The Gateway Program as Part of NASA's Plans for Human Exploration Beyond Low Earth Orbit

Emma Lehnhardt
NASA's Johnson Space Center
2101 E NASA Pkwy
Houston, TX 77058
emma.lehnhardt@nasa.gov

Dylan Connell
NASA's Johnson Space Center
2101 E NASA Pkwy
Houston, TX 77058
dylan.b.connell@nasa.gov

Abstract - **This paper provides an overview and status of Gateway, humanity's first space station in lunar orbit as a vital component of the NASA-led Artemis missions to return humans to the Moon as preparation for the first human missions to Mars. Gateway is an aggregation point in deep space for a variety of spacecraft, including the crewed Orion vehicle, the Human Landing System that will ferry astronauts to and from the lunar surface, logistics supply craft, and vehicles transiting further into deep space beyond the Earth-Moon system, such as to Mars. NASA is building on decades of partnership with space agencies on three continents and multiple commercial partners to design, build, and launch Gateway's core elements to near-rectilinear halo orbit (NRHO) around the Moon, where it will operate for a minimum of 15 years. Gateway is humanity's next in-space science utilization platform, and its first in deep space, with three science payloads already selected to study solar and cosmic radiation.**

This paper will provide an overview of the Gateway space station's major components in various stages of development, including the Power and Propulsion Element (PPE), Habitation and Logistics Outpost (HALO), the International Habitation (I-Hab) module, ESPRIT Refueling Module (ERM), the planned airlock, advanced external robotics systems, Deep Space Logistics supply craft, and next-generation autonomous Vehicle System Manager software. It will also provide an overview of how Gateway will be utilized for science, and highlight the space station's multilateral governance structure and international agreements.

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1. INTRODUCTION

NASA's Gateway Program is an international collaboration to establish humanity's first space station to orbit the Moon as a critical component of the NASA-led Artemis missions to return humans to the Moon for scientific discovery and chart a path for the first human missions to Mars.

The need for a long-duration, multi-purpose platform in lunar orbit has been established as a key characteristic of the Artemis architecture derived from the Moon-to-Mars Strategy and Objectives [1].

Gateway will be a human-tended space station in lunar orbit serving as a staging point for human exploration of the lunar surface and a science utilization platform. Initial Gateway missions will entail 30-day crewed missions to assemble Gateway elements, conduct lunar surface missions, and conduct science. Gateway will be a port for deep space transportation, including landers transiting to and from the lunar surface, or spacecraft embarking to destinations beyond the Moon, including Mars.

Gateway's unique 6.5-day polar orbit around the Moon, known as near-rectilinear halo orbit (NRHO), will facilitate year-round deep space scientific and technology demonstrations, with scientific experiments and contributions provided by NASA, its international partners, academia, and commercial entities.

Gateway's polar orbit supports the long-term success of Artemis, permitting access for astronauts and their spacecraft to the entire lunar surface, including the lunar South Pole that is the focus of the Artemis missions. It will facilitate uninterrupted communications between the Moon and Earth, offers unique opportunities for science within the deep space environment, and it is highly stable, translating to greater efficiency and lower costs. NRHO also provides distinct benefits for accessibility via a variety of launch systems and spacecraft, aggregation, low orbit maintenance costs, maneuverability, communications, and lunar surface access. [2] NASA's Cislunar Autonomous Positioning System Technology Operations and Navigation Experiment (CAPSTONE) mission, which launched in June 2022, is currently exploring this new orbit [3]. By providing operational data from an actual spacecraft operating in NRHO, CAPSTONE will verify some of the assumptions and key technologies needed by Gateway to safely function in lunar space.

This paper will provide an overview of the Gateway space station's major components in various stages of development as of September 2023, an overview of how Gateway will be utilized for science, and highlight the space station's multilateral governance structure and international agreements.

2. GATEWAY OVERVIEW

2.1 Management and Governance

Managed from NASA's Johnson Space Center in Houston, Texas, the Gateway Program consists of multiple elements (also called projects or modules) that are led by various NASA Centers across the United States and by International Partners.

The Vision and Mission statements for the Gateway Program are:

- Mission: Creating the cislunar springboard for cooperative and sustainable human deep space exploration.

- Vision: A vibrant and lasting human presence in deep space.

The Gateway Program received approval for acquisition strategy from NASA Headquarters in 2018, authorization to proceed into Formulation in early 2019, and the Program Office was established at JSC in early calendar year 2019. Multiple Gateway projects, systems, and components have finalized Preliminary Design Reviews (PDRs) and Critical Design Reviews (CDRs). The Program held its PDR for the Gateway initial capability, the integrated Power and Propulsion Element (PPE) and Habitation and Logistics Outpost (HALO) elements, in late summer 2022, with a technical close-out in December 2022 and programmatic close-out in May 2023.

2.2 International Partnerships

Through Gateway, NASA is building on decades of international partnership that began in earnest with the Space Shuttle Program era and expanded significantly with the International Space Station Program (ISS) to extend multilateral cooperation from low-Earth orbit to the deep space lunar context.

Gateway's international partnerships are chiefly an expansion of the partnerships established with ISS. Memoranda of Understanding (MOU) provide the formal commitment between the U.S. Government and partner governments to fulfil Gateway partnership and contributions. These MOUs are established under the authority of the ISS Intergovernmental Agreement (IGA). All ISS Partners except the State Space Corporation (Roscosmos) are partners in the Gateway Program. MOUs with the Canadian Space Agency (CSA), ESA (European Space Agency), and the Japan Aerospace Exploration Agency (JAXA) were finalized by late calendar year 2020. These agreements will in part enable astronauts from Canada, Europe, Japan, and potentially other countries flying on Artemis missions to Gateway.

These partnerships mark a critical part of NASA's efforts to lead an unprecedented global coalition to the Moon, further contributing to the creation of a dynamic lunar exploration architecture. International Partners are embedded members within the Gateway development team, with membership on Gateway Control Boards and technical integration embedded at all levels.

In October 2020, ESA signed an agreement with NASA to contribute habitation and refueling modules, enhanced lunar communications to Gateway and two more European Service Modules (ESMs) for the Orion Spacecraft. The ESA-provided International Habitation module (I-Hab) will enhance Gateway capabilities for scientific research, life support systems and crew living quarters. These capabilities enable longer duration crewed Gateway missions. The refueling module will include crew observation windows. The enhanced HALO lunar communications system (HLCS) will be integrated with the Habitation and Logistics Outpost (HALO) module and provide high-rate communications relay between Gateway and the lunar surface.

In December 2020, Canada signed an agreement with NASA to participate in Gateway and provide advanced external robotics. The CSA-provided external robotics system includes a next-generation robotic arm, Canadarm3, for Gateway. Canadarm3 will move end-over-end to reach many parts of Gateway's exterior, where it will plug into specially designed interfaces. CSA also will provide robotic interfaces for Gateway modules to enable payload installation including the first two scientific instruments launching on PPE and HALO.

In December 2020, Japan finalized an agreement with NASA to provide several capabilities for Gateway's I-Hab that will provide the heart of the space station's life support capabilities and additional space where crew will live, work, and conduct research during Artemis missions. JAXA's planned contributions include I-Hab's environmental control and life support system, batteries, thermal control, and imagery components. These capabilities are critical for sustained Gateway operations during crewed and uncrewed periods. JAXA will also provide logistics resupply via the HTV-XG spacecraft, an evolution from the HTV and HTV-X logistics carriers that resupply ISS. NASA and JAXA have reached an agreement on the first HTV-XG resupply vehicle. HTV-XG1 will provide 4mT of pressurized logistics with flight to Gateway in 2030.

3. STATUS OF GATEWAY ELEMENTS

3.1 Gateway Initial Capability

The integrated PPE and HALO are the foundational elements of Gateway. In March 2020, NASA decided to integrate the two elements on Earth and launch them together.

PPE is a high-power, 60-kilowatt solar electric propulsion spacecraft that will provide power, high-rate communications, attitude control, orbit maintenance, and orbital transfer capabilities for Gateway. NASA manages the project out of the Glenn Research Center in Cleveland, Ohio. Maxar Technologies was awarded the contract for

PPE in 2019, [4] successfully conducting a first Preliminary Design Review (PDR) in July 2021. In Spring 2022, the PPE engineering team started an extensive end-to-end testing campaign of PPE's advanced electric propulsion system thrusters. Based on the success of the work to date, the team successfully completed the next phase of the testing campaign with Aerojet Rocketdyne, an L3 Harris Technologies company, in the summer of 2023 which provided the project with greater insight into the thrusters' capabilities as an integrated system [5]. A Critical Design Review (CDR) is expected in 2023. [6]

HALO is one of two of Gateway's habitation elements where Artemis astronauts will live and conduct research on Gateway. The pressurized living quarters will provide command and control systems for the lunar outpost and docking ports for visiting spacecraft, including Orion, lunar landers, and logistics resupply craft. The HALO module will serve as the backbone for command and control and power distribution across Gateway and will perform other functions, including hosting science investigations via internal and external payload accommodations and communicating with lunar surface expeditions. HALO will enable the aggregation of additional habitable elements to expand Gateway capabilities, leveraging contributions from Gateway international partners for robust capabilities. Batteries provided by the Japan Aerospace Exploration Agency (JAXA) will power HALO until PPE solar arrays can be deployed and during eclipse periods. Robotic interfaces provided by the Canadian Space Agency will host payloads and provide base points for Canadarm3 robotic operations. ESA will provide the HALO Lunar Communications System (HLCS) to enable high-data-rate communications between the lunar surface and Gateway.

HALO is managed out of NASA's Johnson Space Center in Houston. Northrop Grumman of Dulles, Virginia was awarded a contract for the preliminary design of HALO in 2020, and the remaining content for HALO was finalized between NASA and Northrop Grumman through a contract signed in July 2021. [7] HALO successfully completed PDR in summer of 2021 and completed a CDR in summer 2022. Construction of Gateway's HALO module, including structural welding in Italy, is expected to conclude in the coming months, followed by static loads test and proof pressure test. The HALO structure will then be delivered to Northrop Grumman's facilities in Gilbert, Arizona, where it will begin the process of being outfitted with its various components to support Artemis. [8]

In February 2021, NASA selected SpaceX to provide launch services for PPE and HALO. As of 2022, the integrated modules are referred to as the co-manifested vehicle (CMV) or the initial capability. After integration on Earth, the CMV is targeted to launch no earlier than October 2025 on a Falcon Heavy rocket from Launch Complex 39A at Kennedy. [9]

Some of the scientific payloads that will fly on Gateway Initial Capability have already been selected. [10, 11, 12] They include:

- The European Radiation Sensors Array (ERSA) will help provide an understanding of how to keep astronauts safe by monitoring the radiation exposure in Gateway's unique orbit.
- The Heliophysics Environmental and Radiation Measurement Experiment Suite (HERMES) is NASA's space weather instrument suite that will observe solar particles and solar wind created by the Sun.
- The ESA Internal Dosimeter Array (IDA) will include instruments provided by JAXA. Radiation measurements and data provided by the IDA will allow for the study of radiation shielding effects and improve radiation physics models for cancer, cardiovascular, and central nervous system effects, helping assess crew risk on exploration missions.

3.2 Deep Space Logistics and Gateway Logistics Services

As astronauts prepare for missions to the lunar surface, they will need deliveries of critical pressurized and unpressurized cargo. The Kennedy Space Center manages the Deep Space Logistics (DSL) project office, which includes management of Gateway Logistics Services (GLS) contract.

In March 2020, NASA selected SpaceX of Hawthorne, California, as the first U.S. commercial provider under Gateway Logistics Services contract. [13] SpaceX and the DSL team are currently conducting special studies in advance of providing authority to proceed for the first GLS mission. These studies, which include detailed analysis on required capabilities and mission planning of a logistics mission, continue to evolve the DSL concept with Gateway as the Program matures in its lifecycle. Current concepts are focused on providing astronauts with a pantry style closet, allowing easy access to cargo as well as accommodating the collection, storage, and eventual disposal of waste accumulated at Gateway.

Working in conjunction with Gateway's international partners, DSL has partnered with JAXA to share lessons learned and inform their development of the HTV-XG logistics resupply vehicle. DSL also remains engaged, in conjunction with SpaceX, with CSA as they develop the GERS system to ensure full compatibility of Canadarm3 with future logistics efforts.

3.3 I-Hab and ESPRIT

The European Space Agency (ESA) will contribute habitation and refueling to Gateway. The I-Hab will enhance Gateway capabilities for scientific research, life support systems and crew living quarters, which will enable longer duration crewed Gateway missions. The Japan Aerospace Exploration Agency (JAXA) plans to provide several capabilities for Gateway's I-Hab, including its environmental control and life support systems, batteries, thermal control, and imagery components, which will be integrated into the module by ESA prior to launch. Gateway's I-Hab module will utilize similar life support systems to those currently on the ISS. As a technology risk mitigation, a scaled version of the JAXA developed Gateway CO2 removal system (CDRS) will be flown and

demonstrated on ISS. This tech demo will help validate the CDRS design and flush out any issues prior to launching the CDRS in I-Hab where crews will depend on it for longer duration stays at Gateway.
Fabrication of I-Hab is currently underway at TAS-I in Torino, Italy. Primary structure elements have been assembled and are currently in the welding process. Design of the JAXA ECLSS system is progressing with PDR completed in the summer of 2023 and key component testing within the carbon dioxide removal system ongoing.

The ESPRIT Refuelling Module (ERM) provides additional fuel capacity to resupply PPE, windows, and enhanced lunar communications. ESPRIT stands for European System Providing Refueling, Infrastructure, and Telecommunications. These capabilities are realized in two components, the HALO Lunar Communications System (HLCS) which is integrated and launched with HALO, and the ESPRIT Refueling Module which is a separate module that will be docked to HALO on a future mission.
ESA is under contract with Thales Alenia Space for both the I-Hab and ESPRIT modules. [14] I-Hab completed its PDR in Fall 2021 with primary structure fabrication underway. ESA recently provided a design modification to ERM adding capability to launch with 1.5MT of cargo and volume for 6.5m3 of on-orbit stowage. The module size grew to 3m in diameter with a refueling ring located around the pressurized habitable compartment. In the summer of 2022, ESA conducted a delta systems readiness review to review these changes.
Gateway refueling of Xenon and bipropellant from ERM storage tanks to PPE tanks will utilize new technologies. Development of the refueling system has advanced with breadboard testing of the integrated ERM-HALO-PPE fueling system occurring in the summer of 2022.

3.4 Gateway External Robotics System

The Canadian Space Agency (CSA) will provide an advanced Gateway external robotics system (GERS), that includes a next-generation robotic arm, or Canadarm3. Canadarm3 will move end-over-end to reach many parts of Gateway's exterior. Canadarm3 will be used to conduct maintenance, to berth and inspect vehicles, and install science payloads. In addition, CSA will also provide Gateway external robotic interfaces (GERI) across the Gateway modules. Robotic interfaces on PPE and HALO host the ERSA and HERMES payloads enabling early utilization. The GERI PDR was complete summer of 2022. MacDonald, Dettwiler and Associates Ltd. (MDA) was selected by CSA for both the Canadarm3 and external robotic interfaces. [15, 16] Canadarm3 completed System Requirements Review in January 2022 and is progressing toward a PDR in early 2024. Canadarm3 will be delivered to Gateway via a Gateway logistics flight.

3.5 Airlock

The Gateway integrated spacecraft will also need an airlock module. The Gateway Airlock Module (ALM) will be a multi-purpose element providing the capability for crewed spacewalks, also called Extravehicular Activities (EVAs), while supporting scientific research and day-to-day Gateway operations with a specialized Science Airlock. By leveraging the capabilities provided by Canadarm3, the Science Airlock will allow scientific experiments and Gateway hardware to move between the pressurized cabin and unpressurized destinations outside of Gateway. The ALM is also planned to provide an additional docking port for visiting vehicles, supplementary storage, and the capability for un-attended robotic maintenance of the Gateway.

As of September 2023, NASA is in active discussions with an international entity to provide a Gateway Airlock. The result of these conversations will be announced in the future.

3.6 Vehicle System Manager Software

Gateway's Vehicle System Manager (VSM) software will allow Gateway to operate autonomously, representing a leap forward in spacecraft capability. VSM will provide activity planning, resource management, vehicle control, and fault management for Gateway.

In each of these areas, there is an initial level of capability to be delivered at launch, with plans to continue development and grow to greater capability. The initial deployment of VSM will focus on maintaining vehicle safety by focusing on full fault management capabilities and deploying only enough resource and timeline planning functionality to support that. The final deployment of VSM will add significant planning and control optimization functionality to support nominal operations for up to 21 days without ground support, even accommodating fault and failure conditions.

The VSM project held its CDR in September 2023 and its next major milestone is the Test Readiness Review (TRR) targeted for December 2024.

4. SUMMARY

In summary, Gateway will provide unprecedented access to the Moon and enable sustainable exploration to the lunar surface and beyond, ushering in a new era of science for the benefit of all.

Hardware fabrication of Gateway's first elements is actively taking place in facilitates throughout the world. The year ahead will be busy with assembly, integration and testing of the initial Gateway elements, along with construction and design of later elements.

Gateway symbolizes the expansion of NASA's international and commercial partnerships into deep space. Significant progress is underway to establish humanity's first permanent outpost in orbit around the Moon.

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