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Gateway to the Future: Lessons learned in development of the refueling systems for NASA's first lunar space station

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Developed in collaboration with international and commercial partners, Gateway will be humanity's first crewed space station around the Moon as a vital component of NASA's Artemis Program for exploration to the Moon, Mars and beyond. As part of it's focus on developing a sustainable, long term lunar capability, both Xenon based Solar Electric Propulsion System, as well as bi-propellant Reaction Control System of Gateway are designed to be on-orbit refuelable. Through design studies, numerical modeling, hardware development, and substantial testing, the system architecture has undergone significant changes to meet mission requirements and utilize evolving hardware capabilities between concept formulation and the successful completion of its Critical Design Review. This paper presents key lessons learned during this process, highlighting specific design elements and test results that contribute to a robust and adaptable refueling system for the Gateway.

I. Acronyms

- Advanced Electric Propulsion System (AEPS)
- Co-Manifest Vehicle (CMV)
- Dinitrogen Tetraoxide (NTO)
- European System Providing Refueling, Infrastructure, and Telecommunications (ESPRIT)
- ESPRIT Refueling Module (ERM)
- European Space Agency (ESA)
- Habitation and Logistics Outpost (HALO)
- Human Landing System (HLS)
- International Space Station (ISS)
- Near Rectilinear Halo Orbit (NRHO)
- Monomethylhydrazine (MMH)
- Power and Propulsion Element (PPE)
- Solar Electric Propulsion (SEP)
- Reaction Control System (RCS)

II. Introduction

Gateway, an essential element of NASA's Artemis missions along with the Space Launch System (SLS) rocket, Orion spacecraft, Human Landing System (HLS), and surface mobility, will be a small human tended space station orbiting the Moon to support human exploration of the lunar surface and serve as a staging point for deep space exploration.

Within the earliest conceptual design, Gateway was envisioned as a deep space platform for annual crew expeditions to validate operational concepts for missions much farther into the solar system, particularly Mars, with a parallel intent to use Gateway as an aggregation point and refurbishing and refueling depot for a reusable deep space transport to bring humans to Mars.[4] With the issuance of Space Policy 1[10] in 2017, a emphasis on lunar focused development was taken and infused into architecture requirements of Gateway. Implemented into core Gateway requirements, it has been established that Gateway shall be utilized to enable, demonstrate and prove technologies that are enabling for lunar surface missions that feed forward to Mars.[5]

In it's current form, the Gateway is comprised of an integrated and assembled series of elements which operate in a Near Rectilinear Halo Orbit (NRHO) within the vicinity of the moon. The initial Gateway configuration will be comprised of a Power and Propulsion Element (PPE) and a Habitation and Lo-

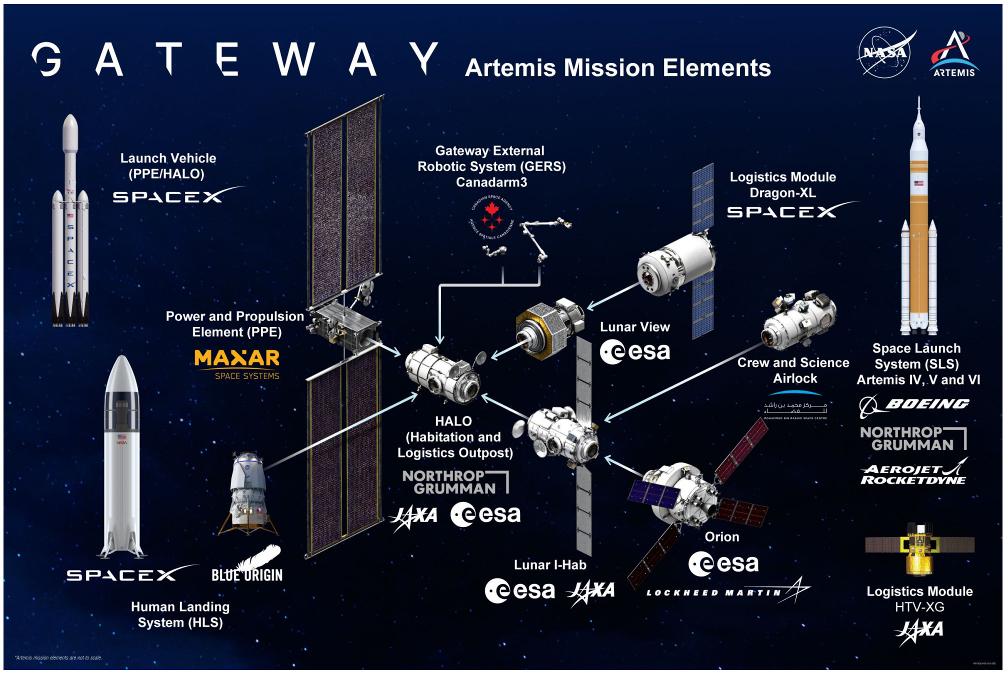

Fig. 1
The elements of Gateway

gistics Output (HALO) which are integrated on the ground to form the 'Co-Manifest Vehicle (CMV)' and launched together on a SpaceX Falcon Heavy Rocket.

The Power And Propulsion Elements contain features a 50kW Solar Electric Propulsion (SEP) system comprised of three 12 kW Advanced Electric Propulsion (AEPS) thrusters from Aerojet Rocketdyne and four BHT-6000 thrusters from Busek.[7]NASA's Advanced Electric Propulsion System (AEPS), has been in development tracing to 2012 and is a critical technology for sustainable lunar and martian exploration.[8] Launched on a Falcon Heavy, the CMV will nominally be inserted into a low elliptical orbit and will then perform a lengthy spiral out maneuver utilizing the PPE's SEP system to transfer to the NRHO. By way of comparison, the high performance SEP system within the PPE element, provides approximately an additional 40% delivered mass to the NRHO compared to a fast transit orbit transfer performed using traditional chemical propellants.[14] In addition to the SEP system, the PPE element of Gateway also contains a traditional Reaction Control System (RCS) comprised of momentum storage, as well as a bi-propellant propulsion system which utilizes Monomethylhydrazine (MMH) and Dinitrogen Tetraoxide (NTO).

In orbit, the RCS and SEP system work in tandem to perform orbit transfers, attitude control and pointing, reorientation maneuvers, and unload momentum storage. While current state of the art commercial satelite bus technology have demonstrated system configurations using entirely SEP,[11] novel requirements of Gateway, such as the on-orbit docking of multiple elements, crew exercise loads, and large reorientation maneuvers, require sufficiently high loads and impulse that traditional RCS systems are still required.

Launching on Artemis V, the European System Providing Refueling, Infrastructure, and Telecommunications (ESPRIT) is a Refueling Module ('ERM' or Lunar View) provided by the European Space Agency (ESA). The ERM provides propellant resupply capability to Gateway of all required propellants witin the PPE: Xenon, MMH, and NTO. Additionally, the ERM provides a small crew habitable volume with 5 windows. In early concepts, the ERM was envisioned as being directly docked to PPE allowing simplified fluid transfer between the PPE and ERM modules. However, due to larger program trades to launch PPE and HALO as the CMV, the ERM was relocated to a radial port on the HALO. One drawback of this architecture is the substantial increase in fluid volume between the ERM and PPE tanks.

Fig. 2: Rendering of Gateway with Orion docked to the ESPRIT Refueling Module

III. Architecture Background

Dating back to project formulation, top level architecture trades have been completed through a series of Integrated Analysis Cycles or 'IACs' which have evaluated spacecraft mission design constraints and requirements required for the spacecraft. The first IAC cycle, was completed from October 2017 to March 2018. Prior to the contract award of the first element of Gateway, the PPE, initial estimates for propellant consumption were approximately 800 kg of hydrazine, and 2000 kg of xenon. The 2000 kg of Xenon represented significantly less than was envisioned in prior SEP conceptual demonstration missions, such as the Asteroid Retrieval Mission (ARM), which had estimated to require $\approx$ 5,000 kg of Xenon, though provided a capacity far above the original estimates of $\approx$ 1,000 kg of Xenon required to perform the cislunar transfer of the PPE element following launch of the element on a commercially provided launch vehicle.

To assess the feasibility of these requirements against existing capabilities, a contractual solicitation titled 'Next Space Technologies for Exploration Partnerships' or NextSTEP, Broad Agency Announcement (BAA) was pursued, with 5 contracts awarded for studies in partnership with NASA toward maturation of the PPE concept.[4] During these study contracts, several key capabilities, including propellant estimates for both hydrazine and Xenon where then cross referenced against commercially available commercial satellite bus capabilities. Under these study contracts, Gateway's estimates for required propellant throughput capability, were evaluated compared to the throughput capability of flight heritage hydrazine thrusters, and commercially available tank sizes. It was observed that these propellant requirements were well within the capabilities of existing flight proven commercial satellite buses. One output of the NextSTEP BAA, was the identification of a commercial interest in maturation of on-orbit satellite servicing capabilities, such as refueling.

Early concept studies had evaluated the feasibility and necessity of having an on-orbit refueling capability. As is well documented, the International Space Station is routinely refueled on-orbit to enable re-boost activities. The FGB (Zarya or "Sunrise") incorporates two docking interfaces that support propellant transfer, the aft docking port and the forward-nadir docking port. The FGB and ISS systems were designed from the beginning to have a robust refueling system and the design solution is complex though extremely reliable.[12]

While ISS has proven the capability of refueling earth storable / hypergolic propellants, a notable complexity of the system is the required use of complex metal bellows tanks and an integrated compressor system for ullage management.[12] This, in large part is driven by a material non-compatibility with Oxidizer systems, such as NTO. To avoid this complexity and facilitate an approach in better alignment with current commercial satellite capabilities, the Gateway RCS system was originally envisioned as utilizing a monopropellant hydrazine system. This would enable medium performance systems, but take advantage of simple and commercially available elastomeric diaphragm tanks for a simple refueling archi-

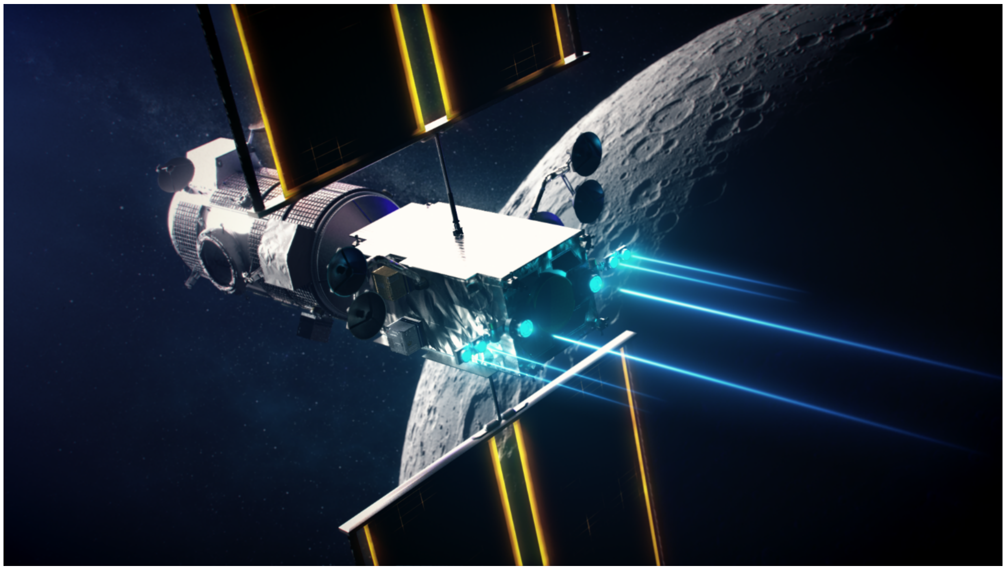

Fig. 3
Image of the Comanifest Vehicle during it's spiral out to NRHO. SEP and RCS systems are visible across the spacecraft

tecture.

In keeping with the commercial interest identified in the NextSTEP BAA, a high level architecture trade was performed to infuse commercial interest in development of on-orbit satellite capabilities with mission goals of ensuring long term sustainability of the Gateway. To implement, requirements were written to define the 'forward' docking interface of PPE (towards HALO), as being an International Docking System Standard (IDSS) compliant, interoperable, docking system. Additionally, a commercially defined 'aft' refueling capability was required to be implemented, which would contain several high level requirements, such as NASA evaluated and approved hazard processess, but would otherwise be free for the selected provider to define interfaces to maximally align with commercial development goals as part of a public-private partnership model.

Responding to program direction, the first two elements of Gateway (PPE and HALO) are to be mated on the ground and launched together on a 'Comanifest Vehicle' and represent the initial configuration of Gateway. The propellant system of PPE is connected via redundant hard lines to HALO which propagate to the docking system. The docking system connecting HALO to ERM contains a customized set of fluid transfer couplers, 2 per each commodity, which allow the the fluid systems to connect during the docking process. The development of these couplers has been challenging due to demanding leak rate and cleanliness requirements, while requiring high degree's of angular misalignment which trace to the docking systems themselves.

With several IAC's performed, implementation and feasibility assessed, on May 24, 2019, NASA awarded a PPE contract to Maxar Technologies for implementation of the PPE around their heritage LS-1300 series spacecraft bus.

IV. System Development

Since the selection of PPE, and the on-going maturation of the Gateway spacecraft, their has been considerable development of the overall architecture, and detailed concept of the Gateway propulsion systems. A overview of several key development findings, and changes in approach have been implemented.

IV.i Program Structure

Initially, the Gateway propulsion and refueling systems were designed to be based around a minimal set of technical requirements, with interfaces defined to enable safe execution of refueling. Requirements were defined for each propellant, the total wet mass of each propellant, and a set of controllability requirements to ensure sufficient impulse and pointing.

In practice, several integrated challenges manifested that made this approach problematic in the end. Primary among these was the need to provide higher level of technical details to enable safe operation of the three elements and fluid transfer couplers required to execute refueling.

As the system matured, two additional program level documents were created and approved to further define capability of the refueling system. The first, GP 10126 - The Gateway Refueling Subsystem Specification, was created with ≈ 40 defined technical requirements to ensure the seamless interaction of the elements involved in refueling. These requirements define system capabilities, such as maximum transfer rates, pressures, and temperature ranges of operation. They also provide updated assumptions for operational approaches to be used in future Integrated Analysis Cycles (IACs), such as the maximum number of refueling events for each propellant over the life of the Gateway.

The second document, GP 10140, The Gateway Refueling Integrated Systems Concept Plan, defines in-depth cross-systems approach for the interaction of the many systems across the Gateway required to seamlessly interact to execute refueling of both commodities.

To ensure minimal impacts to the commercially-centric PPE, requirements and the Integrated Systems Concept Plan were both created with an explicit goal to minimize impacts to the PPE design. Maximum design pressures and temperature ranges, for example, flowed directly from heritage capability of the LS-1300 based PPE spacecraft. In this way, while the number of requirements increased, the number of requirements which impacted the PPE and the cost impact of redesign was minimized .

IV.ii Concept of Operations

The initial capability of the Gateway will be delivered to the target Near Rectilinear HALO Orbit (NRHO) via a low-thrust Lunar Transit spiral trajectory.[14] During the Artemis V mission, the ESA provided 'ESPRIT' or Lunar View refueling module will be delivered to the Gateway and provide refueling capability. Operation of the Gateway will consist of regular crewed flights on a semi-annual basis, followed by extended periods of uncrewed quiescence where the Gateway will be operated through combinations of autonomous operations, as well as ground command.

Since it's inception, refueling of the Gateway has been baselined to occur only during uncrewed periods. There are two primary reasons for this approach. First, this provides the lowest risk to the crew. Second, however; is that this provides the easiest technical approach. For example, while Gateway is crewed, the spacecraft will be subject to non-trivial loads from life support venting, exercise loads, and attitude constraints, all of which may require regular use of on-board propulsion capability.

The Gateway is designed to operate in a L2 Southern NRHO, with a 9:2 lunar synodic resonance[14] which provides a roughly 6.5 day orbital period. Based on maturation of vehicle analysis, it has been identified that the use of the onboard RCS system will likely be required to maintain proper attitude at every perilune pass. In evaluation of the integrated safe operation of the system, it was determined that while possible, use of the propulsion system while being refueled will be precluded. Thus, an operational timeline for RCS refueling was constrained to be performed within the 6.5 day time window.

While in it's NRHO orbit, the SEP system is regularly used for momentum storage unloads, which can alternatively be performed using the onboard RCS system. Consequently, their is not a driving timeline constrain for refueling Xenon, and analysis shows that transfer of the propellant may take up to 3 weeks. The primary rate constraint on this has been identified to be related to the thermal management of both Xenon tanks during transfer. Due to recompression heating, significant heat loads are experienced on the PPE, and even with beneficial thermal attitudes, maximum heat transfer rates provide the bottle neck for transfer.

A key programmatic decision in the maturation of the refueling system, was in the operational model used to perform refueling. While entirely ground commanded operational execution could arguably be the most straight forward operational paradigm, Gateway has several technical objectives, including the advancement of on-board autonomy , which factored into the decision to execute refueling by way of ground authorized automated tasks execution, via Gateways Vehicle System Manger (VSM).[1] The VSM interacts with ground controllers to sequence pre-programmed tasks, and direct commands to Module Level System Managers (MSMs), which further cascade direction down to device level tasks (e.g. open a valve). Upon direction from the ground, the VSM will orchestrate an explicit predefined task list across the elements as needed, and provide telemetry back to ground operators, and then pausing at the end of the tasks for authorization to further proceed. Gateway's VSM system is also designed to handle integrated vehicle level Fault Detection, Isolation, and Recovery (FDIR). Given possible short time to effect failure modes, the VSM also provides functionality for cross module virtual links, designed for low latency data transmissions, when required.

IV.iii RCS Propellant Testing and Trades

During initial architecture trades, top level assumptions for propellant selection to be used for the reaction control system were to be high TRL propellants, capable of moderate performance, long term storage in alignment with a 15 year mission life. Further, the system was envisioned to have Mars forward extensibility via on-orbit refueling. These combinations led to the selection of monopropellant hydrazine, as had also been selected for NASA's OSAM mission based on a similar set of criteria.[3] One drawback of the use of hydrazine is the known sensitivity to compression detonation.[2] Even in early design and analysis cycles, numerical models were developed to assess system performance and identify possible concerns for compression detonation. High uncertainties in peak pressures during waterhammer, especially for system configurations which required an initial propellant transfer ('priming') from the ERM to the PPE with evacuated lines at hard vacuum.

To inform on these model uncertainties, an initial test campaign was envisioned and performed by a joint NASA and ESA team, with support from the ERM Prime Contractor, Thales Alenia Space - France, and Thales Alenia Space - UK. In the testing, both water and HFE-7100 were used to bound hydrazine, MMH, and NTO fluid responses. This test campaign has been of remarkable success and has significantly reduced risk to spacecraft operation and confirmed inital assumptions for system pressures and responses to planned operational environments.[6,9,13]

Concurrent to priming analysis, spacecraft mission design efforts were on-going and identified that the number of expected hot fire pulses, and particularly, the number of cold starts needed over Gateway's 15 year life, would be challenging to meet within the PPE on a commercially available monopropellant thrusters due to catayst bed limitations. While initial research had identified a likely commercial availability here, growth of expected propellant throughput and the number of cold starts required identified this as a likely life limiting issue. In consequence, Gateway moved from a monoprop hydrazine based system, to a traditional bi-propellant system, using MMH and NTO (MON-3) as the propellants. While ensuring that the thruster throughput requirements were able to be met, this did drive complexity back

Fig. 4
Gateway Integrated Breadboard Test Rig

into the refueling system as it removed the possibility of the use of an elastomeric diaphragm tank.

In response to this, a new architecture was proposed and pursued. Instead of pivoting to a complex bellows tanks, but understanding that venting of ullage vapors is problematic from both an external environments and momentum reaction perspective, a choice was made to launch PPE with a nontrivial amount of ullage in the tank and operate in a blow-down configuration. After consumption of a certain amount of propellant, during refueling events, the ullage is recompressed as propellant is resupplied into the tanks returning the tanks to their starting state. This novel solution allowed the used of traditional commercially available tanks, while removing the problematic challenge of ullage management.

Following the past approach used by ISS, well prior to refueling, the common fluid system is required to be leak checked. Helium is provided by the ERM to perform leak check of the system, while Xenon is used as the working fluid for leak checks and transfer in the Xenon system. ISS performs a leak check for approximately 90 minutes, corresponding to approximately 1 revolution of the earth to allow enough signal to noise to evaluate any signature of a leak, while accommodating for any thermal variations experienced in the system. Analysis on Gateway has shown that due to significantly increased fluid volume compared to ISS, and less sensitive instrumentation, that the leak check may take several days. This leak check is also envisioned to occur during extended period of uncrewed quiescence when their is not any time constraints.

Following the leak check of the Gateway, the Helium is required to be vented overboard. The PPE contains several propellant vents which can be used for venting the inert gas following leak checks, as well as purging propellant lines at the end of the transfer. The initial approach baselined in the Gateway was to require diffuse vents to limit the amount of induced momentum onto the spacecraft. After further evaluation, it was determined that it would be advantageous to instead require overboard venting while the RCS system was online and able to react any induced environments. As a consequence, venting of the leak check fluids are performed prior to propellant refueling, and purging of lines is performed after the resumption of nominal spacecraft operations after refueling.

One related trade has been in the operational model used during RCS refueling. The initial approach had been to require that each RCS propellant be refuelled a single commodity at a time. This was primarily due to a perceived concern of any mixing of the species in the event of a leak, or contingency venting. However, it was identified that several scenarios existed in which a fault (e.e.g failed closed valve) during the transfer of a species may preclude resumption of normal Gateway operations due to the thruster mixture ratio being well outside of qualified ranges. To avoid this, a scheme of refueling each species in an alternating fashion has been base lined. In this approach, the total amount of each commodity is increased by several 10's of KG at a time, in a stair stepping way, alternating between species. In this way, Gateway maintains 'abort out' capability without fear of loss of attitude control from a wide range of credible faults.

IV.iv Changes in program approach

Early in the development of Gateway, refueling was identified as an area of commercial interest as part of a public-private partnership. Initial estimates of propellant consumption identified that 15 year life of Gateway could be met without the need to refuel RCS propellants, while Xenon refueling was only required for orbital transfers. In recent years however, on-orbit propellant consumption has significantly increased. At the conclusion of the recent IAC-10 efforts, it was identified that refueling of RCS propellants will be required within the 15 year life of Gateway, thus making the criticality of the systems functioning much higher.

An additional change has been the approach for visiting vehicle docking. While the primary means of refueling the PPE element have been through the ERM, their was envisioned originally an capability for a 'PPE aft' refueling capability. As PPE matured, this spacecraft capability proved to be quite complex in practice as was removed. A primary design obstacle was the interaction and blocking of the

Fig. 5
The PPE Module of Gateway preparing for tank installation

propulsion thrusters on the aft of PPE by the aft refueling vehicle. Given the timeline of Xenon refueling, to execute an aft refueling would be either limited to a 6 day refueling sortie to ensure use of the propulsion system for use at perilune. While possible for the RCS system, this proved impractical for Xenon refueling using pressure driven transfer without significant modification to enable added heat rejection on the PPE tanks. As a consequence of this trade, the PPE aft refueling has been eliminated, and a notional visiting vehicle capability with refueling access has been added to the aft docking system of the ERM.

V. Lessons Learned

The Gateway's refueling system continues to mature, with several key hardware deliveries, such as tank installation into the composite central cylinder, reflecting a mature spacecraft configuration. Since formulation, several key trades have been performed, and many tests and analysis have been completed. Their have also been several problematic areas identified which should be noted with the community, in hopes that these issues can be avoided, or more aggressively mitigated in other programs.

- Uncertainties in numerical modeling simultations of waterhammer, especially priming into long evauated propellant lines, was prone to very large errors.

- Waterhammer has been a design driver for both storable liquid propellants, as well as super critical Xenon, and should be anticipated through margin and design features early in the design phase

- Across many areas of the system, early stage - low dollar testing (such a breadboards, or development couplers) was in almost all cases, an extremely effective risk mitigation mechanism
- The development of on-orbit engaging fluid couplers has proven very challenging. Design solutions which strive for simplicity should be given a strong emphasis over complex mechanisms.
- Cleanliness requirements, especially for the SEP system, has been challenging in practice to implement.
- The thermal management of the Xenon system has proven challenging. Extended transfer timelines (more than 3 weeks) have been implemented on Gateway which may not be practical in other spacecraft architectures.
- Fault response should be considered early in development. Fault tolerant design of hardware was insufficient in all cases to ensure safe operation which drove novel operational modes, for example stair-step refueling of RCS propellants
- Efforts to human rate commercial components, especially tanks, has been challenging and costly. Design information should be shared between all parties as early as possible to enable cost effective risk mitigation which minimizes schedule impacts

VI. Conclusion

The Gateway represents a key milestone in the advancement of long term, sustainable, human exploration of the moon and beyond. Many programmatic goals, such as refueling of a commercial based satellite bus, presented significant technical challenges. It has however, resulted in the development of a low cost, robust architecture for Gateway with minimal design risk. Primary challenges in the architecture development to this point have centered around cross element integration problems (such as the operating paradigm and use of autonomy), and interfaces, especially fluid couplers and waterhammer dynamics. On-going testing of critical pieces of hardware and integrated testing is underway simultaneous to the build up of flight hardware within the PPE.

While originally envisioned as a technical demonstration identified as an opportunity for public private partnership, changes and growth in the scope of Gateway have resulted in refueling becoming a critical and required function for Gateway to meet it's requirements for a 15 year service life in the lunar NRHO system. The architecture constructed, provides key capability to meet this need using a mix of commercial hardware and development, forward leaning cross program integration, and effective and ambitious international partnerships to execute within the cost and schedule constraints of the program. This approach, while with challenges, represents a new and effective model for ambitious challenges in human exploration to the moon, and beyond.

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