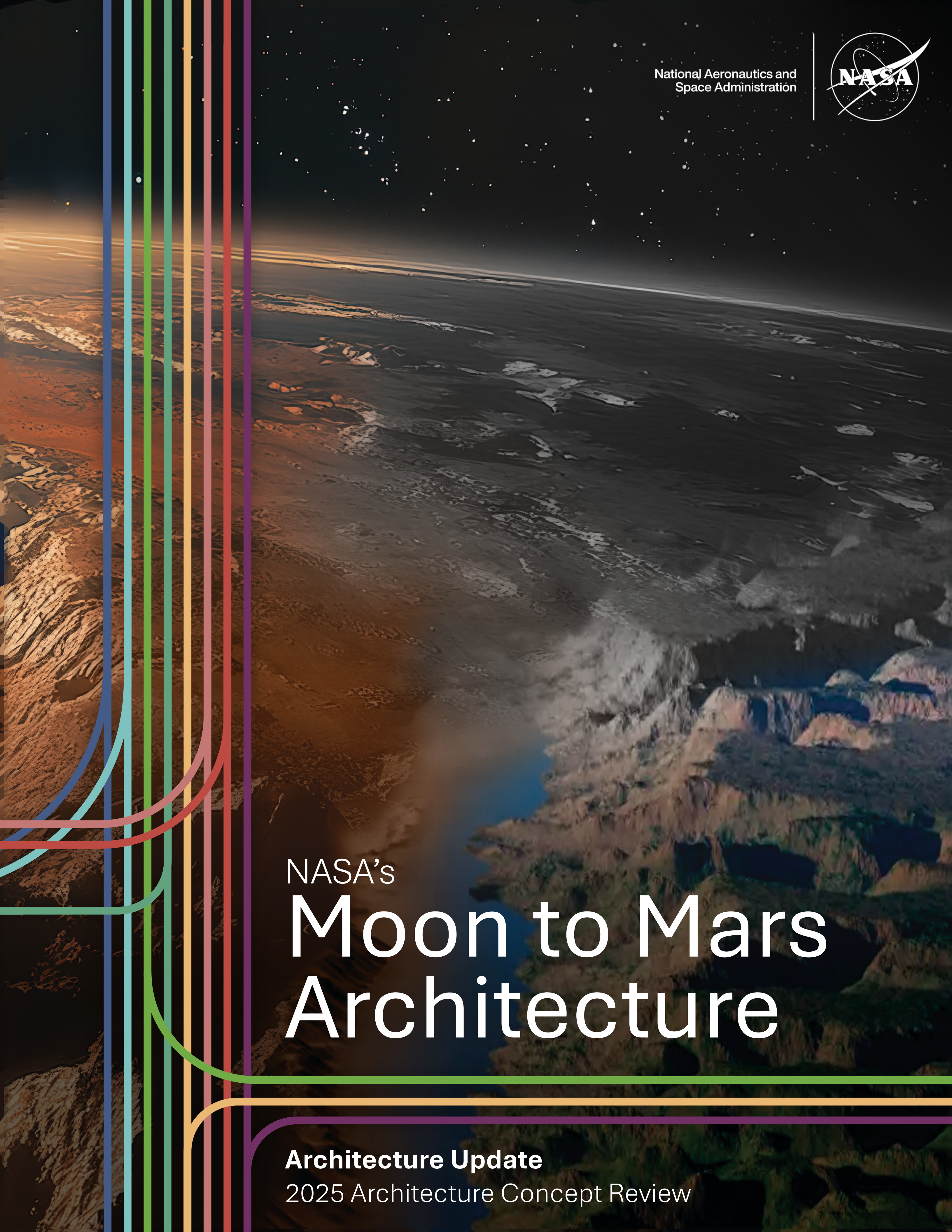
National Aeronautics and Space Administration



NASA's
Moon to Mars Architecture

Architecture Update

2025 Architecture Concept Review

TABLE of CONTENTS

Moon to Mars Architecture Update
2025 Architecture Concept Review

Exploration Systems Development Mission Directorate
National Aeronautics and Space Administration

www.nasa.gov/architecture

ARCHITECTURE UPDATE

Executive Summary

As previously established, the Moon to Mars Architecture products were developed to communicate the state of the architecture, relationships between systems, and open needs for future collaboration to achieve the long-term objectives for exploration. While conversations continue about potential changes in implementation, the products represent the contracted baseline and will be updated and responsive to changes if and when they occur.

In terms of products, the major update this year to the Architecture Definition Document — released alongside this document — introduces a new look, feel, and structure that maximize readability and usefulness for stakeholders across the space exploration world. It includes updates that directly respond to stakeholder feedback across past revisions. The revision includes updates to the objective decomposition (which distills agency-developed objectives into operational capabilities) and element functional mappings — with the full decomposition spreadsheets available on NASA's Moon to Mars Architecture website.

In 2025, NASA added two new elements to support lunar exploration: a robotic mobility system to move logistics around the lunar surface and a nuclear fission power system that will provide external power augmentation for exploration systems. The agency debuted architecture-driven data gaps that capture key knowledge needs to enable future exploration. The agency also narrowed the range for the number of astronauts that its initial Mars missions will send to the surface of the Red Planet. You can read more about these developments later in this document.

This architecture update summarizes the latest additions to NASA's Moon to Mars Architecture and the agency's Architecture Definition Document. Descriptions of the 2025 architecture white papers released are provided for awareness where more detailed rationale is available for key findings or decisions. Those materials can be found on the agency's architecture website, *www.nasa.gov/architecture*, along with an overview of the Moon to Mars Architecture development effort.

We thank you for your ongoing support, communication, and feedback; these products will continue to be responsive to and communicate any changes as implemented.

NEW ELEMENT

Lunar Utility Rover

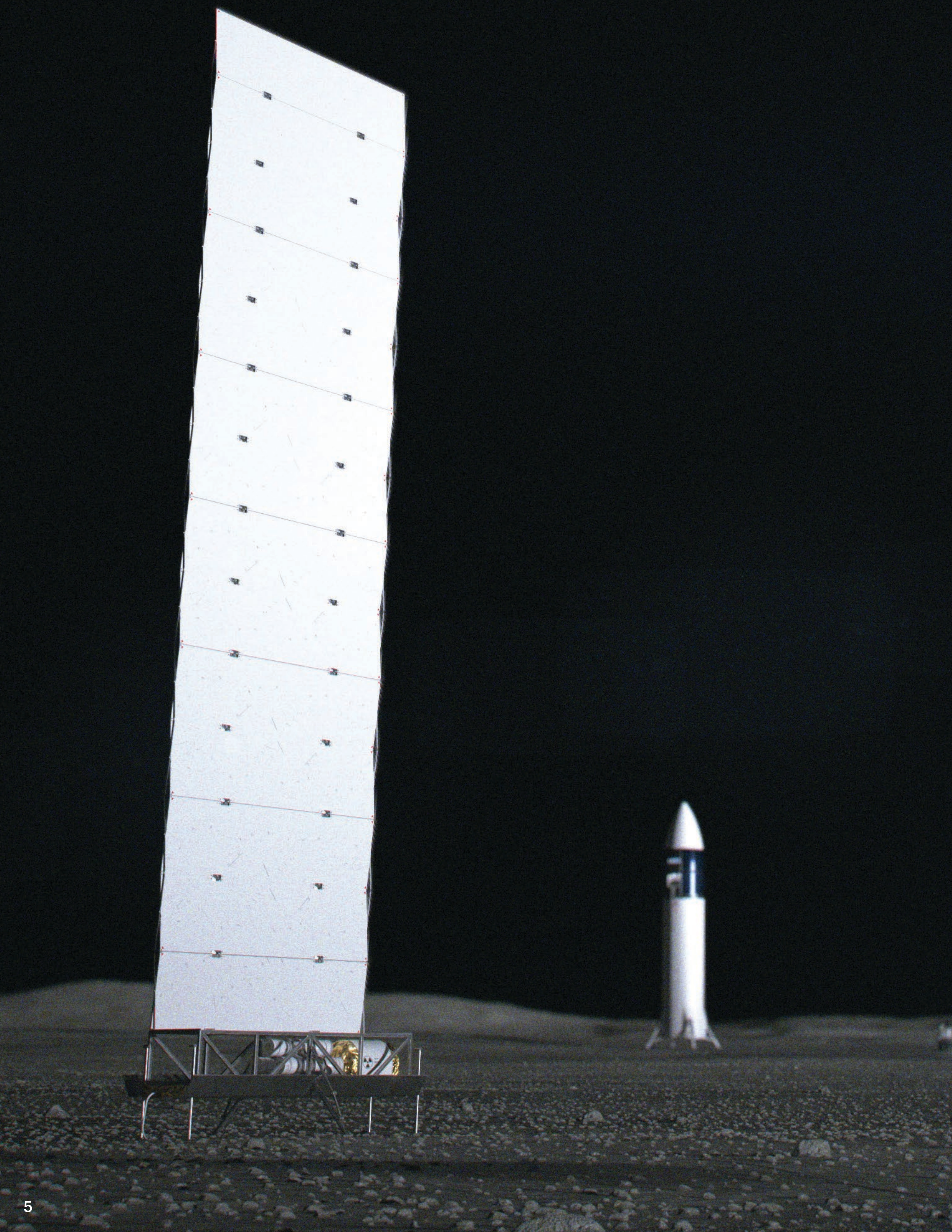
The lunar utility rover element is an uncrewed, unpressurized rover that provides cargo and payload mobility, extravehicular activity (EVA) support, and utilization opportunities. It can also transport a moderate amount of cargo — thousands of kilograms — and will provide power and data interfaces for transported cargo and payloads. It supports multiple operational modes, including local astronaut control, teleoperation from Earth, semi-autonomous control, and full autonomous control.

During crewed expeditions, the rover enables utilization directly through operation of its manipulator arm and onboard payloads, and indirectly by supporting crews. The rover could collect, store, and locally distribute data; facilitate communication and utilization data exchange between assets; and capture surface imagery. The rover could also support continuous presence on the lunar surface with capabilities to maintain, repair, and service other exploration systems.

The addition of this element at the 2025 Architecture Concept Review responds to previously identified needs for additional autonomous lunar surface mobility capabilities. (See the 2024 Moon to Mars Architecture white paper, "Lunar Logistics and Mobility," for more details.) The rover will improve NASA's ability to conduct operations and utilization activities between and during crewed missions.

Functional Mapping

Foundational Exploration Segment	
Lunar Utility Rover	
FN-M-501 L	Reposition a limited amount of cargo (100s of kg) in the south pole region on the lunar surface
FN-M-503 L	Reposition a moderate amount of cargo (1000s of kg) at the south pole region on the lunar surface
FN-M-701 L	Operate mobility system(s) in uncrewed mode between crew surface missions
FN-A-104 L	Perform robotic manipulation of payloads, logistics, and/or equipment on the lunar surface
FN-A-105 L	Interface robotic system(s) with logistics carriers on the lunar surface
FN-A-302 L	Provide safeguards for automated asset(s) operating near crew



NEW ELEMENT

Lunar Nuclear Fission System

In 2025, NASA instantiated a nuclear fission power system into its lunar architecture. This external power augmentation can supplement power systems onboard existing elements (e.g., for habitation and mobility systems), support expanded exploration activities (e.g., operations during the lunar winter), and enable technology demonstrations with greater power needs (e.g., for in-situ resource utilization).

Development of this system for the Moon also demonstrates critical Mars-forward technologies, responding to NASA's selection of nuclear fission as the primary surface power generation technology for initial human Mars missions. Additionally, using the system on the lunar surface empowers NASA to develop operational competencies and reduce risk for nuclear power systems in crew architectures at other destinations.

For additional information about NASA's power needs as the architecture evolves, and how lunar power systems address those needs, refer to this year's "Integrated Lunar Power Considerations" white paper. Inclusion of this power system in the architecture lays the foundation for future lunar infrastructure investments supporting a robust, sustained human presence on the Moon's surface.

Functional Mapping

Foundational Exploration Segment	
Lunar Nuclear Fission System	
FN-P-101 L	Generate power in the south pole region on the lunar surface
FN-P-301 L	Distribute power in the south pole region on the lunar surface
FN-P-401 L	Provide power for deployed surface utilization payload(s) and/or equipment

2025 FEATURE

Building Evolvable Lunar Infrastructure

Building Evolvable Lunar Infrastructure

Sustained lunar exploration requires building lunar infrastructure and services that can provide everything astronauts need to live and work on the Moon. These systems must serve the near term needs of missions while offering extensibility to future exploration.

While short, individual missions can bring everything they need with them to the lunar surface, expanding exploration to include longer durations and more locations will require providing external power, logistics, and communications services. These services are akin to the utilities that serve communities on Earth, but with the added challenge of delivering them to and operating them on the lunar surface.

C&PNT

Lunar explorers need to communicate with Earth, establish their position on the Moon, navigate to locations of interest, and maintain common time with other explorers and assets. These services fall into the broad umbrella of C&PNT (communications and positioning, navigation, and timing) and are provided by a mix of government, international, and commercial providers. As exploration expands, these services may need to cover more parts of the Moon, provide increased throughput, or offer more precise accuracy, depending on exploration needs. Growing networks will provide an increasing range of capabilities.

For more information, see the "Communications and Navigation Needs for Foundational Exploration" white paper.

POWER

As the architecture expands to tackle increasingly ambitious missions, the ability to generate and share power becomes essential. While the elements used in early Artemis missions are self-sufficient from a power perspective (i.e., they can generate all the power they need using solar power systems), operating in more locations and for longer at the lunar South Pole will require additional, continuously available power to operate when solar power is not sufficient and to maximize the mass efficiency of individual systems. NASA is initiating elements like the lunar nuclear fission system to fulfill this need and is developing systems that can distribute and store power as needed.

For more information, see the "Integrated Lunar Power Considerations" white paper.

LOGISTICS

Logistics encompass the many supplies that long-duration exploration requires. Logistics services deliver food, water, clothing, gases, utilization equipment, spare parts, and other essentials to the lunar surface and move them to where they will be needed. NASA is encouraging the development of commercial lunar logistics services with its Commercial Lunar Payload Services (CLPS) program, which currently delivers utilization payloads from NASA and other customers to the lunar surface aboard commercially managed missions. As exploration evolves, commercial providers will be able to deliver additional supplies in larger amounts, as well as large pieces of lunar infrastructure.

For more information, see the "Lunar Surface Cargo" and "Lunar Logistics and Mobility" white papers.

Evolving to Meet the Needs of a Lunar Economy

As exploration of the Moon expands, the demand for these services will grow and new providers can add capacity. While NASA is building the infrastructure that will enable the agency and its international partners to explore the Moon together, commercial entities could create demand for additional services and find opportunities to supply them (e.g., providing commercial power on the lunar surface for government or industry customers). With NASA serving as an anchor customer and validating interoperability standards, the future of lunar exploration will involve many organizations providing and utilizing infrastructure to enable science, resource extraction, and technology development.

2025 FEATURE

Growing NASA's Knowledge Base

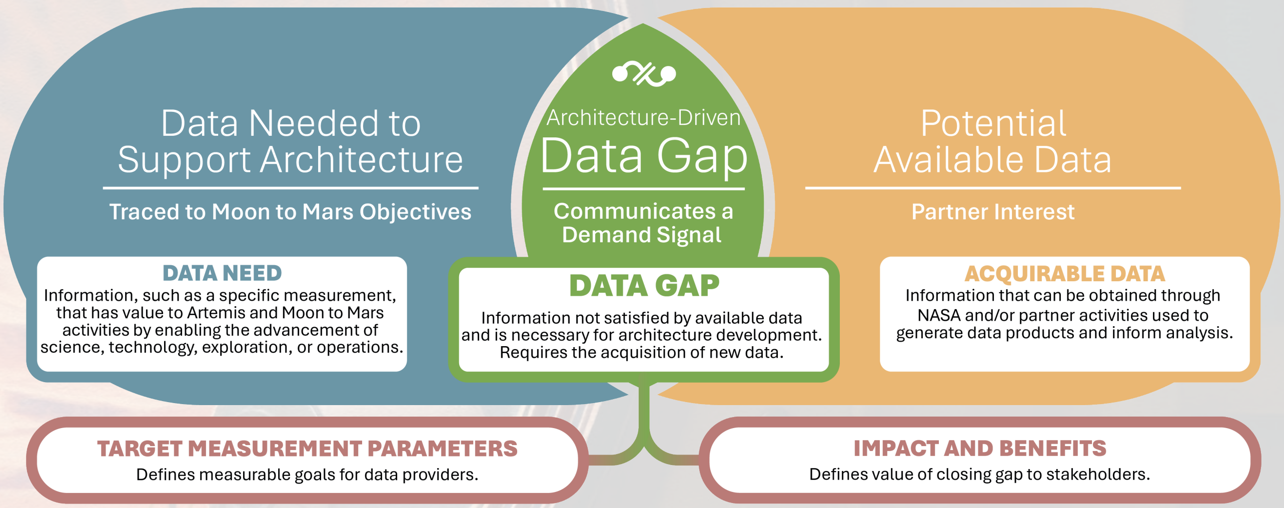
Growing NASA's Knowledge Base

Information drives innovation. To enable and realize agency exploration objectives, NASA will look to its partners to help acquire data gathered on and around the Moon and Mars. **Architecture-driven data gaps** represent missing or incomplete information needed to plan, build, deploy, and operate systems in the lunar and Martian environments.

NASA's Architecture Definition Document captures how the agency will accomplish NASA's Moon to Mars Objectives. The latest revision of the document includes a preliminary list of architecture-driven data gaps, which will evolve annually as NASA closes gaps and identifies new ones.

Just as NASA understands the architecture's technical needs through a **functional decomposition**, which breaks objectives down into the individual capabilities needed to accomplish them, the agency understands the architecture's data needs through **knowledge decomposition** activities, in which the agency seeks to understand the knowledge needed to accomplish the Moon to Mars Objectives.

Through the clear demand signal that these architecture-driven data gaps provide, NASA and its partners can better align their data-gathering efforts to support human exploration of the Moon, Mars, and beyond.



Data Gaps and Technology Gaps

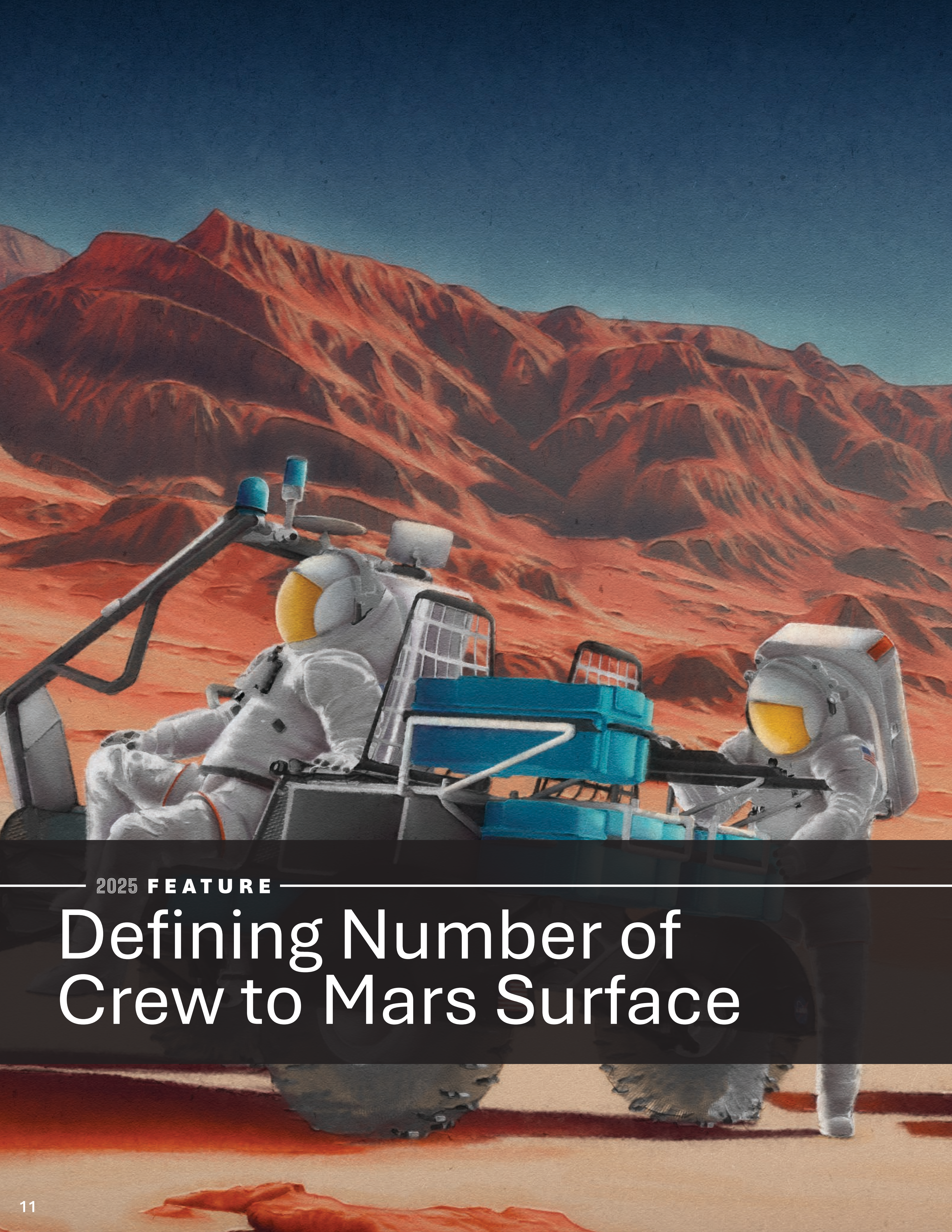
Along with architecture-driven data gaps, NASA also publishes a list of architecture-driven technology gaps in the Architecture Definition Document. The term "gap" is widely used across NASA and the aerospace industry to describe a difference between an existing capability and a current or expected need.

While technology gaps describe the architecture's **technology development** needs, data gaps describe **information needed**. Technology gaps and data gaps can be connected (e.g., new data is needed to inform performance targets for technology development). As the list of data gaps list evolves or is addressed, NASA will continue to track the connections and dependencies between architecture-driven data and technology gaps.

For more information about architecture-driven data gaps, refer to the 2025 "Architecture-Driven Data Gaps" white paper.

ID	Data Gap	Data Utility
DN-002 L	Comprehensive, high-fidelity elevation map coverage of lunar south pole exploration zones and sites	To better enable characterization of lunar landing sites and increase confidence in landing accuracy and mobility system navigation.
DN-007 L	In-situ measurements of the horizontal and vertical distribution, abundance, and physical makeup of shallow bulk water ice	To enable better identification of potential sites for in-situ resource utilization activities.
DN-008 L	Geotechnical properties of highland regolith at the lunar south pole	To enable higher certainty in the landing environment to inform lander design and site selection.
DN-017 L	In-situ measurement of particle velocity during lunar plume surface interaction (PSI) phenomena	To enable better modelling of the interactions between landers and surface regolith to mitigate risk of damage to hardware.

Representative architecture-driven data gaps and examples of data utility from the preliminary list published in Architecture Definition Document revision C.



2025 FEATURE

Defining Number of Crew to Mars Surface

Defining Number of Crew to Mars Surface

In 2025, NASA defined a key part of the Mars architecture, establishing that initial missions to Mars will assume no less than four crew members to the Martian surface, with consideration for up to six crew to enhance mission capability and/or provide risk reduction. This number balances a range of factors that affect mission safety and success, while allowing the agency to maintain flexibility for individual missions.

Crew Health and Safety

The safety and health of astronauts are NASA's most important concern. Mars missions must send a crew complement that prioritizes safety.

For example, NASA extravehicular activities (EVA) follow a "buddy" flight rule, where at least two astronauts work together to provide each other with aid in the event of contingencies like equipment failure or injuries. A solo EVA presents excessive risk, so a mission that sends a single crew member to the surface would be unacceptable.

Operations and Earth Independence

Unlike missions to low Earth orbit or the lunar surface, which can rely on near-instantaneous communication with mission control centers, missions to Mars will need to account for a one-way time delay of up to 22 minutes. This delay means astronauts cannot rely on real-time advice or guidance from mission controllers and must operate with significant autonomy and independence from Earth.

This Earth independence means delayed support from experts on the ground, such that the crew must quickly respond to critical events using their expertise and local systems. While no realistic crew complement could completely replace the services of a mission control center, this need to train for multiple specialized roles drives a larger crew to achieve acceptable risk levels.

A smaller number of crew members may limit the number of responsibilities that crew could train for, which could limit mission objectives. A larger crew complement allows for more specialization, better proficiency retention, and redundancy of role coverage. For example, Recent NASA studies found that four or more crew members can strike a better balance of these factors.

Engineering Complexity

While the agency has not formally constrained the maximum number, sending a larger number of crew (e.g., seven, eight, or more astronauts) introduces new challenges, such as mass and size of descent and ascent vehicles within launch and landing capabilities, as well as mass of additional consumables needed to support these additional crew members, and overall mission cost. While more crew members may increase time available for exploration mission objectives (e.g., science), a larger number of crew quickly becomes a case of diminishing returns and increased challenges.

Findings and Decision

Based on these factors and the results of trade studies and inputs from across the agency, NASA specified that initial human missions to Mars will assume no fewer than four crew members, with considerations for up to six crew members to the Martian surface.

This surface contingent does not necessarily limit the total number of crew in the future, but establishes a key lower bound for number to the surface that balances risk and achieving mission objectives. As the Mars architecture continues to develop, the agency could choose to send additional astronauts to remain in Mars orbit; that part of the trade space remains open.

Learn more about the Mars architecture trade space at: www.nasa.gov/moon-to-mars-architecture-mars-architecture-trade-space

Architecture-Driven Technology Gaps

2025 UPDATES

NASA publishes a list of architecture-driven technology gaps in the Architecture Definition Document annually to help partners guide their technology development efforts in support of space exploration. The agency refines this list each year, adding new technology gaps as they arise, closing gaps as their needs are fulfilled, and updating the priority order to reflect the current state of the architecture.

Revision C of the Architecture Definition Document adds two new technology gaps and removes one former gap, which has been replaced by multiple new architecture-driven data gaps (for more information about data gaps, see the feature on page nine and the "Architecture-Driven Data Gaps" white paper).

For more information about architecture-driven technology gaps, refer to the 2024 architecture white paper or revision C of the Architecture Definition Document.

NEW #0504 Autonomous Lunar Surface Structure Assembly and Construction

Autonomous construction can help support sustained lunar exploration. This technology gap captures the robotic assembly, inspection, outfitting, repair, and site preparation systems that would be necessary to conduct autonomous, in-situ construction.

NEW #0505 In-situ Additive/Subtractive Construction on the Lunar Surface

Additive and subtractive manufacturing on the lunar surface would use in-situ resources (e.g., lunar regolith) to build pathways and walls. This technology gap captures systems that use feedstock derived from local resources for construction.

RECHARACTERIZED #0602 In-situ Resource Identification, Characterization, and Mapping

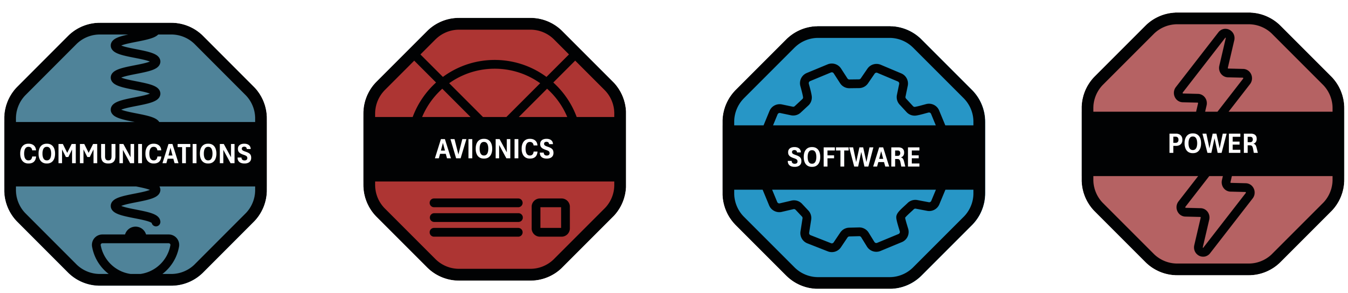
This gap has been removed and replaced with five architecture-driven data gaps (DN-006 L, DN-007 L, DN-008L, DN-010 L, DN-013 L) . For more information, refer to the architecture-driven data gaps in appendix E of Architecture Definition Document revision C.

Deep Space Standards

International standards help space agencies and aerospace companies from around the world collaborate in deep space. These standards — developed in collaboration with the international community and industry partners — define interfaces and environments to facilitate cooperative deep space exploration endeavors. These standards focus on priority topics for the early phases of exploration planning; they are not intended to dictate design features beyond interfaces.

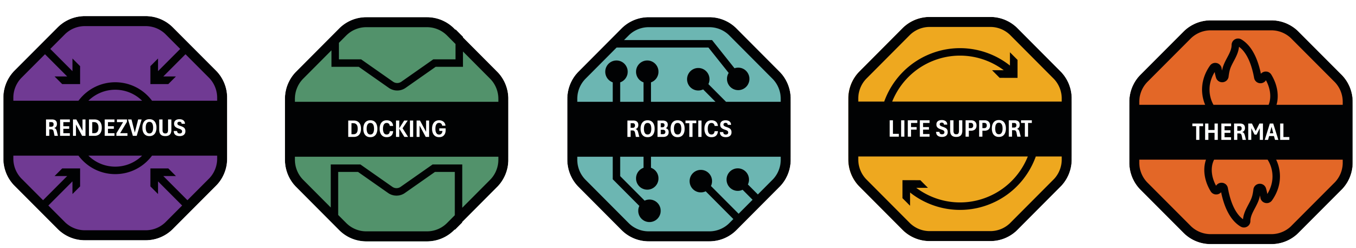
NASA maintains a webpage that captures the standards adopted by NASA's Moon to Mars program and for Gateway, NASA's lunar-orbiting outpost. As the agency adopts new standards, they will appear on this page.

MOON TO MARS ARCHITECTURE STANDARDS



ADOPTED 2024 ADOPTED 2025

ADDITIONAL GATEWAY STANDARDS



https://www.nasa.gov/international-deep-space-standards/

ARCH Performance & Effectiveness

As NASA refines and expands the Moon to Mars Architecture, it also measures how well the architecture is meeting the agency's Moon to Mars Objectives. Measures of performance and measures of effectiveness assess what objectives the architecture is meeting and how well it is meeting them, respectively. These might include, for example, the architecture's ability to provide mobility services on the lunar surface, the actual distance it can support, and how that capability compares with the agency's stated objectives.

The graphic below provides a simplified look at how the architecture's performance has evolved over past Architecture Concept Review (ACR) cycles. These year-over-year changes capture significant growth in key exploration capabilities. For example, the addition of the Pressurized Rover in 2023 significantly increased mobility opportunities, while the addition of the lunar surface fission system this year significantly increases the power that the architecture can provide.

NASA tracks these measurements year-to-year to demonstrate how initiating new elements, building utilization capabilities, and further defining the Moon to Mars Architecture bring the agency closer to meeting all of its exploration goals.

2025 White Papers

WHY MOON AND MARS? BUILDING AN EVOLUTIONARY ARCHITECTURE

Explores how NASA is using an evolutionary crawl-walk-run approach to steadily build capabilities that can overcome the challenges of deep space exploration, expanding on the incremental approach the agency used to build up to the Apollo lunar landings.

ARCHITECTURE-DRIVEN PLANETARY PROTECTION CONSIDERATIONS

Surveys NASA's approach to planetary protection, the process by which NASA safeguards both exploration destinations and the Earth from contamination, and highlights key considerations for human missions to Mars.

ARCHITECTURE DEFINITION

Updates two previous white papers to summarize the six major questions that make up an exploration architecture and how NASA defines the Moon to Mars Architecture to answer those questions.

INTEGRATED LUNAR POWER CONSIDERATIONS

Identifies the key factors that affect generating, storing, and sharing power on the lunar surface, a key capability as exploration expands to increasingly complex operations.

COMMUNICATIONS AND NAVIGATION NEEDS FOR FOUNDATIONAL EXPLORATION

Explains how NASA's communications and navigation needs will expand beyond those of initial Artemis missions as it explores more of the lunar surface and undertakes increasingly ambitious activities there.

ARCHITECTURE-DRIVEN DATA GAPS

Introduces the new catalog of architecture-driven data gaps, areas where NASA requires additional information to achieve its exploration goals.

2026 LOOK-AHEAD

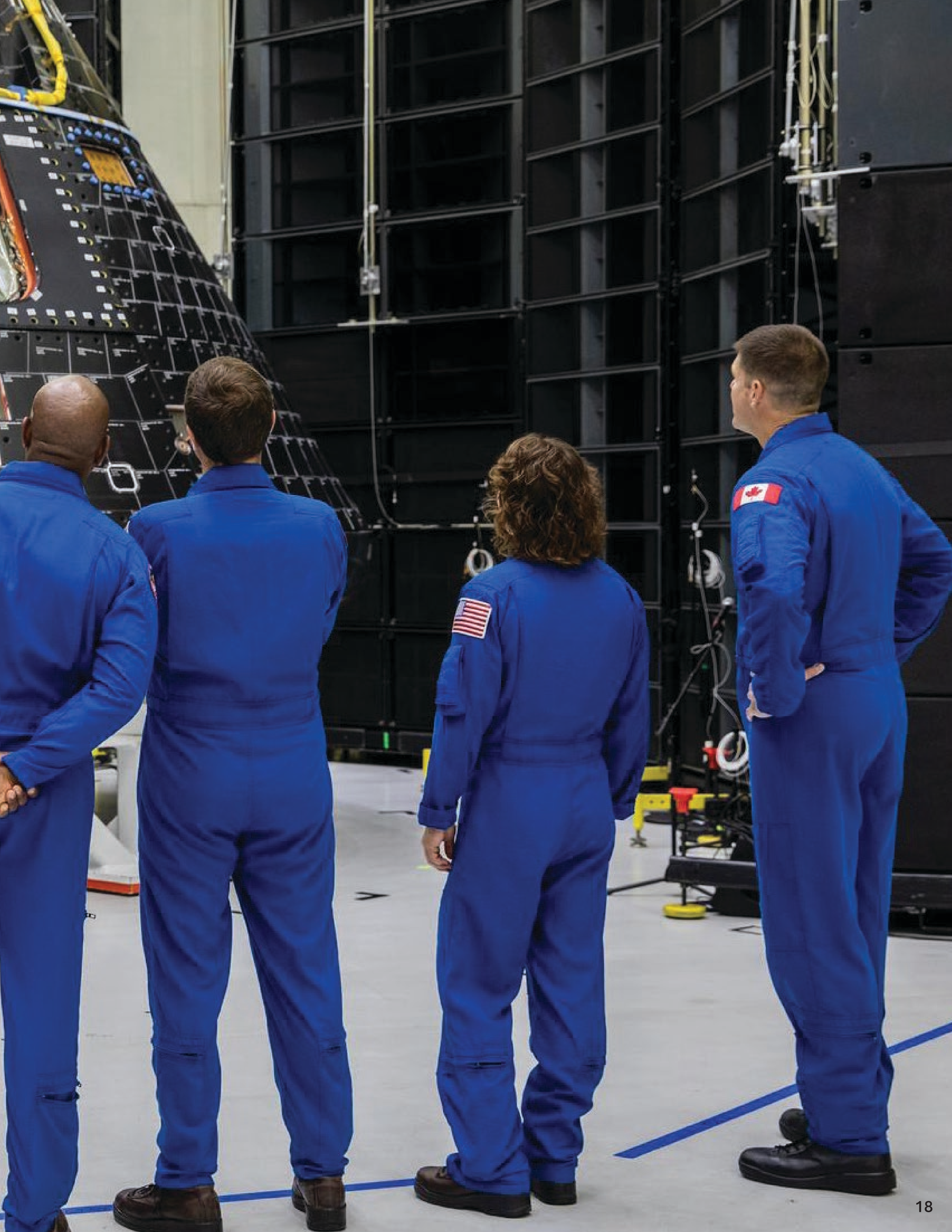
Architecture and Artemis II

In 2026, NASA will continue to refine, update, and develop the Moon to Mars Architecture, adding elements that fulfill capabilities for future segments and conducting architecture definition tasks that bring the first human missions to Mars into focus. The agency will announce new industry engagement opportunities to leverage the capabilities of the commercial sector and will continue to partner with international space agencies to leverage their unique skills. Some key focus areas for 2026 include lunar logistics capabilities, refining NASA's lunar power strategy, and examining the communications and navigation needs of crewed Mars missions.

Additionally, in 2026, NASA will launch Artemis II, the first mission to send astronauts around the Moon since the Apollo era. Artemis II builds on the success of the uncrewed Artemis I in 2022 and will demonstrate a broad range of capabilities needed on deep space missions. The Artemis II test flight will be NASA's first mission with crew aboard the Orion spacecraft launching atop the SLS (Space Launch System) rocket. NASA's Reid Wiseman, Victor Glover, and Christina Koch, and CSA (Canadian Space Agency) astronaut Jeremy Hansen will fly the Orion capsule in Earth orbit to test proximity operations and then around the Moon and back to Earth in a free-return trajectory.

Artemis II, one of the first steps in the Moon to Mars Architecture, will pave the way for the next time astronauts walk on the lunar surface, during Artemis III. NASA and its partners are returning to the Moon and journeying to Mars for all humanity.

ARTEMIS



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