built by Aerojet Rocketdyne, form the core of the IPS. Four additional Busek-built BHT-6000 thrusters fill out the remainder of the onboard SEP capability [5]. The 12 kW-class AEPS and 6-kW class BHT-6000 strings combine to produce more than 2N of thrust during the Lunar Transit to the NRHO. During flight, the SEP system will be operated in two different modes, high thrust and high Isp (specific impulse). The primary difference between the two is the operating voltage of the BHT-6000 strings, which switches from 300V during high thrust operation to 600V during high Isp operation [6]. This bi-modal operation is advertised as a unique design capability of the BHT-6000 by Busek [7]. The unique capability afforded by the PPE IPS enabled the PPE Mission Design Team to develop a low-thrust Lunar Transit trajectory to maximize mass delivery to the NRHO while limiting the time spent transiting through the high-ionizing dose regions of space known as the Van Allen Belts. The PPE SEP system, which will be the most powerful ever flown, is responsible for the delivery of the PPE and HALO to the NRHO, performing orbit maintenance in the NRHO for the 15-year Gateway mission,

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performing two cislunar excursion missions transferring from and returning to the NRHO, and an end of life (EOL) mission to deliver the Gateway to a disposal Distant Retrograde Orbit (DRO) [8].

III. Lunar Transit Trajectory Overview

The initial capability of the Gateway will be delivered to the target NRHO via a low-thrust Lunar Transit spiral trajectory. A commercial SpaceX Falcon Heavy launch vehicle will deposit the combined PPE+HALO spacecraft into a highly elliptic Earth parking orbit. Following a short quiescent period during which the health and performance of spacecraft systems will be verified and characterized, the PPE SEP system will be used to perform the low-thrust transit out of the Earth's gravity well. The transfer is designed in four distinct subphases (**Figure 1**). Each subphase represents a portion of the spiral transfer that is different from each other in terms of operations, physics, optimization scheme, or all three. Throughout all mission phases, utilization of the SEP system is not permitted while the spacecraft is in shadow as the power consumption required by the 50 kW IPS would rapidly overrun the vehicle's battery storage capability. Details of the design of this trajectory have been published previously [4]. At the time of writing, five iterations of the Design Reference Mission (DRM) trajectories have been developed by the PPE Mission Design Team at NASA Glenn Research Center.

Figure 1: Lunar Transit subphase definition

This low-thrust trajectory (**Figure 2**) is highly sensitive to changes in initial conditions and assumptions about the combined PPE+HALO vehicle, the performance of relevant subsystems, the capability of the selected launch vehicle, the desired launch date, and requisite CONOPS during transit. The design of this trajectory is subsequently used by subsystem engineering teams to inform operating environments, drive system requirements, and estimate spacecraft performance. The design of a DRM trajectory is highly dependent on the performance of subsystems such as the solar arrays and the 50kW SEP system. The power available from the power system and the subsequent performance output of the SEP system are themselves dependent on the design of the trajectory. This highly coupled nature of trajectory and spacecraft design has meant that the Lunar Transit mission has been designed and iterated in parallel with the maturation of the PPE and HALO spacecraft.

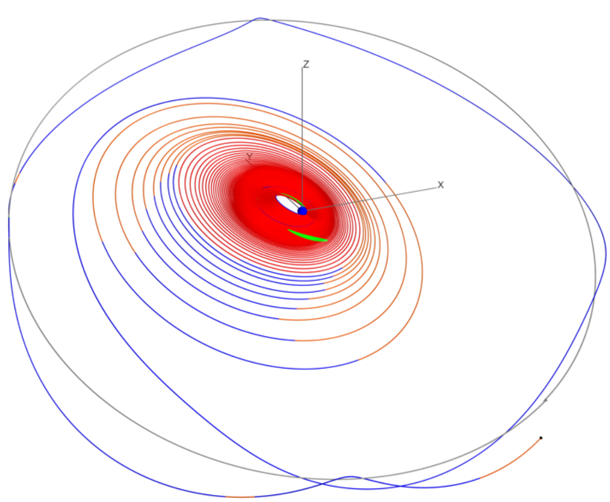

Figure 2: Lunar Transit Trajectory in Earth-centered J2000 Frame

The mass of the combined PPE+HALO spacecraft exceeds the direct-to-NRHO capability of any currently operational commercial launch vehicle. The high efficiency of solar electric propulsion enables this mission architecture by delivering a large spacecraft mass while utilizing a relatively small amount of propellant. Previous work has shown that the use of electric propulsion in this mission enables 40% more mass to be delivered to the NRHO than would be possible when using a chemical propulsion system [4]. In this manner, the PPE serves as a de facto third stage of the Falcon Heavy launch vehicle. During the nominal Lunar Transit, the PPE SEP system is expected to operate nearly continuously for more than 300 days, producing in excess of 3,000 m/s Δv and consuming more than 2,000 kg of xenon [6].

IV. Preliminary Demo Mission Thruster Trades

Early in the project, preliminary analysis was completed to determine the number of thruster strings necessary to perform the full Gateway mission. This number of strings was determined by the requirement to execute all Gateway mission phases from initial Lunar Transit through EOL disposal. The total mass of the Gateway evolves during its mission as elements are added upon delivery to the NRHO.

Under the original Gateway architecture, PPE was to deliver itself, alone, to the NRHO following launch on a CLV. This mission architecture would have included a commercial technology demonstration during PPE’s transit prior to delivery to the NRHO [9]. The initial trade studies assessed the feasibility of completing the Gateway mission using only the BHT-6000 HET, which is more life limited than an AEPS string due to the lack of magnetic shielding in its design. Analysis examined varying numbers of BHTs in order to establish the threshold needed to produce the total impulse required for the Gateway mission. This analysis included operation of the Busek HETs in both high thrust (300V) and high Isp (600V) operating modes.

For the analysis, mission design assumed four mission phases: (1) the technology demonstration where the PPE would deliver itself to the NRHO, (2) On orbit stationkeeping for 15 years of Gateway lifetime, (3) two roundtrip orbit transfers of 1 year each from the NRHO to the DRO at two different assumed Gateway total masses (39 t and 53 t), and (4) EOL transfer to the NRHO [10] [11]. Mission Design assumed that the total impulse/lifetime usage was spread evenly across all available strings. Propellant used for Orbit Maintenances Maneuvers (OMMs) was assumed to be constant from year to year across all 15 years of operations. The two cislunar transfers assumed the use of 4 BHT strings using up to 26.6 kW of power to the PPU.

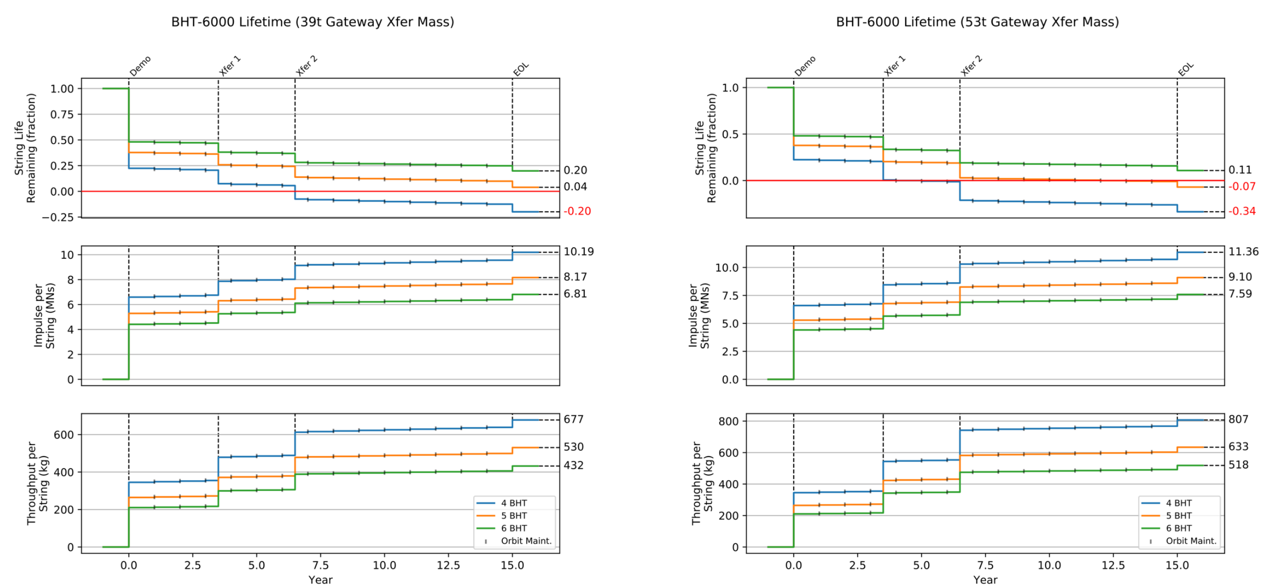

Figure 3: BHT usage timeline for two Gateway cislunar transfer mass options

Figure 3 shows a progression of the lifetime usage of a series of IPS configurations with a varying number of BHT strings over the Gateway mission lifetime, from the initial PPE transfer to the NRHO through EOL disposal. For an assumed Gateway mass of 39t, the baseline 4 BHT IPS does not have sufficient lifetime qualification to complete the Gateway mission (with a -20% margin on thruster operating life). A minimum of 5 BHT strings would be necessary to complete the Gateway mission, with just 4% qualified lifetime remaining across the entire IPS. An additional thruster (bringing the total to 6 BHTs) provides additional margin on mission requirements and results in 20% thruster life remaining at end-of-mission. Assuming a higher Gateway mass of 53t predictably results in higher impulse requirements to complete all aspects of the Gateway mission. At this higher mass, neither a 4 nor a 5 BHT IPS was found to be capable of completing the Gateway mission, with -34% and -7% lifetime remaining respectively. A SEP system composed of 6 individual BHT-6000 strings would be necessary to the Gateway mission, with 11% margin remaining at EOL. An increase in assumed Gateway stack mass from 39t to 53t thus necessitates one additional thruster string. No consideration was given to string failures or recovery scenarios and this analysis occurred very early in the project lifecycle when the vehicle itself was at a low state of maturity.

Figure 4 shows the usage split for the two different transfer mass assumptions. For the 39t and 53t Gateway mass used for the transfer, the Demo portion of the mission accounts for 52-78% of the string lifetime usage. For the 39t and 53t Gateway mass used for orbit transfers account for 17-26% and 27-40% respectively.

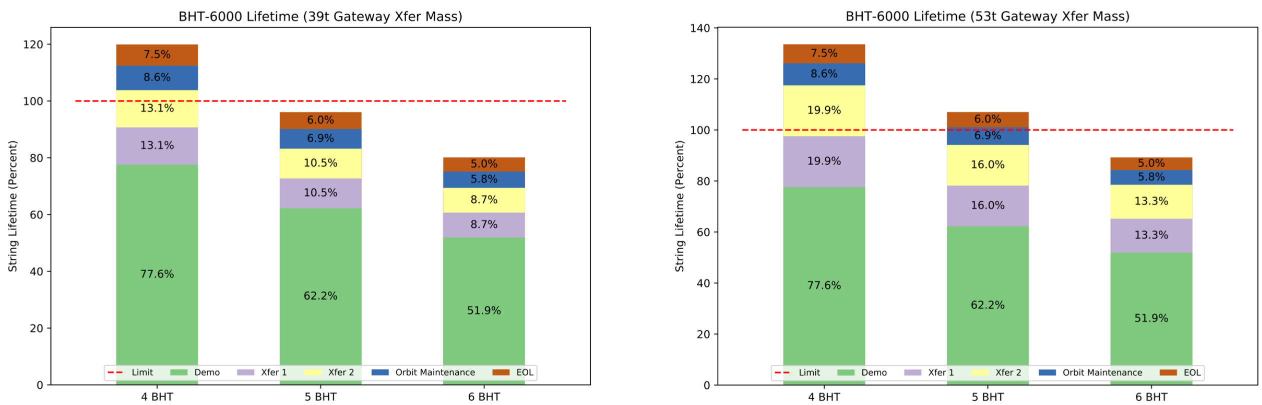

Figure 4: BHT-6000 Lifetime usage comparison Full Gateway Mission Phases

V. Co-manifest Mission BHT Thruster Trades

In 2020, the decision was made to launch the PPE and HALO modules together as a single stack and transit the combined vehicle to the NRHO using the PPE SEP system [4]. This co-manifested architecture decreased the complexity by eliminating multiple launches and on-orbit docking of the vehicles in favor of a single launch of fully integrated initial capability of Gateway. However, by adding the mass of a second, fully equipped human-rated spacecraft, the burden on the PPE SEP system increased significantly. As seen in section IV, an increase in mass also results in an increase in thruster throughput in order to satisfy the total propulsion system throughput associated with the Gateway mission.

Figure 5 shows the thruster lifetime usage split for an assumed 39t and 53t Gateway stack mass where PPE and HALO transit together to the NRHO as a single integrated vehicle. Due to significantly increased mass during Lunar Transit, the thruster throughput required to complete the transit from an Earth parking orbit to the NRHO increased significantly as well. For a 6 BHT SEP system, 51.9% of the available thruster lifetime was required for the Lunar Transit for a sole PPE transiting by itself. After integrating the HALO module, the lifetime for 6 BHT's required for Lunar Transit increased to 71.5%. The result is that for even the lighter Gateway stack mass of 39t, 10 BHT strings would be required to complete the Gateway mission, with 12% remaining across all strings. Assuming the higher stack mass of 53t increases the necessary number of BHT's to 12, also with 12% lifetime remaining.

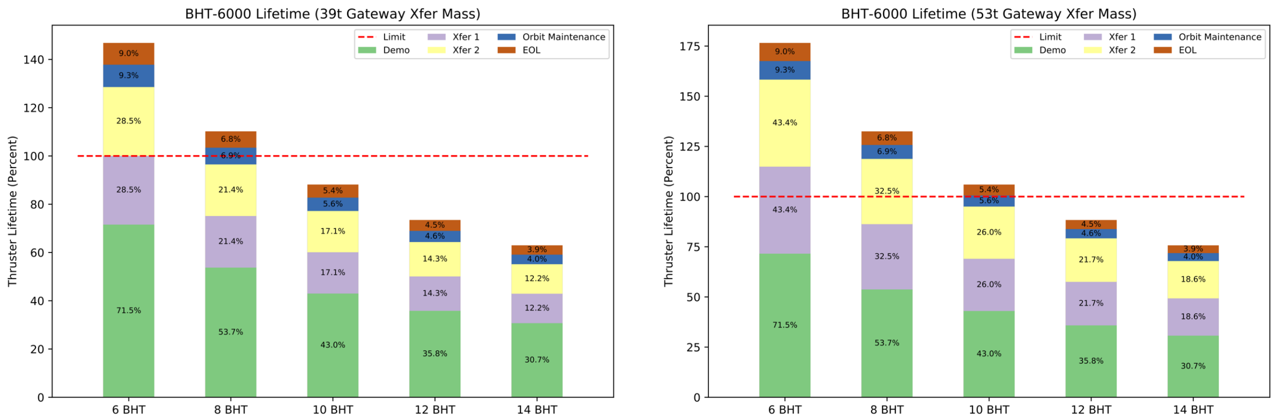

Figure 5: BHT-6000 Lifetime Usage for Combined PPE+HALO Lunar Transit and Gateway Mission

As the most stressing mission phase in terms of SEP usage, any changes in initial conditions of the Lunar Transit trajectory can significantly impact thruster lifetime later in the Gateway mission. The Lunar Transit is a low-thrust spiral trajectory originating in a highly elliptic Earth parking orbit and terminating in the baseline NRHO. Throughout the Lunar Transit, the PPE SEP system is used to increase the energy of the spacecraft's orbit until it achieves a lunar intercept trajectory. The amount of impulse the IPS must deliver in order for PPE to reach the NRHO is a function of the initial mass of the spacecraft and the energy of the initial parking orbit. A more energetic parking orbit (one with a higher apogee) will result in less impulse required of the onboard propulsion system and thus less thruster lifetime used during the Lunar Transit. Analysis was completed to investigate this relationship and determine the dependency of the number of required thrusters with respect to launch vehicle capability.

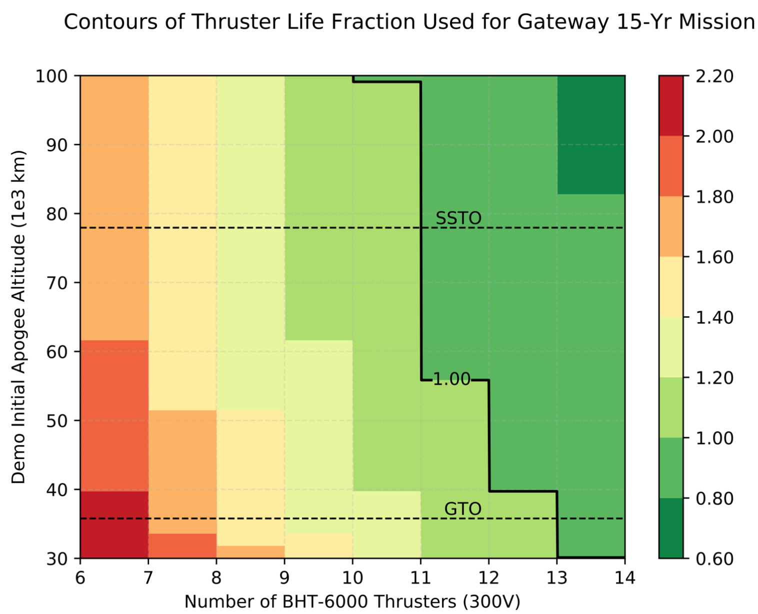

Figure 6: Contours of IPS lifetime fraction used for Lunar Transit as a function of initial apogee altitude and number of BHT-6000 strings

Figure 6 shows contours of IPS lifetime fraction used for Lunar Transit as a function of initial apogee altitude and number of BHT-6000 strings. The impact of launch vehicle performance on the required number of thrusters can be seen clearly, launching into a Geostationary Transfer Orbit (GTO) requires 13 BHT's in order to maintain positive lifetime remaining, while launching to a Super Synchronous Transfer Orbit (SSTO) only requires 10. From this figure, it seems one could choose the number of thrusters they want to fly, then find a launch vehicle capable of pushing the spacecraft to the desired parking orbit. In reality, however, launch vehicles are not infinitely capable and the necessary budget is not often available to purchase the most capable rocket available. PPE and HALO will be launched onboard a commercially available launch vehicle to a finite apogee altitude, and so the number of thrusters required is a dependent variable, not an independent one.

While the PPE is a large spacecraft, based on the heritage Maxar 1300 bus, 12 or more BHT-6000 thrusters with the necessary PPU's, xenon flow systems, and support, control, and auxiliary systems may have presented considerable packaging difficulties. Further, the additional mass of those thrusters and systems were not considered in this analysis. The complications associated with integrating and operating that many HET strings (combined with challenges to fit them onboard) as well as the desire to demonstrate the long-developed 12 kW HERMeS system motivated the use of the NASA-developed AEPS thruster on PPE.

VI. PPE Electric Propulsion System

The design of the Lunar Transit assumes the use of two different thruster string types to perform all low-thrust activities. Three long life AEPS thruster strings, which perform most of the total impulse of the mission phases, and four shorter life BHT thruster strings. This combination of strings enables the long duration mission and the flexibility to maneuver a very large spacecraft with changing configurations as the Gateway is assembled and operated. The high thrust mode distributes power amongst the thruster strings to maximize the total system thrust, and the high Isp mode performs a similar distribution to maximize the total system Isp. To date, all iterations of the reference Lunar Transit assumed a constant input power available to the SEP throughout the mission lifetime. Thrust is set to zero during eclipses when the solar illumination is less than 100%. The division of power between thrusters is dependent upon the operating thruster configuration, the combination of thrusters and desired operating points.

The PPE will supply three major functions to Gateway: power generation, communication, and propulsion. The PPE's power system is centered around two, 60-foot-long Roll Out Solar Arrays (ROSA's) each generating roughly 32 kW of electrical power at beginning of life (BOL) [12]. Once at the NRHO, this power will be used to operate the complete Gateway station including the power-intensive life support systems required for crewed operations. At the beginning of the Gateway mission, however, 50 kW of PPE's generation capability will be allocated to the most powerful electric propulsion system ever flown.

The PPE SEP system is comprised of seven individual thruster strings of two different types. The NASA-developed AEPS will be the highest power hall effect thruster ever flown, with a single thruster utilizing a maximum of 13 kW of input power [13]. This makes a single AEPS more powerful than nearly any electric propulsion-equipped spacecraft currently flying. Three AEPS thrusters form the core of the PPE SEP system, consuming a total of 39 kW of power when operated simultaneously at their maximum throttle setting. The AEPS thrusters will perform the majority of propulsive work during the Lunar Transit of the PPE and HALO, producing approximately 80% of the total impulse required to reach the NRHO. The remaining 20% is produced by four Busek BHT-6000 hall effect thrusters. The BHT-6000 itself is one of the most powerful HET thrusters ever developed for flight, with each string consuming a maximum of 6 kW of power [7]. Four of these thrusters provide additional propulsive capability and control authority to PPE. **Figure 7** shows a diagram of the placement of the thrusters on the PPE, with all three AEPS strings located directly on the aft deck of the spacecraft bus and the four BHT's being placed on booms mounted to either side of the vehicle.

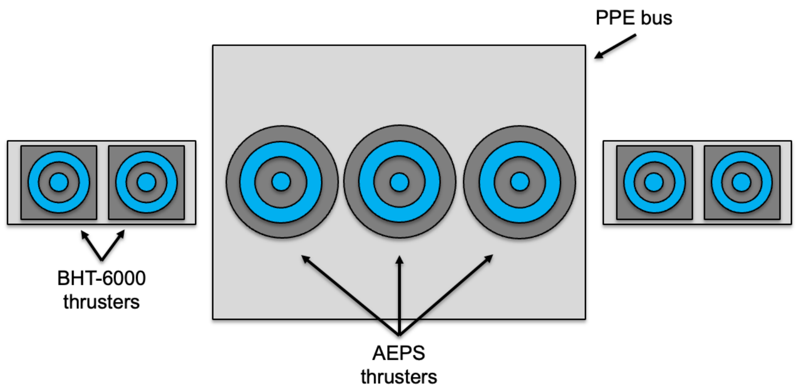

Figure 7: PPE SEP thruster placement diagram

The unparalleled capability of the PPE SEP system affords mission designers a high degree of flexibility in the utilization and application of the thrusters in the design of the low-thrust trajectory. During nominal Lunar Transit operations, five of the seven available thruster strings will be operated simultaneously, all three AEPS and two of the BHTs. The BHT thrusters will be operated in pairs, with one thruster from each side-mounted boom being operated together to prevent an asymmetric thrust vector. All seven strings will be utilized at some point during transit in order to characterize string performance and bake-in the thrusters. The BHT-6000 thruster can be operated in one of two modes as advertised by Busek [7]; high thrust and high Isp. In the high thrust mode, the thruster operates at 300 V and prioritizes thrust output over propellant efficiency. In the high Isp mode, however, the potential of the thruster is increased to 600 V, the associated current at a particular operating point is halved relative to the high thrust condition at the same power input, and specific impulse is increased at the expense of thrust output. **Table 1** shows the performance output differences between these two operating modes. The ability to operate the BHT's in either mode allows mission designers to prioritize different objectives during different phases of the mission. The high thrust setting will primarily be used during the early phases of the mission when the highest priority is escaping the harmful Van Allen Belts as quickly as possible. Once the risk of ionizing radiation exposure has diminished, the SEP system can be placed into high Isp mode to minimize propellant used during the remainder of the transit.

Table 1: PPE IPS High Thrust vs High Isp performance output

Mode	**Thruster Power (kW)**	**Thrust (N)**	**Isp (s)**
High Thrust	46	2.36	2,458
High Isp	48	2.33	2,670

For the purposes of trajectory design and development, all seven HET strings are assumed to be continuously throttleable over their range of acceptable power inputs (**Table 2**). As discussed previously, trajectory design assumes that the thrusters themselves will carry a finite lifetime. This lifetime limits mission design in how long a particular string can be used during the Gateway mission. The AEPS thruster, which employs innovative magnetic shielding, is assumed to be operable during any point in the 15-year Gateway mission. With three of these thrusters, it is assumed that the Gateway will rely heavily or even exclusively on the AEPS strings throughout the spacecraft's life. The BHT-6000 thrusters, which follow a more heritage-based design, are expected to erode more quickly. For the purposes of mission and trajectory design, not just for the Lunar Transit but also for cislunar transfers throughout Gateway's life [10], it is assumed that the BHT-6000's will be life-limited.

Table 2: Thruster throttle ranges *[13] [14]*

Thruster Type	Thruster Power (kW)	Thrust (mN)	Isp (s)
AEPS [13]	9 - 12	444 - 586	2,605 - 2,736
BHT-6000 (High Thrust) [14]	3 - 5	191 - 302	1,794 - 1,898
BHT-6000 (High Isp) [14]	6	286	2,485

VII. Co-manifest Mission AEPS/BHT Thruster Trades

Prior to the decision to fly the PPE and HALO as a single spacecraft, the design of the PPE IPS included two AEPS thrusters and four BHT-6000 strings [6]. Design of the Lunar Transit at this time assumed that all six thrusters would be used simultaneously in 2+4 configuration. Under these assumptions, PPE would be transiting by itself to the NRHO. The lower mass of a lone PPE enabled a launch to a high parking orbit (a near Sun Synchronous Transfer Orbit) and the resulting Δv required to reach the NRHO was just above 2 km/s. With these assumptions, the 2+4 configuration was sufficient to complete the Lunar Transit in addition to the long-term Gateway mission with positive qualification margins on all six thruster strings.

Following the co-manifest of the two vehicles, propulsive requirements on the PPE increased significantly. **Figure 8** shows the evolution of Δv and impulse required across successive design reference missions (DRM's). Following the integration of PPE and HALO, the Δv required to reach the NRHO increased by roughly 700 m/s, largely as a result of the higher vehicle mass necessitating a lower Earth parking orbit. These increases in total vehicle mass and the resulting impact on launch performance has led to significant changes to the design of the trajectory. Further maturation of the design of both elements and of the Lunar Transit trajectory itself has seen the Δv and impulse required to reach the NRHO level off near 3.1 km/s and 50 MNs respectively.

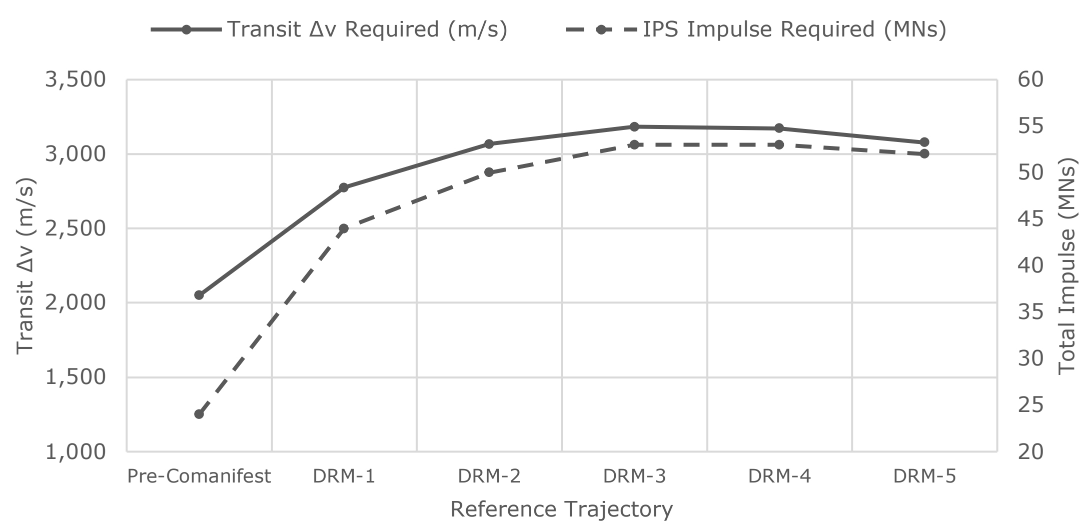

Figure 8: Lunar Transit Δv and total impulse requirements throughout mission development

The decision to launch PPE and HALO on a single CLV would not have been possible without the use of electric propulsion. A 50% increase in required Δv and a significant increase in vehicle mass would have been untenable for a traditional propulsion system. Using chemical propellants, even storable cryogens, massive changes to the vehicle and mission architecture would have been necessary. Through the use of a highly efficient SEP system, with a specific impulse on the order of 2,600s, mission planners were able to harness the tyranny of the rocket equation rather than be trampled by it. With minimal changes to the existing IPS the PPE was able to integrate the complexity of a second module and maintain a viable mission to the Moon.

VIII. Conclusion

The use of a high-power Solar Electric Propulsion system is critical to both the delivery of Gateway to the Moon and to the sustained presence of the station in cislunar space. The PPE SEP system will represent an unprecedented capability, will be an order of magnitude more powerful than any electric propulsion system currently in space, and will be central to a human exploration architecture. The use of high-power SEP in the single launch delivery of a high mass, human rated spacecraft to the NRHO will demonstrate the viability of SEP transportation architectures. This first-of-its-kind mission is the first step towards the high-power vehicles that will enable human exploration to Mars and previously impossible robotic exploration to the outer planets.

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