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Gateway at the Crossroads of Sustainable Lunar Exploration

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Abstract

The Gateway Program has made substantial design a Gateway is only required to operate two lunar surface links at the same time, though the program is trying to maximize capability d development progress toward delivering a small, human-tended lunar space station purposefully designed to enable sustainable human exploration. The Program integrates international partners and providers organizationally and physically as part of the spacecraft. The Power and Propulsion Element (PPE) and the Habitation and Logistics Outpost (HALO) with the European System Providing Refueling, Infrastructure and Telecommunications (ESPRIT) HALO Lunar Communications System (HLCS) have begun manufacturing the long lead components and will be launched first as a Co-Manifested Vehicle (CMV). The International Habitat (I-Hab) and ESPRIT Refueling Module (ERM) are passing life cycle milestones and include capabilities key for human crewmembers, such as windows, private sleeping quarters, and galley functions. The Logistics Module (LM) may provide a variety of services to Gateway depending on each mission. Requirements for the airlock have been developed, including requests that it support the integrated spacecraft with functions like augmenting heat rejection capabilities, and interfaces with new spacesuits will soon be developed in more detail.

As a critical element of the architecture for solar system exploration, Gateway implements key tenets and features of international interoperability standards necessary to operate with multiple visiting vehicles and lunar assets, especially avionics, communications, and docking. Specific choices such as software architecture and standards, power standards, and robotics standards make it possible to utilize heritage or proprietary technology, yet still operate as one spacecraft. Engineering teams are evaluating many possible future missions to be executed at or utilizing the Gateway. The system architecture protects for an evolvable, extensible, and flexible capability.

Designing systems robust enough to serve as a cornerstone of exploration activities for decades while remaining adaptable is not without its challenges. The detailed integration activities have revealed challenges and the need to mature key technologies. Refueling is a key component of achieving long life for Gateway, with unique operations to plan, safety concerns to mitigate, and risk reduction activities to conduct to better understand the system. The constraints and impacts of the design of visiting vehicles is also an important concern, with orientation constraints, control of attitude and orbit of the Gateway with docked visiting vehicles. Tradeoffs between robust maintainable systems and lightweight, compact systems must be balanced. Opportunities still exist for adding additional advanced capabilities to increase and extend Gateway's benefits, such as intravehicular robotics, autonomous Guidance Navigation and Control (GN&C), and augmented control propulsion, heat rejection, or other services.

Keywords: Gateway, Artemis, Interoperability

Acronyms/Abbreviations

ALM	Airlock Module
ASMA	Autonomous System Management Architecture
CMV	Co-Manifested Vehicle
CPL	Co-Manifested Payloads
CSA	Canadian Space Agency
EHP	EVA and Human Mobility Program
ERM	ESPRIT Refueling Module
ESA	European Space Agency
ESPRIT	European System Providing Refueling, Infrastructure and Telecommunications
ERM	ESPRIT Refueling Module
EVA	Extravehicular Activity
EVR	Extravehicular Robotics
GERI	Gateway EVR Interfaces
GERS	Gateway EVR System
GN&C	Guidance Navigation and Control
HALO	Habitation and Lunar Outpost
HLCS	HALO Lunar Communication System
IDSS	International Docking System Standard
IECLSSIS	International Environmental Control and Life Support System Interoperability Standards
IERIIS	International External Robotic Interface Interoperability Standard
I-Hab	International Habitat

IPSIS	International Power System Interoperability Standard
IRSIS	International Rendezvous System Interoperability Standard
ISS	International Space Station
ITSIS	International Thermal Interoperability Standard
IVR	Intravehicular Robotics
JAXA	Japan Aerospace Exploration Agency
VSM	Vehicle System Manager
LM	Logistics Module
NRHO	Near-Rectilinear Halo Orbit
OMM	Orbital Maintenance Manoeuvre
PPE	Power and Propulsion Element
SLS	Space Launch System

1. Introduction

The Gateway Program is breaking new ground for NASA and the international partners contributing to this sustainable space station in lunar orbit. The Gateway is a small space station that will operate in a Near-Rectilinear HALO Orbit (NRHO) around the moon [1]. This stable orbit enables opportunities for arrival of visiting vehicles from Earth and departure from the orbit with less energy that forcing them to go all the way into a circular low lunar orbit. It also allows efficient opportunities to travel to and return from the south pole of the moon. It only exposes the Gateway spacecraft to the high temperature environment near the surface of the moon once per 6.5 day orbit at perilune, and provides deep-space conditions for science experiments for most of the rest of the orbit. The Gateway is planned to operate for at least 15 years from the launch of each element based on current mission assumptions. Since the elements are launched and assembled over several years, the uneven life may seem strangely inconsistent. It is expected that life extension studies would be carried out on each element to find a true limit to Gateway life depending on actual use and design margin, which is likely to be longer than 15 years in the end.

Gateway's capabilities evolve and increase as more elements are delivered. The PPE and HALO are delivered as a CMV with a slow electric propulsion powered spiral out to NRHO. Once delivered to NRHO, they will be capable of serving as a lunar communication relay for missions on the surface using PPE assets for communication with Earth and the lunar surface, and additional lunar surface links with the European Space Agency (ESA) provided HLCS. Gateway is only required to operate two lunar surface links at the same time, selecting which antenna and link is in use based on the capabilities of the other vehicle or asset, but the program is evaluating the true network and software constraints and trying to maximize its capability for simultaneous links. The CMV scope was originally defined to be able to support a lunar surface mission with Orion and a lunar lander and LM if enough consumables are provided, utilizing the 3 available docking ports on HALO, though that is not NASA's current baseline. In the current baseline, the ESA I-Hab is delivered as a Co-Manifested Payload (CPL) in Gateway's first crewed mission for Artemis IV [2], adding private crew quarters and more payload capacity, and Japan Aerospace Exploration Agency (JAXA) provided life support systems that enable longer missions. The ERM delivered as a CPL for Artemis V provides fuel to extend Gateway life, but also viewing windows for the crew and critical storage space. The Canadian Space Agency (CSA) provided Gateway Extravehicular Robotics System (GERS) also arrives via LM on Artemis V to exchange external payloads and perform maintenance or replacement activities for externally mounted hardware that has been designed with compatible interfaces. Finally, Gateway will add an Airlock Module (ALM) with a crew airlock to support any necessary Extravehicular Activity (EVA) using spacesuits provided by NASA's Extravehicular Activity and Human Mobility Program (EHP) as well as a science airlock to allow prepared payloads to be accessed by GERS and deployed outside Gateway, or for GERS components to be brought inside Gateway for maintenance. After Gateway is fully assembled and upigraded capabilities such as a crew exercise device or complete galley have been delivered to support crew needs for missions with 30 days on board Gateway, missions to Gateway will be very flexible, with durations and activities determined primarily by logistics delivery capability and manifesting choices. However, Gateway is still significantly smaller than the ISS and is not intended to be permanently human tended.

Made of up all these elements, Gateway is NASA's first human spaceflight program formulated under the updated definition of "Tightly-Coupled" according to NASA Procedural Requirements 7120.5 *NASA Space Flight Program and Project Requirements* [3]. This means Gateway is program made of multiple independent projects managed by multiple NASA centers and major contributions from international partners, but no single project is capable of executing the mission of the Gateway alone. The project offices and the hardware and software they deliver are interdependent and even more tightly integrated than the US and Russian segments of the International Space Station (ISS). They are also all concurrently in development, with interfaces in negotiation and risks to designs evolving as each project moves through project life cycle timelines on their own independent schedule. This interconnectedness poses integration challenges, but at the same time is a core tenet that makes the Gateway sustainable from a financial and political point of view. Sharing costs for a great endeavour makes it more affordable for each participating partner. And experience from ISS shows that the international agreements and broad industry advocacy from multiple providers can help a program maintain stability over time.

The Gateway is also being designed to be sustainable via engineering design choices on the vehicle. To achieve financial sustainability during development, Gateway architecture and software choices enable reuse of heritage hardware (when appropriate for the cis-lunar environment). For financial sustainability during operations, the Gateway software architecture is designed to reduce the time a staff of ground operators must be available to control the vehicle. For long term sustainable space exploration activities, Gateway is designed to evolve to perform many kinds of missions, accommodate new partners and capabilities, and prepare for life extensions to evolve to meet the needs of human activities in and beyond cislunar space for decades to come.

2. Gateway Maturity and Evolving Capability

Gateway is made up of multiple modules, vehicles, and elements. As a NASA program, Gateway has completed its PDR and transitioned from the Formulation to Implementation phase of the program life cycle. Each of the contributing projects has also completed key life cycle milestones, with more scheduled in the coming year.

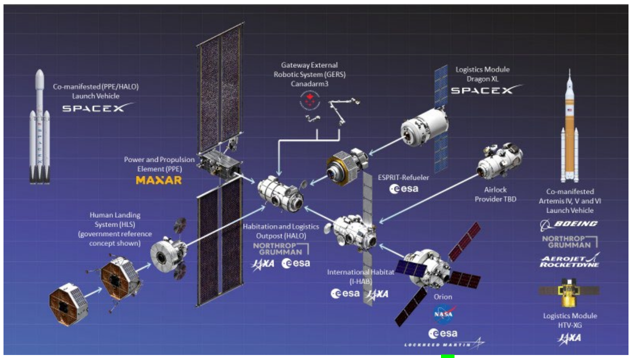

Fig. 1. Gateway Elements [4]

2.1. PPE and HALO as the CMV

PPE is a critical element of Gateway without which the other modules cannot survive and operate provided by Maxar Technologies. As is obvious from the name, it provides the solar array power source for the entire Gateway, as well as electric and chemical propulsion for orbital maintenance and attitude control, and sufficient propellant to support 15 years without refueling under the original nominal mission design assumptions.

The PPE power system utilizes a Maxar heritage power bus, with new solar array technology, and a voltage conversion to provide 120V class power at the interface to the rest of Gateway. The core requirements for Gateway require PPE to provide a minimum 32kW to the rest of the stack when solar electric propulsion (SEP) is not operating, and 24kW when the SEP is operating. The two Roll Out Solar Arrays have a total capacity of just under 60kW at Beginning of Life, and Gateway also levies a requirement on the PPE to enable full use of array power if the available capacity. With all this capability in place, the integrated Gateway is expected to usually be limited by heat rejection capability, not power availability. Batteries provide at least 1.5 hours of the 32kW capability during non-insolation periods, but that may be provided by a combination of power storage across modules.

The PPE propulsion and refueling capabilities are a also a mix of new technology and heritage systems. Solar electric propulsion capabilities using two types of Hall thrusters and Xenon fuel. PPE implements the Advanced Electric Propulsion System technology developed in partnership between NASA and Aerojet Rocketdyne [5], as well as utilizing Busek thrusters [6] which have previously been utilized by Maxar in other spacecraft. Electric propulsion will be utilized for the slow spiral transit from Earth to the NRHO, and for orbital maintenance manoeuvres (OMMs) when crew is not on board. The PPE leverages Maxar's heritage and experience with a bipropellant chemical propulsion systems, and is used for high moment of inertia activities, such as OMMs when crew is on board and Gateway must minimize the time orientations that are not optimal for Orion thermal constraints or communications pointing.

PPE also provides critical communication functions without which Gateway cannot survive. PPE provides the Ka-Band and X-Band communications link to Earth for Gateway, any docked visiting vehicles using Gateway as "bent pipe" path to Earth, and any vehicles or lunar surface assets using Gateway as a relay to Earth. High X-Band and throughput Ka-Band capabilities are provided on High Gain Antennas (HGAs) on both the +Y and -Y sides of the PPE. One Ka-Band and one X-Band designed as a "hybrid" antenna and can be switched to the lunar link frequencies, and thus PPE is capable of providing two of Gateway's links to the lunar surface. PPE also provides omnidirectional X-Band antennas at lower data rates, but important for off-nominal activities or system recovery.

The HALO module provided by Northrop Grumman is the first pressurized, habitable volume of the Gateway and is launched with PPE as a CMV. HALO leverages heritage structures built for the Cygnus cargo delivery vehicle, and has 3 docking ports compatible with the International Docking System Standard (IDSS). HALO hosts two of the three computers on Gateway running the Vehicle System Manager (VSM) software and provides core network capabilities (e.g. Layer 3 switches). HALO has a minimum set of life support on its own, with ventilation, pressure, temperature, and humidity control, and a CO_2 removal capability provided by LiOH intended only for contingencies lasting a few days. Once a more complete life support system is delivered in the I-Hab for Gateway, HALO will be upgraded to install an ESA provided exercise device to support crew health. HALO also carries the HLCS provided as a contribution by ESA, which provides two HGAs and can select between S-Band and K-Band capabilities. HALO also provides S-Band radios for communication with visiting vehicles.

HALO was not intended to be human rated on its own, but it is expected that in coordination with Orion some classes of short duration mission could be conducted with just the CMV and Orion. PPE and HALO were originally planned to be able to conduct a human lunar landing mission with Orion, a lunar lander, and a LM, and could still be evaluated for some variations of lunar surface mission. Even if CMV is not independently human rated, it is still an enabling core component for possible early Artemis missions.

These elements necessary for initial missions are achieving key life cycle milestones and beginning manufacturing of long lead items. The PPE module has already begun manufacturing and assembly of primary structure and propellant tanks and other items that heavily leverage its heritage spacecraft bus. An initial Preliminary Design Review was conducted by Maxar in 2021, but as the Artemis missions, some changes to Gateway capabilities were required. Maxar and NASA have negotiated key requirement changes, and Maxar is preparing for a Critical Design Review expected sometime in the fall-winter of 2023-2024. HALO has just completed their Critical Design Review. The VSM autonomous software capability will complete CDR of its initial capabilities required for CMV launch and transit to NRHO in fall of 2023. Gateway program will follow with CMV level and then program level reviews rolling together these inputs and other data from elements still at earlier points in their life cycle, and confirming the maturity of program content for initial missions.

2.2. The Logistics Modules

It is critical for Gateway to have logistics delivered by an LM providing consumable crew resources like oxygen, water and food, and payloads to enable research activities. Gateway has minimal storage Unlike the PPE and HALO, each LM is provided under a services contract. The first contract award was to SpaceX, but additional awards are expected. Finding the balance for requirements a services contract as part of the larger program has been an interesting exercise. The Gateway program must flow important parent requirements on safety, engineering standards, environments acceptable for human health, etc, in order for the LM to be approved as a part of an Artemis mission in processes like the Certification of Flight Readiness (CoFR) and Flight Readiness Reviews (FRR). But as a services contract, the Gateway program should not overly constrain the design options of the vendor. This does mean that Gateway gives up the opportunity to treat the LM as part of distributed and shared resources managed across Gateway such as power storage, data storage, and reduces the contingency response and especially the recovery options that can be implemented autonomously by the VSM. The LM must still meet interface requirements like other visiting vehicles in order to transmit telemetry and provide a minimum set of responses to contingencies. The Deep Space Logistics (DSL) team must combine these interface requirements and minimum with the agency parent requirements for safety and other standards to create the LM requirements for all vendors.

But there are times when Gateway needs special functions, and these may not be necessary in every mission. One example is the specific interfaces needed to deliver the GERS, which is complex and utilizes significant launch mass, but would only occur on that particular mission. Another function Gateway is considering levying is having LM vendors provide toilet to provide redundancy to Orion capabilities to support longer missions with more robustness, but providing a toilet would mean the crew spends more time in the module and other habitability requirements related to the pressurized volume environment would need to be verified for it to be safe. Gateway has created sets of “Mission Unique” requirements which bundle together functions and relevant standards that can then be applied to particular missions to create flexibility in the use of the LM, without excessively driving cost when not needed.

2.3. The I-Hab and ERM

ESA is providing two pressurized, habitable modules to Gateway: The I-Hab and the ERM.

The I-Hab provides important capabilities for human missions, including a life support system provided by JAXA with condensing heat exchanger and regenerable CO_2 removal system. The I-Hab will provide private crew sleep stations, and accommodate the installation of galley components to provide hot water and a built-in food warmer with greater capacity than Orion’s portable, suit-case food warmer. I-Hab also has greater capability to support payloads. The I-Hab has another function now critical to Gateway success thanks to the capabilities of the deployable radiators that are part of its heat rejection system. Initially, cross-strapping of thermal fluids between HALO and I-Hab was added as a contingency capability. But HALO’s heat rejection capabilities are limited by the physical surface area of its body mounted radiators, which were selected for simplicity to reduce development times. The coordination of visiting vehicles at Gateway during Artemis missions is highly constrained by the orientation needs of Orion (tail to sun) and lunar landers, especially if they store cryogenic propellants or have large surface area that could be exposed to sunlight in certain orientations. Sharing heat rejection between HALO and I-Hab (via a heat exchanger, not mixing fluids) and operating more like an integrated spacecraft thermal bus will now be a nominal expectation for Gateway, especially during the crewed mission periods. The I-Hab, including the JAXA ECLSS, has completed its system level PDR.

The core functionality of the ERM is obvious from its name. The ERM provides a resupply of the Xenon propellant used via electric propulsion systems for delivery of the CMV to lunar orbit, for orbit maintenance of Gateway when crew is not present, and future orbit transfers of Gateway. It also provides resupply of the bi-propellants used for attitude control and orbit maintenance when crew is present. The ERM is also preserving an interface to accommodate an additional refueling vehicle and second refueling activity. Refueling the Gateway in lunar orbit will be critical to providing a long life for the vehicle, but keeping the module and vehicle mass to reasonable sizes that can be delivered on multiple commercial or international launch vehicles or as CPLs launched with the Orion on a Space Launch System (SLS) launch.

The ERM was not initially conceived as a habitation module for the crew to spend a lot of time working and sleeping in. But it adds unique feature to Gateway with 5 observation windows pointed outward from a section of the pressurized cylinder. These are the only observation windows on the Gateway. The interior of the ERM also provides stowage space which is critical for Gateway to attempt to maintain spare parts on board and not lose unused spares as LM enters its disposal burn toward the sun, and then provide them again on an LM for every mission.

2.4. Extravehicular Robotics

The CSA contributions to the Gateway for EVR are sometimes referred to as two different systems, the Gateway Extravehicle Robotics Interfaces (GERI) and the Gateway Extravehicular Robotics System (GERS).

GERI implements the interface classes originally defined in the International External Robotic Interfaces Interoperability Standard (IERIIS) [7]. The GERI components are physically mounted on the other modules, and must be delivered first to support PPE and HALO for the CMV launch date. These include Small, Medium, and Large Orbital Replacement Unit (ORU) Robotic Interfaces known as SORI, MORI, and LORI and collectively as XORIs, which can support payloads that could include scientific payloads experiments, or module specific hardware intended to be robotically maintained. Items designed to be manipulated by the GERS must be designed to meet interfaces for either the Large Robotic Fixture Interface or the Dextrous Grapple Fixture Interface. The GERI interface requirements also include definition of a Free Flyer Grapple Fixture interface to allow Gateway to release these payloads, and even recapture them with the addition of the Free Flyer Capture Tool. Delivery of capabilities such as the larger size class XORIs or particular interface fixtures will not necessarily be initiated until a payload or user for that capability is identified.

GERI also includes the Low Profile Grapple Fixture (LPGF) that provides the GERS the mechanical, structural, and electrical (power and data) interfaces from the module when it is used as a base point. The LPGF can also be used as an interface to provide those same surfaces to a payload. The Gateway program has selected the location of LPGFs on each module both to ensure translation paths for the GERS across the vehicle, and support payloads in key locations good for scientific observation. The GERS is also expected to eventually support EVA crewmembers, and grapple fixtures also need to consider how the enable crew to reach EVA worksites, and connect to EVA translation paths to return to the airlock in the event of a contingency where the EVR system cannot operate.

The GERS is made up of the Exploration Large Arm as well as a smaller, more dextrous arm. CSA is exploring possible industry commonality in the design of this smaller arm component. The Robotics Planning and Control Station will be a crew interface that leverages use of the laptops already provided for crew use on Gateway, but CSA will provide redundant External Robotics Control Processors to install on I-Hab to function as the computers that actually control the GERS. CSA will also provide a Tool and ORU caddy.

GERI CDR and GERS PDR are both expected early in 2024.

2.5. The Airlock and EVA

The final module that will be added to the Gateway according to its current scope is an airlock to be used for crew EVAs and for research payloads that would be extracted or returned by GERS. The Gateway program is still awaiting formal agreement and announcement of a providing partner, but in the interim has drafted an airlock System Requirements Document. The airlock has critical features to provide the airlock and redundant capabilities to return and pressurize (typically a “crew lock” and “equipment lock” configuration, but other architectures may be possible), and to support the spacesuits with resources per the interface requirements being negotiated with EHP. But as the last module delivered to Gateway, the airlock is also being asked to fulfil other functions for the Gateway stack to provide robust capabilities for a long lived spacecraft. Like I-Hab, The Airlock is asked to provide additional heat rejection capability with cross-strapping to I-Hab to share heat in contingencies, or possibly nominal scenarios. As a module likely to often be in a quiescent mode when EVAs aren't being performed, the airlock is expected to house significant memory for data storage, as well as stowage volume for physical storage. The airlock may also be a place where a redundant CO_2 removal capability could be added to the Gateway. In cooperation with the spacesuits, it must be able to support the crew while isolated from the I-Hab and the primary ECLSS. Choices made in how this capability is provided could make the airlock an even more important part of Gateway operations in other scenarios including contingency or even during nominal system maintenance activities. With requirements well prepared, Gateway expects that only a few key feasibility trade studies would be necessary for a partner to quickly progress to System Requirements Review.

3. The Importance of Interoperability

The International Deep Space Interoperability Standards [7] were developed collaboratively with multiple space agencies with comments and input from industry. Their primary goal is to facilitate multi-partner deep space endeavours, including cross-program activities. But the design guidelines they create within the Gateway program can also contribute to making it possible to integrate modules and elements within the program. These standards were developed during the pre-formulation phase of Gateway, and many were led by teams and experts that now are part of the Gateway program.

3.1 Applying Interoperability Standards

For Gateway, the standards were decomposed and flowed down into individual requirements within the program requirements set. The International Communication System Interoperability Standards (ICSIS) defines frequency, modulation, coding and synchronization for command and telemetry link sand high rate communication links. It defines capabilities for Ranging using the command and telemetry links. It includes data link layer framing, network layers, bundle layers and security. It also includes visiting vehicle links and Wi-Fi. An ICSIS update is about to be released that will better define EVA suit interfaces and lunar surface links as implemented on Gateway and in other Artemis programs. The International Avionics System Interoperability Standards (IASIS) details the Time Triggered Ethernet (TTE) interface that was selected for Artemis to enable a flexible architecture that can support time critical commanding and devices with Commercial-Off-the-Shelf ethernet interfaces, and allow components of the system to evolve or be upgraded over time as long as they conform to the network protocols. The International Software System Interoperability Standards (ISwSIS) then defines syntactic and semantic standards necessary implement the CCSDS protocols identified in ICSIS. Some items do need to be defined in more detail in program (or enterprise) level documents for specific implementation or to protect security. Future partners who wish to collaborate in human spaceflight activity and use communication relays or dock vehicles with other assets should develop architectures with interfaces compatible with ICSIS, IASIS, and ISwSIS, but also be prepared to receive specific details from program requirements to implement the integrated software and avionics network created between vehicles.

The IDSS, International Rendezvous System Interoperability Standard (IRSIS), and International External Robotic Interface Interoperability Standard (IERIIS) provide guidance on important physical design features or constraints necessary to operate vehicles together in a successful mission. IDSS defines the physical mating interface of docking systems and necessary performance of capture systems and latches. Specific docking target descriptions and electrical connectors have been removed from the most recent versions IDSS and delegated to program specific documentation and interface requirements. The IRSIS provides a set of parameters to allow developers to design systems and operations for rendezvous, proximity operations, capture and docking or berthing, and undocking and departure. Common coordinate systems and state determination are addressed. Approach corridors, keep out zones, and mating interfaces and envelopes are defined and consideration for plume impingement and other interferences are included. The IERIIS provides similar information for robotics systems and their mobile interface across a spacecraft, with physical interfaces to the vehicle and between payloads and the robotic system, as well as approach and keep out zones and structural design constraints

The International Space Power System Interoperability Standards (ISPSIS), International Thermal System Interoperability Standards (ITSIS), and International Environmental Control and Life Support System Interoperability Standards (IECLSSIS) are especially important for vehicles that need to share any resources with each other. Sometimes that is nearly unavoidable, such as managing pressure as described by IECLSSIS in any two human spacecraft that intend to dock and open their hatches and unavoidably create a shared environment. IPSIS defines standard interfaces for 120V and 28V class interfaces. These interfaces cover vehicles which dock and may transfer power as a nominal or contingency feature. They do not define the characteristics of a spacecraft's internal power bus. This is why Gateway can be compatible with IPSIS but also allow to use a Maxar heritage 100V power bus in the PPE itself. But they are also intended to help drive commonality between vehicle interfaces and portable equipment or other items. If new vehicles can follow the interface, it will be easier to reuse heritage capabilities for powered items for crew use from other programs following the standards, and to physically carry and reuse items across an integrated spacecraft stack.

3.2 Architectures for Interoperable, Tightly-Coupled Elements

The vehicle software architecture uses an Autonomous System Management Architecture (ASMA). This means that each individual provider has significant freedom to design their core systems as they prefer, enabling reuse of heritage software from previous programs as long as they have an interface that can communicate and coordinate up to the Vehicle System Manager (VSM) software that is orchestrating (but not directly controlling) the integrated vehicle activities. The actions an autonomous VSM have many benefits [8]. It will also have an important role to play in limiting the amount of hands-on ground control time required (especially when crew is not present). One of is key tasks is responding to anomalies by safing and trying to recover the vehicle to maximum functionality, which is especially important for preserving the spacecraft when crew is not on board to respond.

Fault management is one of the most important autonomous capabilities provided by VSM. While the ASMA enables a lot of flexibility in the design of the module level software and control systems, it does not necessarily enable total reuse of heritage software. The Gateway architecture for fault management is a distributed architecture between spacecraft modules in which faults are managed at the lowest practical level. The Gateway program is responsible for generating an integrated Gateway Fault Model that collects and organizes vehicle faults and the propagation of fault impacts to the functions affected by a fault. This may be caused by a single fault or considered in combination with other faults and must take into context of the vehicle configurations, modes, and states. To construct fault models to be used by VSM, module providers must supply information on the module design, its fault detection capabilities, its fault responses and safing or corrective actions, and the fault propagation possibilities as described by a Failure Modes and Effects Analysis or otherwise derived by schematics. The modules must also have software and data interfaces established be able to provide the relevant information and command capabilities compatible with the Gateway Fault Model to allow VSM to have appropriate insight and sufficient actions available to direct the modules or respond to contingencies.

The ASMA enables significant capability for the integrated Gateway stack in nominal and contingency situations documented in module to VSM interfaces, but certain situations drive module to module interfaces as well. Refueling activities are a good example of a case where a fault response should be quickly executed in on module based on conditions detected in another. However, modules could design fault responses based on telemetry they are provided on conditions in other modules if it were available. Cross-Module Virtual Links (VLs) are a potential solution to quickly provide this data without requiring VSM to analyze or repackage data provided by one module, but do require each module to implement the VLs in their network definitions.

4. Flexible Capabilities for Many Missions

Gateway is designed to preserve mission flexibility. The priorities and relative timeline of cislunar objectives have evolved since Gateway was originally conceived, and lessons learned from ISS should show us that new needs will be discovered and many new missions and activities developed over the long life of a space station. While only three visiting vehicles are expected to be required to execute a lunar surface mission (a crew delivery and return vehicle like Orion, a lunar lander, and a LM), with the arrival of the I-Hab the Gateway quickly grows to have and maintain 5 docking ports. ERM and the Airlock both use a docking port but also provide a docking port. This capability could be used to protect contingency options, balance life and usage on different ports, or create future extensibility for missions. But as new vehicles are developed that could visit Gateway, it is important to consider the constraints or challenges each of those locations provides in terms of approach trajectories and keep out zones, integrated loads and dynamics, or plume impingement on surfaces like deployable radiators.

Gateway has also preserved interfaces to support expanded habitation capabilities or a potential docking interface for a Mars Transit Habitat. The forward axial interface on the I-Hab has the standard docking poart and resources available for visiting vehicles, but also includes the 120V high power interface and connections for thermal fluid cross-strapping like those used between HALO and I-Hab.

5. Challenges and New Capabilities

Even though system selections were often made based on heritage systems, experience developed through mature technology development projects, or architectures designed for flexibility – the Gateway program has still experienced some technical challenges assembling all the components into a cohesive and robust integrated system.

Refueling is a key technology and system capability that will help Gateway be sustainable for a long life. Refueling the Gateway in lunar orbit will be critical to providing a long life for the vehicle but keeps the module and vehicle mass to reasonable sizes that can be delivered on multiple commercial or international launch vehicles or as CPLs launched with the Orion on an SLS launch. Operations must be designed to live within the capabilities of heritage components. The PPE tanks were not initially built to be refueled, and maintaining safe pressures is very important. The Fluid Transfer Couplers on the NASA Docking System are capable, but existing certification data and test results from previous programs do not encompass the full range of Gateway requirements. The ERM is then left with challenges to design a vehicle that can protect these other components. Gateway has engaged in a joint breadboard level test campaign with Thales Alenia Space - United Kingdom [9] to evaluate integrated system responses and validate models and simulations to be used in design [10]. Gateway is also investing in a test campaign for both risk reduction and to provide test based verification evidence for integrated refueling of the bipropellants using inert propellant simulants in an integrated test bed, and delta-certification of key components using real fuels.

There are other system integration challenges to refueling as well [11]. While fuel can be provided, Gateway must also find efficient ways to balance and extend thruster life or any other non-maintainable components. The process of refueling the PPE from ERM will take days for the bipropellant system and weeks for Xenon. While teams will surely plan this activity during a period with good communication coverage to Earth and prioritize Gateway's use of ground assets during this time, it cannot reasonably be done simply with direct ground commanding. Ensuring that refueling can be conducted safely, but still leaving each module in control of its individual components, is one of the drivers in designing paths and network architectures for effective cross-module communication of telemetry to autonomously take action to quickly control faults or hazards.

The Gateway program also plays a special role in integrating all the vehicles of an Artemis campaign. Gateway has flexibility in what orientations it can support, and what docking ports are available for visiting vehicles. However, the constraints of each visiting vehicle may be not be compatible. This is especially complex when combined with specific mission objectives like delivery of the I-Hab, ERM, and Airlock as CPLs which must go to a specific axial or radial docking ports to receive the right interfaces for their permanent functions on Gateway. Trade studies are being conducted to determine if visiting vehicles may need to deliver a CPL and then relocate to a port that better meets their constraints, or if some visiting vehicles sensitive to a particular orientation should not dock to Gateway until after other activities are conducted even if it results in docking those vehicles while crew is already onboard Gateway.

Designing approach trajectories and docking operations is always an iterative activity between two spacecraft, but the evolution of vehicles to be integrated in Artemis vehicles is posing unique challenges that may lead to more significant requirements for functionality changes for Gateway or visiting vehicles. In order to stay flexible for multiple awardees to provide a lunar lander, Gateway provided a generic interface and assessed controllability of the spacecraft with up to a 45 metric ton reference concept standing in for the lunar lander. If the lander is significantly larger than, then the center of gravity moves well outside Gateway's original assumptions and attitude control of the integrated stack of docked vehicles would need to be provided by the larger vehicle. Gateway had always been aware of risks of thruster plume impingement on sensitive components like deployable radiators during rendezvous and proximity operations, but large vehicles with large thrusters may impart loads as they approach that make it difficult for Gateway to maintain attitude. Gateway is now conducting trade studies on how to optimize use of the heritage components in PPE, or what control algorithms and software commanding architectures could enable joint attitude control using PPE and a docked LM.

As the modules approach CDR, they encounter design challenges and have to evaluate trade offs between different objectives. For example, the Gateway program requires EVR to be the method used for maintenance of external components. This minimizes unnecessary risk to crewmembers during EVAs and makes best use of the long uncrewed portions of the year. As higher fidelity data on component reliability is generated, items that were not intended to have any maintenance during the 15 year required life have been discovered to be higher risk, but adding EVR interfaces late would create design changes with cost and schedule impacts and mass impacts for adding the intermediate EVR platforms and interfaces on vehicles that are already challenged to meet launch mass. Experience on ISS has shown that with custom tools and excellent training, EVA crewmembers have been able to perform many activities that were never originally planned and on systems with less than perfect EVA interfaces and worksite design. The program has to make each of these decisions carefully, balancing the impacts of enforcing the EVR compatibility requirements, versus finding any key changes that would enable EVA crewemembers to have some possibility of performing the replacement or maintenance activities as well as development of tools and the risks inherent in conducting the EVA itself if the component does fail, or doing nothing and accepting the risk of losing the component.

Current activities are focused on the delivery and initial operation of Gateway, but program teams are still scarring interfaces and making long term sustaining plans for upgrades and expansion of Gateway capability. One of the clearest upgrade paths is the expansion of VSM capabilities to include more robust vehicle recovery capabilities, and more autonomous and more detailed activity planning and resource management. The Gateway autonomy requirements were driven by goals to make Mars-forward investments and demonstrate the ability to operate without communication from Earth. Beyond VSM capabilities, like data storage were sized based on the assumption of a 21-day communication outage to be similar to the challenges of a Mars mission. But Gateway's initial Guidance Navigation & Control (GN&C) capabilities require regular updates from Earth for orbit maintenance. One possible upgrade for Gateway would be the addition of an on-board guidance and navigation function to completely perform all of the GN&C functions without input from control teams on Earth. Whatever technology is selected, external components will have to be deployed on an existing XORI or LPGF interface. Another capability that could increase autonomy would be the addition of Intravehicular Robotics (IVR), especially given the long uncrewed portions of the mission. Gateway is maintaining IVR compatible interfaces on payloads, identifying robotic translation paths and power supply access in the vehicles, and applying fiducial markers to preserve the potential of a future IVR system.

6. Conclusion

The Gateway program has achieved important programmatic milestones acknowledging our progress toward delivering and operating a core component of the Artemis architecture and enabling cislunar exploration for years to come. This maturity and progress is also represented by the physical hardware being manufactured, the software products that have been delivered for integration, and the first integrated system tests being conducted for validation and verification. Gateway's architecture still leaves many opportunities to grow and evolve capabilities with new contributions and upgrades. But as the hardware matures and mission designs are developed, the interdependencies and conflicting constraints between vehicles have become more obvious. In order to achieve a new era of flexible and sustainable cislunar exploration, it will be important for all participants to architectures.

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