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Moon to Mars Architecture Definition Document | Revision C - 2025

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December 2025

NASA STI Program Report Series

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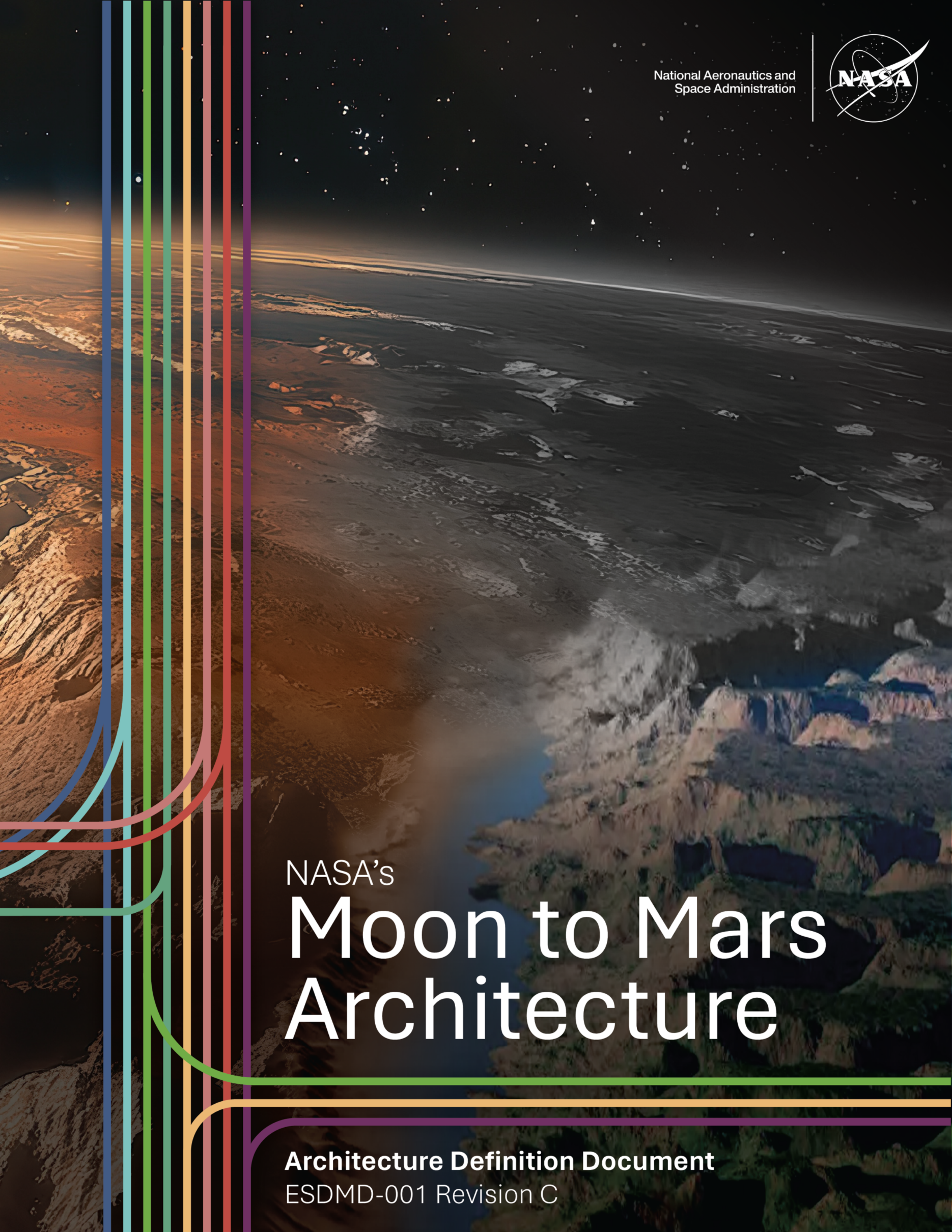

National Aeronautics and
Space Administration

NASA's
Moon to Mars Architecture

Architecture Definition Document

ESDMD-001 Revision C

NASA/TP- 20250010956

Moon to Mars Architecture Definition Document

ESDMD-001 – Revision C

National Aeronautics and Space Administration
Exploration Systems Development Mission Directorate

www.nasa.gov/architecture

Revision and History

The NASA office of primary responsibility for this document is the Exploration Systems Development Mission Directorate (ESDMD) Strategy and Architecture Office (SAO). Visit the Moon to Mars Architecture homepage for the latest version of this document and for more detail on NASA's Moon to Mars exploration campaign.

Revision Identification	Revision Description	Release Date
Initial	Initial Release	04/18/2023
Revision A	2023 Architecture Concept Review Updates • Refined and added sub-architectures (Data Systems and Management, Infrastructure, In-situ Resource Utilization, Robotics) • Refined and expanded objective decomposition, including use cases and functions • Updated Human Lunar Return, Foundational Exploration, and Human to Mars segments • Added the following elements and their functional mappings: Gateway expanded capability configuration, Human-class Delivery Lander, Lunar Terrain Vehicle, and Pressurized Rover • Added and updated assessments for recurring tenets	01/22/2024
Revision A.1 Management Directive 1	Corrections of Minor Errata • Added functions to the Human Landing System for the Human Lunar Return and Foundational Exploration Segments • Updated definitions of "cargo" and "consumables;" removed "large cargo" from glossary	03/27/2024
Revision B	2024 Architecture Concept Review Updates • Refined and expanded objective decomposition • Added Mars characteristics, needs, use cases, and functions for Transportation and Habitation, Mars Infrastructure, and Operations objectives • Updated Human Lunar Return, Foundational Exploration, and Humans to Mars segments • Added the following elements and their functional mappings: initial surface habitat and lunar surface cargo lander • Updated assessments for recurring tenets • Added and expanded architecture decisions • Added architecture-driven technology gaps	12/13/2024
Revision B.1 Management Directive 4	Corrections to Resolve Unallocated Function Discrepancies for the Human Lunar Return Segment Updated list of unallocated functions for the Human Lunar Return segment Identified functions targeted for the Human Lunar Return segment Removed allocation of FN-T-103 L, "transport crew from cislunar space to distributed sites outside of the south pole region on the lunar surface," to UC-T-103 L,	04/04/2025

	“aggregation and physical assembly of spacecraft components in cislunar space”	
Revision C	2025 Architecture Concept Review Updates • Reorganized, simplified, and refreshed content based on stakeholder feedback • Updated objective decomposition • Added Mars use cases and functions for lunar and planetary science, heliophysics science, human and biological science, and physics and physical science objectives • Added the lunar utility rover element and lunar nuclear fission system element • Added content on element definition and pre-formulation methodology • Updated assessments for recurring tenets • Updated "architecture decisions" terminology to "architecture definition" to better capture the process and outcomes of these activities • Refined architecture definition tasks • Refined architecture-driven technology gaps • Added architecture-driven data gaps	12/12/2025

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Executive Summary

The National Aeronautics and Space Administration explores the unknown in air and space, innovates for the benefit of humanity, and inspires the world through discovery. Human exploration of the Moon, Mars, and beyond is key to that mission.

Having established long-term goals in the Moon to Mars Objectives,[1] NASA's Moon to Mars Architecture comprises an innovative, evolutionary approach to pursuing the agency's aims for crewed exploration of deep space. The architecture offers a high-level, unifying structure for the Moon to Mars endeavor. It provides rules, guidelines, and constraints that define a cohesive and coherent framework.

This Architecture Definition Document establishes the process of objective decomposition, outlines the architecture's constituent parts, and provides insight into the ongoing evolution of the architecture. NASA updates the document annually to reflect the maturation of the architecture and progress toward exploration objectives.

This is not a manifest or requirements document. Rather, it is a tool for those seeking to understand or engage with the architecture. This can include commercial industry, international partners, other U.S. government organizations, and implementing programs and projects within NASA.

The Architecture Definition Document is also not a policy document. It is a technical document that reflects the approved baseline for programs of record, contracts, partnerships, and funding. The document reflects changes to the program of record after formal approval of and adoption by the U.S. government. Partnerships appear once formalized through a contract vehicle, bilateral agreement, or other formal arrangement.

When developing this revision of this document (Rev-C), NASA sought to revitalize the content in service to our stakeholders. This includes reorganizing, streamlining, and simplifying content for a more user-friendly experience. Interested readers may still find previous revisions alongside this one on the agency's architecture website.[2]

Revision C incorporates several updates, including adding the lunar utility rover element and the lunar nuclear fission system element. NASA added a new list of architecture-driven data gaps — which capture information that NASA needs to achieve its exploration objectives — to join an updated list of architecture-driven technology gaps. NASA also refined its architecture definition tasks, including capturing three new results that will shape the future of results.

NASA established its Moon to Mars Architecture approach to realize humanity's most ambitious campaign of deep space exploration to date. Ultimately, this document seeks to foster engagement with and understanding of the agency's exploration architecture. The iterative development of NASA's Moon to Mars Architecture relies on contributions from scientists, engineers, and aerospace professionals across all the agency's mission directorates, centers, and technical authorities. The NASA architecture team thanks their many stakeholders for their critical support.

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[1] https://www.nasa.gov/wp-content/uploads/2022/09/m2m-objectives-exec-summary.pdf

[2] https://www.nasa.gov/moontomarsarchitecture/

Moon to Mars Architecture
Definition Document
ESDMD-001

01.

Architecture Foundations

1 Architecture Foundations

An architecture is the high-level, unifying structure that defines a system. It provides a set of rules, guidelines, and constraints that define a cohesive and coherent structure consisting of constituent parts, relationships, and connections that establish how those parts fit and work together. While this definition, from the National Aeronautics and Space Administration (NASA) Systems Engineering Handbook,[3] typically applies to a simple program construct, it also captures the broad range of systems, programs, and projects supporting human exploration of the Moon, Mars, and beyond.

NASA's Moon to Mars exploration campaign is the agency's most complex systems engineering effort to date. Associated programs, projects, and contributing systems will span decades, agencies, countries, cultures, and a variety of commercial, academic, and other types of contributors. This document establishes a common language, framework, and process to communicate and chronicle the evolution of the Moon to Mars Architecture.

1.1 Purpose

The integrated Moon to Mars Architecture creates opportunities to execute ambitious missions to the lunar surface and the first human missions to Mars in parallel. Through near-term lunar exploration, NASA will institute the processes, procedures, and techniques needed to enable exploration of Mars and beyond.

NASA's Moon to Mars Strategy and Objectives Development document[4] addresses challenges associated with architecture definition. The Moon to Mars Objectives document[5] — developed with input from NASA's workforce, industry, academia, and the international space community — outlines NASA's long-term goals for crewed exploration of the Moon and Mars.

This Architecture Definition Document is a systems engineering document that outlines the architecture's iterative, adaptable framework. It captures the methodology, organization, and decomposition necessary to translate broad objectives into functions and use cases that can be allocated to implementable programs and projects. It communicates the agency's long-term vision for architecture evolution, maintains traceability to responsible parties, and iterates on the architecture as innovations and solutions develop.

NASA updates and improves this document through its annual Architecture Concept Review, which solicits input from across the agency's mission directorates, centers, and technical authorities. The annual Architecture Concept Review cycle creates opportunities to continually incorporate cutting-edge technologies and new partnerships with industry, other U.S. government organizations, international entities, and academia.

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[3] https://ntrs.nasa.gov/citations/20170001761

[4] https://www.nasa.gov/wp-content/uploads/2023/04/m2m_strategy_and_objectives_development.pdf

[5] https://www.nasa.gov/wp-content/uploads/2022/09/m2m-objectives-exec-summary.pdf?emrc=683dc475b99b7

1.2 Scope

NASA's Exploration Systems Development Mission Directorate (ESDMD) established the Moon to Mars Architecture to decompose the agency's Moon to Mars Objectives into the crewed and robotic exploration systems and capabilities needed to meet those objectives. This document captures the programs, projects, systems, and contributions that enable the human exploration of the Moon, Mars, and beyond (however, the document may not cover some independent robotic or other non-NASA systems supporting agency exploration goals).

1.2.1 Content Structure

NASA has structured the Architecture Definition Document to reflect its iterative architecture development process. The main body of the document captures the current state of the architecture and ongoing work to further refine it. Appendices provide detailed process breakdowns, technical information, and reference materials.

Section 1: **Architecture Foundations**	Overviews processes that inform architecture development.
Section 2: **Architecture Components**	Captures the current state of the architecture, including its constituent segments, sub-architectures, elements, and other exploration assets.
Section 3: **Architecture Evolution**	Details ongoing architecture development, including architecture roadmapping, architecture-driven technology gaps, definition of new elements, and architecture assessments.
Appendix A: **Architecture Rationale & Considerations**	Offers additional insight into the architecture effort and discusses important considerations for human deep space exploration.
Appendix B: **Architecture Decomposition**	Traces objectives to architecture components, including full objective decomposition and functional mapping tables.
Appendix C: **Architecture Definition**	Captures the full list of completed and forthcoming key architecture definition tasks.
Appendix D: **Architecture-Driven Technology Gaps**	Catalogs and prioritizes architecture-driven technology gaps.
Appendix E: **Architecture-Driven Data Gaps**	Lists architecture-driven data gaps.
Appendix F: **Terminology**	Defines key terms, abbreviations, and quantity descriptors used throughout the document.

1.2.2 Content Scope

This document limits itself to content related to Moon to Mars Architecture development and associated pre-formulation activities. This document intentionally excludes programmatic, partnership, and procurement information outside of that narrow scope. It is important to note the following:

The document is *not* a replacement for existing processes or agreements.	Existing NASA mechanisms and processes for partnerships, procurements, etc., are unchanged. Existing formal governmental processes remain in effect. The architecture approach supports these processes; architecture products reflect formal process results.
The document is *not* procurement direction.	NASA formally documents and manages procurement processes. The agency defines procurement timing, requirements definition, and contract methods within those processes. This document only informs procurement by articulating needed capabilities. Architecture products communicate needs; they do not presuppose solutions.
The document is *not* a manifest.	NASA's Moon to Mars Program Office takes responsibility for flight manifests, sequences, and mission design in concert with associated partners and/or contracts. The architecture reflects capabilities necessary to achieve objectives; the manifesting of flights to achieve objectives is subject to procurement, development, and implementation processes of implementing programs.
The document is *not* a budget request.	NASA may fulfill architecture needs through various means, coordinating through the existing processes, procedures, and budget analysis. Architecture products inform these processes but do not presuppose how the agency allocates resources.
The document is *not* a policy document.	The Architecture Definition Document is a technical document that reflects the approved baseline for programs of record, contracts, partnerships, and funding.

1.3 Methodology

NASA adopts two complementary principles to address its complex exploration goals: ***architect from the right*** and ***execute from the left***. Architecting from the right means beginning with long-term goals (farthest to the right on a timeline) and working backwards to establish the capabilities required to achieve them. Systems derived from this process execute from the left through established systems engineering processes, moving left to right on the timeline toward maturity.

This sub-section discusses NASA's Moon to Mars approach, highlighting how lunar exploration lays essential groundwork for human exploration of the Red Planet. It introduces the objective decomposition process, which refines long-term objectives into actionable capabilities, and the architectural framework that organize those capabilities.

Appendices A and B of this document discuss architecture rationale and objective decomposition, respectively, in more detail. Appendix B includes the full decomposition of the Moon to Mars Objectives.

1.3.1 Why Moon to Mars

While humanity has over 60 years of human spaceflight experience, the vast majority of that experience is concentrated in low Earth orbit. NASA's history of human lunar exploration spans 9 Apollo missions on and around the Moon over the course of 5 years; only 12 humans have walked on the lunar surface. To date, only robotic missions have explored Mars. Exploring each destination requires a different scope and scale, driving specific challenges.

To prepare to land on the Moon in 1969, NASA followed an incremental programmatic approach. The agency learned that humans could live in space through the Mercury Program; learned to operate in space through the Gemini Program; and finally landed on the Moon and safely returned to Earth through the Apollo Program. Robotic precursor missions, like the Ranger and Surveyor projects, also paved the way for human exploration.

The Moon to Mars Architecture follows a similar developmental approach, building foundational deep space exploration capabilities with lunar missions while preparing humanity's first journeys to Mars. NASA's approach builds capabilities across four facets:

National Posture	The Moon to Mars campaign will reinforce the United States' global leadership in space exploration. This includes developing the nation's industrial base, advancing technologies, and expanding economic utilization at the Moon and Mars.
Engineering and Design	The design and deployment of hardware necessary to reach a destination become increasingly challenging as the distance from Earth grows. The performance needed for a Mars mission is far greater than for a Moon mission, which is far greater than for a low Earth orbit mission.
Operations	While NASA and partner space agencies have decades of human spaceflight experience, that experience has mostly been near the Earth. Humanity must develop experience and competency to operate in increasingly remote environments. Closing this gap is a key facet of Moon to Mars activities.
The Human System	Even the shortest missions to Mars will likely exceed the longest stays aboard the International Space Station; NASA will need to ensure that astronauts can respond to extended deconditioning in microgravity, changes in gravity, prolonged isolation and confinement, deep space radiation, and other hazards.

Lunar exploration serves dual purposes: conducting critical science on the Moon while building NASA's capacity to sustain human exploration and economic expansion on the lunar surface and cislunar space, operate in deep space, and enable the first human mission to Mars. The agency does not choose the Moon *or* Mars — parallel development through the Moon *to* Mars Architecture offers profound synergies that will empower NASA to send humanity further afield than ever before.

Appendix A explores key architecture drivers and unique considerations for the Moon and Mars in more detail. Additional detail about the approach may be found in the 2025 Moon to Mars Architecture White Paper, "Why Moon and Mars."[6]

1.3.2 Objective Decomposition Process

NASA's Moon to Mars Objectives define the agency's broad, top-level exploration goals; they represent the desired outcomes of the Moon to Mars Architecture. The objectives are agnostic with respect to implementation; they do not specify architectural or operational solutions. Rather, they provide goals to facilitate the architecture development and a means to measure progress.

The objectives are categorized into the overall goals listed below. The detailed individual objectives for each goal are available in NASA's Moon to Mars Objectives document.

Moon to Mars Objectives: Goals

Lunar and Planetary Science (LPS)	Address high priority planetary science questions that are best accomplished by on-site human explorers on and around the Moon and Mars, aided by surface and orbiting robotic systems.
Heliophysics Science (HS)	Address high priority heliophysics science and space weather questions that are best accomplished using a combination of human explorers and robotic systems at the Moon, at Mars, and in deep space.
Human and Biological Science (HBS)	Advance understanding of how biology responds to the environments of the Moon, Mars, and deep space to advance fundamental knowledge, support safe, productive human space missions and reduce risks for future exploration
Physics and Physical Science (PPS)	Address high priority physics and physical science questions that are best accomplished by using unique attributes of the lunar environment.
Science-Enabling (SE)	Develop integrated human and robotic methods and advanced techniques that enable high-priority scientific questions to be addressed around and on the Moon and Mars.
Applied Science (AS)	Conduct science on the Moon, in cislunar space, and around and on Mars using integrated human and robotic methods and advanced techniques, to inform design and development of exploration systems and enable safe operations.

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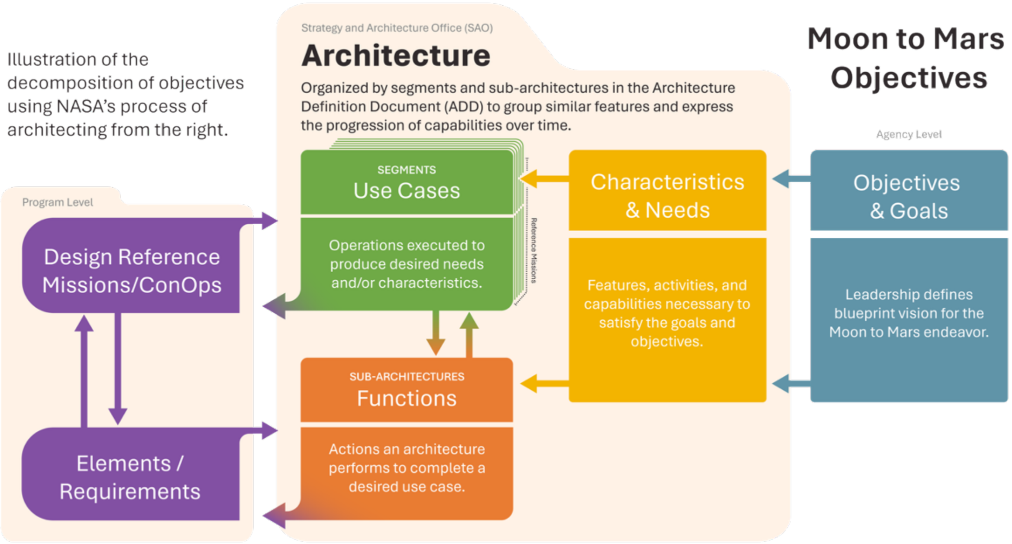
[6] https://www.nasa.gov/moontomarsarchitecture-whitepapers/

Lunar Infrastructure (LS)	Create an interoperable global lunar utilization infrastructure where U.S. industry and international partners can maintain continuous robotic and human presence on the lunar surface for a robust lunar economy without NASA as the sole user, while accomplishing science objectives and testing for Mars.
Mars Infrastructure (MI)	Create essential infrastructure to support initial human Mars exploration campaign.
Transportation and Habitation (TH)	Develop and demonstrate an integrated system of systems to conduct a campaign of human exploration missions to the Moon and Mars, while living and working on the lunar and Martian surface, with safe return to Earth.
Operations (OP)	Conduct human missions on the surface and around the Moon followed by missions to Mars. Using a gradual build-up approach, these missions will demonstrate technologies and operations to live and work on a planetary surface other than Earth, with a safe return to Earth at the completion of the missions.

The objectives also include recurring tenets, cross-cutting themes that inform the entire exploration endeavor. Section 3.4 assesses how the architecture addresses these recurring tenets.

The Moon to Mars Architecture methodology decomposes the objectives into the capabilities needed to achieve them (architecting from the right). This results in capabilities that NASA programs or partner contributions can fulfill.



Objective Decomposition Process and Key Terms

Characteristics and Needs	Features to satisfy the goals and objectives; statements that drive architecture capability necessary to satisfy the Moon to Mars objectives, and identify a problem to be solved, but are not solutions.
Use Cases	Operations that would be executed to produce the desired needs and/or characteristics.
Functions	Actions that an architecture would perform to complete the desired use case.

The first step in this process is to define the characteristics and needs required to satisfy an objective or a group of objectives. While objectives themselves focus on desired outcomes, the characteristics and needs translate those outcomes into the features or products of the exploration architecture necessary to produce those outcomes.

NASA defines characteristics and needs in a form that is still neutral to architectural implementation. Instead, they focus on what the architecture produces or accomplishes. This critical step in the process converts the objectives into actionable exploration activities.

Having defined characteristics and needs, NASA decomposes them into specific implementable functions and use cases, actionable features that could be included in the architecture. Functions are services or actions that the exploration architecture would perform. Use cases describe operations that the architecture employs.

Finally, NASA develops reference missions that can provide desired functions, as well as reference elements and concepts of operations to fulfil those missions. This is the first phase in the development of architectural solutions; it demonstrates the viability of reference elements, reference missions, and concepts of operations in delivering functions and use cases, providing characteristics and needs, and ultimately satisfying objectives.

This objective decomposition process guides development of new systems and capabilities, addressing feasibility, definition, and scope. There is a feedback loop between the decomposition process and the development of new systems: during design and development, programs or projects assess systems to ensure they achieve expected architectural functions. Adjustments during formulation may lead NASA to descope functions/use cases and allocate them to a different system later in the architecture process. NASA continually revisits the mapping of objectives to reference missions, concepts of operations, and systems to ensure objective satisfaction.

For detailed information on objective decomposition, consult the tables in Appendix B or the spreadsheets published concurrently with this document.[7]

1.3.3 Architecture Framework

The scale of the Moon to Mars Architecture requires a framework that partitions the effort into portions that NASA and its partners can execute. This framework embraces systems engineering processes that empowers

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[7] https://www.nasa.gov/moontomarsarchitecture-architecturedefinitiondocuments/

incremental advancements, infusion of new innovations, incorporation of partnerships, and systematic fulfillment of objectives.

In a traditional systems engineering process, NASA would fully establish an architecture up front, define requirements and concept of operations, and begin execution through associated programs and projects. This method — if applied to an architecture of this scale — would require the agency to select mission profiles, technologies, and development schedules up front, biasing the architecture toward mature solutions and capabilities that exist today.

To realize an evolutionary architecture that responds to the changing technological landscape, NASA's iterative Moon to Mars Architecture framework divides the architecture into the sub-architectures and segments discussed in Section 2. Sub-architectures group tightly coupled systems, needs, and capabilities that function together to accomplish objectives. The segments define portions of the architecture with increasing operational complexity and objective satisfaction.

Architecture Framework Key Terms

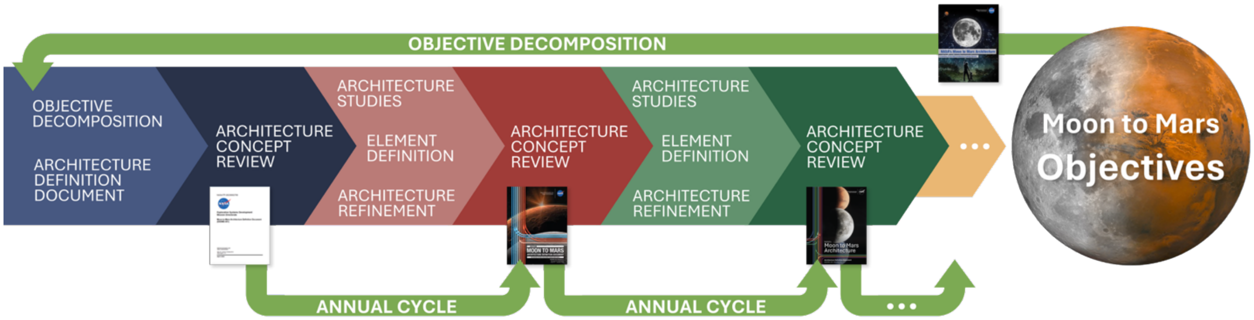
Architecture	The high-level unifying structure that defines a system. It provides a set of rules, guidelines, and constraints that define a cohesive and coherent structure consisting of constituent parts, relationships, and connections that establish how those parts fit and work together.
Segments	Portions of the architecture, identified by one or more notional missions or integrated use cases, illustrating the interaction, relationships, and connections of the sub-architectures through progressively increasing operational complexity and objective satisfaction.
Sub-Architecture	A group of tightly coupled elements, functions, and capabilities that perform together to accomplish architecture objectives.

This framework allows the architecture to add new systems over time. NASA may also add or reassign functions to systems as they mature, reflecting new capabilities and maximizing objective satisfaction.

1.3.4 Architecture Definition Process

Having established objective decomposition process and a framework for partitioning the architecture into executable portions, NASA and its partners have established a process that enables iterative infusion of technologies and capabilities to address objectives.

NASA's ESDMD manages this process through the annual strategic analysis cycle. These cycles prioritize architecture work and studies needed to address open questions, identify architectural drivers to buy down mission risk, coordinate with partners, identify gaps in the architecture, and resolve them. The cycles conclude with study findings and/or updates to the Architecture Definition Document and supporting architecture products, which are reviewed at the annual Architecture Concept Review meeting.



Evolutionary Architecture Process

These iterative cycles enable definition of new elements or systems and modifications to the architecture as existing elements and programs mature. NASA also assesses how emerging technologies and new solutions can address architecture needs during the strategic analysis cycle. The analysis process reflects a variety of viewpoints, perspectives, and ideas from stakeholders and partners.

Strategic analysis cycle trade studies also consider technology advancements, alternative solutions, and different concepts to identify efficiencies or development priorities in future segments. As program execution matures and NASA conducts exploration missions, the architecture accounts for realized system performance and new scientific discoveries. These efforts inform how NASA adds future systems and elements into the architecture.

Moon to Mars Architecture
Definition Document
ESDMD-001

02.

Architecture Components

2 Architecture Components

NASA's Moon to Mars Architecture framework comprises many parts that reflect the incremental buildup of exploration capabilities. This section breaks the architecture down by **segments**, broad phases of exploration; **sub-architectures**, tightly coupled systems, needs, and capabilities that function together to accomplish objectives; and **elements and exploration assets**, the systems and hardware that enable exploration and objective satisfaction, which include **utilization payloads and equipment** that realize science and technology demonstrations.[8] This section details the existing components of the Moon to Mars Architecture.

Architecture Components Key Terms

Segments	Portions of the architecture, identified by one or more notional missions or integrated use cases, illustrating the interaction, relationships, and connections of the sub-architectures through progressively increasing operational complexity and objective satisfaction.
Sub-Architecture	A group of tightly coupled elements, functions, and capabilities that perform together to accomplish architecture objectives.
Element	Any exploration system that enables a high-level functional allocation (e.g., crew transport, habitation, logistics delivery) that is primarily self-sufficient.
Exploration Asset	Any item that is in place and being used as part of the exploration architecture, including payloads.
Utilization Payloads and Equipment	Any item that is primarily in support of and attributed to utilization objectives. Utilization payloads include science/research payloads and technology demonstrations. Equipment includes other internal and external hardware, supporting tools, supplies, etc.

The architecture components described below flow down from the objective decomposition described in Section 1 and captured in Appendix B. NASA has mapped elements summarized in Section 2.3 to the use cases and functions they provide in support of exploration objectives. A full functional mapping for each element is also available in Appendix B; NASA also publishes the full objective decomposition as a spreadsheet concurrently with this document.[9]

For more information on the exploration considerations and drivers that influenced the existing contents of the architecture, see Appendix A.

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[8] *Utilization* is the use of a platform, campaign, and/or mission to conduct science, research, test and evaluation, public outreach, education, and industrialization.

[9] https://www.nasa.gov/moontomarsarchitecture-architecturedefinitiondocuments/

2.1 Segments

NASA structures the Moon to Mars Architecture to empower incremental buildup of capabilities in service to objective satisfaction. Segments delineate the continuum of evolving capabilities and growing objective satisfaction.

Although these segments appear in sequential order, they are not exclusively serialized. While they do build upon each other, NASA pursues parallel development of architecture segment capabilities. This is especially true where lessons learned at one destination inform concurrent architecture development at another destination (i.e., Mars-forward activities performed during lunar segments).

Human Lunar Return
See Section 2.1.1

Initial capabilities necessary to re-establish human presence on and around the Moon.

The **Human Lunar Return** segment includes the initial capabilities, systems, and operations necessary to re-establish human presence and initial utilization (science, etc.) on and around the Moon for the first time in over 50 years. This segment primarily focuses on establishing supporting infrastructure to perform crewed missions to the Moon. Segment systems and capabilities span Earth, cislunar orbiting platforms, and foothold capabilities on the lunar surface. Initial utilization focuses on human-conducted science, sample collection, human research, and more.

Foundational Exploration
See Section 2.1.2

Expansion of lunar capabilities supporting complex orbital, surface, and Mars precursor missions.

The **Foundational Exploration** segment includes increasingly complex missions and excursions to a variety sites of interest on the lunar surface for science and utilization. This segment also helps evaluate the systems, operations, human adaptations, and technologies required for Mars. Segment missions will enable extended durations in cislunar space, coupled with missions to the lunar surface of increasing duration and mobility that address identified research, testing, and demonstration objectives to enable Mars missions. These precursor missions will inform element design, testing, and operation for Mars missions. Foundational Exploration also begins the development of a sustainable human presence with the deployment of demonstrations and capabilities that will enable long-term infrastructure and sustained surface operations.

Sustained Lunar Evolution
See Section 2.1.3

Growing capabilities to enable economic opportunity, global access, and regular human presence.

The **Sustained Lunar Evolution** segment is the broad future state that builds on the Human Lunar Return and Foundational Exploration segments and enables capabilities, systems, and operations to support regional and global utilization (science, etc.), expanded economic opportunity, and a steady cadence of human presence on and around the Moon. Here, we can envision various uses of the lunar surface and cislunar space to enable science, commerce, and further deep space exploration initiatives.

Humans to Mars *See Section 2.1.4*	Initial capabilities necessary to establish a human presence on Mars.

The **Humans to Mars** segment captures the capabilities, systems, and operations necessary to enable the initial human exploration of the Red Planet. These systems will represent transportation, logistics, utilization, and more. This segment is an enabling capability of continued deep space exploration, with additional efforts to be identified as the architecture matures.

Future Segments	Additional segments added for continued exploration of the Moon, Mars, and beyond.

As the architecture accomplishes or adds objectives, NASA will define additional segments to enable continued exploration. These efforts will enable NASA-led efforts to sustain and expand science and discovery on the Moon, Mars, and beyond.

2.1.1 Human Lunar Return

Header Image: *Conceptual illustration of an Artemis astronaut kneeling on the lunar surface sifting regolith through their fingers. In the background, government reference concepts for an unpressurized rover and landing system complete the scene.*
(Credit: NASA)

The **Human Lunar Return** segment includes the inaugural Artemis missions, which will return humans to the Moon for the first time since the Apollo Program. It will demonstrate crewed and uncrewed lunar systems, including initial utilization capabilities.

This segment will demonstrate initial systems to validate performance and establish core capabilities for follow-on segments. It comprises missions that test crew and cargo transportation systems, deploy initial cislunar capabilities to support lunar missions, establish lunar orbital communication relays, and send crew members to the lunar surface and return them safely to Earth.

A variety of other efforts support data-gathering and risk-reduction activities in the Human Lunar Return segment to help inform future architecture definition. These include the Cislunar Autonomous Positioning System Technology Operations and Navigation Experiment (CAPSTONE) mission, instruments on Commercial Lunar Payload Services (CLPS) provider landers, Artemis mission secondary payloads, and more.

2.1.1.1 Summary of Objectives

This segment began with the successful Artemis I mission and continues with Artemis II, which sends crew around the Moon, and Artemis III, which lands crew on the lunar surface. It lays the groundwork for sustained exploration in future segments.

Initial missions deliver science value through operations in cislunar space and on the lunar surface, along with the return of samples to Earth. Key science activities during Human Lunar Return, identified by NASA's Science Mission Directorate, include exploring the lunar South Pole region to understand chronology, composition, and structure of this region of the Moon (LPS-1, LPS-2); understanding volatile composition and the environment of shallow permanently shadowed regions near the lunar South Pole (LPS-3); assessing the history of the Sun as preserved in lunar regolith (HS-2); Characterizing space weather dynamics to enable future forecasting capabilities (HS-2); and characterizing plant, model organism/systems, and human physiological responses in partial-gravity environments (HBS-1).

The Human Lunar Return segment began successfully with the Artemis I mission, which tested crewed transportation to and from cislunar space (TH-1, TH-2), supporting ground infrastructure (OP-4), communications and tracking systems (OP-2), and more.

The next steps are transporting crew to and from cislunar space, initial Gateway deployment (OP-6), rendezvous and docking in lunar orbit, uncrewed demonstrations of human landing systems, landing humans on the Moon (TH-2) and returning them to cislunar space, realizing a surface extravehicular activity (EVA) capability, and uncrewed payload and cargo delivery.

2.1.1.2 Use Cases and Functions

The Human Lunar Return segment establishes the initial capabilities for returning humans to the Moon. The reference missions below collect use cases and functions to accomplish the segment's objectives. A full list of lunar use cases and functions and the functional mappings for all elements and assets in the Human Lunar Return segment are available in Appendix B.

2.1.1.3 Reference Missions and Concepts of Operations

Reference missions provide examples of how NASA can group use cases together to accomplish a particular concept of operations. The two reference missions captured here cover a representative subset of lunar use cases for the Human Lunar Return segment. These reference missions demonstrate how architectural capabilities could be used; they are not specific missions NASA will conduct. (The full list of lunar use cases is available in Appendix B.2.2.)

2.1.1.3.1 Reference Mission: Crewed Initial Lunar Surface Mission

This reference mission returns crew to the lunar surface for the first time since the Apollo Program. It encompasses many use cases that will be repeated throughout the Moon to Mars campaign.

Starting with transportation, use cases include transporting crew and systems from Earth to cislunar space, staging crewed lunar surface missions from cislunar space, assembling integrated assets in cislunar space, transporting crew and systems between cislunar space and the lunar surface, and returning crew and systems from cislunar space to Earth. The surface portion of the reference mission includes use cases that involve crew operations on the lunar surface, frequent crew surface EVAs, and crew-conducted utilization activities (including science, crew health and performance, and other operations) on the surface and in space.

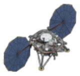
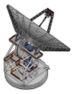
2.1.1.3.2 Reference Mission: Crewed Gateway and Lunar Surface Mission

Building on initial missions that return crew to the lunar surface, this reference mission adds more capabilities in cislunar space. It addresses additional use cases, particularly for lunar orbital operations.

Gateway, a habitable outpost located in near-rectilinear halo orbit (NRHO), enables additional use cases in the Human Lunar Return segment beyond those in the initial crewed mission to the lunar surface. Gateway allows crew members to conduct utilization activities in cislunar space; allows ground personnel and science teams to directly engage with astronauts on the surface and in lunar orbit, augmenting crew effectiveness when conducting science activities; enables crew and/or robotic emplacement and deployment of science instrumentation in lunar orbit with long-term remote operation; and includes autonomous/semi-autonomous mission operations in cislunar space.

2.1.1.4 Elements for Human Lunar Return

This document lists elements mapped to the Human Lunar Return segment below and includes descriptions of each element in Section 2.3. Full mappings of elements to associated use cases and functions they fulfill are in Appendix B.3.

Icon	Element Name	Sub-Architecture	Section	Mapping
	Commercial Lunar Payload Services	Transportation Systems	2.3.1	B.3.1
	Exploration EVA Systems	Mobility Systems	2.3.2	B.3.2
	Exploration Ground Systems	Infrastructure Support	2.3.3	B.3.3
	Gateway Crew-Capable Configuration	Habitation Systems	2.3.4	B.3.4
	Gateway Logistics Element	Logistics Systems	2.3.4.1.4	B.3.4.1.1
	Human Landing System	Transportation Systems	2.3.5	B.3.5.1
	Orion Spacecraft	Transportation Systems	2.3.12	B.3.12
	Space Communications and Navigation Networks	Communications and Positioning, Navigation and Timing Systems	2.3.14	B.3.14
	Space Launch System	Transportation Systems	2.3.15	B.3.15

2.1.1.5 Areas of Future Work

This segment also includes some unallocated functions (see Appendix B.5) that are not yet met by existing systems, reference missions, or planned operations. Areas for additional work, capability enhancement, and further study for the Human Lunar Return segment include the following:

- Increasing utilization down-mass capabilities to the lunar surface
- Accommodating extravehicular utilization payloads (i.e., interfaces, resources)

2.1.2 Foundational Exploration

***Header Image:** Conceptual illustration of Artemis astronauts conducting utilization activities on the lunar surface. In the background, government reference concepts for a surface habitat, pressurized rover, unpressurized rover, and power system complete the scene. (Credit: NASA)*

The **Foundational Exploration** segment builds on the initial capabilities of Human Lunar Return and prepares for other segments by expanding operations, capabilities, and systems supporting complex orbital and surface missions to conduct utilization and Mars-forward precursor missions.

The Foundational Exploration segment continues to use many of the elements from Human Lunar Return while deploying new capabilities. Segment surface missions will feature increased durations, expanded mobility, and regional exploration of the lunar South Pole. Orbital operations will also increase in duration and — when coupled with the surface mission phases — serve as Mars mission analogs, validating systems and concepts of operations.

Foundational Exploration will initiate activities and capabilities influenced by future needs in the Sustained Lunar Evolution and Humans to Mars segments. These activities include reconnaissance, Mars risk reduction, and initial infrastructure supporting long-term lunar access and utilization.

2.1.2.1 Summary of Objectives

The Foundational Exploration segment will expand access to various regions of the lunar surface. These factors will enable more utilization during both crewed and uncrewed mission phases.

2.1.2.1.1 Science Objectives

Enhanced architecture capabilities in this segment improve NASA's ability to address and achieve science objectives. Science priorities identified by stakeholders like NASA's Science Mission Directorate, Human

Research Program, and Space Technology Mission Directorate include studying the Moon's history and geology (LPS-1, LPS-2) with expanded surface exploration range and sampling capabilities, characterizing volatiles (LPS-3), space weather forecasting (HS-1), studying how living organisms respond to partial gravity and deep space environments (HBS-1, HBS-3), and conducting relativity and quantum physics experiments in the lunar environment (PPS-1, PPS-2).

2.1.2.1.2 Infrastructure Objectives

The lunar infrastructure objectives help define the Foundational Exploration segment. Expansion of the power (LI-1), C&PNT and data systems and management (LI-2, LI-3), transportation (LI-5, LI-6), mobility (LI-6), ISRU (LI-7), and utilization (LI-9) sub-architectures alongside surface infrastructure development to support industry (LI-4, LI-8) builds toward the goal of "[creating] an interoperable global lunar utilization infrastructure where U.S. industry and international partners can maintain continuous robotic and human presence on the lunar surface for a robust lunar economy without NASA as the sole user, while also accomplishing science objectives and forward testing for Mars."

2.1.2.1.3 Transportation and Habitation Objectives

The transportation and habitation objectives drive additional capabilities in mobility, habitation, and transportation systems during the Foundational Exploration segment. For example, TH-1, TH-2, and TH-11 address a need for transportation systems to transfer crew and cargo to and from Earth, through cislunar space, and between lunar orbit and the surface, enabling scientific and utilization objectives. TH-3 and TH-4 define Foundational Exploration as a segment building toward and enabling initial crewed missions to Mars through analog missions and technology development that support architecture definition tasks and risk reduction.

2.1.2.1.4 Operations Objectives

Many operations objectives drive capabilities needed for the Foundational Exploration Segment. The overall operations goal is to "conduct human missions on the surface and around the Moon followed by missions to Mars. Using a gradual build-up approach, these missions will demonstrate technologies and operations to live and work on a planetary surface other than Earth, with a safe return to Earth at the completion of the missions." These objectives encompass the need for extended-duration missions in deep space and partial-gravity environments to test systems and crew concepts of operations in preparation for the initial human Mars exploration campaign (OP-1, OP-2, OP-4, OP-5, OP-6, OP-7). Additionally, developing methods of working with robotic systems (OP-9, OP-10) and characterizing in-situ resources (OP-3) defines other aspects of the Foundational Exploration Segment.

2.1.2.2 Use Cases and Functions

The Foundational Exploration segment expands lunar exploration capabilities and locations. The reference missions below collect use cases and functions to accomplish the segment's objectives. A full list of lunar use cases and functions and the functional mappings for all elements and assets in the human lunar return are available in Appendix B.

2.1.2.3 Reference Missions and Concepts of Operations

The notional reference missions below expand on the missions from Human Lunar Return, showing Foundational Exploration's progress toward accomplishing additional objectives. As in Human Lunar Return, these reference missions demonstrate how architectural capabilities could be used; they are not specific missions NASA will conduct. (The full list of lunar use cases is available in Appendix B.2.2.)

2.1.2.3.1 Reference Mission: Unpressurized Mobility

The Foundational Exploration segment will build on lunar surface exploration conducted in the Human Lunar Return segment, which includes crew habitation in an EVA-capable crew lander. NASA may implement additional Foundational Exploration use cases by adding an unpressurized mobility platform to extend EVA range and scientific exploration. This enables crew excursions to locations distributed around landing sites and has the potential to enable other activities, such as robotic assistance of crew exploration and the locating and retrieval of samples and resources; crewed/robotic collection of samples from permanently shadowed regions; and deployment of power generation, storage, and distribution systems at multiple locations around the lunar South Pole, among others.

2.1.2.3.2 Reference Mission: Pressurized Mobility

The Foundational Exploration segment aims to expand exploration for longer durations, conduct scientific and industrial utilization, and perform Mars risk reduction activities. With initial surface crew sizes, one method to accomplish these objectives is adding pressurized mobility systems. These systems may enable use cases such as crew intravehicular activity (IVA) research, expanded durations for crew operations on the lunar surface (including enabling additional habitation functions), logistics and waste management, crew excursions to locations distributed around the landing site, EVA egress/ingress, crew/robotic collection of samples, and crew relocation and exploration in a shirt-sleeve environment.

The addition of pressurized habitation and mobility, as well a potential increase to number of crew, mission durations, and sites, will create additional needs for logistics transport and stowage, trash disposal, maintenance, and other infrastructure services and support. Pressurized mobility operations will also need to mitigate increasingly complex challenges of the lunar environment, such as dust, plasma interactions, radiation, etc.

2.1.2.3.3 Reference Mission: Robotic Uncrewed Operations

Assets on the surface of the Moon during the Foundational Exploration will likely spend most of the year uncrewed, but they can still perform utilization and operational activities. NASA will achieve some objectives with the help of autonomous, local tele-operations, or Earth-based remote operations.

The Communications & Positioning, Navigation, and Timing (C&PNT) sub-architecture (Section 2.2.2) provides additional exploration and utilization opportunities during uncrewed portions of the year. These robotic functions could include cargo unloading, logistics transfers, surface and/or sub-surface sample collection, and infrastructure development (e.g., landing site scouting or preparation).

These functions contribute to use cases like robotic survey of potential crewed landing sites to identify locations of interest (including nearby permanently shadowed regions), uncrewed relocation of mobility elements to landing sites around the lunar South Pole, and autonomous deployment of science and utilization packages.

2.1.2.3.4 Reference Mission: Extended Surface Habitation Operations

With a dedicated habitation capability, the Foundational Exploration segment can achieve additional use cases to support science and utilization, including enhancing mission duration, crew size, crew EVA exploration, sample collection, and emplacement of science and/or utilization packages. For example, additional surface habitation capabilities could enable crew members to perform in-situ science through allocated workspaces. Surface habitation systems could also demonstrate progressively regenerative and self-sustaining environmental control and life support systems, advancing Mars-forward technologies.

Increased functional capabilities that support longer-duration in-space and partial-gravity crew habitation include robust crew medical systems and health kits; space-based manufacturing techniques allowing repairs and replacement; enhanced surface EVAs; and interfaces for logistics transfers (e.g., for solid and fluid consumables, maintenance, utilization, and waste). Systems originally sized to maintain elements during extended uncrewed periods and early Foundational Exploration missions may need augmentation to enable increased objective satisfaction and longer-duration human presence later in the segment.

2.1.2.3.5 Reference Mission: Extended Cislunar Operations at Gateway

A key aspect of Foundational Exploration is preparing for crewed exploration of Mars with lunar precursor missions. In addition to extending the duration for surface missions, the Foundational Exploration segment will also provide numerous, long-duration crew increments in cislunar space to compliment crewed surface mission and to support crew transitions between microgravity and partial gravity. Extended missions in cislunar space at Gateway and accompanying visiting vehicles also increase the time available for IVA science and utilization.

One main use case for accomplishing these characteristics and needs is conducting precursor Mars mission profiles with extended durations in NRHO, followed by lunar surface missions. Although these missions would not be identical to eventual Mars missions, they allow for long-term physiological, psychological, team performance, and operational assessments of crew and systems as precursors to Mars missions.

Other use cases include staging of crewed lunar surface missions from cislunar space; remote diagnosis and treatment of crew health issues during extended increments in cislunar space; crew emplacement and deployment of science and utilization packages in cislunar space (with long-term remote operation as applicable); and crew IVA research in dedicated science workspaces in cislunar space.

2.1.2.3.6 Reference Mission: Cislunar Orbit Only

The Foundational Exploration segment may include periods where strategic objectives or mission implementation require crewed missions to lunar orbit without a subsequent landing on the lunar surface. This exploration strategy would require capabilities to perform human missions to cislunar orbit (i.e., in NRHO) and the ability to control lunar surface assets from Earth and lunar orbit. This capability would allow the crew to conduct near–real-time robotic teleoperations, including cargo unloading, logistics transfer, surface and/or sub-surface sample collection, and infrastructure development (e.g., landing site scouting or preparation).

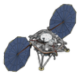
2.1.2.3.7 Reference Mission: Non-polar Lunar Sortie

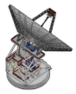
Although lunar surface exploration focuses on the lunar South Pole region, several objectives — particularly those related to science and utilization — could require landing sites beyond the South Pole. Enabling use cases for transporting crew to non-polar landing sites (including enabling functions like crew descent, landing, and ascent at non-polar sites) would allow NASA to explore alternative locations. These missions would be conducted opportunistically — not as the primary mission profile for this segment — and would augment larger crew complements and longer mission durations with shorter missions beyond the primary South Pole exploration area that could require more operational, logistical, and power independence.

2.1.2.4 Elements for Foundational Exploration

The Foundational Exploration segment will continue to use elements introduced in Human Lunar Return while adding new capabilities as they become available. Interoperability between elements will be especially important during the segment.

This document lists elements mapped to the Foundational Exploration segment below and includes descriptions of each element in Section 2.3. Full mappings of elements to associated use cases and functions they fulfill are in Appendix B.3.

Icon	Element Name	Sub-Architecture	Section	Mapping
	Commercial Lunar Payload Services	Transportation Systems	2.3.1	B.3.1
	Exploration EVA Systems	Mobility Systems	2.3.2	B.3.2
	Exploration Ground Systems	Infrastructure Support	2.3.3	B.3.3
	Gateway Crew-Capable Configuration	Habitation Systems	2.3.4	B.3.4
	Gateway Logistics Element	Logistics Systems	2.3.4.1.4	B.3.4.2.1
	Human Landing System	Transportation Systems	2.3.5	B.3.5
	Human-Class Delivery Lander	Transportation Systems	2.3.6	B.3.6
	Initial Surface Habitat	Habitation Systems	2.3.7	B.3.7
	Lunar Nuclear Power System	Power Systems	2.3.8	B.3.8.1
	Lunar Surface Cargo Lander	Transportation Systems	2.3.9	B.3.9
	Lunar Terrain Vehicle	Mobility Systems	2.3.10	B.3.10
	Lunar Utility Rover	Mobility Systems	2.3.11	B.3.11
	Orion Spacecraft	Transportation Systems	2.3.12	B.3.12

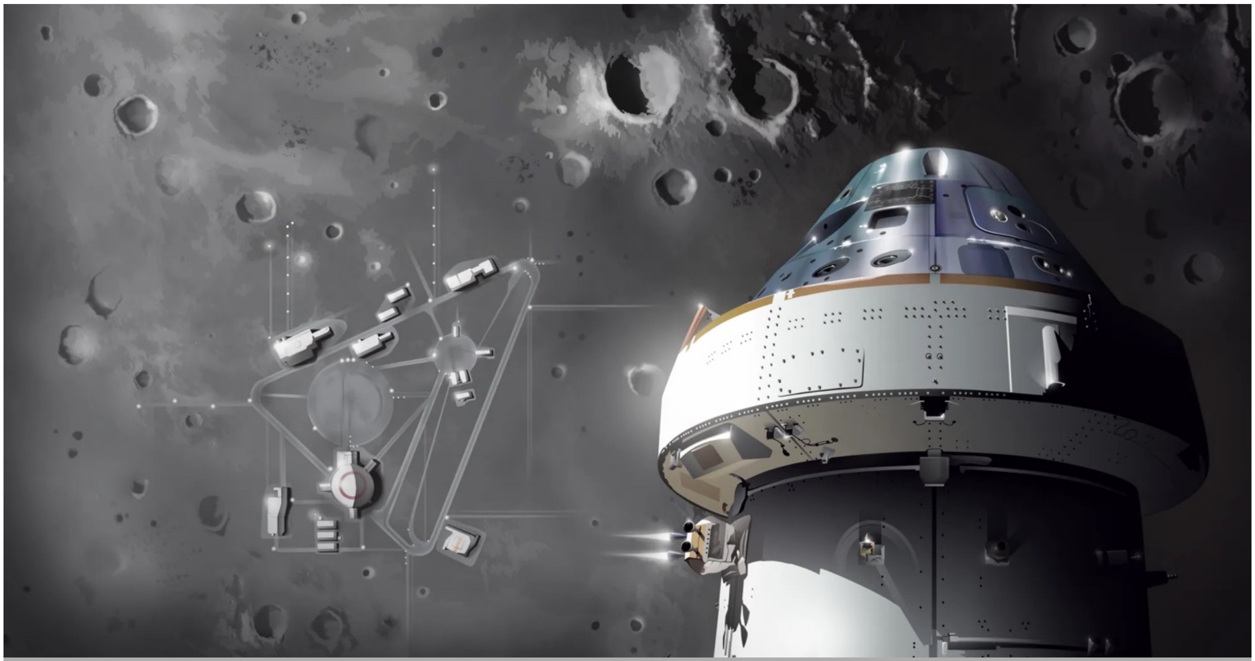
Icon	Element Name	Sub-Architecture	Section	Mapping
	Pressurized Rover	Mobility Systems	2.3.13	B.3.13
	Space Communications and Navigation Networks	Communications and Positioning, Navigation and Timing Systems	2.3.14	B.3.14
	Space Launch System	Transportation Systems	2.3.15	B.3.15

2.1.2.5 Areas of Future Work

This segment also includes some unallocated functions (see Appendix B.5) that are not yet met by existing systems, reference missions, or planned operations. Areas for additional work, capability enhancement, and further study for the Foundational Exploration segment include the following:

- Using lunar assets and operations to prepare for crewed Mars missions
- Identifying a balance of mission types and locations to maximize objective satisfaction and scientific exploration
- Establishing an external power augmentation strategy to maximize exploration capabilities
- Distributing exploration assets and infrastructure to promote extensibility
- Increasing cargo mass delivered to and returned from the lunar surface
- Assessing the role of ISRU in lunar exploration
- Incorporating waste management approaches and element repurposing, recycling, and disposal for extended durations
- Operating assets and maintaining asset health during uncrewed periods
- Maximizing opportunities for uncrewed operations
- Formulating a lunar orbital observation strategy to support utilization and exploration

2.1.3 Sustained Lunar Evolution



***Header Image:** This winning submission from NASA's 2024 architecture art challenge[10] shows a spacecraft orbiting above a lunar surface site with a variety of surface elements. The art challenge asked artists around the world to envision what the Sustained Lunar Evolution segment might look like. (Credit: Jimmy Catanzaro of Henderson, Nevada)*

In the **Sustained Lunar Evolution** segment, NASA and its partners aim to build a future of economic opportunity, expanded utilization (including science), and greater participation on and around the Moon. The focus of Sustained Lunar Evolution is growth beyond the Foundational Exploration segment to enable increased global science capability, long-duration/increased population, and large-scale production of goods and services derived from lunar resources.

This segment is an open canvas for embracing new ideas, systems, and partners to grow a truly sustained lunar presence. The steps for achieving use cases for the Sustained Lunar Evolution segment will involve broad coordination between partners and exploration systems.

At this time, there is insufficient depth to allocate functions beyond high-level capabilities associated with segment objectives. However, this section discusses notional examples of the future use case and the sub-architecture dependencies over time as a placeholder for future architecture development work.

2.1.3.1 Summary of Objectives

Sustained Lunar Evolution features responsible long-term exploration of the surface and the establishment of a robust lunar economy. This segment is driven by RT-9, "foster the expansion of the economic sphere beyond

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[10] https://www.nasa.gov/general/art-inspired-by-exploration-nasa-unveils-architecture-art-challenge-winners/

Earth orbit to support U.S. industry and innovation;" TH-3, "develop system(s) to allow crew to explore, operate, and live on the lunar surface and in lunar orbit with scalability to continuous presence conducting scientific and industrial utilization as well as Mars analog activities;" and the overarching infrastructure goal to "create an interoperable global lunar utilization infrastructure where U.S. industry and international partners can maintain continuous robotic and human presence on the lunar surface for a robust lunar economy without NASA as the sole user, while accomplishing science objectives and testing for Mars."

A sustained architecture at the lunar surface would further enable key objectives in lunar/planetary science, heliophysics, human and biological science, and physics and physical science. It would also enable the agency to fulfill new science objectives identified through discoveries made during other segments.

2.1.3.2 Use Cases and Functions

For Sustained Lunar Evolution, architecting from the right requires the development of economically plausible use cases and functions in coordination with NASA's partners. The segment will incrementally achieve sustained states of increased science capability, increased economic opportunity, and increased duration and population, as guided by the Moon to Mars Objectives. Notional evolutionary paths for these key areas could emerge as follows.

Science capabilities might first expand through additional mobility and range, giving astronauts access to more locations in the lunar South Pole region. Then, increasing sample return capability could enable explorers to send a larger volume of samples to Earth for analysis. Finally, lunar global access for crew and cargo would enable scientific investigations anywhere on the Moon.

Economic opportunity would begin with minimal ISRU and regolith utilization, testing ISRU systems and concepts of operations. Next, the use of ISRU-derived propellants could reduce transportation costs and demonstrate the feasibility of extracting lunar resources. Eventually, lunar ISRU and mining could reach industrial scale, enabling a lunar economy and broader exploration.

The addition of expanded power, logistics, and ISRU capabilities would enable more missions. Mission durations and the number of crew members could grow progressively until the segment sustains one or more permanent lunar outposts and a continuous human lunar presence.

2.1.3.2.1 Increased Science Capability

Several factors enable science in the Sustained Lunar Evolution segment: the ability to deliver scientific instruments to a variety of locations on and around the Moon; the ability to condition, curate, and return samples and data to Earth; and the ability of astronauts to rapidly react to discoveries, identify samples in real time, and maintain scientific equipment.

Prior to this segment, the initial orbital platforms, landers, and regional exploration infrastructure govern science capabilities. Although the Foundational Exploration segment includes the function to return science samples gathered during a 30-day–class mission, the Sustained Lunar Evolution segment will increase science capability as mission duration and available power grow.

Increasing science capability in the Sustained Lunar Evolution segment requires enhancing multiple sub-architectures. For example, communications capabilities must evolve via interoperability, scalability, and reconfigurability to allow concurrent science missions distributed across the lunar globe to send data via high-speed links. NASA and its partners can trade different approaches for satellite constellations, surface relay infrastructure, and technologies such as optical links to enable high-data-rate communications.

2.1.3.2.2 Increased Economic Opportunity

Economic opportunity on and around the Moon means that governments are no longer the sole source of funding for lunar activities. The Sustained Lunar Evolution segment would see non-governmental entities invest in — and profit from — activities at the Moon. NASA aims to reduce the barriers of entry for activities on and around the Moon and provide capabilities other actors can leverage.

Building upon investments initiated in the Human Lunar Return and Foundational Exploration segments, the Sustained Lunar Evolution segment creates opportunities for industry to enable regular and likely reusable lunar access (both robotic and human) to governmental entities, scientific institutions, international space agencies, and other industry partners. The segment will require additional investments in communications, navigation, ISRU, power, and transportation sub-architectures to enhance and create lunar utilization and economic opportunities.

Economic opportunity/profitability could progress along several lines including information transfer, delivering goods, providing services at the Moon, and bringing resources from the Moon to other destinations. Larger-scale economic opportunity begins to emerge as lunar reach and access expand, small-scale ISRU propellant production grows to industrial scale, aggregate power grows from kilowatts to megawatts, and the use of in-situ material and manufacturing becomes more economical than delivering everything from Earth. Once ISRU production is of sufficient scale, exporting propellant and material beyond the lunar surface also creates economic opportunity.

2.1.3.2.3 Increased Duration and Population

Increased science capability influences economic opportunity, which overlaps with the need to increase the population of humans at the lunar South Pole region and the need for that population to stay there longer. However, humans currently require a significant quantity of resources imported from Earth to survive, along with large amounts of pressurized volume in which to live safely. To significantly increase the size and duration of the lunar population, missions will rely on local resources to provide water, support food growth, and build out infrastructure.

As an interim step, multiple partners could provide small, modular systems to act as a bridge between initial Foundational Exploration capabilities and large-scale ISRU systems. A year-round population will require power augmentation (e.g., nuclear fission power) to account for variations in sunlight over the course of the lunar year. At some point in this evolution, the possibility of lunar tourism appears. Tourism operations could leverage Earth-provided modular systems at first and incorporate more lunar resources over time to reduce costs.

2.1.3.3 Reference Missions and Concepts of Operations

Future work for this segment will include defining additional reference missions and detailed concepts of operations.

2.1.3.4 Elements for Sustained Lunar Evolution

Although the sub-architectures will evolve during the Sustained Lunar Evolution segment, further decomposition will introduce use cases and functions that inform development of future systems and elements for the segment.

2.1.3.5 Areas of Future Work

The functional mapping for this segment remains forward work. Areas for additional work, capability enhancement, and further study for the Sustained Lunar Evolution segment include the following:

- Identifying a future state and expanding demand signals to maximize objective satisfaction and empower government, industry, international, and academic partners to explore the Moon
- Supporting the development of policy and standards to enable many actors to explore the Moon together
- Expanding demand signals for advanced technologies and services, including logistics, mobility, robotic servicing, ISRU, habitation, assembly and construction, science systems, and communications, data, and navigation

2.1.4 Humans to Mars

Header Image: *Conceptual illustration of an astronaut kneeling on the surface of the Red Planet. (Credit: NASA)*

The **Humans to Mars** segment will establish a human presence on Mars and empower new science on its surface. Since the earliest days of spaceflight, the Red Planet has captivated humanity. The Moon to Mars Architecture sets a course to finally step foot on a planet beyond humanity's own.

Building on previous segments, this segment will include the initial capabilities and systems necessary to safely travel to Mars, land on its surface, and return safely to Earth. After landing humans on the Red Planet, NASA will prepare for progressively longer and more complex missions there.

2.1.4.1 Summary of Objectives

The Humans to Mars segment will see the first human missions to the Red Planet to achieve the Mars-specific goals outlined in NASA's Moon to Mars Objectives. These objectives include cross-cutting science and operations goals, as well as Mars-specific infrastructure and transportation and habitation goals. These objectives drive NASA's objective decomposition for the Mars architecture.

2.1.4.1.1 Science Objectives

NASA's Moon to Mars Objectives establish many science objectives that are applicable to both lunar and Mars exploration. Mars provides opportunities for different scientific investigations than those that are possible at the Moon, including investigating the origins of life and the existence of past or present life elsewhere in the solar system (LPS-4), which cannot be addressed on the Moon.

2.1.4.1.2 Infrastructure Objectives

In addition to cross-cutting objectives shared with lunar exploration, Mars exploration addresses a unique set of Mars infrastructure objectives. Infrastructure objectives include developing power (MI-1); communications (MI-2); and position, navigation, and timing (MI-3) capabilities for human Mars exploration, as well as demonstrating ISRU capabilities (MI-4).

2.1.4.1.3 Transportation and Habitation Objectives

In addition to cross-cutting objectives shared with lunar exploration, Mars exploration addresses a unique set of transportation and habitation objectives. Transportation and habitation objectives include developing transportation systems that can operate between Earth and the Mars vicinity and surface (TH-5, TH-6), systems enabling crew to explore and conduct science on the Martian surface (TH-7), systems that pair human and robotic explorers (TH-10), and systems that return cargo from Mars to Earth (TH-12).

2.1.4.1.4 Operations Objectives

While there are no operations objectives unique to Mars, Mars and lunar operations are closely intertwined, with lunar operations providing extensibility for Mars missions. Mars missions also have unique operational considerations, especially due to increased distance from Earth.

2.1.4.2 Use Cases and Functions

The objective decomposition for the Humans to Mars segment follows the same philosophy as the lunar exploration segments. NASA decomposes relevant objectives into the use cases and functions necessary to accomplish those objectives.

As a representative example, objective TH-04-M, “Develop in-space and surface habitation systems for crew to live in deep space for extended durations, enabling future missions to Mars,” drives several characteristics and needs. These include capabilities to allow crew to live in deep space, manage crew health and performance, and conduct missions on the Martian surface.

Use cases that contribute to fulfilling those characteristics and needs include enabling crew members to live in deep space and on the Martian surface for varying durations. Functions that map to these use cases include managing crew health and performance, enabling crew exercise, managing waste, and maintaining a pressurized environment.

The full objective decomposition for Mars is available in Appendix B.

2.1.4.3 Reference Mission and Concepts of Operations

Future work for this segment will include defining reference missions and detailed concepts of operations. Many historic Mars architecture studies have developed reference missions and examined the Mars trade space. For more information, refer to resources available on NASA’s Moon to Mars Architecture website.[11]

2.1.4.4 Elements for Humans to Mars

Mapping of elements to use cases and functions for the Humans to Mars segment is forward work. Mars elements fall into the similar sub-architectures as existing lunar exploration elements, which helps NASA assess the extensibility of lunar systems for Mars exploration, or vice versa.

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[11] https://www.nasa.gov/moontomarsarchitecture-marsarchitecturestudies/

Decisions about the design of certain elements and sub-architectures will significantly influence other elements and sub-architectures and could impact agency-level values such as cost, risk, and schedule. NASA has developed an architecture-level roadmapping process that considers the end-to-end architecture when evaluating options across the trade space. More information about architecture roadmapping is available in Section 3.1 and Appendix C.

2.1.4.5 Areas of Future Work

The functional mapping for this segment remains forward work. Areas for additional work, capability enhancement, and further study for the Humans to Mars segment include the following:

- Assessing the Mars trade space, including transportation; return propellant strategies; surface infrastructure needs; entry, descent, landing, and ascent options; and more
- Establishing science objective priorities, including inputs from an ongoing study by the National Academies of Science, Engineering, and Medicine[12]
- Researching human health and performance in the context of Mars missions
- Defining data and knowledge gaps for the Mars architecture and evaluating pathways to close those gaps
- Defining an initial human Mars campaign driven by NASA's three pillars of exploration (science, inspiration, and national posture)

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[12] https://www.nationalacademies.org/our-work/a-science-strategy-for-the-human-exploration-of-mars

2.2 Sub-Architectures

Sub-architectures capture the complex relationships between programs, projects, systems, and operations that must interact in a tightly coupled manner. Dividing the architecture into sub-architectures allows NASA to assess functions and use cases for consistency, gaps, and improvements. It also helps to identify areas for common standards and interoperability.

The Moon to Mars Architecture includes 12 sub-architectures.

Icon	Sub-architecture Name	Decomposition Abbreviation
🤖	Autonomous Systems and Robotics	A
📡	Communications and Positioning, Navigation, and Timing Systems	C
☁	Data Systems and Management	D
🏠	Habitation Systems	H
🏃	Human Systems	X
🛠	Infrastructure Support	G
⛏	In-situ Resource Utilization Systems	I
🛒	Logistics Systems	L
🚙	Mobility Systems	M
⚡	Power Systems	P
🚀	Transportation Systems	T
⚗	Utilization Systems	U

The summary tables below provide a brief overview of the sub-architectures, including the abbreviations used in the objective decomposition.

Autonomous Systems and Robotics

Decomposition Abbreviation **A**

This sub-architecture integrates the unique and complementary capabilities of humans and robotic systems to maximize crew efficiency, provide needed capabilities during uncrewed mission phases, and expand exploration, science, and utilization opportunities across the architecture.

Robots are not only well suited to tedious, highly repetitive, or hazardous tasks, but can also augment the abilities of human explorers through tailored suites of instruments or capabilities. This assistance enables crew to focus on higher-priority activities and improves safety without sacrificing operational effectiveness or mission reach.

Mobile robotics can also improve access to areas of scientific interest; asset handling, repositioning, and utilization; logistics management; and infrastructure assembly, outfitting, and maintenance. They also enable robotic reconnaissance (e.g., scouting, surveying, mapping, collecting samples) in advance of crewed missions.

Communications and Positioning, Navigation, and Timing (C&PNT) Systems

Decomposition Abbreviation **C**

This sub-architecture enables transmission and reception of end-to-end data flows and exploitable signals across all exploration assets. It provides services to accurately and precisely determine current location and orientation; determine path to desired position; and acquire and maintain accurate and precise time from a coordinated lunar time standard traceable to Earth's Coordinated Universal Time.

C&PNT sub-architecture considerations include service regions, delivery mechanisms, and user burden, as well as how they evolve through the segments. Additionally, minimizing manual network management and maximizing interoperability of C&PNT services are key considerations in establishing an architecture that supports many different providers and users (e.g., government, commercial, scientific, international).

The C&PNT sub-architecture and concept of operations will mature in response to user needs. Services may improve (e.g., with high-throughput optical and radio frequency links, autonomous network management, higher accuracy, increased capacity and availability, additional cislunar and lunar surface infrastructure), and service regions may expand beyond the lunar South Pole. Positioning, navigation, and timing (PNT) services may grow to realize Global Navigation Satellite System (GNSS)–like capabilities, providing extended regional or global services. More accurate PNT information will empower precision navigation, tracking, surveying, geolocation services, and temporal and spatial science.

Data Systems and Management

Decomposition Abbreviation **D**

This sub-architecture includes capabilities that work together to manage, compute, store, secure, and protect data within acceptable latency constraints for use throughout the architecture. This sub-architecture is tightly coupled with the C&PNT, Human Systems, and Autonomous Systems and Robotics sub-architectures and considers data interoperability and availability across the architecture.

This sub-architecture encompasses the comprehensive framework that governs how the architecture manages, uses, and stores data as well as the subset of tools, models, processes, representations, and technologies designed to capture, store, process, and retrieve data efficiently and securely. From small-scale payloads to large, complex mission sequences, effective data management across the architecture ensures that NASA can derive valuable insights can be derived from raw data.

The sub-architecture defines avionics and software systems; logical and conceptual data models using element-level data specifications; and relationships between elements. It addresses environment-tolerant avionics hardware; related software and databases; and systems that organize and maintain data. Sub-architecture responsibilities include analyzing data handling across communications and computational systems to ensure effective use of bandwidth and interoperability between current and future technologies.

Habitation Systems

Decomposition Abbreviation **H**

This sub-architecture comprises controlled environments that ensure crew health and performance over the course of missions. The sub-architecture encompasses many exploration assets and capabilities throughout the architecture, each tailored to suit specific locations and the environments (e.g., deep space, lunar surface, Martian surface).

Habitation functions include environmental control, life support, thermal control, EVA support, crew habitability (e.g., hygiene, nutrition, waste management, sleep, exercise), crew health, and crew survival. Habitation structures can vary drastically and can include modular, connected, pressurized volumes of various materials (e.g., inflatable soft goods, metallic structures, in-situ constructed components).

Habitats scale in size and complexity based on crew size, mission duration, operational environment, and their ability to share functionality through interfaces with other exploration systems (e.g., consumables and power transfer). Other factors like gravity environment, crew tasks, and required crew motions also factor into overall volume.

Human Systems

Decomposition Abbreviation **X**

This sub-architecture comprises the capabilities of flight crew, ground/mission teams, and systems required to develop and execute safe and successful crewed and uncrewed missions.

The Human Systems sub-architecture focuses on providing an integrated, multidisciplinary, human-centered approach to design, development, operation, and performance of systems. While Human Systems is tightly coupled with all the other sub-architectures, it is also unique from hardware-based sub-architectures and includes the domains of human factors, habitability and environment, operations, training, maintainability and supportability, and safety.

Thus, the Human Systems sub-architecture addresses human health and well-being, safety, risks, concept of operations, human/hardware/software interfaces and interactions in various environments, functional architecture, design integration, requirements development, verification and validation, and flight certification considerations.

Infrastructure Support

Decomposition Abbreviation **G**

This sub-architecture comprises systems supporting Moon to Mars operations across the Earth (ground), in space, and in extraterrestrial surface domains. It includes the facilities, systems, equipment, and services required to support other sub-architectures.

Many exploration activities require additional equipment and support functions. For example, ground processing and landing and recovery of spaceflight elements and logistics items support the Transportation sub-architecture. On the lunar surface, equipment for handling, accessing, and transferring dry goods and fluid commodities; common and portable lighting support equipment; and prepared regolith structures are all likely to be shared across sub-architectures.

In-Situ Resource Utilization (ISRU) Systems

Decomposition Abbreviation **I**

This sub-architecture comprises systems designed to generate products or consumables from local resources on exploration missions. ISRU involves locating, mapping, and estimating extraterrestrial resource reserves and then extracting and processing them to generate products instead.

The practice of ISRU reduces mission dependance on delivering products and consumables from Earth. As humans stay longer and go farther into space, ISRU practices empower Earth independence and more sustainable commercial operations.

ISRU starts with resource identification, characterization, and mapping. This can include natural resources (e.g., regolith, water, atmosphere, etc.) and mission waste (e.g., crew trash, discarded hardware, etc.) ISRU production opportunities that can reduce mission cost or enable new operations include water, oxygen, and metals; human consumables and food production; feedstock for construction, manufacturing, and energy; and commodities for transportation vehicles, mobility systems, and propellant depots.

Logistics Systems

Decomposition Abbreviation **L**

This sub-architecture includes systems and capabilities needed for packaging, handling, staging, and transferring logistics items. These items include equipment, materials, supplies, and consumables needed to meet functional needs. The sub-architecture also includes approaches and capabilities for addressing trash and waste management (including meeting planetary protection requirements).

Initially, logistics items and consumables are limited to those that arrive with crew. As time advances, the architecture introduces additional capabilities that fulfill broadening logistics needs, including supporting longer durations (e.g., for Mars missions). As the sub-architecture matures, it takes advantage of increased automation and/or in-situ sourcing of logistics resources.

The amount and types of logistics items needed, along with their interfaces with surface elements, drive the type and quantity of the logistics carriers needed. Carrier types could include those suitable for EVA transfer (e.g., carriable through a hatch or an airlock).

Mobility Systems

Decomposition Abbreviation **M**

This sub-architecture comprises capabilities that convey crew and/or cargo on and around a destination, including EVA systems. It spans robotic and crewed systems with both pressurized and unpressurized capabilities that extend exploration and utilization ranges.

For the Human Lunar Return segment, spacesuits provide local lunar surface mobility. As the sub-architecture progresses to later segments, NASA adds mobility systems that provide unpressurized and pressurized local surface mobility for crewed and uncrewed periods. These systems provide faster and farther traverses as well as significantly increased carrying capacity. Autonomous and/or tele-operations enable key activities during uncrewed periods such as logistics resupply, outfitting, laying and connecting cables, and additional science and utilization opportunities.

Additional capabilities provided by this sub-architecture may include the aggregation of infrastructure, including for larger elements like habitation and power systems. Associated mobility elements would transport these systems (up to 15 tons) from landing sites to points of use, which can be kilometers away in mountainous terrain.

Power Systems

Decomposition Abbreviation **P**

This sub-architecture comprises capabilities that supply electrical energy to elements and exploration assets. These capabilities include components and hardware for power generation (e.g., solar arrays, fission surface power), power distribution (e.g., electrical cables, induction, power management, control and distribution electronics), and energy storage (e.g., batteries, regenerative fuel cells).

Interoperability is a key aspect of the Power Systems sub-architecture. This includes standardization of power interfaces (i.e., either hard or inductive connections) and the development of compatible power quality standards. The power sub-architecture includes coordination of missions where elements provide their own power as well as developing electrical energy infrastructure to support future needs and an over-all robust, resilient, and reliable architecture.

Initially, the architecture presumes that each element and exploration asset can provide the power and energy storage needed to perform their intended missions. As the architecture progresses, the sub-architecture expands to include options such as internal augmentation, external augmentation, and/or a lunar power grid (utilizing standard bi-directional power interfaces). The potential use of multiple power units enables a broader deployment strategy with an increase in operational locations and enhanced capabilities for users.

Transportation Systems

Decomposition Abbreviation **T**

This sub-architecture comprises capabilities that provide transportation functions for all phases of Moon and Mars exploration for both crew and cargo. This includes launch; transportation through space; entry, descent, and landing; ascent; and Earth re-entry.

Transportation systems interface with a variety of systems and payloads in a variety of space and surface environments. These include habitation and other human support systems, ground and in-space communications systems, as well as refueling or recharging systems.

Initial lunar segments will include transportation capabilities for the transit of crew and cargo to cislunar space, the landing of crew and cargo on the lunar surface, ascent of crew and limited cargo to cislunar space, and the safe return of crew and cargo to Earth. As missions expand to Mars, the transportation sub-architecture will evolve to include Mars transit; entry, descent, and landing; and ascent systems for cargo and crew.

Utilization Systems

Decomposition Abbreviation **U**

Utilization encompasses a range of activities that occur as part of the exploration campaign. These include science, research, test and evaluation, public outreach, education, and industrialization. The Utilization Systems sub-architecture comprises capabilities whose primary function is accomplishing these science, technology, and other activities, including sample and utilization cargo return to Earth.

All sub-architectures ultimately support utilization; and utilization systems levy functions and use cases across all other sub-architectures. For instance, the return of a frozen lunar surface sample would not only necessitate the use of dedicated utilization payloads and equipment for collection, stowage, and conditioning, but also leverage systems such as mobility and C&PNT to reach the sample, power for long-term surface stowage, and transportation and ground systems to return the sample to a facility on Earth.

Similarly, some items may serve multiple functions (e.g., engineering cameras designed for operations but can provide valuable data to science). However, the Utilization Systems sub-architecture includes systems that focus primarily on utilization.

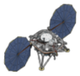
2.3 Elements

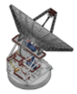
Elements are major systems and hardware that enable exploration and empower NASA to achieve the Moon to Mars Objectives. They include prominent systems like the Orion spacecraft, Human Landing System, and Space Launch System, as well as spacesuits, vehicles, logistics systems, habitation, communications systems, and more. This Architecture Definition Document captures the formal allocation of use cases and functions to the defined element and maps the element to associated segments and sub-architectures.

NASA derives these elements through objective decomposition. Functional mappings for Human Lunar Return and Foundational Exploration segment elements are included in Appendix B.3. Functional mapping for the Sustained Lunar Evolution and Humans to Mars segments is forward work. NASA will add additional exploration assets in future revisions to close capability gaps.

The Architecture Definition Document only includes funded elements that the agency has formally committed to developing. It is a technical document that reflects the approved baseline for programs of record, contracts, partnerships, and funding. The agency avoids premature addition of element concepts to preserve opportunities for innovation, technology enhancements, and partnerships.

In addition to exploration elements, crew members (i.e., astronauts), payloads, and utilization equipment satisfy many use cases and functions. For more information on payloads and utilization equipment, consult Section 2.4 and Appendix B.4.

Icon	Element/Asset Name	Sub-Arch	Segments		Section	Mapping
	Commercial Lunar Payload Services				2.3.1	B.3.1
	Exploration EVA Systems				2.3.2	B.3.2
	Exploration Ground Systems				2.3.3	B.3.3
	Gateway				2.3.4	B.3.4
	Gateway Logistics Element				2.3.4.1.4	B.3.4
	Human Landing System				2.3.5	B.3.5

Icon	Element/Asset Name	Sub-Arch	Segments		Section	Mapping
	Human-Class Delivery Lander	🚀		◉	2.3.6	B.3.6
	Initial Surface Habitat	🏠		◉	2.3.7	B.3.7
	Lunar Surface Cargo Lander	🚀		◉	2.3.8	B.3.8
	Lunar Terrain Vehicle	🚙		◉	2.3.9	B.3.9
	Lunar Utility Rover	🚙		◉	2.3.10	B.3.10
	Orion Spacecraft	🚀	●	◉	2.3.11	B.3.11
	Pressurized Rover	🚙		◉	2.3.12	B.3.12
	Space Communications and Navigation Networks	📡	●	◉	2.3.13	B.3.13
	Space Launch System	🚀	●	◉	2.3.14	B.3.14

2.3.1 Hic Commercial Lunar Payload Services

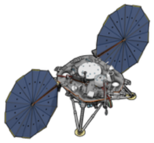
Element Description

NASA’s Commercial Lunar Payload Services (CLPS) program offers rapid acquisition of lunar delivery services from American companies for payloads that advance science, technology, and exploration capabilities and/or empower commercial development of the Moon. Investigations and demonstrations launched on these flights will help NASA study Earth’s nearest neighbor as part of the Artemis program.

NASA encourages CLPS providers to deliver commercial and other partner payloads in addition to NASA payloads. NASA has awarded 15 task orders to seven different CLPS lander providers for delivery of more than 60 payloads to the lunar surface during the Human Lunar Return exploration segment. As NASA progresses to the Foundational Exploration segment, CLPS can provide lunar delivery capabilities in addition to those offered by other elements, like the Human-class Delivery Lander.

NASA plans to award additional CLPS task orders as mission and payload definition continues, continuing annual calls for new payload suites through the Payload and Research Investigations from the Surface of the Moon (PRISM) solicitation, which enables high-priority science and complements other NASA-sponsored payloads.

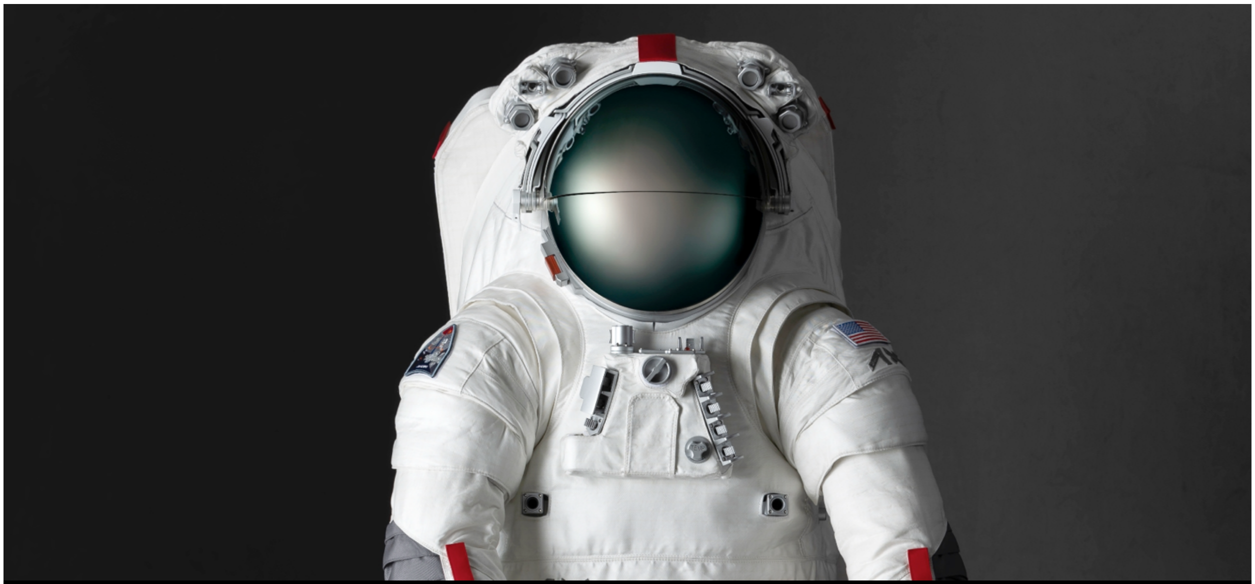
Implementing Program	Functional Mappings
CLPS Program *Science Mission Directorate*	**Appendix B** *B.3.1*

Segments		Sub-Architecture	Element Icon
Human Lunar Return	Foundational Exploration	Transportation Systems	

Header Image: *This picture, captured from the surface of the Moon, shows Firefly’s Blue Ghost lunar lander, which performed operations on the Moon from March 2-16, 2025, in the foreground, and Earth in the sky above it. (Credit: Firefly Aerospace)*

Architecture Definition Document – Element One Pager

2.3.2 Exploration EVA System



Element Description

The Exploration Extravehicular Activity (xEVA) System is a next-generation spacesuit that allows crew members to perform extravehicular exploration, research, construction, servicing, repairs, and utilization on the lunar surface. It includes a portable life support system and maximizes mobility and freedom of movement.

The suit enables traverse and utilization activities, which may include augmentation by robotic systems and rovers. The xEVA System includes suits, tools, and vehicle interface equipment. Astronauts will wear these spacesuits as they take humanity's first steps on the lunar surface since the Apollo Program during the Human Lunar Return segment.

During the Foundational Exploration segment, robotics and mobility systems on the lunar surface augment EVA traverses and tasks performed with xEVA systems. With the addition of airlock at Gateway, the xEVA system also allows crew members to perform extravehicular exploration, research, construction, servicing, repair operations, utilization, and science in cislunar orbit. As the architecture progresses, NASA could procure xEVA suits from different vendors or include upgrades.

Implementing Program	Functional Mappings
EVA and Human Surface Mobility Program *Moon to Mars Program Office*	**Appendix B** *B.3.2*

Segments		Sub-Architecture	Element Icon
Human Lunar Return	Foundational Exploration	Mobility Systems	

Header Image: *The flight design of Axiom Space's Axiom Extravehicular Mobility Unit (AxEMU) lunar spacesuit that NASA astronauts will wear during the Artemis III mission. (Credit: Axiom Space)*

Architecture Definition Document – Element One Pager

2.3.3 Exploration Ground Systems

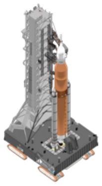
Element Description

NASA’s Exploration Ground Systems (EGS) program develops and operates systems and facilities that process, launch, and recover vehicles. EGS provides critical ground infrastructure for processing, launch, and landing of the Space Launch System and Orion spacecraft.

EGS utilizes the Vehicle Assembly Building at Kennedy Space Center for integration, testing, and vertical stacking of the Space Launch System on the Mobile Launcher platform. EGS moves the stacked vehicle on the mobile launcher to Launch Pad 39B via the crawler-transporter. Vehicle testing, final propellant servicing, launch countdown, and launch occur at the pad.

As EGS progresses through the Human Lunar Return segment to Foundational Exploration, it offers additional capabilities, such as the transition to the Mobile Launcher 2, which enables Space Launch System Block 1B missions. As human exploration expands deeper into the solar system, NASA applies capabilities and lessons learned by EGS in earlier segments to the challenges of increasingly ambitious missions and destinations.

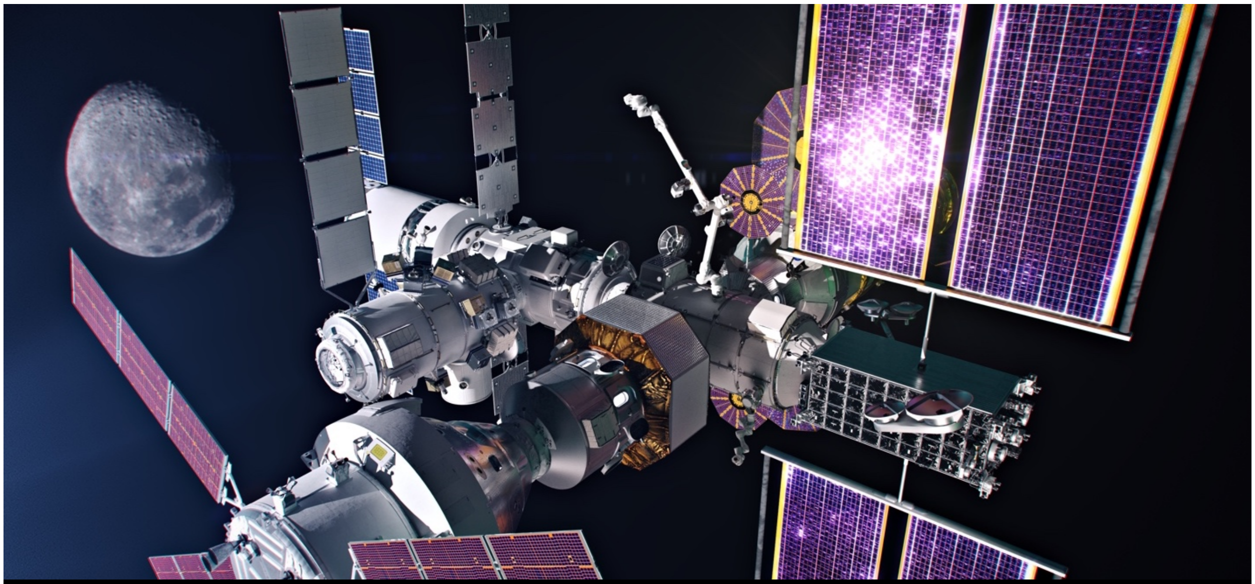
Implementing Program	Functional Mappings
Exploration Ground Systems *Moon to Mars Program Office*	**Appendix B** *B.3.3*

Segments		Sub-Architecture	Element Icon
Human Lunar Return	Foundational Exploration	Infrastructure Support	

Header Image: *Exploration Ground Systems teams transport the Artemis II Space Launch System core stage to the Vehicle Assembly Building at NASA’s Kennedy Space Center in Florida. (Credit: NASA)*

Architecture Definition Document – Element One Pager

2.3.4 Gateway



Element Description

Gateway is a lunar-orbiting outpost in NRHO comprising incrementally launched and assembled modules provided by NASA and international partner space agencies. As the architecture progresses, Gateway evolves to enable more complex exploration operations and Mars-forward demonstrations.

During the Human Lunar Return segment, the **Gateway Crew-Capable Configuration** comprises the capabilities and components outlined in Section 2.3.4.1. This configuration offers the minimum core functions to support initial crewed missions to the lunar surface. It includes pressurized volumes, life support, propulsion, power, communications, avionics, docking ports, and opportunities for internal and external science and utilization. Deep Space Logistics services supply critical cargo deliveries to the station.

During the Foundational Exploration segment, the **Gateway Expanded Capability Configuration** adds the capabilities and components outlined in Section 2.3.4.2. This configuration grows crewed and uncrewed exploration and utilization opportunities on Gateway through external robotics, an airlock, refueling capabilities, and enhanced telecommunications systems.

Implementing Program	Functional Mappings
Gateway Program *Moon to Mars Program Office*	**Appendix B** *B.3.4*

Segments		Sub-Architecture	Element Icon
Human Lunar Return	Foundational Exploration	Habitation Systems	

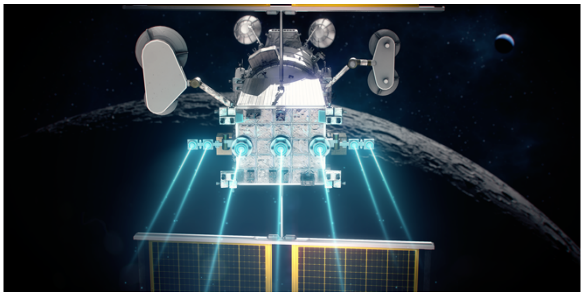
Header Image: *Rendering of the full configuration of the Gateway space station. Gateway will be humanity's first space station around the Moon and will help the agency test technologies and operational paradigms for crewed Mars missions. (Credit: NASA)*

Architecture Definition Document – Element One Pager

2.3.4.1 Gateway Crew-Capable Configuration

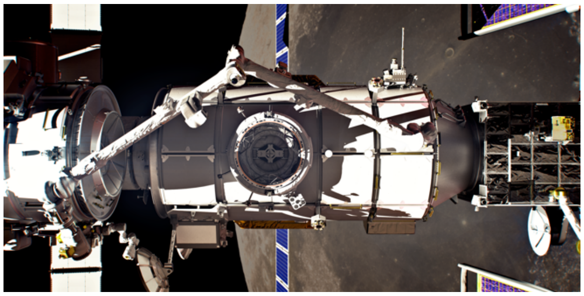
Gateway capabilities realized during the Human Lunar Return segment are referred to as the Gateway Crew-Capable Configuration. Associated Gateway components and partnerships include:

2.3.4.1.1 Power and Propulsion Element

Component Description	Component Rendering
The Power and Propulsion Element (PPE) provides electrical power; attitude and translational control; and communication for Gateway. The PPE maintains attitude using reaction wheels and a chemical propulsion system. When uncrewed, it performs translation maneuvers and orbital maintenance using a solar electric propulsion system. This propulsion system also serves as a technology demonstration for potential solar electric propulsion for Mars missions. The PPE has power storage and systems necessary to convert and distribute power to the rest of Gateway. It includes internal avionics systems and is one part of the integrated command and control architecture for Gateway. PPE also performs other functions, such as hosting external payloads and science investigations.	
	Partner Agencies
	Not Applicable

Architecture Definition Document – Gateway Components and Partnerships

2.3.4.1.2 Habitation and Logistics Outpost

Component Description	Component Rendering
The Habitation and Logistics Outpost (HALO) is one of two habitation modules where astronauts will live, exercise, eat meals, rest, conduct research, and prepare for lunar surface missions. This pressurized living quarters provides docking ports for visiting spacecraft like the Orion spacecraft, lunar landers, and logistics resupply spacecraft. HALO also serves as the backbone for Gateway command, control, and power distribution. Additionally, HALO performs other core functions, including hosting internal and external science investigations, communicating with Earth, visiting vehicles, and assets on the lunar surface, and providing stowage for consumables and payloads. The European Space Agency is leading development of the HALO Lunar Communication System.	
	Partner Agencies
	esa European Space Agency

Architecture Definition Document – Gateway Components and Partnerships

2.3.4.1.3 Lunar I-Hab

Component Description

The Lunar I-Hab is Gateway's second habitable element, a pressurized module that will provide multiple docking ports for visiting vehicles and other modules, as well as crew quarters, galley, and stowage.

In addition, I-Hab provides services for internal and external payloads and provides attachment points to allow end-to-end translation of external robotics.

The European Space Agency is leading development of the Lunar I-Hab. The Japan Aerospace Exploration Agency is making significant contributions to this Gateway component, providing the environmental control support system, thermal cooling pumps, and batteries.

Component Rendering

Partner Agencies

esa

European Space Agency

Japan Aerospace Exploration Agency

Architecture Definition Document – Gateway Components and Partnerships

2.3.4.1.4 Gateway Logistics Element

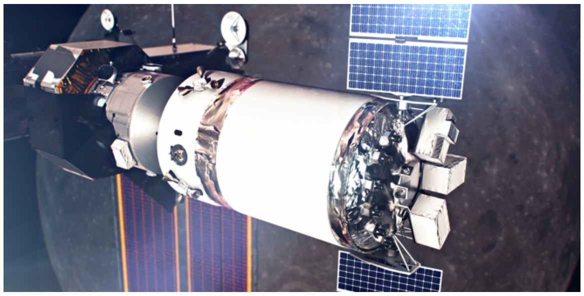
Component Description

Gateway Logistics Element transports cargo, payloads, and consumables to Gateway. These logistics flights supply the space station with critical deliveries necessary to maximize the length of crew stays. NASA anticipates at least one logistics services delivery for each Gateway mission of 30 days.

The logistics module will provide consumable resupply, outfitting equipment, and cargo delivery including utilization and spares. Each module is also capable of providing additional stowage volume while attached to Gateway, and trash disposal upon departure.

The associated Gateway Logistics Services contract and technical capabilities are extensible to deliver unique payload configurations and supply cargo deliveries to other destinations beyond Gateway. Additional capabilities may be added in future segments.

Component Rendering



Partner Agencies

Not Applicable

Architecture Definition Document – Gateway Components and Partnerships

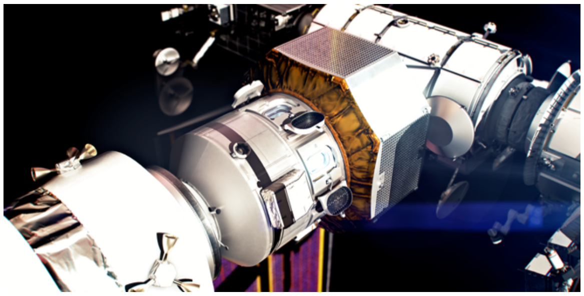
2.3.4.2 *Gateway Expanded Capability Configuration*

Gateway capabilities realized during the Foundational Exploration segment are referred to as the Gateway Expanded Capability Configuration. Associated Gateway components and partnerships added during this segment include:

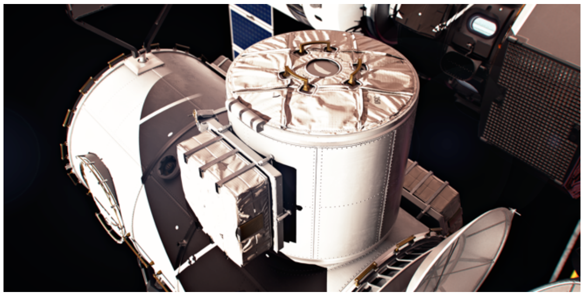
2.3.4.2.1 Gateway External Robotic System / Canadarm3

<table>
<tr><th>Component Description</th><th>Component Rendering</th></tr>
<tr><td rowspan="3">The Gateway External Robotic System includes a robotic arm, the Canadarm3, provided by the Canadian Space Agency.
The system uses cutting-edge software and robotics to help maintain, repair, and inspect Gateway. It captures visiting vehicles, assists astronauts during spacewalks, and enables external utilization on Gateway in NRHO. The system will self-deploy and translate to multiple locations on the Gateway using low-profile grapple fixtures.</td><td></td></tr>
<tr><th>Partner Agencies</th></tr>
<tr><td>Canadian Space Agency</td></tr>
<tr><td colspan="2">Architecture Definition Document – Gateway Components and Partnerships</td></tr>
</table>

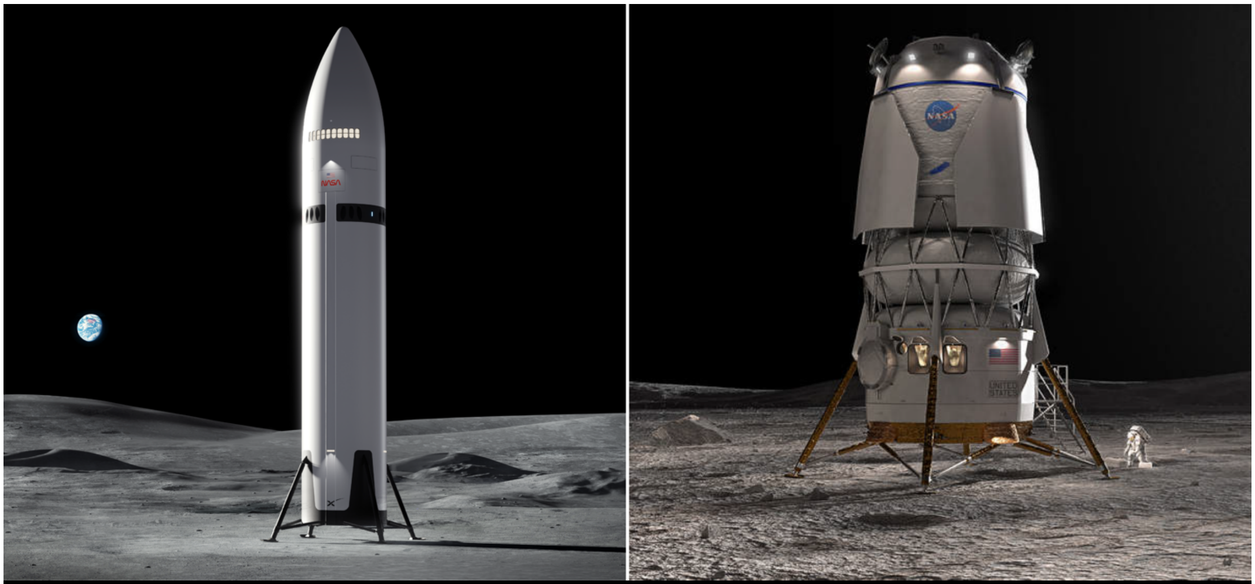
2.3.4.2.2 Lunar View

<table>
<tr><th>Component Description</th><th>Component Rendering</th></tr>
<tr><td rowspan="3">The Lunar View module — previously known as European System Providing Refueling Infrastructure and Telecommunication (ESPRIT) Refueling Module (ERM) — provided by the European Space Agency, is a habitable module that transports cargo to Gateway, provides storage space once docked, will provide refueling capabilities to the PPE through HALO, and offers views of space and the Moon through its windows.</td><td></td></tr>
<tr><th>Partner Agencies</th></tr>
<tr><td>esa
European Space Agency</td></tr>
<tr><td colspan="2">Architecture Definition Document – Gateway Components and Partnerships</td></tr>
</table>

2.3.4.2.3 Crew and Science Airlock

Component Description	Component Rendering
The Crew and Science Airlock, provided by the United Arab Emirates Mohammad Bin Rashid Space Centre, allows for the transfer of crew and utilization payloads to and from Gateway's habitable modules and the vacuum of space and provides EVA capability for the Gateway crew. These transfers empower maintenance and expanded science on the lunar orbiting space station. In addition, the airlock provides services for internal and external payloads.	 **Partner Agencies** Mohammed Bin Rashid Space Centre
Architecture Definition Document – Gateway Components and Partnerships	

2.3.5 Human Landing System



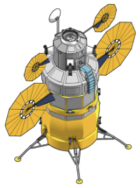
Element Description

The Human Landing System (HLS) transports crew members, support payloads, cargo, and logistics between a crew staging vehicle orbiting the Moon (e.g., Orion or Gateway) and the lunar surface. On the lunar surface, HLS offers a habitable volume, consumables, and other features that enable crew surface stays and the execution of lunar surface EVAs. HLS also accommodates utilization payloads inside the cabin and attached to its exterior. Specific HLS capabilities depend on the design implementation approach of its commercial provider.

The initial HLS configuration for the Human Lunar Return segment supports two crew and operates between Orion in NRHO and a landing site in lunar South Pole region. This configuration also delivers cargo and support logistics to NRHO from Earth prior to the crewed phase of the mission.

During the Foundational Exploration segment, the HLS integrated lander configuration supports a crew of up to four, enabling missions to leverage additional habitable surface assets. Segment missions could include landing at non-polar sites and operating for extended durations in the lunar South Pole region. The integrated lander configuration's improved performance increases up and down mass to and from the lunar surface and darkness survivability.

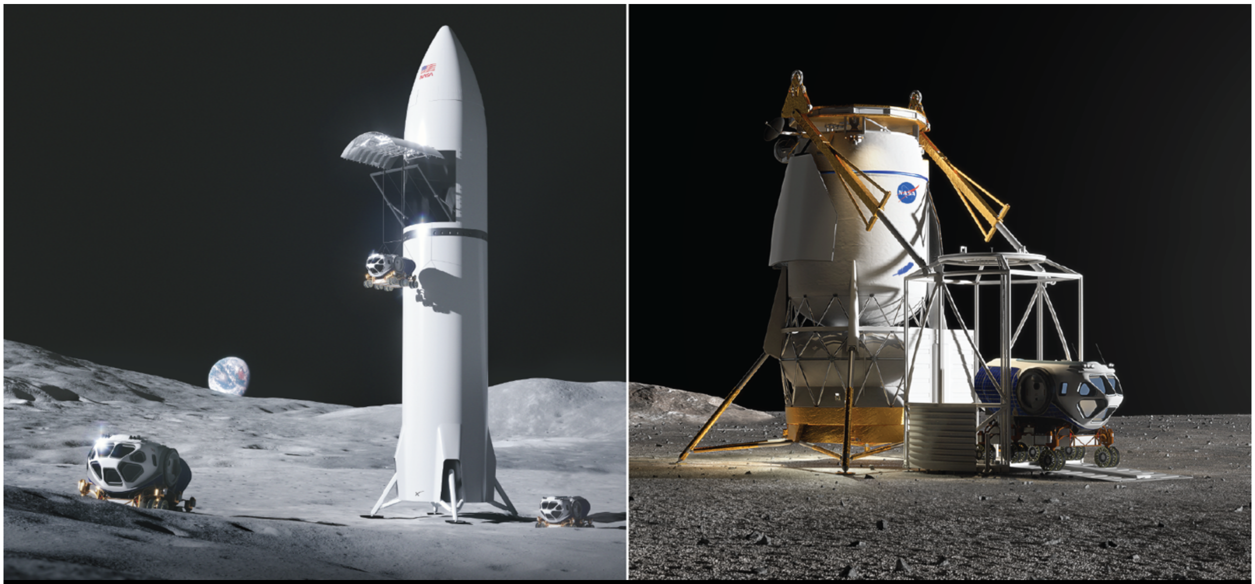
Implementing Program	Functional Mappings
Human Landing System Program *Moon to Mars Program Office*	**Appendix B** *B.3.5*

Segments		Sub-Architecture	Element Icon
Human Lunar Return	Foundational Exploration	Transportation Systems	

Header Image: *Renderings of the two commercial systems for the Human Landing System: the SpaceX Starship and Blue Origin Blue Moon lander. (Credit: SpaceX/Blue Origin)*

Architecture Definition Document – Element One Pager

2.3.6 Human-Class Delivery Lander



Element Description

The Human-class Delivery Lander (HDL) supports delivery missions to the lunar South Pole region during the Foundational Exploration segment. HDL can deliver a wide range of small to large lunar surface assets as cargo, including cargo that remains integrated with the lander on the lunar surface. HDL also offers offloading capabilities, delivering cargo directly to the lunar surface.

Examples of large cargo include the Pressurized Rover, surface habitation elements, and future surface power elements. HDL can also deliver smaller cargo items, either co-manifested with larger items or as many small items grouped together.

HDL is not intended to deliver crew. Crew interaction with the large cargo lander occurs primarily through EVA access to cargo. For cargo that remains integrated with the lander — such as a surface habitat — this includes EVA ingress/egress capability.

During transit from Earth and while on the lunar surface, HDL supports cargo with needed services until the it is ready to operate independently. Once the lander completes operations and enables cargo to operate independently, it transitions to a safe condition/state.

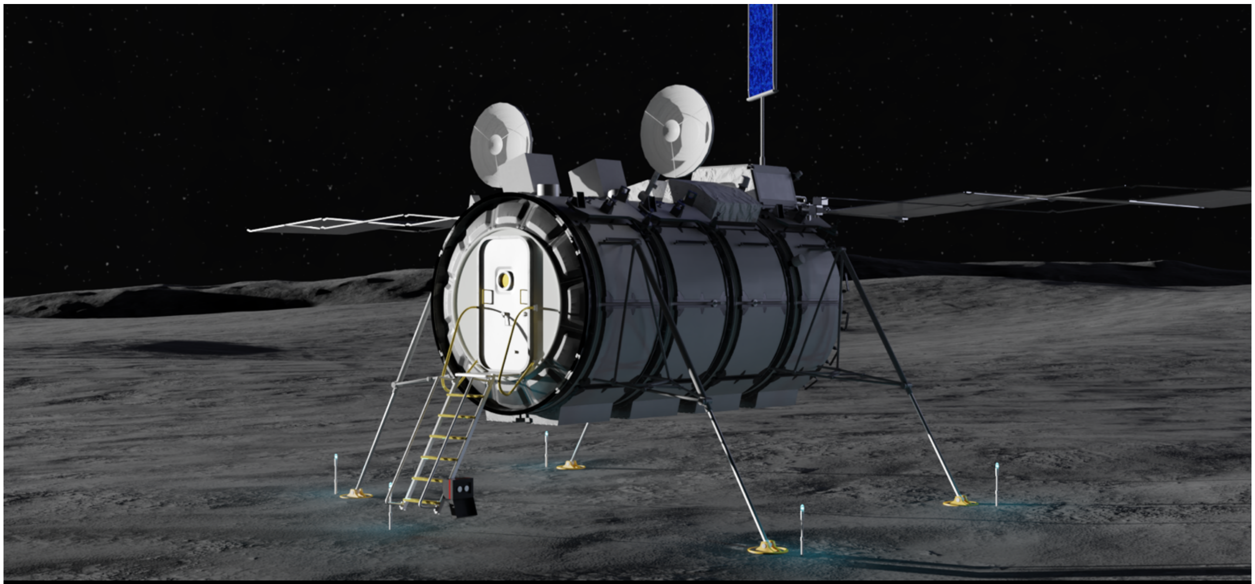
Implementing Program	Functional Mappings
Human Landing System Program *Moon to Mars Program Office*	**Appendix B** *B.3.6*

Segments		Sub-Architecture	Element Icon
	Foundational Exploration	Transportation Systems	

Header Image: *Renderings of the two commercial systems for the Human-Class Delivery Lander: the SpaceX Starship and Blue Origin Blue Moon lander. (Credit: SpaceX/Blue Origin)*

Architecture Definition Document – Element One Pager

2.3.7 Initial Surface Habitat



Element Description

The Foundational Exploration segment introduces dedicated surface habitation to the architecture. The initial surface habitat offers expanded exploration capabilities, establishes opportunities for Mars-forward precursor missions, and increases crew size, exploration range, and utilization opportunities.

The habitat can house two crew members as they live and work on the lunar surface from a minimum of 7 and up to 33 days with logistics resupply. The habitat enables crew EVAs, as well as science and technology utilization during both crewed and uncrewed periods. It supports general habitation functions, such as provisioning medical systems, accommodating utilization hardware, supplying environmental control and life support, and supporting logistics transfer.

Implementing Program	Functional Mappings
Human Landing System Program *Moon to Mars Program Office*	**Appendix B** *B.3.7*

Segments		Sub-Architecture	Element Icon
	Foundational Exploration	Habitation Systems	

Header Image: *Rendering of a government reference concept for the initial surface habitat.*
NASA and its partners are iterating on a final design for implementation of this element. (Credit: NASA)

Architecture Definition Document – Element One Pager

2.3.8 Lunar Nuclear Fission System

Element Description

In 2025, NASA instantiated a nuclear fission power system into its lunar architecture. This external power augmentation can supplement onboard solar power systems for 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.

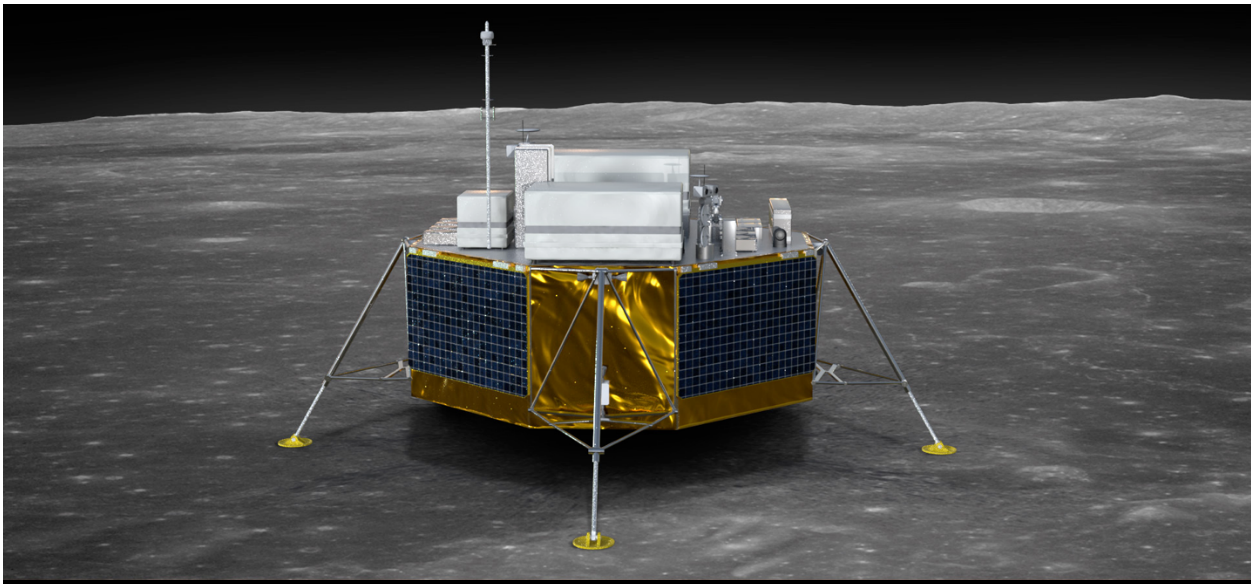
Implementing Program	Functional Mappings
Fission Surface Power *NASA's Glenn Research Center*	**Appendix B** *B.3.8*

Segments		Sub-Architecture	Element Icon
	Foundational Exploration	Power Systems	

Header Image: *Rendering of a government reference concept for a lunar surface power system utilizing nuclear fission. (Credit: NASA)*

Architecture Definition Document – Element One Pager

2.3.9 Lunar Surface Cargo Lander

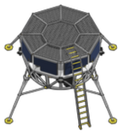


Element Description

The lunar surface cargo lander delivers assets to the Moon, much like the HDL or CLPS elements. However, the anticipated capability of the element is much smaller than HDL, delivering moderate amounts of cargo to the lunar surface.

NASA targets the lunar surface cargo lander for delivery of logistics, utilization, power, communications, and other payloads. The element provides all the services necessary to maintain its cargo from launch vehicle integration through landing on the lunar surface and until cargo offloading or independent operations.

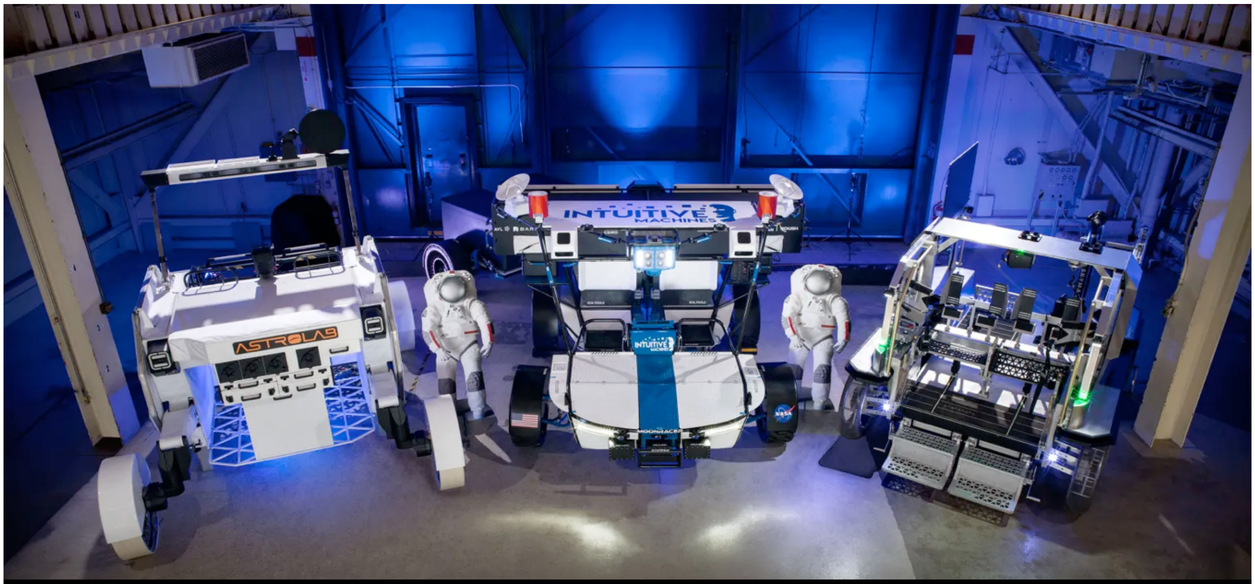
Implementing Program	Functional Mappings
Human Landing System Program *Moon to Mars Program Office*	**Appendix B** *B.3.9*

Segments		Sub-Architecture	Element Icon
	Foundational Exploration	Transportation Systems	

Header Image: *Rendering of a government reference concept for the lunar surface cargo lander element. NASA and its partners are iterating on a final design for implementation of this element. (Credit: NASA)*

Architecture Definition Document – Element One Pager

2.3.10 Lunar Terrain Vehicle



Element Description

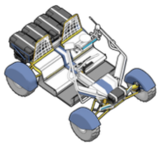
The Lunar Terrain Vehicle (LTV) is an unpressurized rover capable of transporting crew and cargo across the lunar surface. It also supports science, exploration, and operations objectives.

The LTV provides reliable and safe transportation between waypoints for two suited crewmembers and cargo. Cargo can include various payloads, work packages, logistics supplies, science tools, samples, and associated stowage containers. The LTV can be operated autonomously, by teleoperators, or by a single suited crewmember.

The LTV can also act as a surface communications relay and provide positioning, navigation, and timing data to support crewed and uncrewed traverses, as well as uncrewed science operations. This capability can enhance network coverage, increases exploration ranges, enable landing site reconnaissance, and support payload utilization.

The LTV can also increase safety through redundancy, serving as a companion platform in the event another mobility system fails to return to a crew habitat. Two mobility platforms operating together allows for farther crewed traverses than would be possible utilizing a single platform.

Implementing Program	Functional Mappings
EVA and Human Surface Mobility Program *Moon to Mars Program Office*	**Appendix B** *B.3.10*

Segments		Sub-Architecture	Element Icon
	Foundational Exploration	Mobility Systems	

Header Image: *From left to right: Astrolab's FLEX, Intuitive Machines' Moon RACER, and Lunar Outpost's Eagle lunar terrain vehicle at NASA's Johnson Space Center. (Credit: NASA)*

Architecture Definition Document – Element One Pager

2.3.11 Lunar Utility Rover

Element Description

The lunar utility rover is an uncrewed, unpressurized rover that provides cargo and payload mobility, EVA support, and utilization support. It can also transport a moderate amount of cargo (thousands of kg) and will provide power and data interfaces for transported cargo and payloads. It supports multiple operational modes, including local astronaut control, teleoperated (from Earth), semi-autonomous, and full autonomous control. During crewed expeditions, the rover will support longer traverses and increase available science targets by carrying support cargo.

It could explore the lunar South Pole; scout future human and cargo landing sites and traverse paths; and gather data to support utilization objectives. The rover could conduct science activities directly (through operation of its manipulator arm and onboard payloads), and indirectly (through crew support). It 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 perform maintenance, repair, and servicing of other assets.

Implementing Program	Functional Mappings
EVA and Human Surface Mobility Program *Moon to Mars Program Office*	**Appendix B** *B.3.11*

Segments		Sub-Architecture	Element Icon
	Foundational Exploration	Mobility Systems	

Header Image: *Artist's rendering of a reference concept for the lunar utility rover concept. (Credit: NASA)*

Architecture Definition Document – Element One Pager

2.3.12 Orion Spacecraft

Element Description

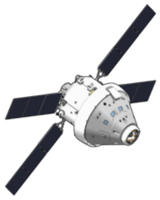
The Orion spacecraft serves as the primary crew vehicle for Artemis missions for transporting crew between Earth and lunar orbit. The vehicle can conduct regular in-space operations in conjunction with payloads delivered by the Space Launch System and can dock with the Human Landing System and Gateway in cislunar orbit.

The Orion spacecraft includes the Crew Module, Service Module, and Launch Abort System. The Crew Module can transport four crew members beyond the Moon, providing a safe habitat from launch through landing and recovery.

The Service Module, made up of the NASA-provided Crew Module Adapter and the ESA-provided European Service Module, provides support to the crew module from launch through separation prior to entry. The Service Module provides in-space propulsion for orbital transfer, power and thermal control, attitude control, and high-altitude ascent aborts. While mated with the crew module, the Service Module also provides water and air to support the crew.

The Launch Abort System, positioned on a tower atop the Crew Module, can activate within milliseconds to propel the vehicle to safety and position the Crew Module for a safe landing.

Implementing Program	Functional Mappings
Orion Program *Moon to Mars Program Office*	**Appendix B** *B.3.12*

Segments		Sub-Architecture	Element Icon
Human Lunar Return	Foundational Exploration	Transportation Systems	

Header Image: *Orion captures a unique view of Earth and the Moon, seen from a camera mounted on one of the spacecraft's solar arrays during the uncrewed Artemis I mission. (Credit: NASA)*

Architecture Definition Document – Element One Pager

2.3.13 Pressurized Rover

Element Description

The Japan-provided Pressurized Rover is a mobile vehicle designed to support crew habitation, utilization, operations, and Mars analog objectives. The Pressurized Rover provides reliable and safe transportation of two crew members inside a pressurized cabin.

It can support various payloads, work packages, logistics, science tools, samples, and associated stowage containers. The rover can be operated manually by a single crew member from the cabin, remotely by tele-operators on Earth, or via some autonomous operations. The rover can perform extended exploration missions lasting up to 28 days with up to 14 days between cargo resupplies. The Pressurized Rover can support increased traverse distance, when the Lunar Terrain Vehicle is available as a backup mobility asset in the event of a failure.

Japan Aerospace Exploration Agency

This element is provided by the **Japan Aerospace Exploration Agency** in collaboration with the Japanese automotive industry.

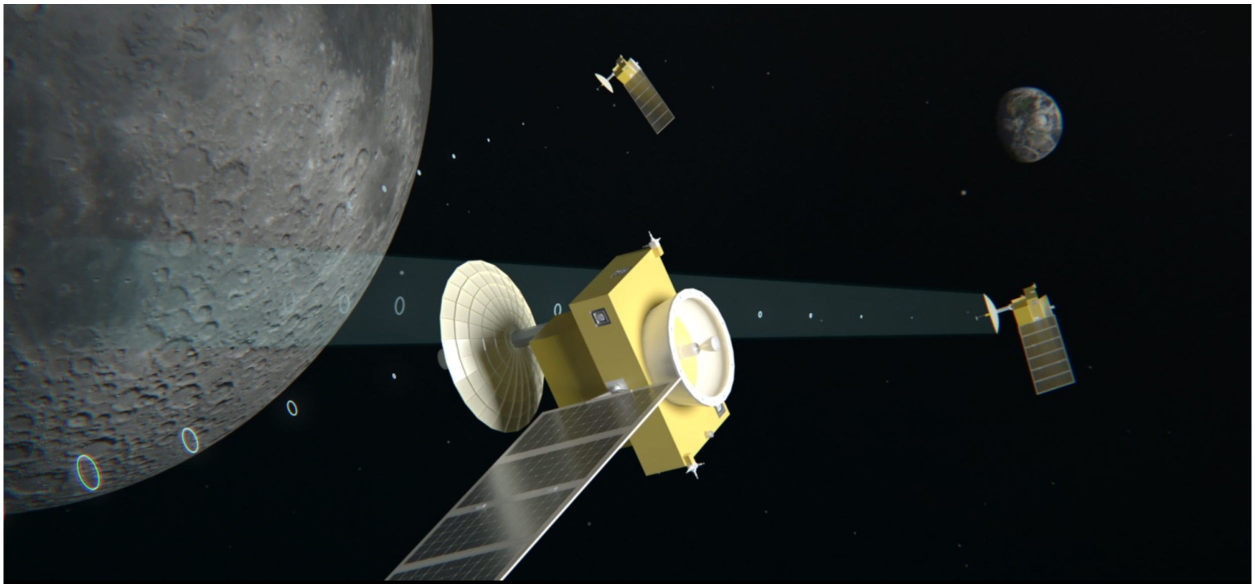
Implementing Program	Functional Mappings
EVA and Human Surface Mobility Program *Moon to Mars Program Office*	**Appendix B** *B.3.13*

Segments		Sub-Architecture	Element Icon
	Foundational Exploration	Mobility Systems	

Header Image: *A concept image of the JAXA/Toyota Lunar Cruiser Pressurized Rover on the surface of the Moon. (Credit: JAXA/Toyota)*

Architecture Definition Document – Element One Pager

2.3.14 Space Communications and Navigation Networks



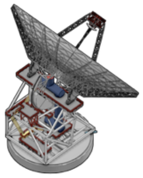
Element Description

NASA's Space Communications and Navigation (SCaN) program provides communications, positioning, navigation, and timing services to missions through two subnets: the **Near Space Network** (NSN) and the **Deep Space Network** (DSN). These networks include direct-with-Earth, space relay, and surface assets and services offered through government, commercial, and international providers. The networks also comprise efforts to augment or improve those assets and services.

The NSN provides services out to two million kilometers from Earth through commercial and government ground stations globally and cislunar space relays. The NSN Lunar Communications Relay and Navigation Systems (LCRNS) project validates commercial lunar relay services procured to support the Moon to Mars Architecture. The NSN, through the Commercial Services contract, is contracting with commercial service providers to establish communication and PNT services that will be able to support cislunar users. The DSN comprises an array of ground stations featuring large diameter antennas capable of supporting missions throughout the solar system and beyond, including at the Moon and Mars. The DSN also supports the Mars Communications Relay Network, currently used to relay data from Mars surface missions back to Earth.

> **Note:** *NASA decomposes the functional mappings for this integrated element into functions generally provided by the networks, and those specifically provided by LCRNS. For more detail about the evolution of communications and PNT services, see Section 2.2.2 for the C&PNT sub-architecture.*

Implementing Program	Functional Mappings
Space Communications and Navigation Program *Space Operations Mission Directorate*	**Appendix B** *B.3.14*

Segments		Sub-Architecture	Element Icon
Human Lunar Return	Foundational Exploration	C&PNT Systems	

Header Image: *A concept image of lunar relay satellites transmitting data to the lunar surface .*
(Credit: NASA)

Architecture Definition Document – Element One Pager

2.3.14.1 Network Partners

NASA provides network services through distributed assets operated by NASA, international partners, and commercial service providers. Two agency-managed networks — the Near Space Network and Deep Space Network — integrate these assets and the distributed teams that support them into a suite of capabilities for lunar users.

The Near Space Network[13] comprises geographically distributed ground stations and space relay assets operated by NASA and government, industry, and international partners. The network engages new and existing partners to realize a suite of new capabilities for cis-lunar and lunar surface communications and PNT. The Deep Space Network[14] comprises three facilities around the globe, approximately 120 degrees apart in longitude.

2.3.14.2 Interoperability Considerations

NASA seeks to empower network users with a long-term, scalable, and interoperable C&PNT architecture. This requires thoughtful coordination, planning, and establishment of interface and operational standards in coordination with international and industry partners, as well as a common understanding of user needs.

LunaNet is an internationally coordinated framework for lunar C&PNT service interoperability extensible to Mars and beyond. It envisions a set of cooperating networks providing C&PNT services to users in transit to, around, and on the Moon. The LunaNet Interoperability Specification is a structure of mutually agreed-upon standards, protocols, and interface requirements to realize this vision.[15] Similarly, the International Communications System Interoperability Standard — adopted into the architecture during the 2024 Architecture Concept Review — enables collaborative operations for the user community.[16] Nonetheless, industry standards that deviate from International Communications System Interoperability Standard protocols may be implemented if the result is a more robust, industry-proven telecommunications approach.

NASA's current spectrum plans — developed in coordination with the International Telecommunications Union, and the Space Frequency Coordination Group — are documented in the International Communication System Interoperability Standard.[17] Implementation support for these plans come from the Consultative Committee for Space Data Systems, the International Communication System Interoperability Standards, and the LunaNet Interoperability Standard.

Reference systems and time are fundamental to safe navigation, precision science, communications systems, and interoperability at the Moon. NASA must define, adopt, and implement lunar reference systems (including reference frames) in the early stages of architecture development. As at Earth, individual nations implement international standards, so close coordination is essential.

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[13] https://www.nasa.gov/communicating-with-missions/nsn/

[14] https://www.nasa.gov/communicating-with-missions/dsn/

[15] https://www.nasa.gov/directorates/somd/space-communications-navigation-program/lunanet-interoperability-specification/

[16] https://ntrs.nasa.gov/citations/20240016079

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

U.S. policy on these topics is available[18,19] and international coordination is underway.[20] For more information about lunar reference frame considerations, see the associated 2024 Moon to Mars Architecture white paper.[21]

2.3.14.3 Network Evolution

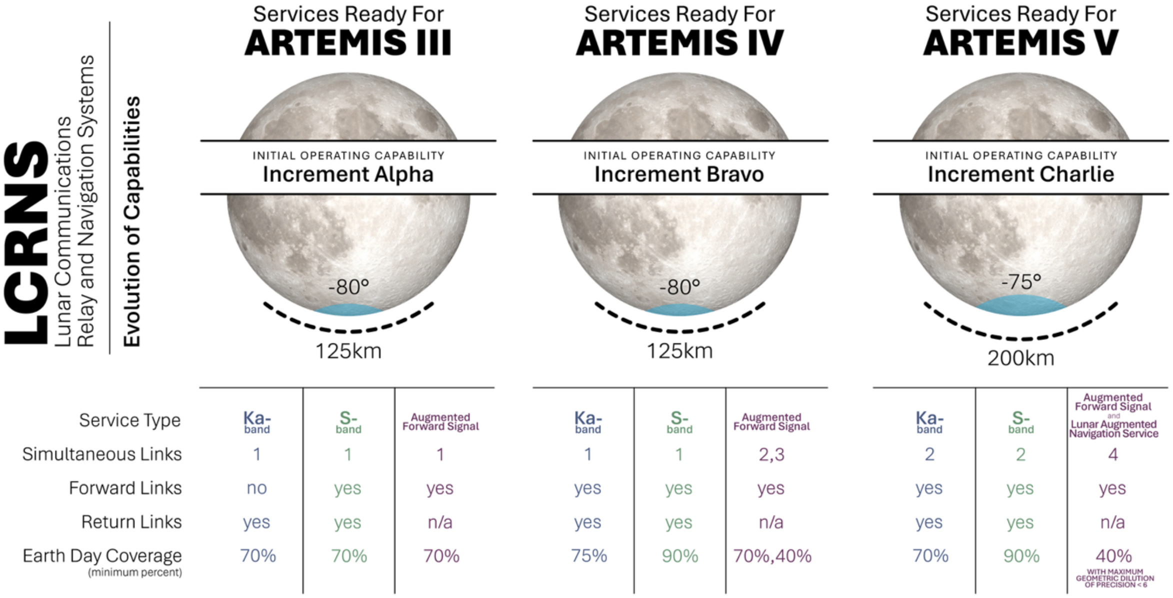
Though they have existed since the earliest days of human spaceflight, NASA's networks continuously evolve to meet the needs of future users. For the architecture, this means phased implementation of new services and capabilities that expand connectivity, network access and timeliness, and accuracy in transit to, around, and on the Moon and Mars.

Through technology demonstrations and operational experience, NASA seeks to build a robust foundation for a scalable C&PNT infrastructure. This evolution will empower a sustained presence at the Moon, foster a robust lunar economy, and realize capabilities needed for human Mars exploration.

2.3.14.3.1 Human Lunar Return

During the Human Lunar Return segment, lunar users rely on C&PNT services provided through a combination of assets at Earth, in lunar orbit, and demonstrations of systems on the lunar surface. Operationally, this will include direct-with-Earth communications and space relay services provided through LCRNS.

Initially, LCRNS will cover a service volume from 80° S to the South Pole of the Moon and up to 125 km altitude. One bidirectional S-band link, one simultaneous Ka-band return link, and a broadcast Augmented Forward Signal will support C&PNT services. As NASA progresses toward the Foundational Exploration segment, LCRNS service will expand its service volume to 75° S and up to 200 km and include two bidirectional, simultaneous S-band and Ka-band links, as well as multiple Augmented Forward Signal links.



	ARTEMIS III			ARTEMIS IV			ARTEMIS V		
Service Type	Ka-band	S-band	Augmented Forward Signal	Ka-band	S-band	Augmented Forward Signal	Ka-band	S-band	Augmented Forward Signal and Lunar Augmented Navigation Service
Simultaneous Links	1	1	1	1	1	2,3	2	2	4
Forward Links	no	yes	yes	yes	yes	yes	yes	yes	yes
Return Links	yes	yes	n/a	yes	yes	n/a	yes	yes	n/a
Earth Day Coverage (minimum percent)	70%	70%	70%	75%	90%	70%,40%	70%	90%	40% WITH MAXIMUM GEOMETRIC DILUTION OF PRECISION < 6

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[18] https://bidenwhitehouse.archives.gov/wp-content/uploads/2024/04/Celestial-Time-Standardization-Policy.pdf

[19] https://bidenwhitehouse.archives.gov/wp-content/uploads/2024/12/Lunar-Reference-System-Policy.pdf

[20] https://www.iau.org/Iau/Iau/Publications/List-of-Resolutions.aspx *(2024 Resolutions II and III)*

[21] https://www.nasa.gov/wp-content/uploads/2024/12/acr24-lunar-reference-frames.pdf?emrc=4de7e5

Lunar Communications, Relay, and Navigation Services Evolution

Surface-to-surface communications may initially rely on legacy systems (e.g., ultra-high frequency and WiFi) during the Human Lunar Return segment. However, NASA is leveraging terrestrial standards (e.g., 3GPP/5G) to increase mobility, positioning, and system capacity by the early Foundational Exploration segment.

PNT capabilities comprise direct-with-Earth and space relay assets as providers of radionavigation sources. User-side capabilities include onboard sensors and systems that collect, process, and filter navigation data. These can include optical sensors (e.g., cameras, light detection and ranging (lidar) payloads), solar compasses, and inertial measurements units to determine specific force, angular rate, and orientation.

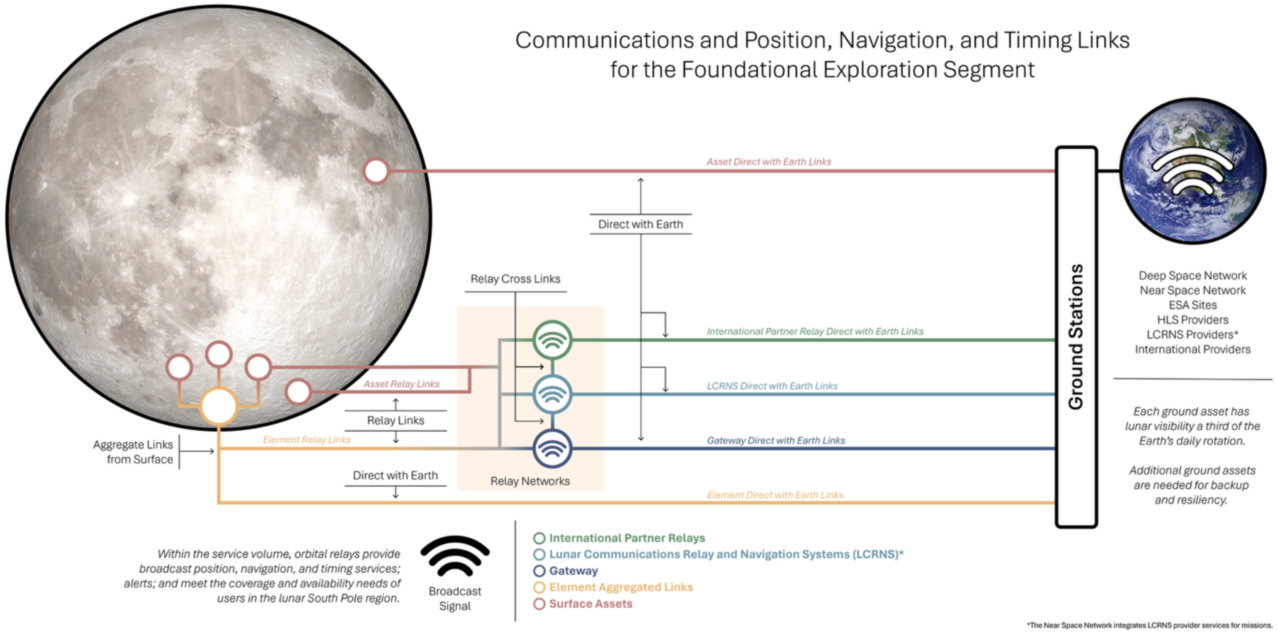
2.3.14.3.2 Foundational Exploration

Building on capabilities realized during the Human Lunar Return segment, C&PNT capabilities expand during the Foundational Exploration segment, offering greater coverage, availability, accuracy, and system capacity.

During the segment, the number of surface users and data volume increase, necessitating new and augmented C&PNT services. Additionally, the deployment of telerobotic and autonomous elements increases demand for both data transfer and navigation data.

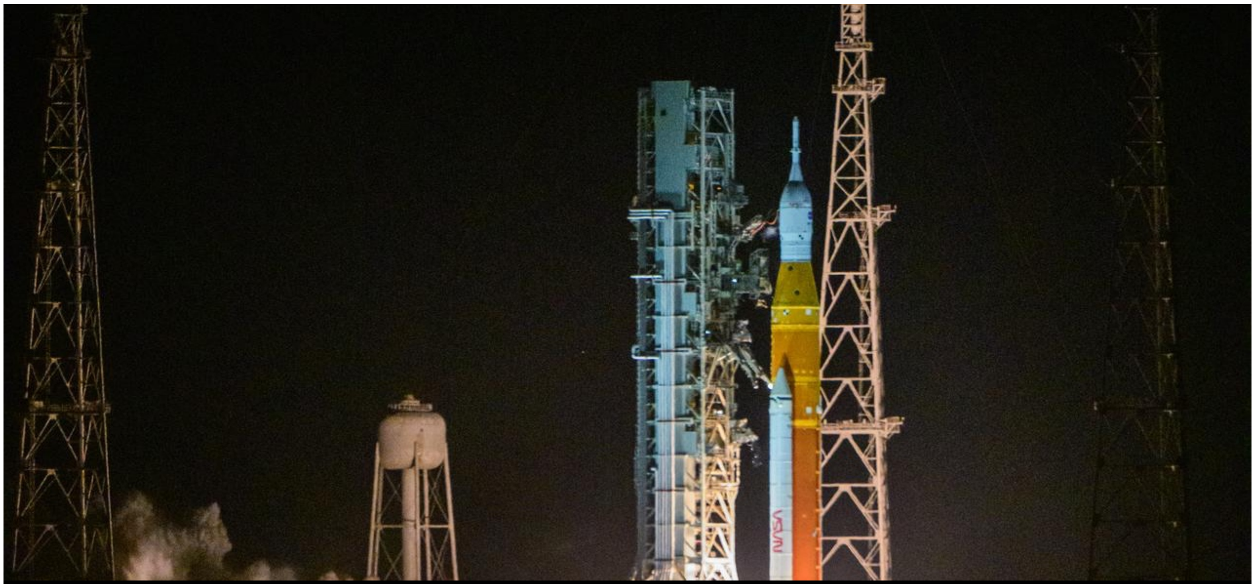
New surface wireless networking infrastructure enables direct communication between lunar surface assets and aggregation of data for backhaul transmission to Earth. Additionally, these C&PNT assets offer supplemental positioning, navigation, and timing data to surface users dependent on a synchronized network.

Through LCRNS, orbital relay capabilities grow at the lunar South Pole and to other regions of interest. Lunar relay services also improve accurate navigation and expand over the global lunar surface volume.



C&PNT Sub-Architecture for the Foundational Exploration Segment

2.3.15 Space Launch System



Element Description

The Space Launch System (SLS) is a super-heavy-lift launch vehicle that provides the foundation for human exploration beyond low Earth orbit. SLS is the only launch vehicle that can send Orion, astronauts, and payloads directly to the Moon on a single launch. It transports humans and payloads efficiently, effectively, and — most importantly — safely, enabling complex missions in cislunar space and beyond.

The SLS's evolvable design makes it possible to conduct more types of missions. This includes human missions to Mars; assembly of large structures; and robotic, scientific, and exploration missions to destinations like the Moon, Mars, Saturn, and Jupiter.

The first SLS crew transportation system, called Block 1, uses an Interim Cryogenic Propulsion Stage to send the Orion spacecraft on to the Moon. Block 1 was used for Artemis I and is planned for Artemis II and III. The Block 1B variant uses an Exploration Upper Stage to enable more advanced missions, such as carrying the Orion spacecraft along with a co-manifested large cargo payload in a single launch.

Block 1 and Block 1B Crew are the only SLS variants for the Human Lunar Return Segment. Future segments include the Block 1B Cargo, Block 2 Crew, and Block 2 Cargo variants, which add key capabilities.

Implementing Program	Functional Mappings
Space Launch System Program *Moon to Mars Program Office*	**Appendix B** *B.3.14*

Segments		Sub-Architecture	Element Icon
Human Lunar Return	Foundational Exploration	Transportation Systems	

Header Image: *NASA's Space Launch System rocket carrying the Orion spacecraft launches on the Artemis I flight test, Wednesday, Nov. 16, 2022, from Launch Complex 39B at NASA's Kennedy Space Center in Florida. (Credit: NASA)*

Architecture Definition Document – Element One Pager

2.4 Utilization Payloads and Equipment

One of the Moon to Mars Architecture's key services is the transportation, delivery, deployment, and operation of utilization payloads and equipment to cislunar space and the lunar surface, plus the return of samples and other cargo to Earth. Utilization payloads and equipment encompass any item that primarily addresses utilization objectives. Payloads include science and research payloads and technology demonstrations. Equipment includes tools, supplies, and other supporting materials.

Examples of utilization payloads include:

- Secondary payloads aboard transportation systems (e.g., SLS CubeSats)
- Externally mounted sensors on transportation and habitation systems
- Science experiments and technology demonstrations deployed on the lunar surface by crew or robotic landers
- Internally operated experiments in crew volumes
- Portable devices used to make scientific observations (e.g., cameras)
- Scientific samples and data

Several NASA organizations develop utilization payloads for the Moon to Mars Architecture, including the Space Technology Mission Directorate and the Science Mission Directorate. The Science Mission Directorate payloads are small but sophisticated measurement systems required for addressing the pure and applied science objectives. The science instruments (utilization payloads) and the geology tools and containers (utilization equipment) — and their accommodation by the larger systems of the architecture — are critical to enabling the agency's science objectives. Space Technology Mission Directorate payloads demonstrate and mature cutting-edge technologies to build new capability and capacity that support future exploration and address a wide range of Moon to Mars Objectives.

Information about planned utilization payloads can be found at the websites for those NASA mission directorates. NASA will formalize how science payloads map to Moon to Mars science objectives and point to reference locations as part of the next revision of the Architecture Definition Document.

Examples of utilization equipment include:

- Tools and containers used to collect scientific samples (e.g., geological, biological)
- Freezers for conditioning samples

Some payloads (e.g., cameras, medical equipment) are dual use, supporting both utilization and operations, depending on the context.

The functions fulfilled by payloads and equipment are captured in Appendix B.4.

Moon to Mars Architecture
Definition Document

ESDMD-001

03.

Architecture Evolution

3 Architecture Evolution

Section 2 captures the existing components of the architecture: its overall structure, segments, sub-architectures, and elements in operation or in development. However, the architecture is far from “complete” — it evolves continuously. When NASA needs to update and improve the architecture — including defining future segments, identifying new technology needs, and adding new elements — it follows the processes outlined below.

This section begins by highlighting NASA’s architecture roadmapping approach, including a high-level summary of the key definition tasks that NASA uses to shape the architecture. More information about the architecture roadmapping process, as well as the full list of completed and upcoming key definition tasks, is available in Appendix C.

Next, the section explains NASA’s approach to identifying two types of gaps in the architecture: architecture-driven technology gaps and architecture-driven data gaps.

The architecture-driven technology gap process identifies capability gaps that require new or significantly matured technologies to enable the architecture and accomplish the Moon to Mars Objectives. The full list of technology gaps is available in Appendix D.

The architecture-driven data gaps capture information and data products needed for NASA to conduct future lunar and Mars missions. The full list of architecture-driven data gaps is available in Appendix E.

This section also summarizes NASA’s element definition and pre-formulation processes for exploration elements. This process enables the agency to add new systems to the architecture (including contributions from industry and international partners) that fulfill additional use cases and functions and accomplish the Moon to Mars Objectives. Ultimately, NASA adds elements initiated through this process to the list of elements in Section 2.3.

Finally, this section assesses the architecture’s adherence to the Moon to Mars Architecture’s recurring tenets. These assessments detail existing efforts to follow these tenets and highlight additional areas for forward work as the architecture continues to evolve.

3.1 Architecture Definition

Developing an exploration architecture requires stakeholders across NASA to examine numerous individual topics via architecture definition tasks. These tasks enable the agency to examine open, undefined parts of the architecture, answer questions about the architecture, and narrow down the ***trade space*** — the range of options for exploration missions. Once complete, they enable NASA to set an architectural ground rule, make a decision, select a methodology, or otherwise shape the architecture. Definition tasks bring future exploration into focus.

Every definition task is important, but certain tasks (i.e., *"key" definition tasks*) significantly influence the end-to-end architecture and flow down to impact many other areas of the trade space. These warrant much more scrutiny to balance a variety of priorities and demands.

NASA's architecture roadmapping approach identifies and tracks key definition tasks within the Moon to Mars Architecture. It only includes definition tasks that significantly influence the architecture and/or require collaboration between multiple, cross-agency authorities to answer an agency-level question. Identifying and sequencing these key definition tasks ensures that NASA works efficiently and remains a smart buyer of capabilities and services.

This section outlines considerations for these key definition tasks and summarizes the outcomes of completed key definition tasks. Appendix C summarizes the architecture roadmapping process and captures the full lists of both completed and future architecture key definition tasks.

3.1.1 Unique Considerations by Destination

Although NASA landed humans on the Moon with Apollo, the current lunar architecture represents a significantly more complex endeavor with many unique considerations. The Moon to Mars Architecture must maintain flexibility to incrementally build functionality and achieve the Moon to Mars Objectives.

Most of NASA's human spaceflight experience has taken place in LEO; lunar concepts of operations differ significantly from LEO spaceflight. While aborts back to Earth can be initiated relatively quickly, aborts or rescue operations for missions to the lunar South Pole or NRHO are more complex and would take days (versus hours from the International Space Station).

The South Pole's unique lighting, terrain, and other environmental conditions present unique strategic planning challenges. While the South Pole is attractive from a scientific perspective (and possibly to commercial interests), the architecture will need to address these challenges with capabilities like power sharing; mobility; communications and positioning, navigation, and timing; and others.

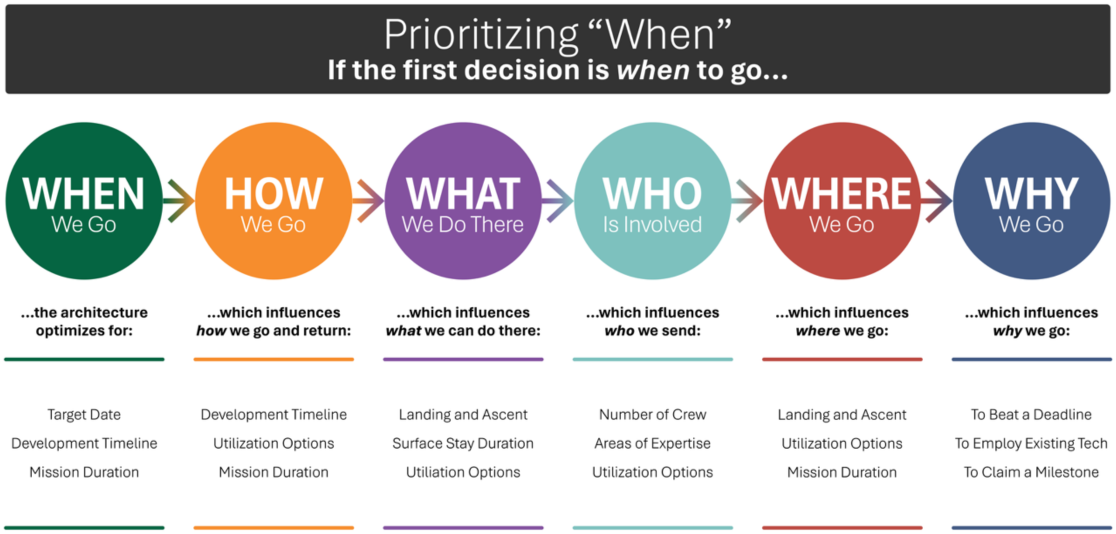
Lunar and Mars missions will also require crew members to transition between microgravity and partial gravity environments, including eventually doing so after extended durations in microgravity. Lunar astronauts will not be able to rely on the ground support that astronauts returning from the International Space Station and other LEO missions count on. Testing concepts of operations for surface exploration with deconditioned crew members on the Moon is also a crucial Mars-forward activity.

Missions to Mars represent significant increases in complexity across many dimensions, including distance traveled, communications delays, Earth-independent operations, time crew members spend in the deep space environment, and total mission duration. These challenges far exceed NASA's current LEO spaceflight experience. Lunar missions create opportunities to develop systems and concepts of operations to address some of these challenges, but Mars missions still represent an orders-of-magnitude increase in difficulty.

3.1.2 Architecture Roadmapping Approach

An exploration architecture must answer a set of guiding questions: *Where do we go? Why do we go? Where do we go? How do we get there and back? What do we do there? Who is involved?*

NASA establishes a recommended sequence for answering these architecture questions via key definition tasks in the architecture roadmapping process. The complex relationships between definition drivers and stakeholder needs influence the sequence in which the agency conducts definition tasks. The sequence also affects the remaining architecture trade space, as illustrated below. Beginning with the question of "When?" for example, creates flow-down implications and constraints for other questions:



Beginning with "Why?," however, foregrounds NASA's Moon to Mars Objectives and the agency's pillars of exploration. This flow ensures that all of the questions that follow from "Why?" address the agency's exploration objectives, rather than targeting a specific constraint, like a mission deadline:

NASA uses architecture roadmapping to identify, catalog, and sequence key definition tasks. Roadmapping ensures NASA conducts definition tasks in an effective order, prioritizing those with many flow-down impacts and minimizing re-work. This roadmapping approach also ensures NASA coordinates across internal stakeholders.

For more information about the flow of guiding questions and architecture roadmapping, refer to the "Architecture Definition" white paper.[22]

3.1.3 Summary of Key Definition Tasks

The lists below capture completed key definition tasks in limited detail. For lists of completed and open key definition tasks in full detail, refer to Appendix C.

3.1.3.1 Legacy Decisions

Lunar key definition tasks include both legacy decisions (decisions NASA made prior to the initial publication of the Architecture Definition Document) and priority key definition tasks. Legacy decisions shape many aspects of the Moon to Mars Architecture.

3.1.3.1.1 LD-01-L: Enable Human Exploration on the Surface of Planetary Bodies

NASA will send human explorers — not just robotic missions — to explore the Moon and Mars, laying the foundation for the agency's exploration ambitions and the Moon to Mars Architecture.

3.1.3.1.2 LD-02-L: Deep Space Element(s) in Microgravity for Long-duration, Crewed Exploration

To achieve long-duration crewed exploration in deep space, NASA will deploy Gateway in lunar orbit to host crew, support crewed missions to the lunar surface, conduct science, and develop deep space capabilities (habitation, propulsion, communications, operations).

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[22] https://www.nasa.gov/moontomarsarchitecture-whitepapers/

3.1.3.1.3 LD-03-L: Lunar Landing Region Selection

The lunar South Pole region will be the initial landing area for crewed missions, enabling NASA to take advantage of its unique lighting conditions and the possible presence of volatiles (e.g., ice).

3.1.3.1.4 LD-04-L: Crewed Lunar Orbit

Crewed lunar orbital operations will use NRHO, which enables continuous communications with Earth and consistent access to the lunar South Pole.

3.1.3.1.5 LD-05-L: Integrated Crewed Lunar Mission Cadence

NASA will conduct integrated (combined orbital and surface operations) crew missions on an annual cadence, maximizing exploration opportunities while meeting the production and processing needs of NASA and its partners.

3.1.3.1.6 LD-06-L: Number of Crew to Cislunar Space

NASA will send up to four crew members during an integrated mission, including both orbital and surface operations.

3.1.3.1.7 LD-07-L: Crewed Lunar Surface Stay Duration Capability

Crewed lunar surface missions will target surface durations of up to 33 consecutive Earth days for initial segments, with initial missions lasting for approximately 6 Earth days.

3.1.3.2 Completed Key Definition Tasks

3.1.3.2.1 LD-101: Lunar External Power Augmentation

The agency will pursue power augmentation trades that balance element design, aggregate power demand, total surface landed mass, mission-to-mission flexibility, and architecture robustness.

3.1.3.2.2 LD-102: Lunar Logistics Strategy

The agency will pursue a hybrid strategy for delivering required logistics to elements on the lunar surface using a variety of solutions ranging from small portable carriers to large mated carriers.

3.1.3.2.3 LD-103: Lunar Surface Communications Strategy

In 2025, the agency adopted a combination of Space-to-Space Communications Systems, WiFi 6, and 3GPP (5G) as the foundational technologies for the agency’s lunar surface communication network.

3.1.3.2.4 MD-07: Mars Primary Surface Power Generation Technology

At the 2024 Architecture Concept Review, the agency selected nuclear power technology (specifically, fission power) over non-nuclear power technology (in particular, photovoltaic arrays with energy storage) as the primary surface power generation technology for the initial human missions to Mars.

3.1.3.2.5 MD-02: Initial Human Mars Segment Target State

At the 2025 Architecture Concept Review, the agency made a down-select for the initial Humans to Mars segment target state that outlines a vision for the segment and will guide future architecture definition tasks.

3.1.3.2.6 MD-04: Mars Architecture Loss of Crew Risk Methodology

At the 2025 Architecture Concept Review, the agency selected a risk methodology that uses a combination of qualitative and quantitative risk assessment to for evaluating risk at the architecture level and enabling risk-informed decision making.

3.1.3.2.7 MD-05: Number of Crew to Mars Surface

At the 2025 Architecture Concept Review, the agency determined that initial human missions to Mars will send between four and six crew members to the Martian surface.

3.2 Architecture-Driven Technology Gaps

As NASA identifies use cases and functions for future lunar and Mars missions, it also identifies gaps between available functional capabilities and desired future capabilities. While many of these capability gaps may be closed with engineering or operational solutions, a subset of these capability gaps will require technology investment for future missions to ensure necessary performance or capabilities beyond the current state of the art. In the context of this document, these architecture-driven technology gaps are defined as areas where technology development is required to close the gap between the current state of the art and the Moon to Mars Architecture's anticipated performance or capability targets.

It is important to note that this is a narrow definition: a technology gap is not simply an area of the architecture that requires further work or the initiation of an element. If NASA can initiate a project or program to meet an architectural need using existing technology, then that area is not a technology gap. Architecture-driven technology gaps require entirely new technologies or significant performance advancement in existing technologies to establish a capability needed to achieve the Moon to Mars Objectives.

Detailed information about the architecture-driven technology gaps may be found in the associated white paper published in 2024.[23] Appendix D captures the full list of architecture-driven technology gaps, including their priority order based on the prioritization formula in Section 3.2.2. This list will evolve as gaps close and NASA identifies new gaps.

3.2.1 Technology Gap Identification

NASA identifies technology gaps by assessing architecture documentation, including use cases and functions decomposed from NASA's exploration objectives, key architecture definition tasks, and historical data. Engineers compare the state of the art for a technology with the notional architecture performance targets to identify architecture-driven technology gaps.

Each architecture-driven technology gap includes a gap title, gap description, architecture impact and benefits, target performance metrics, and current state-of-the art metrics. Input from the architecture teams ensures the gap data is fully aligned with the current state of the architecture.

The architecture-driven technology gaps are designed to be solution-agnostic, focusing on a documented capability need, not a specific technology solution to achieve the capability. Appendix D lists the set of architecture-driven technology gaps and contains descriptive data about each gap and its relationships to the architecture (e.g., segments in which the gap is needed, use cases and functions it addresses, and relevant key definition tasks and sub-architectures).

3.2.2 Technology Gap Prioritization

To inform technology investment strategies and investments both internally and externally to NASA, the architecture-driven technology gaps follow a priority order. Four priority metrics — gap attributes that capture an aspect of architecture preference and can be evaluated for every gap — drive this order: criticality, urgency, breadth, and depth.

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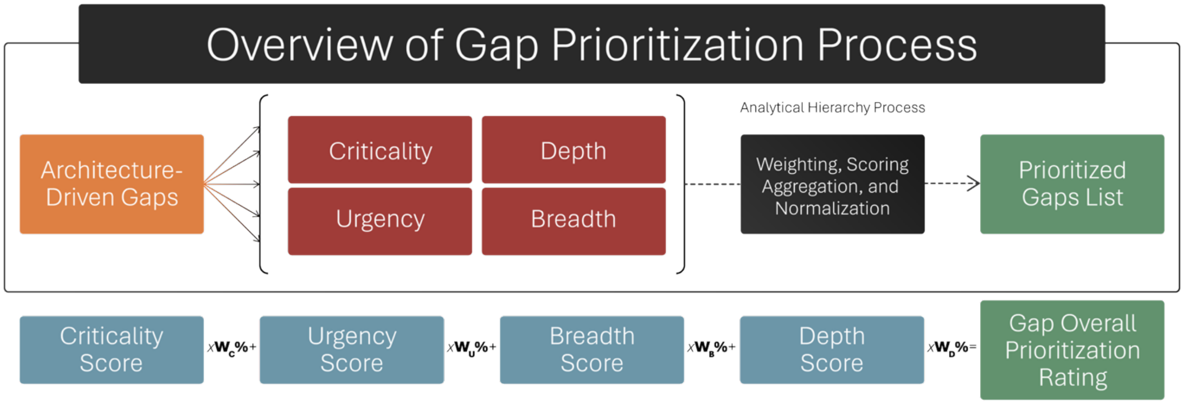
[23] https://www.nasa.gov/wp-content/uploads/2024/12/acr24-architecture-technology-gaps.pdf?emrc=363045

Criticality: measures the degree to which closing the technology gap would enable or enhance the Moon to Mars Architecture. This metric was scored based upon architecture trade studies and alignment with the use case and function decomposition.

Urgency: measures how soon investment in a technology gap is needed to ensure the capability is available for future missions. This metric was scored by comparing gap closure timelines with the estimated technology development timelines to capture long-lead developments.

Breadth: measures the prevalence of a technology gap's applicability across sub-architectures. Technology gaps were mapped to sub-architectures, and gaps that address cross-cutting capabilities scored higher relative to single-application gaps.

Depth: measures the degree to which closing the gap is dependent on future architecture key definition tasks. Gaps were scored based upon mapping to definition tasks, along with an assessment of how much those tasks affect the need for the gap's closure.



Architecture-Driven Technology Gap Prioritization and Weighting Formula

The four priority metrics are weighted and combined to determine an overall prioritization rating. The relative weightings were determined through comparison of each metric's importance to the Moon to Mars Architecture. Architecture teams weighted the metrics in the following descending order: criticality, urgency, breadth, and depth. The resulting prioritized list is included in Appendix D.2. Note that implementation-specific metrics, such as cost, are not considered in the gap prioritization process because they are not tied to an architectural demand signal for the capability.

Technology gaps' overall prioritization rating fall into distinct groupings of preference, referred to as priority bins, which are included in both Appendices D.2 and D.3. Note that all gaps, even those in the lowest priority bin, are highly architecture driven.

The architecture-driven technology gaps and priorities are useful for two main reasons. First, the prioritized list of gaps can be used to inform technology investment strategies that align with the Moon to Mars Architecture needs. This data is expected to inform and help NASA technology development organizations, ESDMD programs, industry, interagency groups, international partners, and academia plan investments. Second, this demand signal provides focus for the architecture teams to engage with technology developers on technology options based upon their potential benefits, schedule drivers, and risk reduction relative to the gaps.

Note: *The prioritized list of gaps is not encompassing of all research and development necessary to prepare for future exploration and does not attempt to capture all outstanding risk. The demand signal is focused only on those capabilities most enabling for the Moon to Mars Architecture, which matures and evolves.*

3.2.3 Technology Gap Evolution

The current list of gaps and gap priorities represents a snapshot in time and will be updated annually as part of the strategic analysis cycle as the Moon to Mars Architecture matures and technology advances. As later segments are better defined, existing technology gaps may be re-prioritized and new architecture-driven technology gaps may be identified.

The focus on architecture-driven technology gaps in this document excludes risks already being tracked or addressed by current programs but can include related technology gaps requiring additional advancement for future segments. The Human Lunar Return Segment contains technology development and investment by the current programs, so the technology gaps captured in this document do not trace to Human Lunar Return. Instead, the gaps map to the other three segments: Foundational Exploration, Sustained Lunar Evolution, and Humans to Mars.

The addition of architecture-driven data gaps (Section 3.3) creates an opportunity to more accurately express both the technology needs and data needs of the Moon to Mars Architecture. Data gaps are a counterpart of technology gaps that communicate the need for information, rather than technology development. Technology gaps may transition to data gaps and vice versa as the architecture's needs evolve and technology development advances. NASA re-evaluates this relationship annually as part of the strategic analysis cycle.

3.3 Architecture-Driven Data Gaps

3.3.1 Introduction

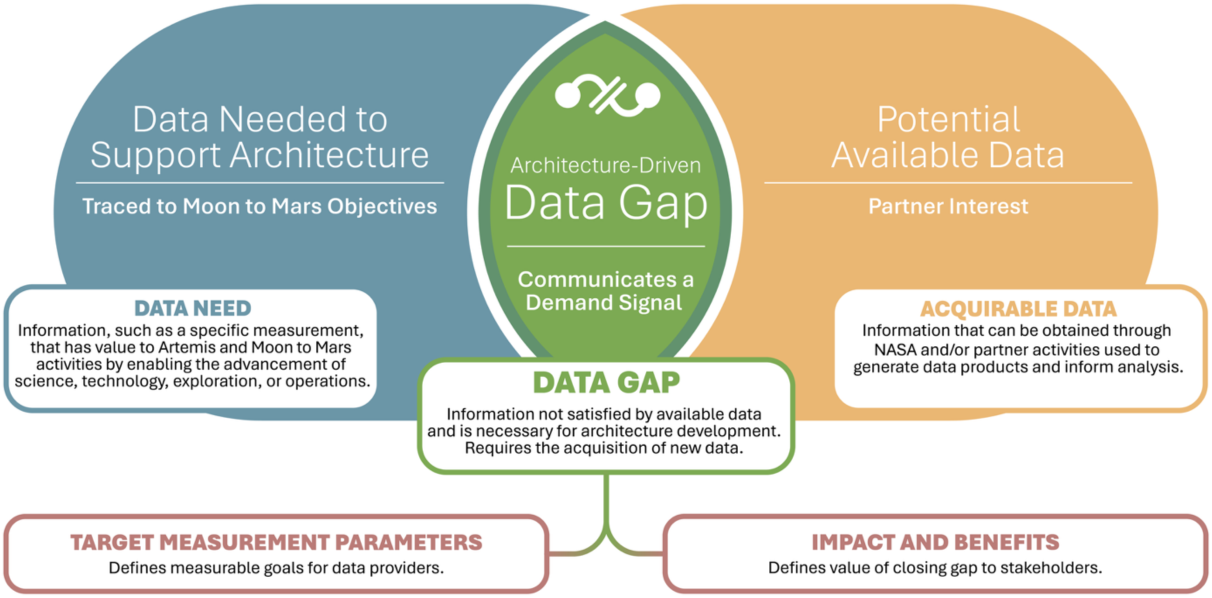
In developing the Moon to Mars Architecture, NASA draws from a range of information to conduct analyses and make decisions throughout the mission design and execution life cycle. In planning for future missions, NASA often identifies data that would better enable the development and/or execution of future missions and may or may not be met by existing information. NASA defines this information as a **data need**: data that, if obtained, would enhance or enable advancement of science, technology, exploration and/or operations to support the development of the Moon to Mars Architecture.

Data needs are not an entirely new concept. Historically, working groups and chartered teams have documented and tracked the types of data that the agency should be interested in acquiring.

NASA identifies a subset of these data needs as **architecture-driven data gaps**: data the agency needs to advance the Moon to Mars Architecture but that is not met by any existing information. Data gaps communicate a demand signal for information that could be provided by NASA or external partner activities/missions.

The identification of data gaps does not diminish the utility of existing data already collected by NASA and partners, which plays a vital role in the development of the architecture. In many cases, NASA already has existing data sources, many of which are high-resolution and represent the state of the art in global science about the Moon and Mars. Data gaps express a desire to build upon NASA's current understanding on the lunar and Martian environments in areas that have major impacts on exploration activities.

The figures below illustrate the interconnectivity between agency data needs and architecture-driven data gaps.



DATA NEED
Information, such as a specific measurement, that has value to Artemis and Moon to Mars activities by enabling the advancement of science, technology, exploration, or operations.

ACQUIRABLE DATA
Information that can be obtained through NASA and/or partner activities used to generate data products and inform analysis.

DATA GAP
Information not satisfied by available data and is necessary for architecture development. Requires the acquisition of new data.

TARGET MEASUREMENT PARAMETERS
Defines measurable goals for data providers.

IMPACT AND BENEFITS
Defines value of closing gap to stakeholders.

Defining Architecture-Driven Data Gaps

Architecture-driven data gaps define the driving need, what data is needed, and why the data is valuable. These clear and measurable criteria enable stakeholders to provide NASA with valuable data and helps decision-makers at NASA acquire the right data. Data gaps do not set requirements; they provide guidance to potential data providers on the data qualities that NASA values most. In most cases, even partially addressing the defined data gap is valuable to the architecture.

Architecture-driven data gaps inform ongoing engagement between NASA, other governmental agencies, industry, academia, and international partners about data that NASA is interested in acquiring. This demand signal helps partners align their activities and investments with the Moon to Mars Architecture's needs.

Addressing data gaps better positions NASA to achieve the Moon to Mars Objectives. Impacts and benefits of closing data gaps include informing human exploration mission operations, element design, and the understanding of crew risk; supporting technology or system maturation efforts; enabling NASA to assess expected architecture performance; or guiding observation and science needs.

3.3.2 Methodology

With this definition established, NASA identifies and characterizes architecture-driven data gaps based on input from across the agency and stakeholders. A standardized template is used to communicate the key aspects of a data gap. The data gaps span all architecture segments. The data gaps capture both the current state of relevant data and the implications for the architecture if NASA does not satisfy the data need.

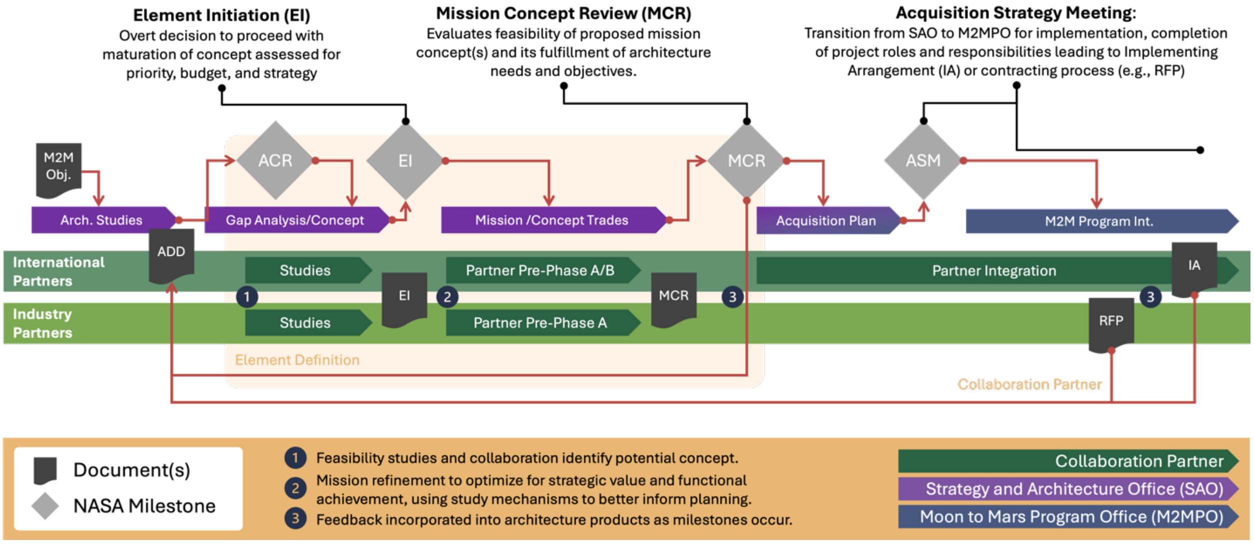
Appendix E captures this year's architecture-driven data gaps list. The list will evolve as gaps close and NASA identifies new gaps. The current list of data gaps represents a snapshot in time. Future revisions of this document will update the list. The current list is an initial representative sample — it is neither comprehensive nor complete. While the current data gaps are not listed in priority order, they all represent near-term, high-priority needs.

3.4 Element Definition and Pre-Formulation

When adding new exploration systems to fill architecture gaps, NASA follows a pre-formulation methodology that defines new elements and incorporates partnerships with industry and international space agencies. This begins with the objective decomposition, where NASA maps exploration assets to needed capabilities and identifies capability gaps. From there, NASA and partner teams analyze these gaps, performing trade studies and developing preliminary concepts that might close them.

As concepts mature through the pre-formulation process, teams develop element concepts into potential programs or projects for implementation. NASA leadership reviews these concepts at agency-defined decision gates. Opportunities for input from industry and international partners exist throughout this process.

At element initiation reviews, NASA approves element concepts for further maturation and feasibility studies. After matured elements are approved at subsequent Mission Concept Reviews, NASA adds the elements into the next revision of the Architecture Definition Document. For concepts developed with international space agencies, NASA adds element partnership information to the document after the U.S. and partner nation formally establish an appropriate international agreement.



Note that the Architecture Definition Document only includes elements that the agency has formally adopted into the architecture. It is a technical document that reflects the approved baseline for programs of record, contracts, partnerships, and funding. The agency avoids premature addition of element concepts to preserve opportunities for innovation, technology enhancements, and partnerships.

Once the concept is sufficiently mature and includes a strategy for acquisition, NASA transitions the element from the Strategy and Architecture Office to the Moon to Mars Program Office for implementation. For a more detailed explanation of the pre-formulation process, visit the Moon to Mars Architecture website.[24]

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[24] www.nasa.gov/architecture

3.5 Recurring Tenet Assessments

In the Moon to Mars Objectives, NASA established a high-level set of recurring tenets to guide the exploration architecture. These tenets embody common themes that are broadly applicable across all the objectives. They provide guidance related to how objectives should be pursued to ensure successful execution of the Moon to Mars endeavor.

RT-1: **International Collaboration**	Partner with international community to achieve common goals and objectives.
RT-2: **Industry Collaboration**	Partner with U.S. industry to achieve common goals and objectives.
RT-3: **Crew Return**	Return crews safely to Earth while mitigating adverse impacts to crew health.
RT-4: **Crew Time**	Maximize crew time available for science and engineering activities within planned mission durations.
RT-5: **Maintainability And Reuse**	When practical, design systems for maintainability, reuse, and/or recycling to support the long-term sustainability of operations and increase Earth independence.
RT-6: **Responsible Use**	Conduct all activities for the exploration and use of outer space for peaceful purposes consistent with international obligations, and principles for responsible behavior in space.
RT-7: **Interoperability**	Enable interoperability and commonality (technical, operations and process standards) among systems, elements, and crews throughout the campaign.
RT-8: **Leverage Low-Earth Orbit**	Leverage infrastructure in low-Earth orbit to support Moon to Mars activities.
RT-9: **Commerce and Space Development**	Foster the expansion of the economic sphere beyond Earth orbit to support U.S. industry and innovation.

Note: *Recurring tenets have implications across all Moon to Mars Objectives. The ordering of recurring tenets does not imply prioritization.*

As NASA develops the architecture, it periodically assesses its adherence to the recurring tenets, evaluating how the current architecture reflects these guiding principles. The assessments are not exhaustive; future revisions will continue to update, evaluate, and assess the architecture's progress and adherence to the tenets.

3.5.1 RT-1: International Collaboration

RT-1: Partner with international community to achieve common goals and objectives.

3.5.1.1 Architecture Assessments

International partnerships are an integral part of the Moon to Mars Architecture. These partnerships help drive human and scientific exploration by leveraging additional resources, advancing mutual interests, and promoting the use of outer space for peaceful purposes. Coordination and cooperation among established and emerging actors in space are foundational principles of the Artemis program.

The Moon to Mars Architecture includes international capabilities and outlines opportunities for additional partnerships to address architecture gaps. NASA and potential partners work together to identify specific technical concepts that address architecture needs. Once a proposed technical capability reaches a sufficient level of maturity and has passed internal NASA reviews, NASA and its partners can formalize the cooperation in an international agreement.

NASA has already established significant international cooperative activities, including the following:

- **European Service Module (ESM):** The European Space Agency (ESA) provides the ESMs, which power the Orion spacecraft for Artemis lunar missions.
- **Gateway:** ESA, the Japan Aerospace Exploration Agency (JAXA), the Canadian Space Agency (CSA), and the Mohammed Bin Rashid Space Centre (MBRSC) in the United Arab Emirates are providing key elements for operating this cislunar outpost.
- **Pressurized Rover:** Japan will provide a pressurized crew rover for the lunar surface that will provide advanced astronaut mobility and science opportunities for Artemis crewed missions to the lunar surface.
- **Additional capabilities:** NASA is conducting joint technical studies with partners including ESA, JAXA, CSA, the Italian Space Agency (ASI), the French Space Agency (CNES), the Australian Space Agency (ASA), the Korean AeroSpace Administration (KASA), the Luxembourg Space Agency (LSA), and MBRSC to develop concepts in support of the Moon to Mars architecture, such as rovers, cargo delivery to the lunar surface, habitation, and lunar communications.
- **Artemis I:** Several international partners provided research payloads to address key knowledge gaps for deep space exploration, including ESA, the German Aerospace Center (DLR), and the Israel Space

Agency (ISA), each of which provided radiation experiments; and JAXA and ASI, which provided CubeSats.

- **Artemis II:** Artemis II will include a Canadian astronaut. Several international partners will provide payloads, including CubeSats from Argentina's Comisión Nacional de Actividades Espaciales (CONAE), DLR, the Saudi Space Agency (SSA), and KASA. DLR will also provide radiation sensors on the Orion vehicle and conduct analysis of biological samples collected in-flight.

- **Lunar science:** NASA is sponsoring CLPS deliveries for payloads from ESA, CSA, CNES, the Korean Astronomy and Space Science Institute (KASI), and the University of Bern, Switzerland. Additionally, international partners will have opportunities to submit proposals to Artemis science solicitations. Through these annual deployed instrument calls, NASA selects scientific payloads to be deployed on the lunar surface by the crew. For example, NASA selected a dielectric analyzer from the University of Tokyo and JAXA for Artemis III. NASA partnered with the UK Space Agency for their instrument contribution to the Lunar Trailblazer mission launched in early 2025.

- **Payload and Research Investigations from the Surface of the Moon (PRISM):** International partners are also joining U.S.-led proposals to PRISM solicitations. CNES is participating in the U.S.-led far-side seismic payload and an electromagnetics experiment. Additionally, university partners from Denmark, Switzerland, and the United Kingdom are participating in U.S.-led lunar surface payloads selected under PRISM.

- **NASA contributions to international-led science missions:** NASA's Science Mission Directorate is also partnering on international partner-led missions to achieve science, exploration, and technology development goals and priorities for the Moon. NASA's contributions include a laser retroreflector on JAXA's Smart Lander for Investigating Moon (SLIM) mission, an infrared imager on CSA's Lunar Exploration Accelerator Program (LEAP) rover, a laser retroreflector on the Indian Space Research Organisation's (ISRO) Chandrayaan-3 mission, and a neutron spectrometer on JAXA's Lunar Polar Exploration (LuPEX) rover launching on ISRO's Chandrayaan-5 lander. NASA operates the ShadowCam, a camera that scans shadowed areas for ice deposits and landing zones, on the Korea Pathfinder Lunar Orbiter (KPLO) launched in 2022.

- **Space life sciences and human research**: NASA discusses cooperative space and life sciences research activities with international partners in the International Space Life Sciences Working Group (ISLSWG). The Gateway Program also established working groups to coordinate human health and biological sciences utilization.

- **Mars science**: NASA partners on and contributes to international Mars science missions. NASA and ESA are partnering to bring the first samples of Mars material back to Earth. The Mars Perseverance rover, currently exploring the Jezero Crater, is collecting scientifically selected samples of Mars material for later return. NASA has been partnering with ESA in planning the Mars Sample Return program as a means for bringing these samples to Earth for more extensive study. NASA is also providing a suite of contributions on the ESA-led Rosalind Franklin Mission, which is the first astrobiology mission to explore potential biosignatures in the Mars rock record. International partners have also contributed to NASA-led Mars orbiters, landers, and rovers. Additionally, JAXA's MMX will survey Mars' two moons Phobos and Deimos and return samples of regolith from Phobos to Earth. NASA is providing two of 13 instruments: NASA's Mars-moon Exploration with GAmma rays and

NEutrons (MEGANE) instrument and the Pneumatic Sampler Mechanism to sample regolith from Phobos.

- **Space communications and positioning, navigation, and timing**: NASA is engaged in discussions with several space agencies regarding potential Artemis cooperation involving ground stations, lunar relays, navigation assets, and lunar surface communications elements. NASA is coordinating its commercial lunar relay procurement in parallel with a similar ESA activity called Moonlight. NASA is collaborating with other U.S. government departments and agencies to define reference systems and time standards through international standards bodies. The International Committee on GNSS's newly formed Lunar PNT Working Group provides a forum for discussing, assessing, and recommending guidance for compatibility, interoperability, and availability among lunar PNT systems. NASA and ESA also collaborate on the ongoing operations of the Mars Relay Network, and co-chair of the International Mars Relay Coordination Working Group, which coordinates longer-term planning for utilization and evolution of the Mars Relay Network. Additionally, NASA has a study agreement with JAXA related to development of a lunar navigation satellite system. NASA also participates in the Space Frequency Coordination Group, which coordinates space spectrum resources among its over 30 member states.

- **Technology:** International space technology partnerships generally focus on low technology readiness levels and fundamental research, the results of which are then shared publicly. For example, NASA is collaborating with ASA on lunar regolith and rocket plume surface interaction in support of scientific and exploration objectives.

- **Public diplomacy/education:** NASA conducts public diplomacy and international outreach for Artemis missions, including engagements in multiple languages for a global audience.

3.5.1.2 Future Considerations

As the architecture evolves, NASA identifies capability gaps and pursues partnerships to close those gaps and achieve the Moon to Mars Objectives. NASA hosts, sponsors, or participates in a variety of multilateral forums to discuss exploration objectives and identify areas for cooperation, including those listed below. These engagements will be crucial for developing future international partnerships.

- NASA hosts annual architecture workshops to provide international partners with updates to the latest Architecture Definition Document and gather stakeholder feedback on how partnerships can help NASA achieve its Moon to Mars Objectives.

- NASA participates in the International Space Exploration Coordination Group, a forum for space agencies to share their objectives and plans for exploration.

- NASA established the Lunar Surface Innovation Consortium to foster communication and potential collaborations among industry, academia, government, and international partners on technologies to enable sustained human and robotic presence on the lunar surface.

- NASA established the Lunar Exploration Analysis Group to provide analysis of scientific, technical, commercial, and operational issues in support of lunar exploration objectives, lunar architecture planning, and activity prioritization.

- The Mars Exploration Program Analysis Group serves as a community-based, interdisciplinary forum for inquiry and analysis to support NASA's Mars exploration objectives. The group is responsible for providing the science input needed to plan and prioritize Mars exploration activities.
- NASA established the Solar System Exploration Research Virtual Institute to bring together domestic researchers and international partners to address fundamental questions about human and robotic exploration of the Moon, near-Earth asteroids, the Martian moons Phobos and Deimos, and the near space environments of these target bodies.
- NASA participates and serves as the executive secretariat for the International Mars Exploration Working Group, which is a coalition of space agencies and institutions around the world that seeks to advance our collective human and robotic future on Mars.
- The International Space Life Sciences Working Group is a forum to coordinate international development and use of spaceflight and special ground research facilities to enhance Moon to Mars Objectives pertaining to space life sciences.
- The Interagency Operations Advisory Group provides a forum for identifying common needs and opportunities for interoperability in mission operations, space communications, and navigation interoperability. The Consultative Committee on Space Data Standards communicates detailed interoperability needs for space communications to the Interagency Operations Working Group, which implements the detailed standards to meet the identified needs.
- NASA participates in the Committee on Space Research Panel on Planetary Protection to ensure that exploration of the Moon and Mars does not result in harmful contamination, of those bodies and that sample return from Mars does not result in adverse changes in the environment of Earth.
- NASA also participates in the Space Frequency Coordination Group, which coordinates global space system spectrum resources between member agencies and states. The group develops technical recommendations to advise stakeholders like the International Telecommunications Union on frequency sharing and utilization in the vicinity of the Moon and Mars.
- NASA and the Department of State engage with the community of Artemis Accords signatories to ensure safe and sustainable space exploration.

3.5.2 RT-2: Industry Collaboration

RT-2: Partner with U.S. industry to achieve common goals and objectives.

3.5.2.1 Architecture Assessments

Industry collaborations are an essential part of the Moon to Mars Architecture. Existing elements and programs already draw on the U.S. industrial base; this integration only grows as the architecture advances.

The elements in the Human Lunar Return segment already leverage commercial partnerships. The EVA and Human Surface Mobility Program (EHP), Gateway, and HLS programs are working with multiple U.S. companies to design, deliver, and/or provide services for critical systems for Artemis. The Moon to Mars Program also holds continual strategic engagements with its partners and suppliers to emphasize the collaborative nature of industry partnerships and ensure critical areas of workforce capabilities, hardware priorities, and overall design, development, testing, and evaluation progress align with mission priorities and schedules.

Historically, NASA has partnered with industry to develop new capabilities and technology. NASA's Space Technology Mission Directorate is collaborating with industry to improve our ability to explore the lunar surface, including habitation, navigation, mobility, power, communication, and in-situ manufacturing. These technologies will enable safer, longer, and more diverse missions.

Through the CLPS Program, NASA has engaged U.S. industry in a new way, pairing members of academia that wish to perform standalone cislunar science missions and corporations that desire to test hardware in the lunar environment with suppliers of multiple launch vehicles and lunar landers. CLPS provides a cost-effective means of transporting a wide variety of payloads with different goals and physical attributes to the cislunar environment or lunar surface.

Future segments will continue to grow these partnerships, with an emphasis on Mars-forward technology development. The Moon to Mars Architecture depends on American industry to provide exploration services and critical technologies in an affordable manner.

3.5.2.2 Future Considerations

Many more opportunities for industry collaboration remain. As commercial LEO destinations come online, NASA should investigate opportunities to use those platforms to advance the state of knowledge around human spaceflight in support of Moon to Mars exploration.

NASA will also partner with industry on lunar commercialization and identify opportunities for industry to support Mars exploration. Potential future areas of industry collaboration include the following:

- Team with industry to develop, verify, and validate new technologies for future missions.
- Partner with industry to mature current technologies, reducing cost and risk.
- Identify how commercial activities could contribute to enabling permanent presence on the moon and future exploration of Mars.
- Involve industry in the development and refinement of future technology/system standards, including for robotic interfaces; software information and management systems; rover systems; in-space servicing, assembly, and manufacturing (ISAM); power systems; and habitation systems.
- Request that industry develop concepts for exploration services. These services could include end-to-end management of pressurized logistics, beginning with loading on Earth and ending with the disposal or reuse of containers and provision of uncrewed transportation capabilities for surface assets. Further, services such as power augmentation and distribution and providing mission consumables and products from in-situ resources to sustain assets or enhanced cargo return will contribute greatly to achieving agency objectives.
- Encourage industry collaboration in specific areas (e.g., ground and space-based communication and PNT, infrastructure, imagery, power generation/distribution, logistics supply and handling, autonomous robotic operations, sample preservation and return, compatible/interchangeable components) through technology demonstration and communication of long-term strategic goals.

3.5.3 RT-3: Crew Return

RT-3: Return crew safely to Earth while mitigating adverse impact to crew health.

3.5.3.1 Architecture Assessments

The wellbeing and safe return of astronauts are of the utmost importance. Considerations for safe crew return start well before the mission and are integrated into system design, test and verification, and end-to-end mission testing and training. The Moon to Mars Architecture adheres to top-level NASA standards to ensure safe crew return:

- NPR 8705.2 Human-Rating Requirements for Space Systems
- NASA-STD-8719.29 NASA Technical Requirements for Human-Rating
- HEOMD-003 Crewed Deep Space Systems Human Rating Certification Requirements and Standards for NASA Missions
- NASA-STD-3001 NASA Space Flight Human-System Standard (Volume 1 and 2)

For each crew mission, integrated system capabilities are subject to NASA's human rating certification criteria, including human rating technical requirements, applicable technical authority design, construction, testing, human system and safety standards, and derived loss of crew/loss of mission requirements. A human-rated system accommodates human needs, effectively utilizes human capabilities, controls hazards with sufficient certainty to be considered safe for human operations, and provides, to the maximum extent practical, the capability to safely recover the crew from hazardous situations.

In addition to the established risk structure that has an existing process for program/mission risk assessments, an additional process that supports architecture decisions and definition has been proposed, contributing to safe crew return.

Crew safety includes multiple layers: hazard controls (and control redundancy) prevent hazards; crew survival methods ensure the crew can return to Earth if a hazard does occur. The architecture derives contingency and abort use cases and functions based on the human rating standard. The results fall into two broad categories: architecture/system capabilities and integrated mission operations:

Architecture/system capabilities provide:

- Failure tolerance to catastrophic hazards (e.g., similar/dissimilar redundancy, reliability, functional down-moding, etc.)
- Medical systems, emergency systems, and crew survival capabilities
- Crew manual control (of vehicle dynamics and systems) and manual override (of software/automation) to prevent a catastrophic hazard
- Crew control of any uncrewed vehicle in the vicinity of the crewed vehicle
- Abort of a mission phase and safe return of the crew
- Crew/vehicle autonomy to return without Earth communication
- Vehicle operation and crew protection at vacuum
- Return of an incapacitated crew to Earth

Integrated mission operations provide:

- A strategy to minimize crew risk and/or the exposure duration during first-time operations or high-risk activities (including, e.g., pre-cursor uncrewed demonstrations and an incremental approach to build up capability)
- Clear mission authority, roles, and responsibilities
- Execution of launch commit criteria and go/no-go flight rules prior to critical events
- Ability to monitor, command, and control vehicles and assist the crew from Earth or another remote location
- Operational constraints to ensure safe crew return in the event of a failure (e.g., EVA and rover range/time limits to return crew within suit consumables)
- Crew supporting critical activities, including rendezvous, proximity operations, docking, and undocking (RPODU); landing, ascent, and EVA; emergency response; rover operations; etc.
- Contingency capabilities (e.g., mission phase termination, catastrophic/critical system failure responses)
- Use of abort and crew survival methods (e.g., safe haven, pressure suits)
- Use of safe modes to preserve crew and vehicle, with documented objectives, triggers, transitions, constraints, allowed crew actions, and recovery timelines.
- Crew training and onboard products for crew to execute all nominal, contingency, and emergency operations with or without Earth communication
- In-flight assessments of crew health and readiness to support activities between crew and ground medical team

The following are mission-specific examples of the architecture/system capabilities and integrated mission operations to safely return the crew to Earth:

- An uncrewed initial lunar mission (Artemis I) demonstrated launch and reentry systems prior to crewed flight
- A crewed initial lunar mission (Artemis II) will demonstrate life support and habitability in the lunar vicinity while minimizing return risk via a free-return trajectory
- A crewed initial lunar surface mission (Artemis III) will demonstrate complex operations, including transferring crew across vehicles and conducting an initial lunar landing and EVA, as a precursor to increasingly complex lunar surface missions
- Crewed Gateway and lunar surface missions will demonstrate crewed and uncrewed mission capabilities in lunar orbit and on the lunar surface
- Future crewed missions will demonstrate landing all crew on the lunar surface, leaving the crew return vehicle (e.g., Gateway, Orion) unoccupied

3.5.3.2 Future Considerations

The Moon to Mars Architecture treats the safety of the crew as an utmost concern. However, significant knowledge gaps about the adverse effects of long-term exposure to the deep space environment remain.

The architecture draws on significant operational heritage and human health research aboard the International Space Station. Long-duration Mars precursor missions conducted in cislunar space and on the lunar surface will address some knowledge gaps and build operational experience. Likewise, lunar missions will build on knowledge about reliability gaps with mission hardware, software, and operations from LEO missions.

However, these missions may not be sufficient to provide the necessary data to fully understand the risk associated with roundtrip missions to Mars. Furthermore, while the assets around cislunar space provide crew with safe haven and Earth-return capabilities, such capabilities may not exist for Mars crews.

If problems arise in LEO, the crew can return to Earth within hours; for lunar missions, crew return will take days. However, crew return during the Mars campaign may take months, since orbital dynamics make abort or contingency crew return extremely challenging; a mid-mission abort may not significantly shorten the return duration. The missions will require higher levels of system reliability, system redundancy, vehicle/crew autonomy, critical sparing and in-flight crew maintenance, abort and crew survival options, crew health/performance/psychological support, and general robustness than previous missions. The fault tolerance approach described above is applicable to lunar missions but may need to be reassessed for Mars missions.

The following challenges represent gaps in crew return capabilities. Some are gaps in the knowledge, experience, and technology required to advance, test, and implement more complex lunar and Mars missions. They cannot be solved through architecture alone; they require experience in increasingly complex operations.

- Mars missions will need to operate with more independence from Earth to account for communications latency and time-to-effect events
- In the event of an unrecoverable loss of communication with Earth during lunar and Mars missions, onboard autonomy should provide a safe crew return, including vehicle capabilities and full resources for the crew to perform their own mission planning, skills training, return trajectory execution, psychological support, and more, potentially for an extended amount of time
- To enable safe crew return and survival capabilities in the event of long-duration loss of communications, including required onboard planning capabilities, trajectory execution, and medical support, requirements should include validated onboard autonomy and crew procedures
- Mars crews will need to be able to monitor, command, and control any uncrewed vehicle in the Mars vicinity to ensure their safe return
- Mars missions will require robust crew survival methods, which may include safe havens, additional resources, rescue systems/vehicles, and more
- Mars missions will require advanced health and performance monitoring and response, both onboard and on the ground
- Multi-year missions will require high-bandwidth telecom capabilities to upload video learning or instructional materials to guide medical procedures or critical equipment repairs

3.5.4 RT-4: Crew Time

RT-4: Maximize crew time available for science, research, and technology development activities within planned mission duration.

3.5.4.1 Architecture Assessments

Maximizing crew time for utilization, separate from other allocations, such as maintenance, is a critical driver for the Moon to Mars Architecture across all segments of the campaign. This enables the architecture to address science, one of NASA's three pillars of exploration.

The lunar campaign segments emphasize crew exploration on the lunar surface. The architecture allocates functions in these segments to minimize maintenance and construction overhead activities. Concurrently, utilization activities at Gateway complement surface exploration activities.

NASA's experiences optimizing crew time at the Moon will guide the planning for initial Mars surface missions. During these missions, it will be especially important to maximize the crew time available for science and engineering activities.

Like RT-3, this approach uses two broad categories: architecture capabilities/system and integrated mission operations:

Architecture/system capabilities:

- Lunar campaign elements have limited time allocated for system maintenance, implemented via system reliability, sparing strategy, crew accessibility, ease of use, operational use, and other methods
- The design and development process integrates engineering, operations, and crew evaluations of vehicle mockups and simulations to enable reliable and efficient operations
- Campaign elements incorporate automation/autonomy for routine housekeeping and system management, with explicit allocation of FM functions (onboard autonomy, ground, crew) and documented time-to-criticality requirements

Integrated mission operations:

- Artemis crew training and integrated full-team Artemis mission simulations (with full team) commence approximately two years and one year before the crew launch, respectively, allowing sufficient time to train critical skills across all vehicles and utilization tasks
- The Artemis training philosophy includes the crew and ground teams in mission planning, decision-making, and execution of critical and complex tasks; ground training applies a time multiplier for every hour of critical/complex mission execution to ensure efficient use of crew time
- For lunar exploration, distribution of system (monitor/control) functions from crew to the MCC enables more crew time for exploration and mission objectives. For Mars exploration, distribution of time critical system responses to essentially co-located assets (e.g., surface autonomy/crew or crew remaining on transit vehicle) and non-time critical responses to MCC enables more surface crew time for exploration and mission objectives.

- The architecture uses tele-robotics, robotic assistance, and autonomous systems to increase crew time and effectiveness for science and utilization (e.g., pre-positioning assets with uncrewed operations)
- Missions include contingency plans and capabilities, including backup crew
- Task lists and alternate plans enable mission teams to efficiently pivot from the nominal plan and optimize the mission results (e.g., reprioritizing on the fly and pursuing get-ahead tasks)

3.5.4.2 Future Considerations

While the increases in exploration infrastructure and capabilities in the Foundational Exploration, Sustained Lunar Evolution, and Humans to Mars segments are intended to increase available crew time, there is some uncertainty associated with the operational complexity, maintenance, and refurbishment demands they bring. NASA will need to further assess the relationship between expanded capabilities and crew time to utilization to inform system design and operational planning.

3.5.5 RT-5: Maintainability and Reuse

RT-5: When practical, design systems for maintainability, reuse, and/or recycling to support the long-term sustainability of operations and increase Earth independence.

3.5.5.1 Architecture Assessments

The Moon to Mars Architecture must incorporate system maintainability, reuse, and/or recycling using common equipment in support of long-term operations and Earth independence. Almost every element in the architecture incorporates some level of reuse, but understanding the risks associated with maintainability and reuse and their impact on safety, science, and long-term sustainability goals will be vital as the architecture matures. Beyond the sustainability of elements with maintenance, there is also the opportunity to further enhance crew safety by enabling the repair of systems that would otherwise put the crew in a survival situation or lead to a catastrophic hazard. This benefit can be further enhanced with the ability to reuse components from one element to meet the needs in another element.

According to NASA-STD-8729.1, maintainability is a measure of the ease with which a system or equipment can be restored to operational status, as a function of equipment design and installation, personnel availability, adequacy of maintenance procedures and support equipment, and the physical environment under which maintenance is performed. In other words, it is the probability that an item will be restored to a specified condition within a given period when the maintenance is performed in accordance with prescribed procedures and resources. It is important to note that maintainability does not equate to maintenance. *Maintainability* is a design attribute, and *maintenance* is a set or type of operational work.

Two main areas drive maintainability and reuse: mass delivery and available crew time. The delivery of mass to lunar orbit, the lunar surface, or Mars relies on limited opportunities and is a known cost and performance driver. Likewise, crew time is precious and drives three maintenance concepts: 1) reducing/limiting maintenance activities, 2) ensuring that maintenance activities are easy to perform, and 3) automating or having robotics perform maintenance tasks where possible. The last item represents an architecture gap that needs additional development.

The Moon to Mars Architecture will promote the use of common components for items that require regular replacement (e.g., air filters). This approach allows multiple elements to share a set of common components, reducing the amount of logistics and increasing contingency options. An EVA compatibility standard ensures common components and worksites are compatible with spacesuits and do not present hazards to crew members.

Because many of the major systems in the Moon to Mars Architecture are designed to operate for multiple years and missions, extended gaps between missions drive systems to react (e.g., providing a status notification, reconfiguring systems, and shutting down specific systems) and may drive self-maintenance operations. Increasing the number of critical maintenance activities that can be automatically or remotely performed increases crew time for utilization.

3.5.5.2 Future Considerations

Maintainability remains a major concern, especially with the desire to maximize crew time for utilization activities. As the architecture continues to evolve and new elements are added and implemented, system designers and architects should consider a range of additional factors.

Reusability of systems may need to evolve over time. Initial vehicles and components may have design issues learned during actual missions that need to be corrected. Systems development should plan for realistic evolution of reusability in implementation; early flights might not be assessed as qualified for reuse.

As a preventative measure, designers should consider reliability early in the design process to reduce future maintenance needs and target practical repair times. System design should incorporate human factors, easy accessibility, standardized replacement methods, and limited specialized tool requirements. The complex lunar environment, the variety of systems being developed, and the need for crew time to perform science, exploration, and technology demonstrations all drive need to reduce mean time to repair.

Architects and designers must also consider uses for decommissioned hardware and develop a strategy for the reuse or repurposing or, where reuse or repurposing are not viable, proper disposal of components as the exploration campaign evolves.

Additional aspects of maintainability that require further study to strike an ideal balance of crew commitments and system reusability include the following:

- Incorporation of robotic systems and autonomous capabilities to perform maintenance on lunar surface systems
- Incorporation of common equipment between elements
- An integrated system to track the location and availability of maintenance items/common components across the Moon to Mars Architecture
- A process to dispose of or reuse systems or selected system components upon completion of their primary mission
- Whether and how to apply a modular open systems approach to enable a long-term autonomous repair capability supporting the Sustained Lunar Evolution segment
- Evaluation of in-flight maintenance strategies and associated risks as a part of the hazard and crew survival analyses

The maintenance approach should consider the long-term benefits and costs of design features that, if applied at the same level across the architecture, could enhance maintainability and reuse of systems. The Moon to Mars Architecture should consider design aspects including:

- Employ system designs for the lunar surface assets that consider extensibility to Mars
- Maintenance items/common components designed to provide notification of a degraded capability or failure to the broader system, allowing for timely corrective actions
- Design of systems/components to be both crew and robotically manipulated so that tasks can be performed with or without crew present under a variety of environmental conditions
- Reduction of the logistics through the use of common limited-life items (e.g., filters, lights)
- Use of common equipment, including battery sizes, enclosures, and contact points (i.e., through standardization or requirements), including enclosures and contact points
- Refurbishment in support of element reuse (these activities are not well defined in the current architecture)
- Recycling of material from components and use of the recovered material to create new replacement items.
- Overall system lifetime limitations and their effects on reuse and maintenance

3.5.6 RT-6: Responsible Use

RT-6: Conduct all activities for the exploration and use of outer space for peaceful purposes consistent with international obligations and principles for responsible behavior in space.

3.5.6.1 Architecture Assessments

The responsible use of space follows guidelines and principles set forth in international agreements, international and national policies, and law. To ensure that humanity collectively benefits from Moon to Mars activities, NASA must consider the responsible use of space from several legal, policy, ethical, and societal perspectives. This assessment summarizes the relevant history and NASA's current activities in support of the responsible use of space.

NASA's founding legislation declares that "it is the policy of the United States that activities in space should be devoted to peaceful purposes for the benefit of all mankind." [25] The U.S. also ratified the Outer Space Treaty of 1967, the primary international legal instrument governing activities in outer space. It states that outer space shall be free for exploration and for peaceful purposes, should benefit all peoples, and should contribute to broad international cooperation in scientific and legal aspects of exploration. Article VI expands the obligation of nations to ensure responsible behavior even when activities are carried out by "non-governmental entities" like commercial companies, including private-sector operations not conducted on behalf of a nation. Article IX aids in mission deconfliction, addresses the avoidance of harmful (forward) contamination, and of adverse consequences to the terrestrial biosphere from introduction of extraterrestrial material (backward contamination), typically managed under planetary protection.

NASA has utilized the UN Committee on the Peaceful Uses of Outer Space to promote the responsible use of space. Notable examples include the Committee's work to develop and promote guidelines for the long-term

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[25] National Aeronautics and Space Act of 1958 https://history.nasa.gov/spaceact.html

sustainability of outer space activities, space debris mitigation, and the safe use of nuclear power sources in outer space. While not seeking restrictive legal regimes to address such issues, the U.S. has pursued voluntary frameworks for addressing issues that serve as strong encouragement for all nations engaged in space activities to adopt similar national measures. Established by the UN Committee on the Peaceful Uses of Outer Space in 2024, with a three-year mandate, the Action Team on Lunar Activities Consultation is aimed at enhancing consultations concerning activities on or around the Moon. The UN Committee on the Peaceful Uses of Outer Space also recognizes the long-standing role of the Committee on Space Research in maintaining consensus planetary protection guidelines for forward and backward contamination. NASA policies and implementation to demonstrate Outer Space Treaty compliance are informed by the Committee on Space Research and are included in NASA-STD-8719.27.

The Artemis Accords establish a practical set of principles to guide space exploration cooperation among nations, including those participating in NASA's Artemis program. The Accords reinforce key obligations in the 1967 Outer Space Treaty, the commitments by the U.S. and signatory nations to the Registration Convention and the Rescue and Return Agreement, and best practices and guidelines for responsible behavior, including the public release of scientific data.

Key tenets of the Artemis Accords include the following:

- Calls for nations to utilize open international standards, develop new standards when necessary, and strive to support interoperability to the greatest extent practical
  Calls for transparency to provide public information regarding the general nature of operations, which can help to pre-determine the potential for interference between missions
- Commitments to the protection of sites and artifacts with historic value
- Reinforcing that space resource extraction and utilization can and will be conducted under the auspices of the Outer Space Treaty, with specific emphasis on Articles II, VI, and XI

Additional U.S. and NASA policies, including the following, have further developed the concept of responsible use:

- The 2010 National Space Policy[26] enshrined the tenet of "responsible use of space" to promote the long-term sustainability of the space environment, with a focus on the minimization of debris
- The 2020 U.S. National Space Policy[27] further clarifies responsible behavior, including calling for "improved practices for the collection and sharing of information on space objects; protection of critical space systems and supporting infrastructures, with special attention to cybersecurity and supply chains; and measures to mitigate orbital debris"
- The 2021 United States Space Priorities Framework[28] adds additional considerations for responsible behavior, including American leadership in preserving space for future generations, maintaining a robust and responsible U.S. space enterprise, bolstering space situational awareness sharing and space traffic coordination, and minimizing backward contamination

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[26] National Space Policy of the United States of America https://obamawhitehouse.archives.gov/sites/default/files/national_space_policy_6-28-10.pdf

[27] The National Space Policy https://www.federalregister.gov/documents/2020/12/16/2020-27892/the-national-space-policy

[28] United States Space Priorities Framework https://bidenwhitehouse.archives.gov/briefing-room/statements-releases/2021/12/01/united-states-space-priorities-framework/

- NASA's 2024 Space Sustainability Strategy, Volume 1: Earth Orbit[29] defined *space sustainability* as "the ability to maintain the conduct of space activities indefinitely into the future in a manner that is safe, peaceful, and responsible to meet the needs of the present generations while preserving the outer space environment for future activities and limiting harm to terrestrial life," and indicated that a cislunar volume is forthcoming
- While there is no overarching U.S. guidance on ensuring the preservation of exploration sites to meet long-term heritage, technical, scientific, or other conservation objectives, NASA has made some steps in this area:
    - NASA's 2011 report Recommendations to Space-Faring Entities: How to Protect and Preserve the Historic and Scientific Value of U.S. Government Lunar Artifacts[30] provided domestic guidance on the preservation of lunar heritage sites, and the preservation of ongoing science at those sites; these recommendations were enshrined into law in 2020 under the One Small Step to Protect Human Heritage Space Act (P.L. 116-275)[31], which required that NASA add these recommendations into its contracts, grants, agreements, or other arrangements
    - The Lunar Exploration Analysis Group's 2016 Lunar Exploration Roadmap[32] provided goals, objectives, and investigations for lunar science, and detailed preservation priorities to enable future lunar science

In establishing the Artemis Accords, NASA is committing to responsible behavior around Moon to Mars efforts and has identified a need for best practices, guidelines, and standards in many areas. Technical and policy guidance on the responsible use of space and sustainable operations in Moon to Mars efforts should build upon existing practices. NASA is working to identify gaps in best practices for safe, peaceful, and responsible space operations for Moon to Mars exploration and intends to work with Artemis Accords signatories and international technical and standards bodies.

Ongoing operations, including Commercial Lunar Payload Services (CLPS) missions to the Moon, are collecting technical data to enable future responsible behavior. For example, the Stereo Cameras for Lunar Plume-Surface Studies (SCALPSS) studies the effects of the lander's plume on the lunar surface during landings. The ability to predict landing effects is essential to responsible use in the future.

In addition to the UN Committee on the Peaceful Uses of Outer Space, other multilateral groups such as the International Space Exploration Coordination Group, the Inter-Agency Space Debris Coordination Committee, the Interagency Operations Advisory Group, the International Astronomical Union, the International Committee on GNSS, and the International Telecommunications Union can serve as venues to further develop approaches to the sustainable use of space to meet the Moon to Mars Objectives.

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[29] NASA's Space Sustainability Strategy https://www.nasa.gov/wp-content/uploads/2024/04/nasa-space-sustainability-strategy-march-20-2024-tagged3.pdf?emrc=676978822fa0b

[30] NASA's Recommendations to Space-Faring Entities https://www.nasa.gov/wp-content/uploads/2017/10/617743main_nasa-usg_lunar_historic_sites_reva-508.pdf

[31] One Small Step to Protect Human Heritage Space Act https://www.congress.gov/bill/116th-congress/senate-bill/1694#:~:text=One%20Small%20Step%20to%20Protect%20Human%20Heritage%20in%20Space%20Act,-This%20bill%20directs&text=any%20successor%20recommendations%2C%20guidelines%2C%20best,site%20artifacts%20issued%20by%20NASA.

[32] The Lunar Exploration Roadmap https://discovery.larc.nasa.gov/PDF_FILES/02a_LER-2016.pdf

Recent publications including the 2023 planetary science and astrobiology decadal survey[33] and the National Science and Technology Council's cislunar strategy[34] highlight the need to include broader discussion and consideration of ethical and societal questions surrounding Moon to Mars efforts. NASA's 2023 Artemis and Ethics Workshop began a dialog on the cultural and societal implications of future human exploration.

3.5.6.2 Future Considerations

While NASA and its partners have committed to pursuing peaceful exploration and responsible use of space, significant policy questions and framework gaps regarding the protection of future scientific and exploration needs remain. While treaties, law, policy, and guidelines have defined responsible use, implementation is still in development. The Artemis Accords signatories are working on some of these issues now, but the Moon to Mars Architecture must incorporate responsible use and uphold its values throughout implementation.

Given the global impact and influence of space exploration, NASA must think about responsible use broadly, including the impact of exploration on society, including both scientific and cultural impacts. NASA must avoid making premature judgements about behaviors or outcomes and instead enable discussions about costs and benefits, with a goal of maximizing benefits to society while minimizing potential harms. The architecture and systems engineering process can incorporate these discussions.

NASA has a mandate to explore and a set of objectives to meet. Decisions about how those objectives are accomplished must also consider their meaning and impact. NASA will continue to integrate the responsible use of space as the Moon to Mars Architecture evolves.

3.5.7 RT-7: Interoperability

RT-7: Enable interoperability and commonality (technical, operations, and process standards) among systems, elements, and crews throughout the campaign.

3.5.7.1 Architecture Assessments

The Moon to Mars Architecture incorporates a diverse array of NASA programs, with contributions from industry and international partners. Safely and successfully orchestrating the resulting array of systems requires a commitment to interoperability, a core principle in the Artemis Accords.

Artemis programs have applied existing interoperability standards to avionics, communication, PNT, power, rendezvous, environmental control and life support systems (ECLSS), robotics, thermal control, utilization, and software. Interoperability requirements may be tailored for each element to balance the performance of the individual element with the integrated mission architecture. NASA programs are defining initial requirement sets and establishing a baseline level of interoperability across the exploration ecosystem.

In many cases, the necessary categories of interoperability and the baseline interfaces have been identified, but specific implementations are still being developed. During pre-formulation, the Strategy and Architecture Office will assess the need for new interoperability standards and partner with the Moon to Mars Program Office to assign responsibility for developing and applying standards.

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[33] Origins, Worlds, and Life https://nap.nationalacademies.org/catalog/26522/origins-worlds-and-life-a-decadal-strategy-for-planetary-science

[34] National Cislunar Science and Technology Strategy https://bidenwhitehouse.archives.gov/wp-content/uploads/2022/11/11-2022-NSTC-National-Cislunar-ST-Strategy.pdf

The International Deep Space Interoperability Standards[35] serve as the starting point for future interoperability assessments. Currently, nine International Deep Space Interoperability Standards exist and are refined as needed. Two additional standards include identified forward work to be addressed. To the greatest extent possible, interfaces are being developed for extensibility of the Humans to Mars segment.

Other actions taken to improve interoperability within the Moon to Mars Architecture include the following:

- Moon to Mars Program Office flows interoperability standards to elements of the architecture to promote the seamless exchange of services between exploration assets
- The ACR process endorses new and revised interoperability standards to ensure broad awareness and acceptance, and promotes the need to develop new standards
- Architectural studies have mapped functional interoperability between systems assumed to be deployed for a given design reference mission to identify and close gaps; NASA updates these assessments as mission assumptions change
- NASA standardized physical, data, power, payload transfer, and other interfaces for utilization across the Moon to Mars Architecture enabling payloads to move through the architecture and be hosted by various systems; these interfaces are consistent with existing Gateway requirements, the International Space Power System Interoperability Standards, the International External Robotic Interface Interoperability Standards, and other applicable standards
- NASA developed a standard for graphical user interfaces across Artemis, promoting ease of learning, ease of use, a reduction in operator workload, error reduction, an increase in situation awareness, and improved mission safety
- NASA's Icon and Symbol Library promotes consistency in icons and symbols used by Orion, Gateway, HLS, and future lunar and Mars systems, increasing overall crewmember ease of use
- Trade studies are examining lunar power concepts, including bi-directional power sharing between systems, power quality for defined missions, power transmission over long distances, and the need for standardized power connectors on the lunar surface
- The Moon to Mars Program Office maintains an interoperability working group and participates in several forums addressing interoperability, including the Lunar Surface Innovation Consortium, Lunar Exploration Analysis Group, and the Mars Exploration Program Analysis Group, to capture international partner, commercial, and academic perspectives and facilitate community consensus
- A team comprised of representatives from NASA, ESA, and JAXA, with input from the Interagency Operations Advisory Group and other government and commercial entities, developed the LunaNet Interoperability Specification for lunar communication and PNT standards; NASA and ESA service procurements have incorporated this standard.
- NASA's current spectrum plans — developed in coordination with the International Telecommunications Union, and the Space Frequency Coordination Group — are documented in the

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[35] International Deep Space Interoperability Standard https://www.internationaldeepspacestandards.com

International Communication System Interoperability Standard. Implementation support for these plans come from the Consultative Committee for Space Data Systems, the International Communication System Interoperability Standards, and the LunaNet Interoperability Standard.

- The Artemis Flight Operations and Payload Operations Standards capture NASA’s expectations for operational products, processes, and facilities to promote interoperability across all Artemis teams and elements
- A set of requirements that creates an interoperable network enabling lunar surface systems to have data connectivity, command, and control among a distributed set of local and remote users has been developed and strategically applied to current systems. Additional requirements to enable autonomy and cooperative operations between robotic systems and crew have been identified to be applied to new systems as part of their development.

3.5.7.2 Future Considerations

RT-7 guides interface standardization for all elements, but specific designs and requirements for interoperability are still undergoing studies and refinement. In many cases, these studies focus on a subset of relevant elements and may fall short of architecture-wide coordination. Opportunities for further lunar surface interoperability and compatibility include:

- Lunar Surface Docking system that is capable of mating two pressurized systems to provide the transfer of crew and supplies in a shirt-sleeve environment and without the need of pressurization cycles
- The International External Robotic Interface Interoperability Standards currently only addresses robotic attachments in a microgravity environment; it needs additional work to define requirements for operation on the lunar and Martian surfaces
- Maintaining common interfaces across all architectures of the Moon to Mars campaign will ensure maximum crew awareness and efficiency by allowing for a simplified training plan.
- Development of an interoperability specification for communications activities at Mars, analogous to the LunaNet Interoperability Specification referenced in Section 2.3.14.2.
- The Artemis Flight Operations and Payload Operations Standards capture NASA's expectations for execution products and processes to promote interoperability across all Artemis teams and elements.

NASA has initiated efforts to identify, develop, approve, and levy Moon to Mars Architecture interoperability standards to govern cross-program and cross-partner element application. Interoperability artifacts based on architectural needs and feedback from international and commercial partners will drive system configuration, functions, and requirements.

3.5.8 RT-8: Leverage Low Earth Orbit

RT-8: Leverage infrastructure in low Earth orbit to support Moon to Mars activities.

3.5.8.1 Architecture Assessments

The Moon to Mars Architecture builds upon past and current human and robotic spaceflight experience to inform future system design and operational needs.

Enabled by a robust international partnership of five space agencies from 15 countries, the International Space Station has served as a space laboratory of unprecedented scale and sophistication and has hosted a continuous human presence in LEO for more than two decades. During this time, more than 270 astronauts from 21 countries have lived and worked there, conducting over 3,700 scientific experiments. The space station has facilitated the development of mature technological and operational concepts that will inform more complex missions much further from Earth.

Further research, development, and testing will be critical to the successful execution of future deep space and planetary exploration missions. NASA will continue to operate and utilize the space station to support exploration goals through 2030 and is preparing for a successful transition of these capabilities to other destinations in LEO.

NASA's Commercial Low Earth Orbit Development Program (CLDP) is supporting the development of commercially owned and operated LEO destinations from which NASA, along with other customers, can purchase services. As commercial LEO destinations become available, NASA intends to implement a safe and orderly transition from current International Space Station operations to these new destinations. Transition of LEO operations to the private sector will yield efficiencies in the long term, enabling NASA to shift resources toward other objectives.

After space station operations have transitioned to commercial LEO destination operations, ESDMD will coordinate with CLDP to leverage available commercial LEO destination utilization facilities and services that may accommodate Moon to Mars Objectives. Research and development opportunities could include the following:

- Studies of human behavioral and physiological exposure to in-space environments, habitability, and operations
- Development of in-space growth of alternative nutritional sources for human consumption
- Space-related technology demonstrations, tests, and certifications

3.5.8.2 *Future Considerations*

Some potential opportunities to leverage LEO infrastructure remain unexplored, and additional studies and refinement are needed to evaluate all available options. While LEO cannot simulate certain spaceflight hazards with total fidelity, NASA will use LEO destinations to inform human system risks for Mars missions. NASA will continue to take full advantage of the International Space Station before its planned decommission after 2030, after which the agency will enable the development of and transition to other LEO assets. NASA should also create and demonstrate decision support system capabilities in the content of future architectural assumptions.

3.5.9 RT-9: Commerce and Space Development

RT-9: Foster the expansion of the economic sphere beyond Earth orbit to support U.S. industry and innovation.

3.5.9.1 *Architecture Assessments*

NASA and its partners have a clear intent to stimulate the expansion of the economic sphere. The commercial industry and the industrial base have always been at the core of space exploration activities. Historically, its role has included development of technologies and systems, production of hardware, and even execution of missions for use in NASA missions. Over the last few decades, this role has evolved to encompass even greater public-private partnerships, and even primarily commercial endeavors in space.

The Moon to Mars Architecture uses the foundation of policy to further foster commercial industry and economic opportunities beyond Earth orbit. The architecture seeks to expand the economic sphere across all architecture segments, explicitly aiming to build a future of economic opportunity, expanded utilization (including science), and greater commercial participation on and around the Moon and in the rest of the solar system.

Existing policy and legislation provide the basis for NASA's progress toward RT-9. This policy includes semi-permanent or permanent human-scale infrastructure that enables growth in human and robotic space activities and commerce in an operationally diverse manner in multiple locations beyond LEO; U.S. space policy also directs facilitation of commercial exploration and utilization of space resources to meet national needs. The infrastructure, systems, and capabilities that form the bulk of the exploration segments provide the basis for economic activity beyond the agency, including in the areas of power, communications/navigation/timing, and autonomy (including artificial intelligence), and resource exploration.

NASA has begun implementing many recent projects and programs through commercial partnerships with industry. For example, HLS, LCRNS, GLE, xEVA, LTV, and CLPS all feature commercial contracts and partnerships designed to enable use of the systems by other parties. In these elements, NASA has assumed higher than usual programmatic risk (with a benefit of possible reduced financial risk) and, in many cases, has invested in multiple performers with the goal of generating commercial suppliers. Commercial elements, like these, will provide the means to travel to the Moon, maneuver on the surface, and communicate back to Earth — lowering the barrier for entry of potential customers and providing the potential basis for a future lunar economy.

The architecture helps to establish the sources of value that can sustain economic activities beyond Earth's orbit. The architecture cultivates a culture of exploration that encourages governments, companies, and private citizens to venture further into space. It seeks to establish the scientific discoveries and capabilities that will bring continued expeditions to answer key questions about the Moon and the universe. It also pursues resource exploration and the technologies needed to utilize those resources.

Finally, the architecture establishes the Moon and cislunar space as a continued training ground and logistics station for exploration beyond the Moon, to Mars and the rest of the solar system. Simultaneously, the architecture seeks to find areas where governments can encourage, enable, support, and accelerate commercial endeavors consistent with the overall pillars, objectives, use cases, and functions.

3.5.9.2 Future Considerations

While the current architecture makes progress towards this tenet, the undefined Sustained Lunar Evolution segment specifically points to opportunities for increasing the economic sphere, including the following:

- NASA has an opportunity to clarify the difference between economic development and commercial partnerships (economic development is a goal that can be achieved through commercial partnerships)
    - For the purposes of this tenet, the economic consequences of the architecture are of first order importance: for instance, identifying what services NASA will provide and which it will procure.
- NASA has emphasized competition in its commercial lunar procurements; however, with limited sources of commercial and other government agency revenue, some level of vertical or horizontal integration from commercial entities across multiple sub-architectures might provide new opportunities for innovative models for the future

    - This factor is particularly relevant to the Foundational Exploration segment and even more critical for visions of the Sustained Lunar Evolution segment
- The architecture aims to develop a sustained lunar presence and then for NASA to continue to Mars; NASA should plan to sustain such a presence and establish the role of commercial actors

The architecture also gives NASA the means to provide industry with forward guidance to improve their ability to support of the Moon to Mars activities. Some opportunities for forward clarity include the following:

- Clarify, as far in advance as practicable, the role of NASA in future missions and elements, including defining where NASA is going to build, own, or operate capabilities and choosing where NASA intends to procure enduring services that could provide opportunities to industry partners
- Clarify and publish expectations and estimates of future NASA needs, such as power levels or communications bandwidth; these estimates from the architecture would help industry partners position themselves to support NASA's needs
- Clarify NASA's role in resource exploration and utilization, including working with other government agencies in the information, technologies, sub-architectures, systems, and elements to enable industry to leverage the resources of the solar system, wherever it may become economically feasible to do so

Finally, the initial Human Lunar Return and Foundational Exploration segments offer critical opportunities for the agency to gather information and feed forward into future segments to expand the economic sphere. The agency may consider additional opportunities to facilitate economic expansion in the Human Lunar Return and Foundational Exploration segments, including the following:

- NASA should consider the elements within the Human Lunar Return and Foundational Exploration segments that the agency might operate and then provide additional available capacity to commercial partners to enable their activities

- NASA, along with other government agencies, can support resource exploration to gain knowledge of the location and number of resources that might be available for exploitation and to assess their potential economic viability and contributions to the architecture; the results can feed back into the architecture to inform future use cases and elements

- NASA should also consider how it coordinates and guides different industry and foreign partner capabilities to optimize the available funding, given the likely limited non-NASA sources of recurring revenue for lunar activities in the near to mid-term

- NASA can work with industry to define when and how to purchase data to close knowledge gaps versus soliciting entire missions to close gaps

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A.

Appendix A

Architecture Rationale and Considerations

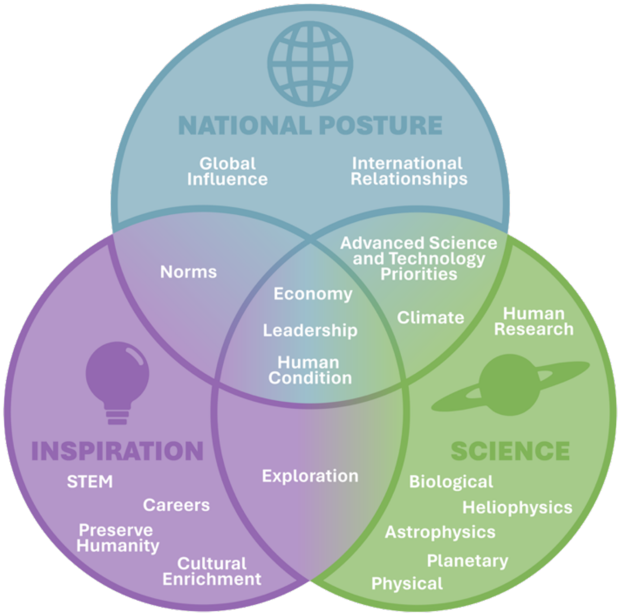
Appendix A: Architecture Rationale and Considerations

This appendix captures the strategic approach, context, background, and important considerations for the Moon to Mars Architecture. First, it covers NASA's exploration strategy — why we explore. It then summarizes the agency's Moon to Mars Objectives — the exploration goals that the architecture aims to achieve. Finally, it provides a deep dive into human exploration considerations for lunar and Mars exploration, including how NASA will build on the success of the Apollo Program and the International Space Station and develop new capabilities for exploring deep space.

A.1 Moon to Mars Strategy

The systems engineering discipline that NASA uses to develop the Moon to Mars Architecture is predicated on motivation: what is the fundamental goal of exploration? Why send humans into space?

For NASA, the value of human exploration of the solar system is rooted in three pillars: science, national posture, and inspiration. Each pillar contains both unique and overlapping values; together, they form the value proposition for exploration.



Three Pillars of Exploration

While different individuals prioritize different values, NASA, as a responsible steward of taxpayer dollars, must balance the entire landscape of motivations for exploring. This balance creates a robust, stable, and long-term architecture that will enable NASA to explore the Moon, Mars, and beyond.

A.1.1 Science

The pursuit of scientific knowledge — exploring and understanding the universe — is integral to the human space exploration endeavor. Just as the James Webb Space Telescope informs us about the history of time, answers gained on the Moon and Mars will build knowledge about the formation and evolution of the solar system and, more specifically, the Earth.

From geology to solar, biological, and fundamental physics phenomena, exploration teaches us about the earliest solar system environment: whether and how the bombardments of nascent worlds influenced the emergence of life, how the Earth and Moon formed and evolved, and how volatiles (e.g., water) and other potential resources were distributed and transported throughout the solar system.

Space exploration teaches us about human and plant physiology in extreme environments, how to mitigate engineering and health risks, and how to perform complex operations in harsh planetary environments. Space provides a unique vantage point to amplify learning on Earth. Biological and physical systems can be observed in partial gravity, bringing out second- and third-order effects that are otherwise overwhelmed in the gravity environment.

The history of our Sun is preserved in lunar soil, examination of which enables solar activity predictions and space weather forecasts, which in turn support lunar and Martian exploration. Specific frequency ranges available for use only in space (because of interference by other Earth-based signals or the atmosphere) allow us to probe the universe's deepest space and time. While remote sensing is a great aid, robotic and human exploration of other bodies in the solar system ultimately reap more data more effectively.

A.1.2 National Posture

By its very nature, achieving a vision of space exploration establishes national strength in science and technology innovation and competitiveness, which supports economic growth and global position. Hard technology problems solved in space have far-reaching implications for other Earth-based challenges and industries, and in many cases, spin off their own disciplines. For example, the term "software engineering" was crafted for the development of the guidance and navigation systems on Apollo spacecraft. Food safety standards and telemedicine likewise originated with NASA's effort to enable longer-duration human space flight.

NASA technology, spin-offs, and investments fuel growth in American industry and support quality, high-paying jobs across the country. NASA's contracts and partnership with domestic commercial space resulted in $15 billion in private investments in space start-up companies in a single year, most of which were with US-based companies. Commercial space activity impacts other industries, such as agriculture, maritime, energy, and homeland security, producing ripple effects throughout the economy.

Because there are no geographic bounds in space, exploration lends itself to international partnerships to achieve feats that might not otherwise be possible. Bolstering international partnerships, economic competitiveness, and global influence likewise reinforces national security interests.

A.1.3 Inspiration

The "Moonshots" of the Apollo Program became a metaphor for how the nation could take on an audacious challenge and succeed through hard work and determination. The Moonshot metaphor has since been applied to seemingly insurmountable challenges, from curing cancer to developing fusion power.

Apollo inspired a new generation of engineers and scientists to pursue education and careers supporting visionary work. The International Space Station and other space partnerships model how people from many nations can live and work together toward a common purpose.

The next steps in space exploration can likewise inspire a new generation in science, technology, engineering, and mathematics studies that support the great enterprises of voyaging into space and overcoming the most difficult challenges on Earth.

A.2 Moon to Mars Objectives

NASA's Moon to Mars Objectives, developed through collaboration with NASA's workforce, international space agencies, industry, and academia and published in 2022, are the agency's goals for space exploration. The 63 objectives, grouped into four categories, capture increasingly ambitious exploration activities through which the agency will explore the Moon, Mars, and beyond.

The objectives incorporate the principles of an objective-based approach, architecting from the right and executing from the left, and constancy of purpose to build a robust, long-term exploration enterprise. The objectives cover four main categories: science, infrastructure, transportation and habitation, and operations. These categories one or more goals surrounding specific subjects, each of which is comprised of multiple individual objectives. Additionally, nine recurring tenets capture cross-cutting themes that guide NASA's overall exploration approach.

The full lists of objectives and recurring tenets are available in NASA's Moon to Mars Objectives document.[36] Section 3.4 captures assessments of the architecture's adherence to the recurring tenets. The full decomposition of the objectives into use cases and functions is captured in Appendix B.

A.3 Human Exploration Considerations

A wide range of exploration considerations — both shared between destinations or unique to the Moon or Mars — shape the architecture. NASA has published many white papers, available on the agency's Moon to Mars Architecture website, that explore these drivers in depth.[37] The white papers analyze specific explorations constraints and challenges, as well as how these factors drive NASA's architecture roadmapping.[38]

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[36] https://www.nasa.gov/wp-content/uploads/2022/09/m2m-objectives-exec-summary.pdf

[37] https://www.nasa.gov/moontomarsarchitecture/

[38] https://www.nasa.gov/moontomarsarchitecture-whitepapers/

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B.

Appendix B

Architecture Decomposition

Appendix B: Architecture Decomposition

B.1 Objective Decomposition

The tables linked below capture the objective decomposition for lunar and Mars objectives, tracing from objectives through characteristics and needs to use case and functions, as described in Section 1.

The objective decomposition also considers the existence of certain support functions — including power, communications, command and data handling, positioning, navigation, and timing — that are inherent to almost all spaceflight elements. These support functions need not be explicitly mapped within every single objective; they are documented, but they are mapped to other objectives that more specifically address the functional area.

Note: *The lunar and Mars objective decompositions follow independent numbering schema; the numbering for Mars use cases and functions does not follow sequentially from the lunar decomposition.*

B.1.1 Lunar Objective Decomposition

https://www.nasa.gov/moontomarsarchitecture-architecturedefinitiondocuments/

B.1.2 Mars Objective Decomposition

https://www.nasa.gov/moontomarsarchitecture-architecturedefinitiondocuments/

Note: *The objective decomposition uses the term "deep space and/or Mars vicinity." "Deep space" is the vast region of space that extends to interplanetary space, including Mars and beyond. The term "Mars vicinity" refers to the region of space around the Mars system, including Mars orbit. As the Mars architecture continues to mature, it will add information about where and how certain use cases and functions are performed, including specific trajectories and orbits. Currently, "Mars vicinity" is the highest appropriate level of specificity. Appendix E captures additional terms and definitions.*

B.2 Use Cases and Functions

B.2.1 List of Lunar Use Cases

UC ID	Lunar Use Case
UC-T-101 L	Transportation of crew from Earth to cislunar space
UC-T-102 L	Staging of crewed lunar surface missions from cislunar space
UC-T-103 L	Aggregation and physical assembly of spacecraft components in cislunar space
UC-T-104 L	Transportation of crew between cislunar space and the lunar surface
UC-T-105 L	Transportation of crew between cislunar space and lunar south pole region landing sites
UC-T-106 L	Transportation of crew from cislunar space to distributed landing sites outside of the south pole region on the lunar surface
UC-T-107 L	Transportation of crew from the lunar surface to cislunar space
UC-T-108 L	Transportation of crew from cislunar space to Earth
UC-T-201 L	Transportation of small cargo from Earth to distributed locations outside of the south pole region on the lunar surface
UC-T-202 L	Transportation of large cargo from Earth to the lunar surface
UC-T-203 L	Transportation of cargo from cislunar space to Earth
UC-T-204 L	Transportation of cargo from the lunar surface to cislunar space
UC-T-301 L	Return of a small amount of unconditioned samples and containers (10s of kg) from the lunar surface to Earth with the samples in sealed sample containers
UC-T-302 L	Return of a large amount of unconditioned samples and containers (100s of kg) from the lunar surface to Earth with the samples in sealed sample containers
UC-T-303 L	Return of a small amount of refrigerated samples and containers (10s of kg) from the lunar surface to Earth with the samples in sealed conditioned sample containers
UC-T-304 L	Return of a large amount of refrigerated samples and containers (100s of kg) from the lunar surface to Earth with the samples in sealed conditioned sample containers
UC-T-305 L	Return of a small amount of frozen samples and containers (10s of kg) from the lunar surface to Earth with the samples in sealed conditioned sample containers
UC-T-306 L	Return of a large amount of frozen samples and containers (100s of kg) from the lunar surface to Earth with the samples in sealed conditioned sample containers
UC-T-307 L	Return of a large amount of cryogenic samples and containers (100s of kg) from the lunar surface to Earth with the samples in sealed conditioned sample containers

UC ID	Lunar Use Case
UC-T-308 L	Return of a small amount of unconditioned samples and containers (10s of kg) from cislunar space to Earth with the samples in sealed sample containers
UC-T-309 L	Return of a large amount of unconditioned samples and containers (100s of kg) from cislunar space to Earth with the samples in sealed sample containers
UC-T-310 L	Return of a small amount of refrigerated samples and containers (10s of kg) from cislunar space to Earth with the samples in sealed conditioned sample containers
UC-T-311 L	Return of a large amount of refrigerated samples and containers (100s of kg) from cislunar space to Earth with the samples in sealed conditioned sample containers
UC-T-312 L	Return of a small amount of frozen samples and containers (10s of kg) from cislunar space to Earth with the samples in sealed conditioned sample containers
UC-T-313 L	Return of a large amount of frozen samples and containers (100s of kg) from cislunar space to Earth with the samples in sealed conditioned sample containers
UC-T-401 L	Landing of crew lander(s) at specific pre-defined locations
UC-T-402 L	Landing of cargo lander(s) at specific pre-defined locations
UC-T-501 L	Testing, contingency planning, and edge-case analyses of in-space systems
UC-G-101 L	Ground support on Earth for the launch of large nuclear assets
UC-G-201 L	Delivery of conditioned cargo to curation facilities or other appropriate facilities on Earth after landing, while maintaining scientific integrity of the samples
UC-G-202 L	Delivery of collected samples to curation facilities or other appropriate facilities on Earth, while maintaining scientific integrity of the samples
UC-G-301 L	Provision of advanced geology training, integrated geology and EVA ops training, as well as detailed objective-specific training to astronauts for science activities
UC-H-101 L	Crew habitation of assets on the lunar surface for short-durations (days to weeks)
UC-H-102 L	Crew habitation of assets on the lunar surface for mid-durations (month+)
UC-H-103 L	Crew habitation of assets for mid-duration (month+) mission(s) in cislunar space
UC-H-104 L	Crew habitation of assets for long-duration (year+) mission(s) in cislunar space
UC-H-105 L	Reuse of habitation system(s) on the lunar surface
UC-H-106 L	Reuse of habitation system(s) in cislunar space
UC-H-201 L	Monitoring of system performance and failures during crewed and uncrewed increments in habitats on the lunar surface
UC-H-202 L	Monitoring of system performance and failures during crewed and uncrewed increments in habitats in cislunar space

UC ID	Lunar Use Case
UC-X-101 L	Medical capabilities on the lunar surface
UC-X-102 L	Medical capabilities in cislunar space
UC-X-103 L	Crew countermeasure capabilities to support the crew for mid-durations (month+) on the lunar surface
UC-X-104 L	Crew countermeasure capabilities to support the crew for mid- (month+) to long-durations (year+) in cislunar space
UC-X-201 L	In-situ crew training on the lunar surface
UC-X-202 L	In-situ crew training in cislunar space
UC-X-203 L	Provision of in-situ training to astronauts for science tasks during mission(s) on the lunar surface
UC-L-201 L	Resupply of cargo and management of waste to/from habitable assets on the lunar surface
UC-L-202 L	Resupply of cargo and management of waste to/from habitable assets in cislunar space
UC-P-101 L	Power generation and energy storage at south pole region on the lunar surface
UC-P-102 L	Power generation and energy storage at multiple distributed locations outside of the south pole region on the lunar surface
UC-P-301 L	Power distribution around power generation and energy storage system(s) in the south pole region on the lunar surface
UC-P-302 L	Power distribution from power generation and energy storage system(s) at multiple distributed locations outside of the south pole region on the lunar surface
UC-P-501 L	Continuous power provision to assets during mission critical activities
UC-P-502 L	Continuous power provision to assets in off-nominal conditions
UC-M-101 L	Conduct of crew extravehicular operations on the lunar surface
UC-M-102 L	Conduct of crew extravehicular operations in cislunar space
UC-M-103 L	Crew use of tools to assist in performing extravehicular activities, sample collection and suit cleaning
UC-M-301 L	Conduct of crew excursions to locations in sunlit areas and non-PSRs at distributed locations outside of the south pole region around landing site
UC-M-302 L	Conduct of crew excursions to locations around landing site in sunlit areas and non-PSRs in the south pole region
UC-M-303 L	Conduct of crew excursions in PSRs around landing site at the south pole region

UC ID	Lunar Use Case
UC-M-401 L	Unloading of large cargo on the lunar surface
UC-M-402 L	Unloading of small cargo on the lunar surface
UC-M-601 L	Demonstration of uncrewed relocation of exploration assets to sites around the lunar south pole region
UC-M-602 L	Demonstration of uncrewed relocation of exploration assets to sites at distributed locations outside of the south pole region on the lunar surface
UC-C-101 L	Communications and data exchange with high bandwidth and high availability between assets on the lunar surface and the Earth
UC-C-102 L	Communications and data exchange with high bandwidth and high availability between assets at a variety of different locations on the lunar surface
UC-C-103 L	Communications and data exchange with high bandwidth and high availability between assets in cislunar space and the Earth
UC-C-104 L	Communications and data exchange with high bandwidth and high availability between assets in cislunar space and the lunar surface
UC-C-201 L	Determination of position, navigation, and timing by crew and assets in cislunar space
UC-C-202 L	Determination of position, navigation, and timing by crew and assets at the south pole region on the lunar surface
UC-C-203 L	Crew or robotics utilization of position, navigation, and timing for accurate sample tracking at the south pole region on the lunar surface
UC-C-204 L	Determination of position, navigation, and timing by crew and assets at distributed sites on the lunar surface
UC-C-205 L	Crew or robotics utilization of position, navigation, and timing for accurate sample tracking at distributed sites on the lunar surface
UC-C-206 L	Determination of position, navigation, and timing by crew and assets at the far side of the lunar surface
UC-C-207 L	Crew or robotics utilization of position, navigation, and timing for accurate sample tracking at the far side on the lunar surface
UC-D-101 L	Aggregation and storage of data on the lunar surface until it is able to be transmitted and confirmed received
UC-D-102 L	Aggregation and storage of data in cislunar space until it is able to be transmitted and confirmed received
UC-D-201 L	Storage and local processing of space weather data
UC-A-101 L	Robotic assistance of crew exploration, site surveying, sample and resource locating, documentation, and sample retrieval from PSRs
UC-A-102 L	Maintenance and repair operations using robotic system(s) in cislunar space as appropriate
UC-A-103 L	Robotic support of logistic operations on the lunar surface as necessary

UC ID	Lunar Use Case
UC-A-104 L	Robotic assistance of crew exploration, site surveying, sample and resource locating, documentation, and sample retrieval from sunlit areas and non-PSRs
UC-A-105 L	Maintenance and repair operations using robotic system(s) on the lunar surface as appropriate
UC-A-106 L	Robotic surveillance of PSRs near potential crewed landing and exploration sites to identify locations of interest
UC-A-107 L	Robotic assistance of activities in space
UC-A-201 L	Remote management of robotic system(s) during surface operation as necessary
UC-A-202 L	Remote management of robotic system(s) during in space operation as necessary
UC-A-301 L	Safe and effective interaction between crew and autonomous asset(s)
UC-A-401 L	Operation of transportation assets(s) in cislunar space from Earth during uncrewed segments
UC-A-402 L	Operation of transportation assets(s) on the lunar surface from Earth during uncrewed segments
UC-I-101 L	Deployment and operation of utilization payload(s) and/or equipment related to demonstration of ISRU on the lunar surface with long-term remote operation
UC-I-102 L	Deployment and operation of utilization payload(s) and/or equipment related to demonstration of oxygen recovery from lunar regolith
UC-I-103 L	Deployment and operation of utilization payload(s) and/or equipment related to demonstration of water recovery from the lunar regolith in the polar regions
UC-I-104 L	Deployment and operation of utilization payload(s) and/or equipment related to demonstration of water transfer from ISRU production assets to other exploration assets
UC-I-105 L	Deployment and operation of utilization payload(s) and/or equipment related to demonstration of gas transfer from ISRU production assets to other exploration assets
UC-I-106 L	Deployment and operation of utilization payload(s) and/or equipment related to demonstration of operational techniques to recover and refine metals from the lunar regolith
UC-I-201 L	Deployment and operation of utilization payload(s) and/or equipment related to autonomous construction demonstration utilization payload(s) on the lunar surface with long-term remote operation
UC-I-202 L	Deployment and operation of utilization payload(s) and/or equipment related to demonstration of autonomous construction techniques, e.g., collection of regolith, processing regolith into feedstock, and regolith construction
UC-I-203 L	Deployment and operation of utilization payload(s) and/or equipment related to demonstration of regolith based additive/subtractive manufacturing techniques
UC-I-204 L	Deployment and operation of utilization payload(s) and/or equipment related to advanced manufacturing demonstration on the lunar surface with long-term remote operation
UC-U-101 L	Orbital survey(s) of lunar surface before, during, and after crew mission
UC-U-102 L	Robotic surveillance of potential crewed landing and exploration sites in sunlit areas and non-PSRs in the south pole region on the lunar surface to identify locations of interest

UC ID	Lunar Use Case
UC-U-103 L	Crew identification of surface samples in sunlit areas and non-PSRs in the south pole region on the lunar surface
UC-U-104 L	Crew identification of surface samples in PSRs
UC-U-105 L	Robotic surveillance of potential crewed landing and exploration sites in sunlit areas and non-PSRs in distributed sites on the lunar surface to identify locations of interest
UC-U-106 L	Robotic surveillance of potential crewed landing and exploration sites in sunlit areas and non-PSRs on the far side on the lunar surface to identify locations of interest
UC-U-107 L	Crew identification of surface samples in sunlit areas and non-PSRs in distributed sites on the lunar surface
UC-U-108 L	Crew identification of surface samples in sunlit areas and non-PSRs in the far side on the lunar surface
UC-U-201 L	Intravehicular science and utilization activities on the lunar surface
UC-U-202 L	Deployment and operation of utilization payload(s) and/or equipment at cislunar asset(s)
UC-U-203 L	Deployment and operation of free-flying assets long-term in a variety of lunar orbits
UC-U-204 L	Setup of utilization payload(s) and/or equipment on the lunar surface with long-term remote operation
UC-U-301 L	Collection, documentation, and packaging of surface and/or shallow subsurface samples, maintaining scientific integrity of the samples, from non-PSRs and sunlit areas in the south pole region on the lunar surface
UC-U-302 L	Collection, recovery, and packaging of deep subsurface samples, maintaining scientific integrity of the samples, from non-PSRs and other sunlit areas in the south pole region on the lunar surface
UC-U-303 L	Collection, recovery, and packaging of surface and/or shallow subsurface samples, maintaining scientific integrity of the samples, from PSRs on the lunar surface
UC-U-304 L	Collection, recovery, and packaging of deep subsurface samples, maintaining scientific integrity of the samples, from PSRs on the lunar surface
UC-U-305 L	Collection, documentation, and packaging of surface and/or shallow subsurface samples, maintaining scientific integrity of the samples, from non-PSRs and sunlit areas in distributed locations on the lunar surface
UC-U-306 L	Collection, documentation, and packaging of surface and/or shallow subsurface samples, maintaining scientific integrity of the samples, from non-PSRs and sunlit areas in the far side on the lunar surface
UC-U-307 L	Collection, recovery, and packaging of deep subsurface samples, maintaining scientific integrity of the samples, from non-PSRs and other sunlit areas in distributed sites on the lunar surface
UC-U-308 L	Collection, recovery, and packaging of deep subsurface samples, maintaining scientific integrity of the samples, from non-PSRs and other sunlit areas in the far side on the lunar surface
UC-U-501 L	Deployment and operation of exploration assets, including utilization payload(s) and/or equipment, related to demonstration of operational techniques to transfer fluid and/or propellant on the lunar surface
UC-U-502 L	Deployment and operation of exploration assets, including utilization payload(s) and/or equipment, related to demonstration of transfer fluid and/or propellant in space
UC-U-503 L	Deployment and operation of exploration assets, including utilization payload(s) and/or equipment, related to demonstration of propellant storage for long-durations (year+) in space

UC ID	Lunar Use Case
UC-U-504 L	Deployment and operation of exploration assets, including utilization payload(s) and/or equipment, related to demonstration of propellant storage for long-durations (year+) on the lunar surface
UC-U-601 L	Crew conduct of biological science and human research activities in cislunar space
UC-U-602 L	Crew conduct of biological science and human research activities on the lunar surface
UC-U-603 L	Crew conduct of biological science and human research activities during crew transit between Earth and cislunar space
UC-U-701 L	Deployment and operation of utilization payloads and/or equipment related to Impact Chronology on the lunar surface with long-term remote operation
UC-U-702 L	Deployment and operation of utilization payload(s) and/or equipment related to Geologic Processes on the lunar surface with long-term remote operation
UC-U-703 L	Deployment and operation of utilization payload(s) and/or equipment related to Solar System Volatiles on the lunar surface at the south pole region with long-term remote operation
UC-U-704 L	Deployment and operation of utilization payload(s) and/or equipment related to Solar System Volatiles at distributed locations on the lunar surface with long-term remote operation
UC-U-705 L	Deployment and operation of Heliophysics utilization payload(s) and/or equipment on the lunar surface with long-term remote operation
UC-U-706 L	Deployment and operation of Heliophysics utilization payload(s) and/or equipment at cislunar asset(s) with long term remote operation
UC-U-707 L	Deployment and operation of utilization payload(s) and/or equipment related to space weather, including the ability to conduct long looks at the Sun, at assets in cislunar space
UC-U-708 L	Deployment and operation of utilization payload(s) and/or equipment related to space weather at assets in deep space
UC-U-709 L	Deployment and operation of utilization payload(s) and/or equipment related to Magnetotail and Solar Wind on the lunar surface with long-term remote operation
UC-U-710 L	Deployment and operation of plasma utilization payload(s) on the lunar surface with long-term remote operation
UC-U-711 L	Deployment and operation of astrophysics and fundamental physics utilization payload(s) and/or equipment on the far side of the lunar surface with long-term remote operation
UC-U-712 L	Conduct of fundamental physics and astrophysics experiments on the lunar surface
UC-U-713 L	Conduct of fundamental physics and astrophysics experiments in cislunar space
UC-U-714 L	Crew conduct of fundamental physics and astrophysics experiments during crew transit between Earth and cislunar space
UC-U-715 L	Deployment and operation of physical systems and fundamental physics utilization payload(s) and/or equipment at asset(s) or as freeflyers in cislunar space with long-term remote operation
UC-U-716 L	Deployment and operation of physical systems and fundamental physics utilization payload(s) and/or equipment on the lunar surface with long-term remote operation
UC-U-717 L	Deployment and operation of utilization payload(s) and/or equipment related to available resources on the lunar surface at the south pole region with long-term remote operation

UC ID	Lunar Use Case
UC-U-718 L	Deployment and operation of utilization payload(s) and/or equipment related to available resources at distributed locations on the lunar surface with long-term remote operation
UC-U-719 L	Monitoring, characterization, and advance warning for natural environmental threats on the lunar surface, e.g., high energy debris, natural radiation level, thermal conditions, plasma environments, and electrostatic charges
UC-U-720 L	Monitoring, characterization, and advance warning for induced environmental threats on the lunar surface, e.g., induced radiation level, thermal conditions, high-energy debris, contamination, electrostatic, and acoustics
UC-U-721 L	Monitoring, characterization, and advance warning for natural environmental threats in cislunar space, e.g., high energy debris, natural radiation level, thermal conditions, plasma environments, and electrostatic charges
UC-U-722 L	Monitoring, characterization, and advance warning for induced environmental threats in cislunar space, e.g., induced radiation level, thermal conditions, high-energy debris, contamination, electrostatic, and acoustics
UC-U-723 L	Deployment and operation of utilization payload(s) and/or equipment related to bio-regenerative oxygen and water recovery at assets in cislunar space
UC-U-724 L	Deployment and operation of utilization payload(s) and/or equipment related to reduced gravity materials and processes science experiments, other extreme environments-related research, and associated modeling to support in-space technologies related to support bioregenerative ECLSS
UC-U-725 L	Deployment and operation of utilization payload(s) and/or equipment related to plant growth at assets in cislunar asset(s)
UC-U-726 L	Deployment and operation of utilization payload(s) and/or equipment related to demonstration of maintenance and repair of asset(s)
UC-U-727 L	Deployment and operation of utilization payload(s) and/or equipment related to demonstration of equipment recovery from surface asset(s)
UC-U-728 L	Deployment and operation of utilization payload(s) and/or equipment related to demonstration of recovery of excess propellant from surface asset(s)
UC-U-801 L	Preservation of lunar far side environment to ensure scientific data integrity
UC-U-802 L	Reduction of blast ejecta to limit the migration of ejecta across the lunar surface
UC-U-803 L	Reduction of path erosion, dust lofting, and sample contamination
UC-U-804 L	Limitation of the spread of dust raised by lunar surface operations
UC-U-805 L	Landing of exploration missions at sites removed from sites of historic significance
UC-U-806 L	Repurposing of hardware and materials brought to the surface for subsequent missions
UC-U-807 L	Conduct of end-of-life operations

B.2.2 List of Lunar Functions

FN ID	Lunar Function
FN-T-101 L	Transport crew from Earth to cislunar space

FN ID	Lunar Function
FN-T-102 L	Transport crew from cislunar space to lunar surface sites in the south pole region
FN-T-103 L	Transport crew from cislunar space to distributed sites outside of the south pole region on the lunar surface
FN-T-104 L	Transport crew from the lunar surface to cislunar space
FN-T-105 L	Transport crew from cislunar space to Earth
FN-T-106 L	Rendezvous, proximity operations, mating and unmating of assets in cislunar space
FN-T-107 L	Enable crew habitation during transit from Earth to cislunar space
FN-T-108 L	Enable crew habitation during transit from cislunar space to lunar surface sites in the south pole region
FN-T-109 L	Enable crew habitation during transit from cislunar space to distributed sites outside of the south pole region on the lunar surface
FN-T-110 L	Enable crew habitation during transit from the lunar surface to cislunar space
FN-T-111 L	Enable crew habitation during transit from cislunar space to Earth
FN-T-112 L	Enable abort(s) to safety
FN-T-201 L	Transport a limited amount of cargo (100s of kg) from Earth to south pole region sites on the lunar surface
FN-T-202 L	Transport a moderate amount of cargo (1000s of kg) from Earth to south pole region sites on the lunar surface
FN-T-203 L	Transport a limited amount of cargo (100s of kg) from Earth to distributed sites outside of the south pole region on the lunar surface
FN-T-204 L	Transport a moderate amount of cargo (1000s of kg) from Earth to distributed sites outside of the south pole region on the lunar surface
FN-T-205 L	Transport a limited amount of cargo (100s of kg) from Earth to the far side of the lunar surface
FN-T-206 L	Transport large asset(s) from Earth to the lunar surface
FN-T-207 L	Transport a small amount of cargo (10s of kg) from the lunar surface to Earth
FN-T-208 L	Transport a large amount of cargo (100s of kg) from the lunar surface to Earth
FN-T-209 L	Transport a small amount of cargo (10s of kg) from the lunar surface to cislunar space
FN-T-210 L	Transport a large amount of cargo (100s of kg) from the lunar surface to cislunar space

FN ID	Lunar Function
FN-T-211 L	Transport a small amount of cargo (10s of kg) from cislunar space to Earth
FN-T-212 L	Transport a large amount of cargo (100s of kg) from cislunar space to Earth
FN-T-213 L	Transport cargo from Earth to cislunar space
FN-T-214 L	Provide delivery of live, actively growing biological specimens to cislunar space, including late load of cargo prior to launch
FN-T-215 L	Transport cargo from Earth to assets in deep space
FN-T-216 L	Deliver free flying asset(s) from Earth to cislunar space
FN-T-217 L	Transport exploration asset(s) from Earth to cislunar space
FN-T-301 L	Provide resources to condition refrigerated sample containers during transit from the lunar surface to Earth
FN-T-302 L	Provide resources to condition frozen sample containers during transit from the lunar surface to Earth
FN-T-303 L	Provide resources to condition cryogenic sample containers during transit from the lunar surface to Earth
FN-T-304 L	Provide resources to condition refrigerated sample containers during transit from the lunar surface to cislunar space
FN-T-305 L	Provide resources to condition frozen sample containers during transit from the lunar surface to cislunar space
FN-T-306 L	Provide resources to condition cryogenic sample containers during transit from the lunar surface to cislunar space
FN-T-307 L	Provide resources to condition refrigerated sample containers during transit from cislunar space to Earth
FN-T-308 L	Provide resources to condition frozen sample containers during transit from cislunar space to Earth
FN-T-309 L	Provide resources to condition cryogenic sample containers during transit from cislunar space to Earth
FN-T-401 L	Provide precision landing for crew transport to the lunar surface
FN-T-402 L	Provide precision landing for cargo transport to the lunar surface
FN-T-403 L	Enable landing on the lunar surface under all lighting conditions
FN-G-101 L	Provide ground services on Earth
FN-G-102 L	Stack and integrate system(s) on Earth

FN ID	Lunar Function
FN-G-103 L	Manage consumables and propellant
FN-G-104 L	Enable vehicle launch(es)
FN-G-105 L	Enable multiple launch attempts for vehicle(s)
FN-G-106 L	Provide ground services on Earth to support large nuclear assets
FN-G-107 L	Enable vehicle launch(es) to support large nuclear assets
FN-G-201 L	Recover crew after Earth landing
FN-G-202 L	Recover cargo after Earth landing
FN-H-101 L	Enable a pressurized, habitable environment on the lunar surface for short durations (days to weeks)
FN-H-102 L	Enable a pressurized, habitable environment on the lunar surface for mid-duration (month+) use
FN-H-103 L	Enable a pressurized, habitable environment in cislunar space
FN-H-104 L	Enable a pressurized, habitable environment in cislunar space for mid-durations (month+)
FN-H-105 L	Enable a pressurized, habitable environment in cislunar space for long-durations (year+)
FN-H-201 L	Operate habitation system(s) in uncrewed mode between crewed missions on the lunar surface
FN-H-202 L	Operate habitation system(s) in uncrewed mode between crewed missions in cislunar space
FN-X-101 L	Provide hardware for crew medical care on the lunar surface
FN-X-102 L	Provide hardware for crew medical care in cislunar space
FN-X-103 L	Provide crew countermeasure system(s) to support the crew for mid-durations (month+) on the lunar surface
FN-X-104 L	Provide crew countermeasure system(s) to support the crew for mid-(month+) to long-durations (year+) in cislunar space
FN-X-201 L	Provide in-mission crew training on the lunar surface
FN-X-202 L	Provide in-mission crew training in cislunar space
FN-L-101 L	Provide mating between pressurized assets on the lunar surface

FN ID	Lunar Function
FN-L-201 L	Transfer pressurized cargo into habitable assets on the lunar surface
FN-L-202 L	Transfer pressurized cargo into habitable assets in cislunar space
FN-L-203 L	Transfer water to habitable assets on the lunar surface
FN-L-204 L	Transfer water to habitable assets in cislunar space
FN-L-205 L	Transfer gases to habitable assets on the lunar surface
FN-L-206 L	Transfer gases to habitable assets in cislunar space
FN-L-301 L	Manage waste from habitable asset(s) on the lunar surface
FN-L-302 L	Manage waste from habitable asset(s) in cislunar space
FN-P-101 L	Generate power in the south pole region on the lunar surface
FN-P-102 L	Generate power at multiple distributed locations outside of the south pole region on the lunar surface
FN-P-201 L	Store energy at multiple distributed locations outside of the south pole region on the lunar surface
FN-P-202 L	Store energy 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-302 L	Distribute power at multiple distributed locations outside of the south pole region on the lunar surface
FN-P-303 L	Distribute power to utilization payloads and/or equipment in cislunar space
FN-P-304 L	Distribute power to utilization payloads and/or equipment in deep space
FN-P-305 L	Provide bi-directional power exchange capability
FN-P-401 L	Provide power for deployed surface utilization payloads(s) and/or equipment
FN-P-402 L	Provide power for deployed external surface utilization payloads(s) and/or equipment for mid- (month+) to long-durations (year+)
FN-M-101 L	Enable crew lunar surface extravehicular activity in sunlit areas and non-PSRs
FN-M-102 L	Enable crew lunar surface extravehicular activity in PSRs

FN ID	Lunar Function
FN-M-103 L	Enable crew lunar surface extravehicular activities at the lunar far side region
FN-M-104 L	Enable crew extravehicular activity in cislunar space
FN-M-201 L	Enable the cleaning of EVA equipment and tools
FN-M-202 L	Enable maintaining and servicing of the EVA system in a habitable environment
FN-M-203 L	Ingress/egress from habitable asset(s) to lunar surface vacuum
FN-M-301 L	Ingress/egress from habitable asset(s) to cislunar vacuum
FN-M-302 L	Enable local unpressurized surface mobility in sunlit areas and non-PSRs in the south pole region on the lunar surface
FN-M-303 L	Enable local unpressurized surface mobility in sunlit areas and non-PSRs at distributed sites on the lunar surface
FN-M-304 L	Enable local unpressurized surface mobility in PSRs at the south pole region of the lunar surface
FN-M-305 L	Enable pressurized surface mobility in sunlit areas and non-PSRs
FN-M-401 L	Unload a limited amount of cargo (100s of kg) on the lunar surface
FN-M-402 L	Unload a moderate amount of cargo (1000s of kg) on the lunar surface
FN-M-403 L	Unload large assets on the lunar surface
FN-M-501 L	Reposition a limited amount of cargo (100s of kg) in the south pole region on the lunar surface
FN-M-502 L	Reposition a limited amount of cargo (100s of kg) at distributed sites 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-504 L	Reposition a small amount of unconditioned samples and containers (10s of kg) on the lunar surface
FN-M-505 L	Reposition a large amount of unconditioned samples and containers (100s of kg) on the lunar surface
FN-M-506 L	Reposition a small amount of refrigerated samples and containers (10s of kg) on the lunar surface
FN-M-507 L	Reposition a large amount of refrigerated samples and containers (100s of kg) on the lunar surface
FN-M-508 L	Reposition a small amount of frozen samples and containers (10s of kg) on the lunar surface

FN ID	Lunar Function
FN-M-509 L	Reposition a large amount of frozen samples and containers (100s of kg) on the lunar surface
FN-M-510 L	Reposition a large amount of cryogenic samples and containers (100s of kg) on the lunar surface
FN-M-601 L	Relocate exploration assets at the south pole region of the lunar surface
FN-M-602 L	Relocate exploration assets at distributed locations outside of the south pole region on the lunar surface
FN-M-701 L	Operate mobility system(s) in uncrewed mode between crew surface missions
FN-C-101 L	Provide communications and data exchange between the lunar surface and Earth
FN-C-102 L	Provide communications and data exchange between Earth and cislunar space
FN-C-103 L	Provide communications and data exchange between assets on the lunar surface
FN-C-104 L	Provide communications and data exchange between Earth and deep space
FN-C-105 L	Provide high bandwidth, high availability communications and data exchange between the lunar surface and Earth
FN-C-106 L	Provide high bandwidth, high availability communications and data exchange between cislunar space and the Earth
FN-C-107 L	Provide high bandwidth, high availability communications and data exchange between assets on the lunar surface
FN-C-108 L	Provide high bandwidth, high availability communications and data exchange between cislunar space and the lunar surface
FN-C-201 L	Provide position, navigation, and timing services at the south pole region on the lunar surface
FN-C-202 L	Provide position, navigation, and timing services at distributed sites on the near side and outside of the south pole region on the lunar surface
FN-C-203 L	Provide position, navigation, and timing services at the far side and outside the south pole region on the lunar surface
FN-C-204 L	Provide position, navigation, and timing services in cislunar space
FN-C-205 L	Provide a coordinated lunar time scale
FN-D-101 L	Collect, store, and locally distribute data on the lunar surface
FN-D-102 L	Collect, store, and locally distribute data in cislunar space
FN-D-103 L	Collect, store, and locally distribute large volumes of data on the lunar surface sufficient to perform real time analysis for in situ decision making

FN ID	Lunar Function
FN-D-104 L	Collect, store, and locally distribute large volumes of data in cislunar space sufficient to perform real time analysis for in situ decision making
FN-D-105 L	Provide data capabilities, including protection for communication, and interface to support crew medical care on the lunar surface
FN-D-106 L	Provide data capabilities, including protection for communication, and interface to support crew medical care in cislunar space
FN-D-201 L	Process data locally on the lunar surface
FN-D-202 L	Process data locally in cislunar space
FN-D-203 L	Process large volumes of data locally on the lunar surface sufficient to perform real time analysis for in situ decision making
FN-D-204 L	Process large volumes of data locally in cislunar space sufficient to perform real time analysis for in situ decision making
FN-A-101 L	Provide robotic systems to assist crew in sunlit areas and non-PSRs on the lunar surface
FN-A-102 L	Provide robotic systems to assist crew in PSRs on the lunar surface
FN-A-103 L	Provide a robotic system capable of conducting reconnaissance
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-106 L	Enable repositioning of externally mounted utilization payloads in cislunar space
FN-A-201 L	Control robotic system(s) in sunlit areas and non-PSRs on the lunar surface from Earth and/or cislunar space
FN-A-202 L	Control robotic system(s) in PSRs on the lunar surface from Earth and/or cislunar space
FN-A-203 L	Control robotic system(s) in cislunar space from Earth and/or cislunar space
FN-A-204 L	Control robotic system(s) in cislunar space by in-situ crew
FN-A-301 L	Monitor robotic system(s) performance and health
FN-A-302 L	Provide safeguards for automated asset(s) operating near crew
FN-A-401 L	Command and control asset(s) from Earth on the lunar surface during uncrewed periods
FN-A-402 L	Command and control asset(s) from Earth in cislunar space during uncrewed periods

FN ID	Lunar Function
FN-A-403 L	Transition assets between crewed and uncrewed mode on the lunar surface
FN-A-404 L	Transition assets between crewed and uncrewed mode in cislunar space
FN-I-101 L	Collect water/ice from the south pole region of the lunar surface
FN-I-102 L	Produce scalable quantities of oxygen from lunar regolith
FN-I-103 L	Produce scalable quantities of water from in-situ materials on the lunar surface
FN-I-104 L	Conduct ISRU utilization payload and/or equipment operations on the lunar surface
FN-I-105 L	Store oxygen on the lunar surface
FN-I-106 L	Store collected water/ice on the lunar surface
FN-I-107 L	Transport scalable quantities of oxygen produced to exploration elements
FN-I-108 L	Transport scalable quantities of water produced to exploration elements
FN-I-201 L	Collect regolith at sub-scale to support demonstration using scalable capability
FN-I-202 L	Conduct regolith recovery demonstration utilization payload and/or equipment operations on the lunar surface
FN-I-203 L	Provide storage for collected regolith
FN-I-204 L	Process and refine scalable quantities of in-situ feedstock resources on the lunar surface
FN-I-205 L	Conduct autonomous construction utilization payload and/or equipment operations on the lunar surface
FN-I-206 L	Conduct advanced manufacturing utilization payload and/or equipment operations on the lunar surface
FN-I-207 L	Conduct regolith-based additive/subtractive manufacturing utilization payload and/or equipment operations on the lunar surface
FN-U-101 L	Observe and sense the lunar surface from lunar orbit
FN-U-102 L	Capture imagery on the lunar surface
FN-U-103 L	Conduct resource identification utilization payload and/or equipment operations on the lunar surface
FN-U-201 L	Provide locations to host utilization payload(s) and/or equipment in deep space

FN ID	Lunar Function
FN-U-202 L	Provide extravehicular utilization accommodation, interfaces, and resources, operable during crewed and uncrewed increments, in cislunar space
FN-U-203 L	Provide extravehicular utilization accommodation, interfaces, and resources, operable during crewed and uncrewed increments, on the lunar surface
FN-U-204 L	Provide intravehicular activity facilities, utilization accommodation, and resources, operable during crewed and uncrewed increments, on the lunar surface
FN-U-205 L	Provide intravehicular activity facilities, utilization accommodation, and resources, operable during crewed and uncrewed increments, in cislunar space
FN-U-206 L	Provide intravehicular utilization accommodation and resources during crew transit between Earth and cislunar space
FN-U-301 L	Provide capability to recover and package subsurface samples, maintaining scientific integrity of the samples, from non-PSRs and sunlit regions on the lunar surface
FN-U-302 L	Provide capability to recover and package subsurface samples, maintaining scientific integrity of the samples, from PSRs on the lunar surface
FN-U-303 L	Provide capability to recover and package surface and/or shallow subsurface samples, maintaining scientific integrity of the samples, from non-PSRs and sunlit regions on the lunar surface
FN-U-304 L	Provide capability to recover and package surface and/or shallow subsurface samples, maintaining scientific integrity of the samples, from PSRs on the lunar surface
FN-U-305 L	Provide capability to recover and package deep subsurface samples, including drill cores, maintaining scientific integrity of the samples, from non-PSRs and sunlit regions on the lunar surface
FN-U-306 L	Provide capability to recover and package deep subsurface samples, including drill cores, maintaining scientific integrity of the samples, from PSRs on the lunar surface
FN-U-401 L	Stow collected unconditioned samples on exploration assets while on the lunar surface, while maintaining scientific integrity of the samples
FN-U-402 L	Stow refrigerated samples during transport from the Lunar Surface to Earth, while maintaining scientific integrity of samples
FN-U-403 L	Stow frozen samples during transport from the Lunar Surface to Earth, while maintaining scientific integrity of samples
FN-U-404 L	Stow cryogenic samples during transport from the Lunar Surface to Earth, while maintaining scientific integrity of samples
FN-U-405 L	Stow refrigerated samples during transport from the Lunar Surface to cislunar space, while maintaining scientific integrity of samples
FN-U-406 L	Stow frozen samples during transport from the Lunar Surface to cislunar space, while maintaining scientific integrity of samples
FN-U-407 L	Stow cryogenic samples during transport from the Lunar Surface to cislunar space, while maintaining scientific integrity of samples
FN-U-408 L	Stow refrigerated samples during transport from cislunar space to Earth, while maintaining scientific integrity of samples
FN-U-409 L	Stow frozen samples during transport from cislunar space to Earth, while maintaining scientific integrity of samples
FN-U-410 L	Stow cryogenic samples during transport from cislunar space to Earth, while maintaining scientific integrity of samples

FN ID	Lunar Function
FN-U-411 L	Stow collected refrigerated samples on exploration assets while on the lunar surface, while maintaining scientific integrity of the samples
FN-U-412 L	Stow collected frozen samples on exploration assets while on the lunar surface, while maintaining scientific integrity of the samples
FN-U-413 L	Stow collected cryogenic samples on exploration assets while on the lunar surface, while maintaining scientific integrity of the samples
FN-U-414 L	Provide resources to condition refrigerated sample containers on the lunar surface
FN-U-415 L	Provide resources to condition frozen sample containers on the lunar surface
FN-U-416 L	Provide resources to condition cryogenic sample containers on the lunar surface
FN-U-501 L	Provide capability to access residual propellant from surface assets
FN-U-502 L	Transfer propellant between assets on the lunar surface
FN-U-503 L	Provide storage of cryogenic propellant on the lunar surface
FN-U-504 L	Provide storage of cryogenic propellant in space
FN-U-505 L	Provide storage of non-cryogenic propellant in space
FN-U-506 L	Provide storage of non-cryogenic propellant on the lunar surface
FN-U-507 L	Conduct fluid and propellant transfer utilization payload and/or equipment operations on the lunar surface
FN-U-508 L	Transfer propellant/fluids between assets in space
FN-U-509 L	Provide propellant management system(s) in partial gravity environment
FN-U-510 L	Provide propellant management system(s) in microgravity environment
FN-U-601 L	Conduct bioregenerative ECLSS utilization payload and/or equipment operations in space
FN-U-602 L	Conduct plant growth utilization payload and/or equipment operations in space

B.2.3 List of Mars Use Cases

UC ID	Mars Use Case
UC-T-101 M	Transportation of crew from Martian surface to Mars vicinity

UC ID	Mars Use Case
UC-T-102 M	Transportation of crew from Mars vicinity to the Martian surface
UC-T-103 M	Staging of crewed Mars mission assets in Earth vicinity
UC-T-104 M	Transportation of crew between Earth surface and Earth vicinity
UC-T-105 M	Transportation of crew between Earth vicinity and Mars vicinity
UC-T-106 M	Staging of crewed Mars surface mission assets in Mars vicinity
UC-T-107 M	Return crew from Earth vicinity to Earth surface
UC-T-108 M	Operation of robust Martian transportation systems
UC-T-201 M	Aggregation and/or physical assembly of assets in Earth vicinity
UC-T-202 M	Transportation of cargo between Earth surface and Earth vicinity
UC-T-203 M	Transportation of cargo between Earth vicinity and Mars vicinity
UC-T-204 M	Aggregation and/or physical assembly of assets in Mars vicinity
UC-T-205 M	Deployment of assets in Earth vicinity
UC-T-206 M	Deployment of assets in deep space and/or Mars vicinity
UC-T-207 M	Transportation of cargo from Mars vicinity to the Martian surface
UC-T-208 M	Transportation of cargo from the Martian surface to Mars vicinity
UC-T-209 M	Transportation of cargo from Earth vicinity back to Earth-based facilities
UC-T-301 M	Return varying sizes of unconditioned samples and containers from the Martian surface to Earth with the samples in sealed sample containers
UC-T-302 M	Return varying sizes of frozen samples and containers from the Martian surface to Earth with the samples in sealed conditioned sample containers
UC-T-303 M	Return varying sizes of cryogenic samples and containers from the Martian surface to Earth with the samples in sealed conditioned sample containers
UC-T-304 M	Transportation of biological experiments and specimens along with crew from Mars vicinity to the Martian surface
UC-T-306 M	Return varying sizes of refrigerated samples and containers from the Martian surface to Earth with the samples in sealed conditioned sample containers

UC ID	Mars Use Case
UC-T-307 M	Return varying sizes of unconditioned samples and containers from deep space and/or Mars vicinity to Earth with the samples in sealed sample containers
UC-T-308 M	Return varying sizes of refrigerated samples and containers from deep space and/or Mars vicinity to Earth with the samples in sealed conditioned sample containers
UC-T-309 M	Return varying sizes of frozen samples and containers from deep space and/or Mars vicinity to Earth with the samples in sealed conditioned sample containers
UC-G-201 M	Delivery of unconditioned cargo to curation facilities or other appropriate facilities on Earth, while maintaining scientific integrity of the samples
UC-G-202 M	Delivery of conditioned cargo to curation facilities or other appropriate facilities on Earth after landing, while maintaining scientific integrity of the samples
UC-G-401 M	Commissioning, servicing, maintenance, and upgrades for assets to maintain and restore appropriate performance in deep space and/or Mars vicinity
UC-G-402 M	Commissioning, servicing, maintenance, and upgrades for assets to maintain and restore appropriate performance on the Martian surface
UC-G-501 M	Demonstration of response to off-nominal, time-critical events during a mission on the Martian surface with Mars communication latency
UC-G-502 M	Demonstration of response to off-nominal, time-critical events during missions in deep space and/or Mars vicinity with communication latency
UC-H-101 M	Habitable assets response to emergencies autonomously to enable crew survival in deep space and/or Mars vicinity
UC-H-102 M	Habitation for extended duration (year+) in deep space and/or Mars vicinity
UC-H-103 M	Habitation for crew exploration missions on the Martian surface
UC-H-104 M	Crew living for extended duration (year+) in deep space and/or Mars vicinity
UC-H-105 M	Crew living for mid-duration (month+) crew exploration mission(s) on the Martian surface
UC-H-106 M	Monitoring of environment in habitable assets and mitigation of relevant asset hazards to protect crew health in deep space and Mars vicinity
UC-H-107 M	Monitoring of environment in habitable assets and mitigation of relevant asset hazards to protect crew health on the Martian surface
UC-H-108 M	Habitable assets response to emergencies autonomously to enable crew survival on Mars surface
UC-H-109 M	Crew living for short-duration (days to weeks) crew exploration mission(s) on the Martian surface
UC-H-110 M	Habitation for short-duration (days to weeks) crew exploration missions on the Martian surface
UC-H-201 M	On-demand, in-situ crew training in deep space for nominal and contingency procedures with consideration of Mars communication latency (non-real-time)
UC-H-202 M	Operation of exploration asset(s) when uncrewed before and/or between crew missions in Earth vicinity

UC ID	Mars Use Case
UC-H-203 M	Operation of exploration asset(s) when uncrewed in Earth vicinity
UC-H-204 M	Operation of exploration asset(s) when uncrewed in Mars vicinity
UC-H-205 M	Operation of exploration asset(s) when uncrewed on Mars surface
UC-X-101 M	Demonstration of integrated crew health and performance support assets and medical care for contingency events or emergency response in deep space and/or Mars vicinity
UC-X-102 M	Demonstration of integrated crew health and performance support assets and medical care for contingency events or emergency response on the Martian surface
UC-X-103 M	Demonstration of operations and emergency response capabilities to enable crew survival in deep space and Mars vicinity
UC-X-104 M	Demonstration of operations and emergency response capabilities to enable crew survival on the Martian surface
UC-X-105 M	Operation of crew health and performance countermeasures assets (e.g., exercise, nutrition, sensorimotor, cardiovascular, immune, radiation) for extended duration (year+) in deep space and/or Mars vicinity
UC-X-106 M	Operation of crew health and performance countermeasures assets (e.g., exercise, nutrition, sensorimotor, cardiovascular, immune, radiation) for crew mission(s) on the Martian surface
UC-X-107 M	Deployment and operation of crew health monitoring assets in deep space and/or Mars vicinity
UC-X-108 M	Deployment and operation of crew health monitoring assets on the Martian surface
UC-X-109 M	Operation of crew health and performance countermeasures assets (e.g., exercise, nutrition, sensorimotor, cardiovascular, immune, radiation) for short-duration (less than one month) crew exploration mission(s) on the Martian surface
UC-X-201 M	On-demand, in-situ crew training on the Martian surface for nominal and contingency procedures with consideration of Mars communication latency (non-real-time)
UC-P-101 M	Operation of power generation and energy storage assets on the Martian surface
UC-P-102 M	Operation of power systems at multiple distributed locations around exploration sites on the Martian surface
UC-P-103 M	Continuous operation of power generation and energy storage assets during crew safety critical mission operations on the Martian surface
UC-P-301 M	Power distribution around power generation and energy storage assets on the Martian surface
UC-P-302 M	Power distribution around power generation and energy storage assets at multiple distributed locations on the Martian surface
UC-P-501 M	Continuous operation of power generation and energy storage assets to support contingency operations on the Martian surface
UC-M-101 M	Crew use of mobility assets and tools to conduct exploration and utilization activities on the Martian surface
UC-M-201 M	Transfer of crew between habitat and external environment in deep space and/or Mars vicinity

UC ID	Mars Use Case
UC-M-202 M	Transfer of crew between habitat and external environment on the Martian surface
UC-M-301 M	Transfer of crew between landing site(s) and/or an exploration/utilization site on the Martian surface
UC-M-401 M	Deployment of assets on the Martian surface
UC-M-402 M	Deployment of robotic assets to assist crew in deep space and/or Mars vicinity
UC-M-403 M	Deployment of robotic assets to assist crew on the Martian surface
UC-M-404 M	Deployment of exploration asset(s) for ISRU demonstration on the Martian surface
UC-M-601 M	Transfer of assets between landing site(s) and/or exploration/utilization site(s) on Martian surface
UC-M-602 M	Demonstration of the identification of and transfer to a site where an asset from a previous mission is located on the Martian surface
UC-C-101 M	Communications and data exchange between assets at multiple distributed locations on the Martian surface and Earth
UC-C-102 M	Communications and data exchange between assets at multiple distributed locations on the Martian surface
UC-C-103 M	Communications and data exchange between assets in deep space and/or Mars vicinity and the Martian surface
UC-C-104 M	Communications and data exchange between assets in deep space and/or Mars vicinity and Earth
UC-C-105 M	Communications and data exchange between assets in deep space and/or Mars vicinity
UC-C-106 M	Utilization of common interface(s) for data transfer and distribution between Mars exploration assets
UC-C-107 M	Aggregation and storage of data on the Martian surface until it is able to be transmitted and confirmed received
UC-C-108 M	Aggregation and storage of data in deep space and/or Mars vicinity until it is able to be transmitted and confirmed received
UC-C-109 M	Crew provides inspirational and educational communications (e.g., interviews, speeches, recordings, etc.) from deep space, Mars vicinity, and/or Mars surface to inspire and inform the general public, students, and teachers
UC-C-110 M	Asset(s) and/or payload(s) provide communications to inspire and inform the general public, students, and teachers
UC-C-111 M	Communications and data exchange between assets on the Martian surface and Earth with sufficient bandwidth and availability to achieve associated science objectives
UC-C-201 M	Identification, tracking, and documentation of the location(s) of collected Mars surface samples
UC-C-202 M	Determination of positioning, navigation, and timing for crew and assets at exploration sites on the Martian surface

UC ID	Mars Use Case
UC-C-203 M	Determination of positioning, navigation, and timing for crew and assets in deep space and Mars vicinity
UC-C-204 M	Demonstration of landing within a defined radius around an intended location on the Martian surface
UC-C-301 M	Remote command and control of assets on Mars surface from assets on Earth, Mars vicinity, and/or other Mars surface locations
UC-C-302 M	Demonstration of remote command and control of robotic assets on Mars surface from assets on Earth, Mars vicinity, and/or other Mars surface locations
UC-C-303 M	Demonstration of remote command and control of robotic assets in-space from assets on Earth, Mars vicinity, and/or Mars surface locations
UC-D-201 M	Storage and local processing of space weather data in deep space and Mars vicinity
UC-A-101 M	Demonstration of robotic systems to perform and/or assist in external utilization activities on the Martian surface
UC-A-102 M	Demonstration of robotic systems to perform and/or assist crew conducting EVA activities on the Martian surface
UC-A-103 M	Demonstration of robotic systems to perform and/or assist in utilization activities internal to crewed assets on the Martian surface
UC-A-104 M	Demonstration of robotic systems to perform and/or assist in commissioning, servicing, maintenance, and/or upgrades of assets to maintain and restore appropriate performance on the Martian surface
UC-A-105 M	Demonstration of robotic systems to perform and/or assist in logistics operations on the Martian surface
UC-A-106 M	Demonstration of robotic systems to perform and/or assist in utilization activities internal to crewed assets in space
UC-A-107 M	Demonstration of robotic systems to perform and/or assist in commissioning, servicing, maintenance, and/or upgrades of assets to maintain and restore appropriate performance in space
UC-A-108 M	Demonstration of robotic systems to perform and/or assist in logistics operations in space
UC-A-109 M	Robotic surveillance of Martian surface near potential crewed landing and exploration sites to identify locations of interest
UC-A-201 M	Demonstration of safe in-situ crew command and control of robotic asset(s) on the Martian surface
UC-A-202 M	Demonstration of safe in-situ crew command and control of robotic asset(s) in deep space and/or Mars vicinity
UC-A-301 M	Safe and effective interaction between crew and autonomous asset(s)
UC-A-401 M	Planning and execution of crew tasks on Mars surface with autonomy and reduced reliance on Earth based systems
UC-A-402 M	Planning and execution of crew tasks in deep space and/or Mars vicinity with autonomy and reduced reliance on Earth based systems
UC-A-403 M	Demonstration of autonomous operation of assets on Mars surface with reduced commands from crew or Earth-based systems

UC ID	Mars Use Case
UC-A-404 M	Demonstration of autonomous operation of assets in deep space and/or Mars vicinity with reduced commands from crew or Earth-based systems
UC-A-405 M	Flight control and mission integration in nominal and off-nominal scenarios on Mars surface with Mars communication latency
UC-A-406 M	Flight control and mission integration in nominal and off-nominal scenarios in deep space and/or Mars vicinity with Mars communication latency
UC-I-101 M	Operation of exploration assets for resource utilization on the Martian Surface
UC-I-102 M	Demonstration of scalable ISRU production, storage, and/or transfer on the Martian surface
UC-I-201 M	Demonstration of construction and/or manufacturing using surface-born resources on the Martian surface
UC-U-102 M	Demonstration of surveying the Martian surface to identify and locate potential site(s) for resource utilization
UC-U-103 M	Identification of surface samples in non-special regions on the Martian surface
UC-U-104 M	Identification of surface samples in special regions on the Martian surface
UC-U-105 M	Monitoring of deep space, Martian orbit, and Martian surface natural environments, including incoming and albedo radiation using systems in deep space and/or Mars vicinity
UC-U-106 M	Monitoring of deep space, Martian orbit, and Martian surface natural environments, including incoming and albedo radiation using systems on the Martian surface
UC-U-201 M	Intravehicular science and utilization activities on the Martian surface
UC-U-202 M	Intravehicular science and utilization activities in deep space and/or Mars vicinity
UC-U-301 M	Collection, documentation, and packaging of surface and/or shallow sub-surface samples, maintaining scientific integrity of the samples, from special regions on the Martian surface
UC-U-302 M	Collection, documentation, and packaging of surface and/or shallow sub-surface samples, maintaining scientific integrity of the samples, from non-special regions on the Martian surface
UC-U-303 M	Collection, recovery, documentation, and packaging of deep sub-surface samples, maintaining scientific integrity of the samples, from non-special regions on the Martian surface
UC-U-305 M	Collection, recovery, documentation, and packaging of deep sub-surface samples, maintaining scientific integrity of the samples, from special regions on the Martian surface
UC-U-501 M	Demonstration of recovery of excess propellant from tanks of previous asset(s) on the Martian surface
UC-U-701 M	Deployment and operation of utilization payloads and/or equipment related to Impact Chronology on the Martian surface with long-term remote operation
UC-U-702 M	Conduct sample science, including preliminary analysis for geochemistry, mineralogy, and organic content, and solution chemistry of the soluble component of solid samples as well as ice and/or liquid samples on the Martian surface.
UC-U-703 M	Conduct borehole measurements at varying depths on the Martian Surface, including ionizing radiation and heat flow.

UC ID	Mars Use Case
UC-U-704 M	Deployment and operation of utilization payloads and/or equipment related to geologic processes on the Martian surface with long-term remote operation
UC-U-705 M	Deployment and operation of utilization payloads and/or equipment related to Solar System Volatiles on the Martian surface with long-term remote operation
UC-U-706 M	Deployment and operation of utilization payloads and/or equipment related to in-space weather on the Martian surface with long-term remote operation
UC-U-708 M	Deployment and operation of utilization payloads and/or equipment related to fundamental plasma processes on the Martian surface with long-term remote operation
UC-U-709 M	Deployment and operation of utilization payload(s) and/or equipment related to the solar wind at assets in Mars vicinity
UC-U-710 M	Conduct of biological science and human research activities on the Martian surface
UC-U-711 M	Conduct of biological science and human research activities in deep space and/or Mars vicinity
UC-U-713 M	Deployment and operation of external utilization payload(s) and/or equipment related to biological science analysis and human research in deep space and/or Mars vicinity
UC-U-712 M	Deployment and operation of external utilization payloads and/or equipment related to biological science analysis and human research on the Martian surface with long-term remote operation
UC-U-714 M	Conduct of fundamental physics experiments on the Martian surface
UC-U-715 M	Conduct of fundamental physics experiments in deep space and/or Mars vicinity
UC-U-716 M	Deployment and operation of utilization payload(s) and/or equipment related to physical systems and fundamental physics in deep space and/or Mars vicinity with long-term remote operation
UC-U-717 M	Deployment and operation of utilization payload(s) and/or equipment related to physical systems and fundamental physics on the Martian surface with long term remote operation
UC-U-801 M	Enable reduction of long-term environmental impact of waste and housekeeping
UC-U-802 M	Enable planetary stewardship through sustainable resource utilization, maintaining scientific integrity, and reduction of environmental impact
UC-U-803 M	Demonstration of reuse of assets on the Martian surface
UC-U-804 M	Demonstration of the reuse of hardware and materials brought to the surface during subsequent missions on the Martian surface
UC-U-805 M	Disposal of assets in a manner that ensures future viable usage of exploration sites on the Martian surface
UC-U-806 M	Control bioburden release by assets on the Martian surface
UC-U-807 M	Control transfer of Mars environmental contamination into crewed assets
UC-U-808 M	Deployment and operation of utilization payloads and/or equipment related to presence of Earth life on at various distances from landing sites the Martian surface with long-term remote operation

B.2.4 List of Mars Functions

FN ID	Mars Function
FN-T-101 M	Staging of crewed Mars mission(s) in Earth vicinity
FN-T-102 M	Transport crew from Martian surface to Mars vicinity
FN-T-103 M	Transport crew from Earth surface to Earth vicinity
FN-T-104 M	Transport crew between Earth vicinity and Mars vicinity
FN-T-201 M	Deploy robotic assets into operational configuration in deep space and/or Mars vicinity
FN-T-202 M	Transport cargo from Mars vicinity to the Martian surface
FN-T-203 M	Enable rendezvous, proximity operation, docking, berthing, and undocking of exploration assets in Earth vicinity
FN-T-204 M	Transport cargo from Earth surface to Earth vicinity
FN-T-205 M	Enable rendezvous, proximity operation, docking, berthing, and undocking of exploration assets in Mars vicinity
FN-T-206 M	Unload asset(s) in Earth vicinity
FN-T-207 M	Deploy assets into operational configuration in Earth vicinity
FN-T-208 M	Unload asset(s) in deep space and/or Mars vicinity
FN-T-209 M	Deploy assets into operational configuration in deep space and/or Mars vicinity
FN-T-210 M	Transfer propellant into storage system(s) and/or transportation system(s)
FN-T-211 M	Maintain necessary environmental conditions for propellant in storage system(s) or transportation system(s)
FN-T-212 M	Store propellant
FN-T-213 M	Transport cargo between Earth vicinity and Mars vicinity
FN-T-214 M	Transport assets from Mars vicinity to locations on the Mars surface, in Mars vicinity, or in deep space suitable for end of life disposal
FN-T-215 M	Transport cargo from Martian surface to Mars vicinity
FN-T-216 M	Store cargo during ascent from the Martian surface

FN ID	Mars Function
FN-T-217 M	Prepare cargo for Earth surface return from Earth vicinity
FN-T-218 M	Provide delivery of live, actively growing biological specimens to deep space and/or Mars vicinity, including late load of cargo prior to launch
FN-T-302 M	Provide resources to condition frozen sample containers during transit from Martian surface to Earth
FN-T-305 M	Provide resources to condition frozen sample containers during transit from the Martian surface to Mars vicinity
FN-T-306 M	Provide resources to condition frozen sample containers during transit from Mars vicinity to Earth
FN-T-307 M	Provide resources to condition cryogenic sample containers during transit from Martian surface to Earth
FN-T-308 M	Provide resources to condition cryogenic sample containers during transit from the Martian surface to Mars vicinity
FN-T-309 M	Provide resources to condition cryogenic sample containers during transit from Mars vicinity to Earth
FN-T-310 M	Provide resources to condition refrigerated sample containers during transit from Martian surface to Earth
FN-T-311 M	Provide resources to condition refrigerated sample containers during transit from the Martian surface to Mars vicinity
FN-T-312 M	Provide resources to condition refrigerated sample containers during transit from Martian vicinity to Earth
FN-T-401 M	Transport crew from Mars vicinity to the Martian surface
FN-T-402 M	Transport crew from Earth vicinity to Earth surface
FN-T-403 M	Transport cargo from Earth vicinity to Earth surface
FN-T-404 M	Provide Mars atmospheric entry for cargo
FN-G-101 M	Provide ground services on Earth
FN-G-102 M	Stack and integrate assets on Earth
FN-G-103 M	Enable vehicle launch(es)
FN-G-104 M	Enable multiple launch attempts for transportation from Earth surface to Earth vicinity
FN-G-201 M	Recover crew after Earth landing
FN-G-202 M	Recover cargo after Earth landing

FN ID	Mars Function
FN-G-203 M	Relocate cargo in a clean environment, minimizing contamination to/from the container, between sites and facilities on Earth's surface
FN-G-401 M	Monitor the performance and health of assets on the Martian surface (demonstration)
FN-G-402 M	Manipulate robotic/EVA/IVA tools and hardware to perform asset servicing, maintenance, upgrades, or replacements on the Martian surface
FN-G-403 M	Inspect assets on the Martian surface
FN-G-404 M	Manipulate robotic/EVA/IVA tools and hardware to perform asset servicing, maintenance, upgrades, or replacements for extended duration (year+) in deep space and/or Mars vicinity
FN-G-405 M	Inspect assets during extended duration (year+) in deep space and/or Mars vicinity
FN-G-406 M	Inspect performance of servicing, maintenance, upgrade, or replacement activities to evaluate success on the Martian surface
FN-G-407 M	Monitor the performance and health of assets in deep space and/or Mars vicinity (demonstration)
FN-G-408 M	Detect asset anomalies or off-nominal performance on the Martian surface
FN-G-409 M	Diagnose asset anomalies or off-nominal performance on the Martian surface
FN-G-410 M	Determine if asset servicing/maintenance is needed on the Martian surface
FN-G-411 M	Detect asset anomalies or off-nominal performance in deep space and/or Mars vicinity
FN-G-412 M	Diagnose asset anomalies or off-nominal performance in deep space and/or Mars vicinity
FN-G-413 M	Determine if asset servicing/maintenance is needed in deep space and/or Mars vicinity
FN-G-501 M	Control and monitor transfer of Mars environmental contamination into and between habitable assets on the Martian surface
FN-H-101 M	Stabilize and mitigate hazardous conditions autonomously within habitable assets in deep space and/or Mars vicinity
FN-H-102 M	Enable crew habitation during transit from Mars vicinity to Martian surface
FN-H-103 M	Provide private areas for crew, including for individual crew members, for extended duration (year+) in deep space and/or Mars vicinity
FN-H-104 M	Manage and store logistics for extended duration (year+) in deep space and/or Mars vicinity
FN-H-105 M	Manage a pressurized habitable environment for crew for extended duration (year+) in deep space and/or Mars vicinity
FN-H-106 M	Protect crew and assets from natural and induced environmental hazards (e.g., vibration, atmospheric contamination, backwards planetary protection considerations, fire induced contamination, radiation, dust, electrostatic charging, etc.) for extended duration (year+) in deep space and/or Mars vicinity

FN ID	Mars Function
FN-H-107 M	Provide private areas for crew, including for individual crew members, for crew mission(s) on the Martian surface
FN-H-108 M	Manage and store logistics for crew mission(s) on the Martian surface
FN-H-109 M	Manage a pressurized habitable environment for crew mission(s) on the Martian surface
FN-H-110 M	Protect crew and assets from natural and induced environmental hazards (e.g., vibration, atmospheric contamination, fire induced contamination, radiation, dust, electrostatic charging, etc.) for crew mission(s) on the Martian surface
FN-H-111 M	Demonstrate remediation of hazardous conditions within habitable assets for extended duration (year+) crew mission(s) in deep space and/or Mars vicinity
FN-H-112 M	Provide safe haven for extended duration (year+) in deep space and/or Mars vicinity
FN-H-113 M	Demonstrate recovery of habitable environment during extended duration (year+) mission in deep space and/or Mars vicinity
FN-H-114 M	Provide safe haven for crew mission(s) on the Martian surface
FN-H-115 M	Demonstrate recovery of habitable environment for crew mission(s) on the Martian surface
FN-H-116 M	Manage a pressurized habitable environment for crew in Earth vicinity
FN-H-117 M	Manage a pressurized habitable environment for crew in Mars vicinity
FN-H-118 M	Monitor the pressurized environment and induced environments to detect potential hazards to crew within habitable assets in deep space and/or Mars vicinity
FN-H-119 M	Monitor the pressurized environment and induced environments to detect potential hazards to crew within habitable assets on the Martian surface
FN-H-120 M	Enable crew habitation during transit from the Martian surface to Mars vicinity
FN-H-121 M	Stabilize and mitigate hazardous conditions autonomously within habitable assets on Mars surface
FN-H-123 M	Demonstrate emergency ingress/egress assets that support crew health, performance, and safety in off-nominal scenarios for extended duration (year+) crew mission(s) in deep space and/or Mars vicinity
FN-H-124 M	Demonstrate emergency ingress/egress assets that support crew health, performance, and safety in off-nominal scenarios for crew mission(s) on the Martian surface
FN-H-125 M	Demonstrate ready access to and suitable stowage for emergency medical equipment during EVAs and in habitable assets for extended duration (year+) crew mission(s) in deep space and/or Mars vicinity
FN-H-126 M	Demonstrate ready access to and suitable stowage for emergency medical equipment during EVAs and in habitable assets for crew mission(s) on the Martian surface
FN-H-127 M	Demonstrate use of crew survival equipment and assets for extended duration (year+) crew mission(s) in deep space and/or Mars vicinity
FN-H-128 M	Demonstrate use of crew survival equipment and assets for crew mission(s) on the Martian surface

FN ID	Mars Function
FN-H-129 M	Demonstrate remediation of hazardous conditions within habitable assets for crew mission(s) on the Martian surface
FN-X-101 M	Manage crew health and performance (medical, physiological, psychological, environmental, task support, etc.) for extended duration (year+) crew mission(s) in deep space and/or Mars vicinity
FN-X-102 M	Manage crew health and performance for mid-duration (month+) crew mission(s) on the Martian surface
FN-X-103 M	Enable crew exercise in deep space and/or Mars vicinity
FN-X-104 M	Prepare nutrition logistics for extended duration (year+) in deep space and/or Mars vicinity
FN-X-105 M	Enable crew exercise on the Martian surface
FN-X-106 M	Provide nutrition logistics for crew mission(s) on the Martian surface
FN-X-107 M	Deploy crew health monitoring assets for extended duration (year+) in deep space and/or Mars vicinity
FN-X-108 M	Manage crew health and performance for short-duration (less than one month) crewed mission(s) on the Martian surface
FN-X-109 M	Demonstrate treatment of emergency crew health conditions for extended duration (year+) crew mission(s) in deep space and/or Mars vicinity
FN-X-110 M	Demonstrate treatment of emergency crew health conditions for crew mission(s) on the Martian surface
FN-X-111 M	Demonstrate equipment to manage incapacitated crew rescue, to move crew member to suitable shelter or treatment area for extended duration (year+) crew mission(s) in deep space and/or Mars vicinity
FN-X-112 M	Demonstrate equipment to manage incapacitated crew rescue, to move crew member to suitable shelter or treatment area for crew mission(s) on the Martian surface
FN-X-201 M	Enable on-demand, in-situ training of crew in deep space for nominal and contingency procedures
FN-X-202 M	Enable on-demand, in-situ training of crew on the Martian surface for nominal and contingency procedures
FN-X-113 M	Manage crew health and performance for short-duration (days to weeks) crew mission(s) on the Martian surface
FN-L-201 M	Manage the transfer and storage of logistics in Earth vicinity
FN-L-202 M	Move logistics and/or cargo into habitable assets for crew mission(s) on the Martian surface
FN-L-203 M	Manage waste/trash from servicing, maintenance, or upgrade activities (demonstration)
FN-L-301 M	Manage waste/trash and housekeeping for nominal and contingency use for extended duration (year+) crew mission(s) in deep space and/or Mars vicinity
FN-L-302 M	Manage waste/trash and housekeeping for nominal and contingency use for crew mission(s) on the Martian surface

FN ID	Mars Function
FN-P-101 M	Generate power on the Martian surface
FN-P-102 M	Generate power at multiple distributed locations on the Martian surface
FN-P-201 M	Store energy on the Martian surface
FN-P-202 M	Store energy at multiple distributed locations on the Martian surface
FN-P-301 M	Distribute power to assets in Earth vicinity
FN-P-302 M	Distribute power to assets in deep space and/or Mars vicinity
FN-P-303 M	Distribute power to assets on the Martian surface
FN-P-304 M	Distribute power to utilization payloads and/or equipment in deep space and/or Mars vicinity
FN-P-401 M	Provide power for deployed external surface utilization payloads(s) and/or equipment for long durations (months to years+)
FN-M-201 M	Provide ingress/egress between habitable volumes and external environment that maintain crew health, performance and safety in deep space and/or Mars vicinity
FN-M-202 M	Provide ingress/egress between habitable volumes and external environment that maintain crew health, performance and safety on the Martian surface
FN-M-301 M	Transfer crew between sites on the Martian surface
FN-M-401 M	Deploy robotic assets into operational configuration on the Martian surface
FN-M-402 M	Deploy assets into operational configuration on the Martian surface
FN-M-403 M	Unload asset(s) on the Martian surface
FN-M-404 M	Deploy ISRU demonstration assets into operational configuration on the Martian surface
FN-M-501 M	Transfer assets between sites on the Martian surface
FN-M-502 M	Reposition varying sizes of unconditioned samples and containers on the Martian surface
FN-M-503 M	Reposition varying sizes of frozen samples and containers on the Martian surface
FN-M-504 M	Reposition varying sizes of cryogenic samples and containers on the Martian surface
FN-M-505 M	Reposition varying sizes of refrigerated samples and containers on the Martian surface

FN ID	Mars Function
FN-C-101 M	Provide communications and data exchange between assets on the Martian surface
FN-C-102 M	Provide communications and data exchange between assets on the Martian surface and Earth
FN-C-103 M	Provide communications and data exchange between assets in deep space and/or Mars vicinity and the Martian surface
FN-C-104 M	Provide communications and data exchange between assets in deep space and/or Mars vicinity and Earth
FN-C-105 M	Provide communications and data exchange between the Martian surface and Earth, deep space/Mars vicinity, and/or other locations on the Martian surface
FN-C-106 M	Provide communications and data exchange between assets at a variety of exploration locations on the Martian surface
FN-C-107 M	Provide communications and data exchange between assets in deep space and/or Mars vicinity
FN-C-108 M	Provide communications and data exchange between Earth and Earth vicinity
FN-C-109 M	Provide communications and data exchange between assets on the Martian surface and Earth with sufficient bandwidth and availability to achieve associated science objectives
FN-C-110 M	Provide communications and data exchange between assets in deep space/Mars vicinity and Earth with sufficient bandwidth and availability to achieve associated science objectives
FN-C-201 M	Provide coordinated position, navigation, and timing services on the Martian surface
FN-C-202 M	Provide position, navigation, and timing services in deep space and/or Mars vicinity
FN-C-203 M	Provide position, navigation, and timing services in Earth vicinity
FN-C-204 M	Provide coordinated position, navigation, and timing services during Mars entry, descent, and landing
FN-C-205 M	Provide coordinated position, navigation, and timing services during Mars ascent
FN-C-206 M	Provide precision landing for transport of assets to Earth's surface
FN-C-207 M	Provide precision landing for transport of assets to the Martian surface (demonstration)
FN-C-301 M	Command and control assets in Earth vicinity from a remote location (e.g., Earth-based facilities)
FN-C-302 M	Command and control assets in deep space and/or Mars vicinity from a remote location (e.g., Earth-based facilities) (demonstration)
FN-C-303 M	Command and control assets on the Martian surface from a remote location (e.g., Earth-based facilities, other Mars surface locations)
FN-C-304 M	Operate exploration asset(s) when uncrewed before and/or between crewed missions in Earth vicinity

FN ID	Mars Function
FN-C-305 M	Transition asset in and out of uncrewed mode in Earth vicinity
FN-C-306 M	Transition asset in and out of uncrewed mode in Mars vicinity
FN-C-307 M	Transition asset in and out of uncrewed mode on Mars surface
FN-C-308 M	Transition an asset in and out of uncrewed mode on the Martian surface (demonstration)
FN-C-309 M	Operate asset(s) when uncrewed between crewed missions on the Martian surface (demonstration)
FN-C-310 M	Transition assets into end-of-life mode
FN-D-101 M	Collect, store, and distribute data on the Martian surface
FN-D-102 M	Collect, store, and distribute data in deep space and/or Mars vicinity
FN-D-103 M	Document and store data about a Martian surface site location
FN-D-104 M	Collect, store, and locally distribute large volumes of data in deep space and Mars vicinity sufficient to perform real time analysis for in situ decision making
FN-D-201 M	Provide Earth-independent decision support for time-critical asset malfunctions on Mars surface (demonstration)
FN-D-202 M	Process large volumes of data locally in deep space and Mars vicinity sufficient to perform real time analysis for in situ decision making
FN-A-101 M	Assist crew conducting utilization activities with robotic systems on the Martian surface (demonstration)
FN-A-102 M	Assist crew surveying areas of interest and identify potential utilization locations with robotic systems on the Martian surface (demonstration)
FN-A-103 M	Assist crew recovering and packaging samples with robotic systems on the Martian surface (demonstration)
FN-A-104 M	Robotic systems operate and/or monitor utilization experiments internal to crewed assets on the Martian surface (demonstration)
FN-A-105 M	Robotic systems assist crew operating and/or monitoring utilization experiments internal to crewed assets on the Martian surface (demonstration)
FN-A-106 M	Use robotic systems to assist crew performing system maintenance and upgrades of assets on the Martian surface (demonstration)
FN-A-107 M	Use robotic systems to assist crew moving logistics and/or cargo into habitable elements on the Martian surface (demonstration)
FN-A-108 M	Use robotic systems to assist crew organizing logistics and waste/trash on the Martian surface (demonstration)
FN-A-109 M	Use robotic systems to assist managing waste/trash and housekeeping for nominal and continency use on the Martian surface (demonstration)

FN ID	Mars Function
FN-A-110 M	Use robotic systems to assist crew operating utilization experiments internal to crewed assets in space (demonstration)
FN-A-111 M	Detect and diagnose asset anomalies or off-nominal performance using robotic systems in space (demonstration)
FN-A-112 M	Use robotic systems to assist crew performing system maintenance and upgrades of assets in space (demonstration)
FN-A-113 M	Use robotic systems to assist crew moving logistics and/or cargo into habitable elements in space as (demonstration)
FN-A-114 M	Use robotic systems to assist crew organizing logistics and waste/trash in space as (demonstration)
FN-A-115 M	Use robotic systems to assist managing waste/trash and housekeeping for nominal and contingency use in space (demonstration)
FN-A-116 M	Enable robotic assistance of crew in deep space and/or Mars vicinity
FN-A-117 M	Enable robotic assistance of crew on the Martian surface
FN-A-118 M	Use robotic systems to move logistics and/or cargo into habitable elements in space (demonstration)
FN-A-119 M	Use robotic systems to organize logistics and waste/trash in space (demonstration)
FN-A-120 M	Use robotic systems to manage waste/trash and housekeeping for nominal and contingency use in space (demonstration)
FN-A-121 M	Detect and diagnose asset anomalies or off-nominal performance using robotic systems on the Martian surface (demonstration)
FN-A-122 M	Inspect performance of servicing, maintenance, upgrade, or replacement activities to evaluate success using robotic systems on the Martian surface (demonstration)
FN-A-123 M	Robotic systems perform maintenance and upgrades of assets on the Martian surface (demonstration)
FN-A-124 M	Use robotic systems to operate utilization experiments internal to crewed assets in space (demonstration)
FN-A-125 M	Inspect performance of servicing, maintenance, upgrade, or replacement activities to evaluate success using robotic systems in space (demonstration)
FN-A-126 M	Operate robotic systems to perform maintenance and upgrades assets in space (demonstration)
FN-A-127 M	Conduct utilization activities external to crewed elements with robotic systems on the Martian surface (demonstration)
FN-A-128 M	Use robotic systems to move logistics and/or cargo into habitable elements on the Martian surface (demonstration)
FN-A-129 M	Use robotic systems to organize logistics and waste/trash on the Martian surface (demonstration)
FN-A-130 M	Use robotic systems to manage waste/trash and housekeeping for nominal and contingency use on the Martian surface (demonstration)

FN ID	Mars Function
FN-A-131 M	Conduct reconnaissance of Martian surface site locations using robotic systems
FN-A-132 M	Enable repositioning of externally mounted utilization payloads on assets in deep space and/or Mars vicinity
FN-A-201 M	Command and control robotic assets on the Martian surface from a remote location (e.g., Earth-based facilities, other Mars surface locations) (demonstration)
FN-A-202 M	Enable the control of robotic asset(s) by crew on the Martian surface (demonstration)
FN-A-203 M	Enable the control of robotic asset(s) by crew in deep space and/or Mars vicinity (demonstration)
FN-A-301 M	Provide safety features on robotic and/or autonomous asset(s) operating near crew
FN-A-401 M	Execute higher-level commands and make in-situ decisions autonomously for assets on the Martian surface (demonstration)
FN-A-402 M	Execute higher-level commands and make in-situ decisions autonomously for assets in deep space and/or Mars vicinity (demonstration)
FN-A-403 M	Provide Earth-independent decision support for time-critical asset malfunctions in deep space and/or Mars vicinity (demonstration)
FN-I-101 M	Collect in situ materials/feedstock on the Martian surface (demonstration)
FN-I-102 M	Produce commodities on the Martian surface (demonstration)
FN-I-103 M	Process, refine, and verify the quality of commodities on the Martian surface (demonstration)
FN-I-104 M	Store commodities on the Martian surface (demonstration)
FN-I-105 M	Transfer ISRU commodities between assets and/or sites on the Martian surface (demonstration)
FN-I-106 M	Transition ISRU assets from operation to end-of-life while minimizing impacts to long-term science objectives and sustainability (demonstration)
FN-I-107 M	Identify and characterize in-situ material/feedstock on the Martian surface (demonstration)
FN-I-201 M	Unload or manufacture pieces or parts to support construction and/or manufacturing on the Martian surface (demonstration)
FN-I-202 M	Assemble pieces of a construction project on the Martian surface (demonstration)
FN-I-203 M	Inspect and validate accuracy and performance of manufacturing and/or construction activities on the Martian surface (demonstration)
FN-U-101 M	Provide real-time situational awareness with reduced reliance on ground support on Mars surface (demonstration)
FN-U-103 M	Collect data about a Martian surface site location

FN ID	Mars Function
FN-U-104 M	Identify asset(s) on the Martian surface (demonstration)
FN-U-105 M	Survey areas of interest and identify potential scientific utilization locations with robotic systems on the Martian surface (demonstration)
FN-U-106 M	Identify potential exploration sites on the Martian surface
FN-U-107 M	Identify potential utilization locations on the Martian surface
FN-U-108 M	Provide real-time situational awareness with reduced reliance on ground support in deep space and/or Mars vicinity (demonstration)
FN-U-109 M	Capture imagery on the Martian surface
FN-U-110 M	Identify surface samples in non-special regions on the Martian surface
FN-U-111 M	Identify surface samples in special regions on the Martian surface
FN-U-112 M	Provide capabilities for monitoring of deep space, Martian orbit, and Martian surface natural environments, including incoming and albedo radiation using systems in deep space and/or Mars vicinity
FN-U-113 M	Provide capabilities for monitoring of deep space, Martian orbit, and Martian surface natural environments, including incoming and albedo radiation using systems on the Martian surface
FN-U-201 M	Conduct resource utilization payload and/or equipment operations on the Martian surface
FN-U-202 M	Identify and characterize resources for potential resource utilization at a given site (demonstration)
FN-U-203 M	Provide extravehicular utilization accommodation, interfaces, and resources, operable during crewed and uncrewed increments, in deep space and/or Mars vicinity
FN-U-204 M	Provide accommodation, interfaces, and resources for biological experiments and specimens on crewed assets for Mars entry, descent, and landing
FN-U-206 M	Provide intravehicular activity facilities, utilization accommodation, and resources, operable during crewed and uncrewed increments, on the Martian surface
FN-U-207 M	Provide intravehicular activity facilities, utilization accommodation, and resources in deep space and/or Mars vicinity
FN-U-208 M	Provide extravehicular utilization accommodation, interfaces, and resources, operable during crewed and uncrewed increments, on the Martian surface
FN-U-301 M	Provide capability to recover and package, minimizing contamination to/from the container, Martian surface and shallow subsurface samples in special regions
FN-U-302 M	Document collected Martian samples
FN-U-303 M	Provide capability to recover and package Martian surface and shallow subsurface samples, maintaining scientific integrity of the samples, from non-special regions on the Martian surface
FN-U-304 M	Provide capability to recover and package samples with robotic systems on the Martian surface (demonstration)

FN ID	Mars Function
FN-U-305 M	Identify the location(s) of collected Mars surface samples
FN-U-306 M	Provide capability to recover and package Martian deep subsurface samples, maintaining scientific integrity of the samples, from non-special regions on the Martian surface
FN-U-307 M	Document the Martian surface site location where samples were collected
FN-U-309 M	Provide capability to recover and package Martian deep subsurface samples, maintaining scientific integrity of the samples, from special regions on the Martian surface
FN-U-402 M	Stow collected unconditioned samples on exploration assets while on the Martian surface, while maintaining scientific integrity of the samples
FN-U-403 M	Stow collected frozen samples on exploration assets while on the Martian surface, while maintaining scientific integrity of the samples
FN-U-404 M	Stow frozen samples during transport from the Martian Surface to Earth, while maintaining scientific integrity of samples
FN-U-405 M	Stow frozen samples during transport from the Martian Surface to Mars vicinity, while maintaining scientific integrity of samples
FN-U-406 M	Stow frozen samples during transport from Mars vicinity to Earth, while maintaining scientific integrity of samples
FN-U-407 M	Provide resources to condition frozen sample containers on the Martian surface
FN-U-408 M	Stow collected cryogenic samples on exploration assets while on the Martian surface, while maintaining scientific integrity of the samples
FN-U-409 M	Stow cryogenic samples during transport from the Martian Surface to Earth, while maintaining scientific integrity of samples
FN-U-410 M	Stow cryogenic samples during transport from the Martian Surface to Mars vicinity, while maintaining scientific integrity of samples
FN-U-411 M	Stow cryogenic samples during transport from Mars vicinity to Earth, while maintaining scientific integrity of samples
FN-U-412 M	Provide resources to condition cryogenic sample containers on the Martian surface
FN-U-413 M	Stow collected refrigerated samples on exploration assets while on the Martian surface, while maintaining scientific integrity of the samples
FN-U-414 M	Stow refrigerated samples during transport from the Martian Surface to Earth, while maintaining scientific integrity of samples
FN-U-415 M	Stow refrigerated samples during transport from the Martian Surface to Mars vicinity, while maintaining scientific integrity of samples
FN-U-416 M	Stow refrigerated samples during transport from Mars vicinity to Earth, while maintaining scientific integrity of samples
FN-U-417 M	Provide resources to condition refrigerated sample containers on the Martian surface
FN-U-418 M	Stow collected unconditioned samples during transport from Mars vicinity to Earth, while maintaining scientific integrity of samples

FN ID	Mars Function
FN-U-501 M	Recover propellant from assets on the Martian surface (demonstration)
FN-U-502 M	Transfer propellant into storage asset(s) and/or transportation asset(s) on the Martian surface (demonstration)
FN-U-503 M	Maintain necessary environmental conditions for propellant in storage asset(s) or transportation asset(s) (demonstration)
FN-U-504 M	Store propellant on the Martian surface (demonstration)
FN-U-701 M	Conduct science and collect science data on the Martian surface
FN-U-702 M	Deploy and operate external surface utilization payloads on the Martian surface
FN-U-703 M	Provide capabilities for conducting sample science, including preliminary analysis for geochemistry, mineralogy, and organic content, and solution chemistry of the soluble component of solid samples as well as ice and/or liquid samples on the Martian surface.
FN-U-704 M	Provide capabilities to conduct borehole measurements at varying depths on the Martian Surface, including ionizing radiation and heat flow.
FN-U-801 M	Repurpose and/or recycle asset equipment on the Martian surface (demonstration)
FN-U-802 M	Enable planetary protection protocols for end-of-life for assets in Mars vicinity
FN-U-803 M	Enable planetary protection protocols for end-of-life for assets on the Martian surface
FN-U-804 M	Control bioburden release from assets to Mars surface and environment

B.3 Element Function Mappings

Note: *Human Lunar Return segment elements form the basis for satisfying functional needs. These element mappings help identify functional gaps that must be addressed in follow-on segments.*

Note: *This document does not map some supporting capabilities as elements. For example, while commercial launch vehicles will play a vital role in the architecture, they are not mapped here, as they are subject to future implementations and procurements.*

B.3.1 Commercial Lunar Payload Services

B.3.1.1 Human Lunar Return

Human Lunar Return Segment	
Commercial Lunar Payload Services	
FN-T-201 L	Transport a limited amount of cargo (100s of kg) from Earth to south pole region sites on the lunar surface
FN-T-403 L	Enable landing on the lunar surface under all lighting conditions
FN-M-401 L	Unload a limited amount of cargo (100s of kg) on the lunar surface

B.3.1.2 Foundational Exploration

Foundational Exploration Segment	
Commercial Lunar Payload Services	
FN-T-201 L	Transport a limited amount of cargo (100s of kg) from Earth to south pole region sites on the lunar surface
FN-T-203 L	Transport a limited amount of cargo (100s of kg) from Earth to distributed sites outside of the south pole region on the lunar surface
FN-T-205 L	Transport a limited amount of cargo (100s of kg) from Earth to the far side of the lunar surface
FN-T-403 L	Enable landing on the lunar surface under all lighting conditions
FN-M-401 L	Unload a limited amount of cargo (100s of kg) on the lunar surface

B.3.2 Exploration EVA Systems

B.3.2.1 Human Lunar Return

Human Lunar Return Segment	
Exploration EVA Systems	
FN-M-101 L	Enable crew lunar surface extravehicular activity in sunlit areas and non-PSRs
FN-M-102 L	Enable crew lunar surface extravehicular activity in PSRs
FN-M-201 L	Enable the cleaning of EVA equipment and tools
FN-U-102 L	Capture imagery on the lunar surface
FN-U-303 L	Provide capability to recover and package surface and/or shallow subsurface samples, maintaining scientific integrity of the samples, from non-PSRs and sunlit regions on the lunar surface

B.3.2.2 Foundational Exploration

Foundational Exploration Segment	
Exploration EVA Systems	
FN-M-101 L	Enable crew lunar surface extravehicular activity in sunlit areas and non-PSRs
FN-M-102 L	Enable crew lunar surface extravehicular activity in PSRs
FN-M-104 L	Enable crew extravehicular activity in cislunar space
FN-M-201 L	Enable the cleaning of EVA equipment and tools
FN-U-102 L	Capture imagery on the lunar surface
FN-U-301 L	Provide capability to recover and package subsurface samples, maintaining scientific integrity of the samples, from non-PSRs and sunlit regions on the lunar surface
FN-U-302 L	Provide capability to recover and package subsurface samples, maintaining scientific integrity of the samples, from PSRs on the lunar surface
FN-U-303 L	Provide capability to recover and package surface and/or shallow subsurface samples, maintaining scientific integrity of the samples, from non-PSRs and sunlit regions on the lunar surface
FN-U-304 L	Provide capability to recover and package surface and/or shallow subsurface samples, maintaining scientific integrity of the samples, from PSRs on the lunar surface

B.3.3 Exploration Ground Systems

B.3.3.1 Human Lunar Return

Human Lunar Return Segment	
Exploration Ground Systems	
FN-G-101 L	Provide ground services on Earth
FN-G-102 L	Stack and integrate system(s) on Earth
FN-G-103 L	Manage consumables and propellant
FN-G-104 L	Enable vehicle launch(es)
FN-G-105 L	Enable multiple launch attempts for vehicle(s)
FN-G-201 L	Recover crew after Earth landing
FN-G-202 L	Recover cargo after Earth landing

B.3.3.2 Foundational Exploration

Foundational Exploration Segment	
Exploration Ground Systems	
FN-G-101 L	Provide ground services on Earth
FN-G-102 L	Stack and integrate system(s) on Earth
FN-G-103 L	Manage consumables and propellant
FN-G-104 L	Enable vehicle launch(es)
FN-G-105 L	Enable multiple launch attempts for vehicle(s)
FN-G-201 L	Recover crew after Earth landing
FN-G-202 L	Recover cargo after Earth landing

B.3.4 Gateway

B.3.4.1 Human Lunar Return (Gateway Crew-Capable Configuration)

Human Lunar Return Segment	
Gateway Crew-Capable Configuration	
FN-T-106 L	Rendezvous, proximity operations, mating and unmating of assets in cislunar space
FN-H-103 L	Enable a pressurized, habitable environment in cislunar space
FN-H-202 L	Operate habitation system(s) in uncrewed mode between crewed missions in cislunar space
FN-X-102 L	Provide hardware for crew medical care in cislunar space
FN-L-202 L	Transfer pressurized cargo into habitable assets in cislunar space
FN-L-302 L	Manage waste from habitable asset(s) in cislunar space
FN-C-101 L	Provide communications and data exchange between the lunar surface and Earth
FN-C-102 L	Provide communications and data exchange between Earth and cislunar space
FN-C-105 L	Provide high bandwidth, high availability communications and data exchange between the lunar surface and Earth
FN-C-106 L	Provide high bandwidth, high availability communications and data exchange between cislunar space and the Earth
FN-C-108 L	Provide high bandwidth, high availability communications and data exchange between cislunar space and the lunar surface
FN-D-102 L	Collect, store, and locally distribute data in cislunar space
FN-D-106 L	Provide data capabilities, including protection for communication, and interface to support crew medical care in cislunar space
FN-U-202 L	Provide extravehicular utilization accommodation, interfaces, and resources, operable during crewed and uncrewed increments, in cislunar space
FN-U-205 L	Provide intravehicular activity facilities, utilization accommodation, and resources, operable during crewed and uncrewed increments, in cislunar space
FN-P-303 L	Distribute power to utilization payloads and/or equipment in cislunar space

B.3.4.1.1 Gateway Logistics Element

Human Lunar Return Segment	
Gateway Logistics Element	
FN-T-106 L	Rendezvous, proximity operations, mating and unmating of assets in cislunar space

Human Lunar Return Segment	
Gateway Logistics Element	
FN-T-213 L	Transport cargo from Earth to cislunar space
FN-T-214 L	Provide delivery of live, actively growing biological specimens to cislunar space, including late load of cargo prior to launch
FN-L-202 L	Transfer pressurized cargo into habitable assets in cislunar space
FN-L-204 L	Transfer water to habitable assets in cislunar space
FN-L-206 L	Transfer gases to habitable assets in cislunar space
FN-L-302 L	Manage waste from habitable asset(s) in cislunar space

B.3.4.2 Foundational Exploration (Gateway Expanded Capability Configuration)

Foundational Exploration Segment	
Gateway Expanded Capability Configuration	
FN-T-106 L	Rendezvous, proximity operations, mating and unmating of assets in cislunar space
FN-H-103 L	Enable a pressurized, habitable environment in cislunar space
FN-H-202 L	Operate habitation system(s) in uncrewed mode between crewed missions in cislunar space
FN-X-102 L	Provide hardware for crew medical care in cislunar space
FN-L-202 L	Transfer pressurized cargo into habitable assets in cislunar space
FN-L-302 L	Manage waste from habitable asset(s) in cislunar space
FN-P-303 L	Distribute power to utilization payloads and/or equipment in cislunar space
FN-M-301 L	Ingress/egress from habitable asset(s) to cislunar vacuum
FN-C-101 L	Provide communications and data exchange between the lunar surface and Earth
FN-C-102 L	Provide communications and data exchange between Earth and cislunar space
FN-C-105 L	Provide high bandwidth, high availability communications and data exchange between the lunar surface and Earth
FN-C-106 L	Provide high bandwidth, high availability communications and data exchange between cislunar space and the Earth
FN-C-108 L	Provide high bandwidth, high availability communications and data exchange between cislunar space and the lunar surface

Foundational Exploration Segment Gateway Expanded Capability Configuration	
FN-D-102 L	Collect, store, and locally distribute data in cislunar space
FN-D-106 L	Provide data capabilities, including protection for communication, and interface to support crew medical care in cislunar space
FN-D-202 L	Process data locally in cislunar space
FN-A-106 L	Enable repositioning of externally mounted utilization payloads in cislunar space
FN-A-203 L	Control robotic system(s) in cislunar space from Earth and/or cislunar space
FN-A-204 L	Control robotic system(s) in cislunar space by in-situ crew
FN-A-404 L	Transition assets between crewed and uncrewed mode in cislunar space
FN-U-202 L	Provide extravehicular utilization accommodation, interfaces, and resources, operable during crewed and uncrewed increments, in cislunar space
FN-U-205 L	Provide intravehicular activity facilities, utilization accommodation, and resources, operable during crewed and uncrewed increments, in cislunar space
FN-U-508 L	Transfer propellant/fluids between assets in space

B.3.4.2.1 Gateway Logistics Element

Foundational Exploration Segment Gateway Logistics Element	
FN-T-106 L	Rendezvous, proximity operations, mating and unmating of assets in cislunar space
FN-T-213 L	Transport cargo from Earth to cislunar space
FN-T-214 L	Provide delivery of live, actively growing biological specimens to cislunar space, including late load of cargo prior to launch
FN-L-202 L	Transfer pressurized cargo into habitable assets in cislunar space
FN-L-204 L	Transfer water to habitable assets in cislunar space
FN-L-206 L	Transfer gases to habitable assets in cislunar space
FN-L-302 L	Manage waste from habitable asset(s) in cislunar space

B.3.5 Human Landing System

B.3.5.1 Human Lunar Return

Human Lunar Return Segment	
Human Landing System	
FN-T-102 L	Transport crew from cislunar space to lunar surface sites in the south pole region
FN-T-104 L	Transport crew from the lunar surface to cislunar space
FN-T-106 L	Rendezvous, proximity operations, mating and unmating of assets in cislunar space
FN-T-108 L	Enable crew habitation during transit from cislunar space to lunar surface sites in the south pole region
FN-T-110 L	Enable crew habitation during transit from the lunar surface to cislunar space
FN-T-201 L	Transport a limited amount of cargo (100s of kg) from Earth to south pole region sites on the lunar surface
FN-T-209 L	Transport a small amount of cargo (10s of kg) from the lunar surface to cislunar space
FN-T-210 L	Transport a large amount of cargo (100s of kg) from the lunar surface to cislunar space
FN-T-401 L	Provide precision landing for crew transport to the lunar surface
FN-T-403 L	Enable landing on the lunar surface under all lighting conditions
FN-H-101 L	Enable a pressurized, habitable environment on the lunar surface for short durations (days to weeks)
FN-H-103 L	Enable a pressurized, habitable environment in cislunar space
FN-L-202 L	Transfer pressurized cargo into habitable assets in cislunar space
FN-L-301 L	Manage waste from habitable asset(s) on the lunar surface
FN-L-302 L	Manage waste from habitable asset(s) in cislunar space
FN-M-202 L	Enable maintaining and servicing of the EVA system in a habitable environment
FN-M-203 L	Ingress/egress from habitable asset(s) to lunar surface vacuum
FN-M-401 L	Unload a limited amount of cargo (100s of kg) on the lunar surface
FN-U-102 L	Capture imagery on the lunar surface

Human Lunar Return Segment	
Human Landing System	
FN-U-401 L	Stow collected unconditioned samples on exploration assets while on the lunar surface, while maintaining scientific integrity of the samples
FN-U-414 L	Provide resources to condition refrigerated sample containers on the lunar surface

B.3.5.2 Foundational Exploration

Foundational Exploration Segment	
Human Landing System	
FN-T-102 L	Transport crew from cislunar space to lunar surface sites in the south pole region
FN-T-103 L	Transport crew from cislunar space to distributed sites outside of the south pole region on the lunar surface
FN-T-104 L	Transport crew from the lunar surface to cislunar space
FN-T-106 L	Rendezvous, proximity operations, mating and unmating of assets in cislunar space
FN-T-108 L	Enable crew habitation during transit from cislunar space to lunar surface sites in the south pole region
FN-T-109 L	Enable crew habitation during transit from cislunar space to distributed sites outside of the south pole region on the lunar surface
FN-T-110 L	Enable crew habitation during transit from the lunar surface to cislunar space
FN-T-201 L	Transport a limited amount of cargo (100s of kg) from Earth to south pole region sites on the lunar surface
FN-T-203 L	Transport a limited amount of cargo (100s of kg) from Earth to distributed sites outside of the south pole region on the lunar surface
FN-T-209 L	Transport a small amount of cargo (10s of kg) from the lunar surface to cislunar space
FN-T-210 L	Transport a large amount of cargo (100s of kg) from the lunar surface to cislunar space
FN-T-304 L	Provide resources to condition refrigerated sample containers during transit from the lunar surface to cislunar space
FN-T-305 L	Provide resources to condition frozen sample containers during transit from the lunar surface to cislunar space
FN-T-401 L	Provide precision landing for crew transport to the lunar surface
FN-T-403 L	Enable landing on the lunar surface under all lighting conditions
FN-H-103 L	Enable a pressurized, habitable environment in cislunar space
FN-L-202 L	Transfer pressurized cargo into habitable assets in cislunar space

Foundational Exploration Segment	
Human Landing System	
FN-L-302 L	Manage waste from habitable asset(s) in cislunar space
FN-P-305 L	Provide bi-directional power exchange capability
FN-M-202 L	Enable maintaining and servicing of the EVA system in a habitable environment
FN-M-203 L	Ingress/egress from habitable asset(s) to lunar surface vacuum
FN-M-401 L	Unload a limited amount of cargo (100s of kg) on the lunar surface
FN-D-101 L	Collect, store, and locally distribute data on the lunar surface
FN-D-102 L	Collect, store, and locally distribute data in cislunar space
FN-D-105 L	Provide data capabilities, including protection for communication, and interface to support crew medical care on the lunar surface
FN-U-102 L	Capture imagery on the lunar surface
FN-U-405 L	Stow refrigerated samples during transport from the Lunar Surface to cislunar space, while maintaining scientific integrity of samples
FN-U-415 L	Provide resources to condition frozen sample containers on the lunar surface

B.3.6 Human-Class Delivery Lander

B.3.6.1 Foundational Exploration

Foundational Exploration Segment	
Human-Class Delivery Lander	
FN-T-206 L	Transport large asset(s) from Earth to the lunar surface
FN-T-402 L	Provide precision landing for cargo transport to the lunar surface
FN-T-403 L	Enable landing on the lunar surface under all lighting conditions
FN-P-305 L	Provide bi-directional power exchange capability
FN-M-403 L	Unload large assets on the lunar surface

B.3.7 Initial Surface Habitat

B.3.7.1 Foundational Exploration

Foundational Exploration Segment	
Initial Surface Habitat	
FN-H-101 L	Enable a pressurized, habitable environment on the lunar surface for short durations (days to weeks)
FN-H-201 L	Operate habitation system(s) in uncrewed mode between crewed missions on the lunar surface
FN-X-101 L	Provide hardware for crew medical care on the lunar surface
FN-L-101 L	Provide mating between pressurized assets on the lunar surface
FN-L-201 L	Transfer pressurized cargo into habitable assets on the lunar surface
FN-P-305 L	Provide bi-directional power exchange capability
FN-P-401 L	Provide power for deployed surface utilization payloads(s) and/or equipment
FN-P-402 L	Provide power for deployed external surface utilization payloads(s) and/or equipment for mid- (month+) to long-durations (year+)
FN-M-202 L	Enable maintaining and servicing of the EVA system in a habitable environment
FN-M-203 L	Ingress/egress from habitable asset(s) to lunar surface vacuum
FN-C-101 L	Provide communications and data exchange between the lunar surface and Earth
FN-C-103 L	Provide communications and data exchange between assets on the lunar surface
FN-C-105 L	Provide high bandwidth, high availability communications and data exchange between the lunar surface and Earth
FN-C-107 L	Provide high bandwidth, high availability communications and data exchange between assets on the lunar surface
FN-C-108 L	Provide high bandwidth, high availability communications and data exchange between cislunar space and the lunar surface
FN-D-105 L	Provide data capabilities, including protection for communication, and interface to support crew medical care on the lunar surface
FN-D-201 L	Process data locally on the lunar surface
FN-A-403 L	Transition assets between crewed and uncrewed mode on the lunar surface
FN-U-203 L	Provide extravehicular utilization accommodation, interfaces, and resources, operable during crewed and uncrewed increments, on the lunar surface

Foundational Exploration Segment	
Initial Surface Habitat	
FN-U-204 L	Provide intravehicular activity facilities, utilization accommodation, and resources, operable during crewed and uncrewed increments, on the lunar surface
FN-U-401 L	Stow collected unconditioned samples on exploration assets while on the lunar surface, while maintaining scientific integrity of the samples
FN-U-414 L	Provide resources to condition refrigerated sample containers on the lunar surface
FN-U-415 L	Provide resources to condition frozen sample containers on the lunar surface

B.3.8 Lunar Nuclear Fission System

B.3.8.1 Foundational Exploration

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

B.3.9 Lunar Surface Cargo Lander

B.3.9.1 Foundational Exploration

Foundational Exploration Segment	
Human-Class Delivery Lander	
FN-T-202 L	Transport a moderate amount of cargo (1000s of kg) from Earth to south pole region sites on the lunar surface
FN-T-204 L	Transport a moderate amount of cargo (1000s of kg) from Earth to distributed sites outside of the south pole region on the lunar surface
FN-T-402 L	Provide precision landing for cargo transport to the lunar surface
FN-T-403 L	Enable landing on the lunar surface under all lighting conditions

B.3.10 Lunar Terrain Vehicle

B.3.10.1 Foundational Exploration

Foundational Exploration Segment	
Lunar Terrain Vehicle	
FN-P-305 L	Provide bi-directional power exchange capability
FN-M-302 L	Enable local unpressurized surface mobility in sunlit areas and non-PSRs in the south pole region on the lunar surface
FN-M-304 L	Enable local unpressurized surface mobility in PSRs at the south pole region of the lunar surface
FN-M-501 L	Reposition a limited amount of cargo (100s of kg) in the south pole region on the lunar surface
FN-M-504 L	Reposition a small amount of unconditioned samples and containers (10s of kg) on the lunar surface
FN-M-506 L	Reposition a small amount of refrigerated samples and containers (10s of kg) on the lunar surface
FN-M-508 L	Reposition a small amount of frozen samples and containers (10s of kg) on the lunar surface
FN-M-601 L	Relocate exploration assets at the south pole region of the lunar surface
FN-M-701 L	Operate mobility system(s) in uncrewed mode between crew surface missions
FN-C-103 L	Provide communications and data exchange between assets on the lunar surface
FN-D-101 L	Collect, store, and locally distribute data on the lunar surface
FN-A-104 L	Perform robotic manipulation of payloads, logistics, and/or equipment on the lunar surface
FN-A-302 L	Provide safeguards for automated asset(s) operating near crew
FN-A-403 L	Transition assets between crewed and uncrewed mode on the lunar surface
FN-U-102 L	Capture imagery on the lunar surface
FN-U-401 L	Stow collected unconditioned samples on exploration assets while on the lunar surface, while maintaining scientific integrity of the samples
FN-U-411 L	Stow collected refrigerated samples on exploration assets while on the lunar surface, while maintaining scientific integrity of the samples
FN-U-412 L	Stow collected frozen samples on exploration assets while on the lunar surface, while maintaining scientific integrity of the samples

B.3.11 Lunar Utility Rover

B.3.11.1 Foundational Exploration

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

B.3.12 Orion Spacecraft

B.3.12.1 Human Lunar Return

Human Lunar Return Segment	
Orion Spacecraft	
FN-T-101 L	Transport crew from Earth to cislunar space
FN-T-105 L	Transport crew from cislunar space to Earth
FN-T-106 L	Rendezvous, proximity operations, mating and unmating of assets in cislunar space
FN-T-107 L	Enable crew habitation during transit from Earth to cislunar space
FN-T-111 L	Enable crew habitation during transit from cislunar space to Earth
FN-T-112 L	Enable abort(s) to safety
FN-T-211 L	Transport a small amount of cargo (10s of kg) from cislunar space to Earth
FN-T-217 L	Transport exploration asset(s) from Earth to cislunar space
FN-H-103 L	Enable a pressurized, habitable environment in cislunar space
FN-L-202 L	Transfer pressurized cargo into habitable assets in cislunar space

Human Lunar Return Segment	
Orion Spacecraft	
FN-L-302 L	Manage waste from habitable asset(s) in cislunar space
FN-U-205 L	Provide intravehicular activity facilities, utilization accommodation, and resources, operable during crewed and uncrewed increments, in cislunar space
FN-U-206 L	Provide intravehicular utilization accommodation and resources during crew transit between Earth and cislunar space

B.3.12.2 Foundational Exploration

Foundational Exploration Segment	
Orion Spacecraft	
FN-T-101 L	Transport crew from Earth to cislunar space
FN-T-105 L	Transport crew from cislunar space to Earth
FN-T-106 L	Rendezvous, proximity operations, mating and unmating of assets in cislunar space
FN-T-107 L	Enable crew habitation during transit from Earth to cislunar space
FN-T-111 L	Enable crew habitation during transit from cislunar space to Earth
FN-T-112 L	Enable abort(s) to safety
FN-T-211 L	Transport a small amount of cargo (10s of kg) from cislunar space to Earth
FN-T-217 L	Transport exploration asset(s) from Earth to cislunar space
FN-T-307 L	Provide resources to condition refrigerated sample containers during transit from cislunar space to Earth
FN-T-308 L	Provide resources to condition frozen sample containers during transit from cislunar space to Earth
FN-H-103 L	Enable a pressurized, habitable environment in cislunar space
FN-L-202 L	Transfer pressurized cargo into habitable assets in cislunar space
FN-L-302 L	Manage waste from habitable asset(s) in cislunar space
FN-U-206 L	Provide intravehicular utilization accommodation and resources during crew transit between Earth and cislunar space

B.3.13 Pressurized Rover

B.3.13.1 Foundational Exploration

Foundational Exploration Segment	
Pressurized Rover	
FN-H-101 L	Enable a pressurized, habitable environment on the lunar surface for short durations (days to weeks)
FN-H-201 L	Operate habitation system(s) in uncrewed mode between crewed missions on the lunar surface
FN-X-101 L	Provide hardware for crew medical care on the lunar surface
FN-L-201 L	Transfer pressurized cargo into habitable assets on the lunar surface
FN-P-305 L	Provide bi-directional power exchange capability
FN-M-202 L	Enable maintaining and servicing of the EVA system in a habitable environment
FN-M-203 L	Ingress/egress from habitable asset(s) to lunar surface vacuum
FN-M-305 L	Enable pressurized surface mobility in sunlit areas and non-PSRs
FN-M-505 L	Reposition a large amount of unconditioned samples and containers (100s of kg) on the lunar surface
FN-M-507 L	Reposition a large amount of refrigerated samples and containers (100s of kg) on the lunar surface
FN-M-509 L	Reposition a large amount of frozen samples and containers (100s of kg) on the lunar surface
FN-M-510 L	Reposition a large amount of cryogenic samples and containers (100s of kg) on the lunar surface
FN-M-601 L	Relocate exploration assets at the south pole region of the lunar surface
FN-M-701 L	Operate mobility system(s) in uncrewed mode between crew surface missions
FN-C-103 L	Provide communications and data exchange between assets on the lunar surface
FN-D-101 L	Collect, store, and locally distribute data on the lunar surface
FN-D-105 L	Provide data capabilities, including protection for communication, and interface to support crew medical care on the lunar surface
FN-A-103 L	Provide a robotic system capable of conducting reconnaissance
FN-A-403 L	Transition assets between crewed and uncrewed mode on the lunar surface

Foundational Exploration Segment	
Pressurized Rover	
FN-U-102 L	Capture imagery on the lunar surface
FN-U-401 L	Stow collected unconditioned samples on exploration assets while on the lunar surface, while maintaining scientific integrity of the samples

B.3.14 Space Communications and Navigation Networks

B.3.14.1 Human Lunar Return

B.3.14.1.1 Near Space Network and Deep Space Network

Human Lunar Return Segment	
Near Space Network and Deep Space Network	
FN-C-101 L	Provide communications and data exchange between the lunar surface and Earth
FN-C-102 L	Provide communications and data exchange between Earth and cislunar space
FN-C-105 L	Provide high bandwidth, high availability communications and data exchange between the lunar surface and Earth
FN-C-106 L	Provide high bandwidth, high availability communications and data exchange between cislunar space and the Earth
FN-C-204 L	Provide position, navigation, and timing services in cislunar space

B.3.14.1.2 Lunar Communications Relay and Navigation Systems

Human Lunar Return Segment	
Lunar Communications Relay and Navigation Systems	
FN-C-101 L	Provide communications and data exchange between the lunar surface and Earth
FN-C-105 L	Provide high bandwidth, high availability communications and data exchange between the lunar surface and Earth
FN-C-106 L	Provide high bandwidth, high availability communications and data exchange between cislunar space and the Earth
FN-C-201 L	Provide position, navigation, and timing services at the south pole region on the lunar surface
FN-C-204 L	Provide position, navigation, and timing services in cislunar space

B.3.14.2 Foundational Exploration

B.3.14.2.1 Near Space Network and Deep Space Network

Foundational Exploration Segment	
Near Space Network and Deep Space Network	
FN-C-101 L	Provide communications and data exchange between the lunar surface and Earth
FN-C-102 L	Provide communications and data exchange between Earth and cislunar space
FN-C-104 L	Provide communications and data exchange between Earth and deep space
FN-C-105 L	Provide high bandwidth, high availability communications and data exchange between the lunar surface and Earth
FN-C-106 L	Provide high bandwidth, high availability communications and data exchange between cislunar space and the Earth
FN-C-204 L	Provide position, navigation, and timing services in cislunar space
FN-A-201 L	Control robotic system(s) in sunlit areas and non-PSRs on the lunar surface from Earth and/or cislunar space
FN-A-202 L	Control robotic system(s) in PSRs on the lunar surface from Earth and/or cislunar space
FN-A-401 L	Command and control asset(s) from Earth on the lunar surface during uncrewed periods
FN-A-402 L	Command and control asset(s) from Earth in cislunar space during uncrewed periods

B.3.14.2.2 Lunar Communications Relay and Navigation Systems

Foundational Exploration Segment	
Lunar Communications Relay and Navigation Systems	
FN-C-101 L	Provide communications and data exchange between the lunar surface and Earth
FN-C-105 L	Provide high bandwidth, high availability communications and data exchange between the lunar surface and Earth
FN-C-106 L	Provide high bandwidth, high availability communications and data exchange between cislunar space and the Earth
FN-C-201 L	Provide position, navigation, and timing services at the south pole region on the lunar surface
FN-C-204 L	Provide position, navigation, and timing services in cislunar space

B.3.15 Space Launch System

B.3.15.1 Human Lunar Return

Human Lunar Return Segment	
Space Launch System	
FN-T-101 L	Transport crew from Earth to cislunar space
FN-T-112 L	Enable abort(s) to safety
FN-T-216 L	Deliver free flying asset(s) from Earth to cislunar space
FN-G-102 L	Stack and integrate system(s) on Earth
FN-G-104 L	Enable vehicle launch(es)
FN-G-105 L	Enable multiple launch attempts for vehicle(s)

B.3.15.2 Foundational Exploration

Foundational Exploration Segment	
Space Launch System	
FN-T-101 L	Transport crew from Earth to cislunar space
FN-T-112 L	Enable abort(s) to safety
FN-T-216 L	Deliver free flying asset(s) from Earth to cislunar space
FN-G-102 L	Stack and integrate system(s) on Earth
FN-G-104 L	Enable vehicle launch(es)
FN-G-105 L	Enable multiple launch attempts for vehicle(s)

B.4 Utilization Payloads and Equipment Function Mappings

Note: *Science/research payloads and technology demonstrations are forward work.*

B.4.1 Human Lunar Return

Human Lunar Return Segment	
Equipment	
FN-U-303 L	Provide capability to recover and package surface and/or shallow subsurface samples, maintaining scientific integrity of the samples, from non-PSRs and sunlit regions on the lunar surface

B.4.2 Foundational Exploration

Utilization payloads function mappings are forward work and will appear in subsequent revisions.

Foundational Exploration Segment	
Equipment	
FN-U-303 L	Provide capability to recover and package surface and/or shallow subsurface samples, maintaining scientific integrity of the samples, from non-PSRs and sunlit regions on the lunar surface
FN-U-304 L	Provide capability to recover and package surface and/or shallow subsurface samples, maintaining scientific integrity of the samples, from PSRs on the lunar surface
FN-U-402 L	Stow refrigerated samples during transport from the Lunar Surface to Earth, while maintaining scientific integrity of samples
FN-U-403 L	Stow frozen samples during transport from the Lunar Surface to Earth, while maintaining scientific integrity of samples
FN-U-405 L	Stow refrigerated samples during transport from the Lunar Surface to cislunar space, while maintaining scientific integrity of samples
FN-U-406 L	Stow frozen samples during transport from the Lunar Surface to cislunar space, while maintaining scientific integrity of samples
FN-U-408 L	Stow refrigerated samples during transport from cislunar space to Earth, while maintaining scientific integrity of samples
FN-U-409 L	Stow frozen samples during transport from cislunar space to Earth, while maintaining scientific integrity of samples

B.5 Unallocated Functions by Use Case

B.5.1 Human Lunar Return

B.5.1.1 Communications and Positioning, Navigation, and Timing

UC-C-202 L	Determination of position, navigation, and timing by crew and assets at the south pole region on the lunar surface
FN-C-205 L	Provide a coordinated lunar time scale
Architecture Definition Document – Unallocated Functions by Use Case	

UC-C-203 L	Crew or robotics utilization of position, navigation, and timing for accurate sample tracking at the south pole region on the lunar surface
FN-C-205 L	Provide a coordinated lunar time scale
Architecture Definition Document – Unallocated Functions by Use Case	

B.5.1.2 Utilization

UC-U-103 L	Crew identification of surface samples in sunlit areas and non-PSRs in the south pole region on the lunar surface
FN-C-205 L	Provide a coordinated lunar time scale
Architecture Definition Document – Unallocated Functions by Use Case	

UC-U-301 L	Collection, documentation, and packaging of surface and/or shallow subsurface samples, maintaining scientific integrity of the samples, from non-PSRs and sunlit areas in the south pole region on the lunar surface
FN-C-205 L	Provide a coordinated lunar time scale
Architecture Definition Document – Unallocated Functions by Use Case	

Note: *All the use cases listed above share a single unallocated function for the Human Lunar Return segment, FN-C-205 L: "Provide a coordinated lunar time scale."*

B.5.2 Foundational Exploration

B.5.2.1 Autonomous Systems and Robotics

UC-A-101 L	Robotic assistance of crew exploration, site surveying, sample and resource locating, documentation, and sample retrieval from PSRs
FN-A-102 L	Provide robotic systems to assist crew in PSRs on the lunar surface

Architecture Definition Document – Unallocated Functions by Use Case

UC-A-103 L	Robotic support of logistic operations on the lunar surface as necessary
FN-A-105 L	Interface robotic system(s) with logistics carriers on the lunar surface

Architecture Definition Document – Unallocated Functions by Use Case

UC-A-104 L	Robotic assistance of crew exploration, site surveying, sample and resource locating, documentation, and sample retrieval from sunlit areas and non-PSRs
FN-A-101 L	Provide robotic systems to assist crew in sunlit areas and non-PSRs on the lunar surface

Architecture Definition Document – Unallocated Functions by Use Case

UC-A-201 L	Remote management of robotic system(s) during surface operation as necessary
FN-A-301 L	Monitor robotic system(s) performance and health

Architecture Definition Document – Unallocated Functions by Use Case

UC-A-202 L	Remote management of robotic system(s) during in space operation as necessary
FN-A-301 L	Monitor robotic system(s) performance and health

Architecture Definition Document – Unallocated Functions by Use Case

B.5.2.2 Communications and Positioning, Navigation, and Timing

UC-A-204 L	Determination of position, navigation, and timing by crew and assets at distributed sites on the lunar surface
FN-C-202 L	Provide position, navigation, and timing services at distributed sites on the near side and outside of the south pole region on the lunar surface

Architecture Definition Document – Unallocated Functions by Use Case

UC-A-205 L	Crew or robotics utilization of position, navigation, and timing for accurate sample tracking at distributed sites on the lunar surface
FN-C-202 L	Provide position, navigation, and timing services at distributed sites on the near side and outside of the south pole region on the lunar surface

Architecture Definition Document – Unallocated Functions by Use Case

UC-A-206 L	Determination of position, navigation, and timing by crew and assets at the far side of the lunar surface
FN-C-203 L	Provide position, navigation, and timing services at the far side and outside the south pole region on the lunar surface

Architecture Definition Document – Unallocated Functions by Use Case

UC-A-207 L	Crew or robotics utilization of position, navigation, and timing for accurate sample tracking at the far side on the lunar surface
FN-C-203 L	Provide position, navigation, and timing services at the far side and outside the south pole region on the lunar surface

Architecture Definition Document – Unallocated Functions by Use Case

B.5.2.3 Data Systems and Management

UC-D-201 L	Storage and local processing of space weather data
FN-D-103 L	Collect, store, and locally distribute large volumes of data on the lunar surface sufficient to perform real time analysis for in situ decision making
FN-D-104 L	Collect, store, and locally distribute large volumes of data in cislunar space sufficient to perform real time analysis for in situ decision making
FN-D-203 L	Process large volumes of data locally on the lunar surface sufficient to perform real time analysis for in situ decision making
FN-D-204 L	Process large volumes of data locally in cislunar space sufficient to perform real time analysis for in situ decision making

Architecture Definition Document – Unallocated Functions by Use Case

B.5.2.4 Habitation

UC-H-101 L	Crew habitation of assets on the lunar surface for short-durations (days to weeks)
FN-L-301 L	Manage waste from habitable asset(s) on the lunar surface

Architecture Definition Document – Unallocated Functions by Use Case

UC-H-102 L	Crew habitation of assets on the lunar surface for mid-durations (month+)
FN-H-102 L	Enable a pressurized, habitable environment on the lunar surface for mid-duration (month+) use
FN-L-301 L	Manage waste from habitable asset(s) on the lunar surface

Architecture Definition Document – Unallocated Functions by Use Case

UC-H-103 L	Crew habitation of assets for mid-duration (month+) mission(s) in cislunar space
FN-H-104 L	Enable a pressurized, habitable environment in cislunar space for mid-durations (month+)

Architecture Definition Document – Unallocated Functions by Use Case

UC-H-104 L	Crew habitation of assets for long-duration (year+) mission(s) in cislunar space
FN-H-105 L	Enable a pressurized, habitable environment in cislunar space for long-durations (year+)

Architecture Definition Document – Unallocated Functions by Use Case

B.5.2.5 In-situ Resource Utilization

UC-I-101 L	Deployment and operation of utilization payload(s) and/or equipment related to demonstration of ISRU on the lunar surface with long-term remote operation
FN-I-104 L	Conduct ISRU utilization payload and/or equipment operations on the lunar surface
FN-U-103 L	Conduct resource identification utilization payload and/or equipment operations on the lunar surface

Architecture Definition Document – Unallocated Functions by Use Case

UC-I-102 L	Deployment and operation of utilization payload(s) and/or equipment related to demonstration of oxygen recovery from lunar regolith
FN-I-102 L	Produce scalable quantities of oxygen from lunar regolith
FN-I-105 L	Store oxygen on the lunar surface
FN-I-107 L	Transport scalable quantities of oxygen produced to exploration elements
FN-I-201 L	Collect regolith at sub-scale to support demonstration using scalable capability
FN-I-203 L	Provide storage for collected regolith
FN-U-103 L	Conduct resource identification utilization payload and/or equipment operations on the lunar surface

Architecture Definition Document – Unallocated Functions by Use Case

UC-I-103 L	Deployment and operation of utilization payload(s) and/or equipment related to demonstration of water recovery from the lunar regolith in the polar regions
FN-I-101 L	Collect water/ice from the south pole region of the lunar surface
FN-I-103 L	Produce scalable quantities of water from in-situ materials on the lunar surface
FN-I-106 L	Store collected water/ice on the lunar surface
FN-I-108 L	Transport scalable quantities of water produced to exploration elements
FN-U-103 L	Conduct resource identification utilization payload and/or equipment operations on the lunar surface

Architecture Definition Document – Unallocated Functions by Use Case

UC-I-104 L	Deployment and operation of utilization payload(s) and/or equipment related to demonstration of water transfer from ISRU production assets to other exploration assets
FN-L-203 L	Transfer water to habitable assets on the lunar surface

Architecture Definition Document – Unallocated Functions by Use Case

UC-I-105 L	Deployment and operation of utilization payload(s) and/or equipment related to demonstration of gas transfer from ISRU production assets to other exploration assets
FN-L-205 L	Transfer gases to habitable assets on the lunar surface

Architecture Definition Document – Unallocated Functions by Use Case

UC-I-106 L	Deployment and operation of utilization payload(s) and/or equipment related to demonstration of operational techniques to recover and refine metals from the lunar regolith
FN-I-201 L	Collect regolith at sub-scale to support demonstration using scalable capability
FN-I-202 L	Conduct regolith recovery demonstration utilization payload and/or equipment operations on the lunar surface
FN-I-204 L	Process and refine scalable quantities of in-situ feedstock resources on the lunar surface
FN-U-103 L	Conduct resource identification utilization payload and/or equipment operations on the lunar surface

Architecture Definition Document – Unallocated Functions by Use Case

UC-I-201 L	Deployment and operation of utilization payload(s) and/or equipment related to autonomous construction demonstration utilization payload(s) on the lunar surface with long-term remote operation
FN-I-204 L	Process and refine scalable quantities of in-situ feedstock resources on the lunar surface
FN-I-205 L	Conduct autonomous construction utilization payload and/or equipment operations on the lunar surface

Architecture Definition Document – Unallocated Functions by Use Case

UC-I-202 L	Deployment and operation of utilization payload(s) and/or equipment related to demonstration of autonomous construction techniques, e.g., collection of regolith, processing regolith into feedstock, and regolith construction
FN-I-201 L	Collect regolith at sub-scale to support demonstration using scalable capability
FN-I-204 L	Process and refine scalable quantities of in-situ feedstock resources on the lunar surface
FN-I-205 L	Conduct autonomous construction utilization payload and/or equipment operations on the lunar surface

Architecture Definition Document – Unallocated Functions by Use Case

UC-I-203 L	Deployment and operation of utilization payload(s) and/or equipment related to demonstration of regolith based additive/subtractive manufacturing techniques
FN-I-201 L	Collect regolith at sub-scale to support demonstration using scalable capability
FN-I-204 L	Process and refine scalable quantities of in-situ feedstock resources on the lunar surface
FN-I-207 L	Conduct additive/subtractive manufacturing utilization payload and/or equipment operations on the lunar surface

Architecture Definition Document – Unallocated Functions by Use Case

UC-I-204 L	Deployment and operation of utilization payload(s) and/or equipment related to advanced manufacturing demonstration on the lunar surface with long-term remote operation
FN-I-206 L	Conduct advanced manufacturing utilization payload and/or equipment operations on the lunar surface

Architecture Definition Document – Unallocated Functions by Use Case

B.5.2.6 Logistics

UC-L-201 L	Resupply of cargo and management of waste to/from habitable assets on the lunar surface
FN-L-203 L	Transfer water to habitable assets on the lunar surface
FN-L-205 L	Transfer gases to habitable assets on the lunar surface
FN-L-301 L	Manage waste from habitable asset(s) on the lunar surface

Architecture Definition Document – Unallocated Functions by Use Case

B.5.2.7 Mobility

UC-M-103 L	Crew use of tools to assist in performing extravehicular activities, sample collection and suit cleaning
FN-U-305 L	Provide capability to recover and package deep subsurface samples, including drill cores, maintaining scientific integrity of the samples, from non-PSRs and sunlit regions on the lunar surface
FN-U-306 L	Provide capability to recover and package deep subsurface samples, including drill cores, maintaining scientific integrity of the samples, from PSRs on the lunar surface

Architecture Definition Document – Unallocated Functions by Use Case

UC-M-301 L	Conduct of crew excursions to locations in sunlit areas and non-PSRs at distributed locations outside of the south pole region around landing site
FN-C-202 L	Provide position, navigation, and timing services at distributed sites on the near side and outside of the south pole region on the lunar surface
FN-M-303 L	Enable local unpressurized surface mobility in sunlit areas and non-PSRs at distributed sites on the lunar surface

Architecture Definition Document – Unallocated Functions by Use Case

UC-M-602 L	Demonstration of uncrewed relocation of exploration assets to sites at distributed locations outside of the south pole region on the lunar surface
FN-C-202 L	Provide position, navigation, and timing services at distributed sites on the near side and outside of the south pole region on the lunar surface
FN-M-602 L	Relocate exploration assets at distributed locations outside of the south pole region on the lunar surface

Architecture Definition Document – Unallocated Functions by Use Case

B.5.2.8 Power

UC-P-101 L	Power generation and energy storage at south pole region on the lunar surface
FN-P-101 L	Generate power in the south pole region on the lunar surface
FN-P-202 L	Store energy in the south pole region on the lunar surface

Architecture Definition Document – Unallocated Functions by Use Case

UC-P-102 L	Power generation and energy storage at multiple distributed locations outside of the south pole region on the lunar surface
FN-P-102 L	Generate power at multiple distributed locations outside of the south pole region on the lunar surface
FN-P-201 L	Store energy at multiple distributed locations outside of the south pole region on the lunar surface

Architecture Definition Document – Unallocated Functions by Use Case

UC-P-301 L	Power distribution around power generation and energy storage system(s) in the south pole region on the lunar surface
FN-P-301 L	Distribute power in the south pole region on the lunar surface

Architecture Definition Document – Unallocated Functions by Use Case

UC-P-302 L	Power distribution from power generation and energy storage system(s) at multiple distributed locations outside of the south pole region on the lunar surface
FN-P-302 L	Distribute power at multiple distributed locations outside of the south pole region on the lunar surface

Architecture Definition Document – Unallocated Functions by Use Case

B.5.2.9 Transportation

UC-T-203 L	Transportation of cargo from cislunar space to Earth
FN-T-212 L	Transport a large amount of cargo (100s of kg) from cislunar space to Earth

Architecture Definition Document – Unallocated Functions by Use Case

UC-T-301 L	Return of a small amount of unconditioned samples and containers (10s of kg) from the lunar surface to Earth with the samples in sealed sample containers
FN-T-207 L	Transport a small amount of cargo (10s of kg) from the lunar surface to Earth

UC-T-302 L	Return of a large amount of unconditioned samples and containers (100s of kg) from the lunar surface to Earth with the samples in sealed sample containers
FN-T-208 L	Transport a large amount of cargo (100s of kg) from the lunar surface to Earth
FN-T-212 L	Transport a large amount of cargo (100s of kg) from cislunar space to Earth

Architecture Definition Document – Unallocated Functions by Use Case

UC-T-303 L	Return of a small amount of refrigerated samples and containers (10s of kg) from the lunar surface to Earth with the samples in sealed conditioned sample containers
FN-T-207 L	Transport a small amount of cargo (10s of kg) from the lunar surface to Earth
FN-T-301 L	Provide resources to condition refrigerated sample containers during transit from the lunar surface to Earth

Architecture Definition Document – Unallocated Functions by Use Case

UC-T-304 L	Return of a large amount of refrigerated samples and containers (100s of kg) from the lunar surface to Earth with the samples in sealed conditioned sample containers
FN-T-208 L	Transport a large amount of cargo (100s of kg) from the lunar surface to Earth
FN-T-212 L	Transport a large amount of cargo (100s of kg) from cislunar space to Earth
FN-T-301 L	Provide resources to condition refrigerated sample containers during transit from the lunar surface to Earth

Architecture Definition Document – Unallocated Functions by Use Case

UC-T-305 L	Return of a small amount of frozen samples and containers (10s of kg) from the lunar surface to Earth with the samples in sealed conditioned sample containers
FN-T-207 L	Transport a small amount of cargo (10s of kg) from the lunar surface to Earth
FN-T-302 L	Provide resources to condition frozen sample containers during transit from the lunar surface to Earth

Architecture Definition Document – Unallocated Functions by Use Case

UC-T-306 L	Return of a large amount of frozen samples and containers (100s of kg) from the lunar surface to Earth with the samples in sealed conditioned sample containers
FN-T-208 L	Transport a large amount of cargo (100s of kg) from the lunar surface to Earth
FN-T-212 L	Transport a large amount of cargo (100s of kg) from cislunar space to Earth
FN-T-302 L	Provide resources to condition frozen sample containers during transit from the lunar surface to Earth

Architecture Definition Document – Unallocated Functions by Use Case

UC-T-307 L	Return of a large amount of cryogenic samples and containers (100s of kg) from the lunar surface to Earth with the samples in sealed conditioned sample containers
FN-T-208 L	Transport a large amount of cargo (100s of kg) from the lunar surface to Earth
FN-T-212 L	Transport a large amount of cargo (100s of kg) from cislunar space to Earth
FN-T-303 L	Provide resources to condition cryogenic sample containers during transit from the lunar surface to Earth
FN-T-306 L	Provide resources to condition cryogenic sample containers during transit from the lunar surface to cislunar space
FN-T-309 L	Provide resources to condition cryogenic sample containers during transit from cislunar space to Earth
FN-U-404 L	Stow cryogenic samples during transport from the Lunar Surface to Earth, while maintaining scientific integrity of samples
FN-U-407 L	Stow cryogenic samples during transport from the Lunar Surface to cislunar space, while maintaining scientific integrity of samples
FN-U-410 L	Stow cryogenic samples during transport from cislunar space to Earth, while maintaining scientific integrity of samples
FN-U-413 L	Stow collected cryogenic samples on exploration assets while on the lunar surface, while maintaining scientific integrity of the samples
FN-U-416 L	Provide resources to condition cryogenic sample containers on the lunar surface

Architecture Definition Document – Unallocated Functions by Use Case

UC-T-309 L	Return of a large amount of unconditioned samples and containers (100s of kg) from cislunar space to Earth with the samples in sealed sample containers
FN-T-212 L	Transport a large amount of cargo (100s of kg) from cislunar space to Earth

Architecture Definition Document – Unallocated Functions by Use Case

UC-T-311 L	Return of a large amount of refrigerated samples and containers (100s of kg) from cislunar space to Earth with the samples in sealed conditioned sample containers
FN-T-212 L	Transport a large amount of cargo (100s of kg) from cislunar space to Earth

Architecture Definition Document – Unallocated Functions by Use Case

UC-T-313 L	Return of a large amount of frozen samples and containers (100s of kg) from cislunar space to Earth with the samples in sealed conditioned sample containers
FN-T-212 L	Transport a large amount of cargo (100s of kg) from cislunar space to Earth

Architecture Definition Document – Unallocated Functions by Use Case

B.5.2.10 Utilization

UC-U-101 L	Orbital survey(s) of lunar surface before, during, and after crew mission
FN-U-101 L	Observe and sense the lunar surface from lunar orbit

Architecture Definition Document – Unallocated Functions by Use Case

UC-U-102 L	Robotic surveillance of potential crewed landing and exploration sites in sunlit areas and non-PSRs in the south pole region on the lunar surface to identify locations of interest
FN-A-103 L	Provide a robotic system capable of conducting reconnaissance

Architecture Definition Document – Unallocated Functions by Use Case

UC-U-105 L	Robotic surveillance of potential crewed landing and exploration sites in sunlit areas and non-PSRs in distributed sites on the lunar surface to identify locations of interest
FN-A-103 L	Provide a robotic system capable of conducting reconnaissance
FN-C-202 L	Provide position, navigation, and timing services at distributed sites on the near side and outside of the south pole region on the lunar surface

Architecture Definition Document – Unallocated Functions by Use Case

UC-U-106 L	Robotic surveillance of potential crewed landing and exploration sites in sunlit areas and non-PSRs on the far side on the lunar surface to identify locations of interest
FN-A-103 L	Provide a robotic system capable of conducting reconnaissance
FN-C-203 L	Provide position, navigation, and timing services at the far side and outside the south pole region on the lunar surface

Architecture Definition Document – Unallocated Functions by Use Case

UC-U-107 L	Crew identification of surface samples in sunlit areas and non-PSRs in distributed sites on the lunar surface
FN-C-202 L	Provide position, navigation, and timing services at distributed sites on the near side and outside of the south pole region on the lunar surface

Architecture Definition Document – Unallocated Functions by Use Case

UC-U-108 L	Crew identification of surface samples in sunlit areas and non-PSRs in the far side on the lunar surface
FN-C-203 L	Provide position, navigation, and timing services at the far side and outside the south pole region on the lunar surface

Architecture Definition Document – Unallocated Functions by Use Case

UC-U-201 L	Intravehicular science and utilization activities on the lunar surface
FN-P-301 L	Distribute power in the south pole region on the lunar surface
FN-P-302 L	Distribute power at multiple distributed locations outside of the south pole region on the lunar surface

Architecture Definition Document – Unallocated Functions by Use Case

UC-U-302 L	Collection, recovery, and packaging of deep subsurface samples, maintaining scientific integrity of the samples, from non-PSRs and other sunlit areas in the south pole region on the lunar surface
FN-U-305 L	Provide capability to recover and package deep subsurface samples, including drill cores, maintaining scientific integrity of the samples, from non-PSRs and sunlit regions on the lunar surface
Architecture Definition Document – Unallocated Functions by Use Case	

UC-U-304 L	Collection, recovery, and packaging of deep subsurface samples, maintaining scientific integrity of the samples, from PSRs on the lunar surface
FN-U-306 L	Provide capability to recover and package deep subsurface samples, including drill cores, maintaining scientific integrity of the samples, from PSRs on the lunar surface
Architecture Definition Document – Unallocated Functions by Use Case	

UC-U-305 L	Collection, documentation, and packaging of surface and/or shallow subsurface samples, maintaining scientific integrity of the samples, from non-PSRs and sunlit areas in distributed locations on the lunar surface
FN-C-202 L	Provide position, navigation, and timing services at distributed sites on the near side and outside of the south pole region on the lunar surface
Architecture Definition Document – Unallocated Functions by Use Case	

UC-U-306 L	Collection, documentation, and packaging of surface and/or shallow subsurface samples, maintaining scientific integrity of the samples, from non-PSRs and sunlit areas in the far side on the lunar surface
FN-C-203 L	Provide position, navigation, and timing services at the far side and outside the south pole region on the lunar surface
Architecture Definition Document – Unallocated Functions by Use Case	

UC-U-307 L	Collection, recovery, and packaging of deep subsurface samples, maintaining scientific integrity of the samples, from non-PSRs and other sunlit areas in distributed sites on the lunar surface
FN-C-202 L	Provide position, navigation, and timing services at distributed sites on the near side and outside of the south pole region on the lunar surface
FN-U-305 L	Provide capability to recover and package deep subsurface samples, including drill cores, maintaining scientific integrity of the samples, from non-PSRs and sunlit regions on the lunar surface
Architecture Definition Document – Unallocated Functions by Use Case	

UC-U-308 L	Collection, recovery, and packaging of deep subsurface samples, maintaining scientific integrity of the samples, from non-PSRs and other sunlit areas in the far side on the lunar surface
FN-C-203 L	Provide position, navigation, and timing services at the far side and outside the south pole region on the lunar surface
FN-U-305 L	Provide capability to recover and package deep subsurface samples, including drill cores, maintaining scientific integrity of the samples, from non-PSRs and sunlit regions on the lunar surface

Architecture Definition Document – Unallocated Functions by Use Case

UC-U-501 L	Deployment and operation of exploration assets, including utilization payload(s) and/or equipment, related to demonstration of operational techniques to transfer fluid and/or propellant on the lunar surface
FN-U-507 L	Conduct fluid and propellant transfer utilization payload and/or equipment operations on the lunar surface

Architecture Definition Document – Unallocated Functions by Use Case

UC-U-503 L	Deployment and operation of exploration assets, including utilization payload(s) and/or equipment, related to demonstration of propellant storage for long-durations (year+) in space
FN-U-504 L	Provide storage of cryogenic propellant in space
FN-U-505 L	Provide storage of non-cryogenic propellant in space
FN-U-510 L	Provide propellant management system(s) in microgravity environment

Architecture Definition Document – Unallocated Functions by Use Case

UC-U-504 L	Deployment and operation of exploration assets, including utilization payload(s) and/or equipment, related to demonstration of propellant storage for long-durations (year+) on the lunar surface
FN-U-503 L	Provide storage of cryogenic propellant on the lunar surface
FN-U-506 L	Provide storage of non-cryogenic propellant on the lunar surface
FN-U-509 L	Provide propellant management system(s) in partial gravity environment

Architecture Definition Document – Unallocated Functions by Use Case

UC-U-701 L	Deployment and operation of utilization payloads and/or equipment related to Impact Chronology on the lunar surface with long-term remote operation
FN-M-303 L	Enable local unpressurized surface mobility in sunlit areas and non-PSRs at distributed sites on the lunar surface
FN-M-502 L	Reposition a limited amount of cargo (100s of kg) at distributed sites on the lunar surface

Architecture Definition Document – Unallocated Functions by Use Case

UC-U-702 L	Deployment and operation of utilization payload(s) and/or equipment related to Geologic Processes on the lunar surface with long-term remote operation
FN-M-303 L	Enable local unpressurized surface mobility in sunlit areas and non-PSRs at distributed sites on the lunar surface
FN-M-502 L	Reposition a limited amount of cargo (100s of kg) at distributed sites on the lunar surface

Architecture Definition Document – Unallocated Functions by Use Case

UC-U-704 L	Deployment and operation of utilization payload(s) and/or equipment related to Solar System Volatiles at distributed locations on the lunar surface with long-term remote operation
FN-M-303 L	Enable local unpressurized surface mobility in sunlit areas and non-PSRs at distributed sites on the lunar surface
FN-M-502 L	Reposition a limited amount of cargo (100s of kg) at distributed sites on the lunar surface

Architecture Definition Document – Unallocated Functions by Use Case

UC-U-708 L	Deployment and operation of utilization payload(s) and/or equipment related to space weather at assets in deep space
FN-P-304 L	Distribute power to utilization payloads and/or equipment in deep space
FN-T-215 L	Transport cargo from Earth to assets in deep space
FN-U-201 L	Provide locations to host utilization payload(s) and/or equipment in deep space

Architecture Definition Document – Unallocated Functions by Use Case

UC-U-709 L	Deployment and operation of utilization payload(s) and/or equipment related to Magnetotail and Solar Wind on the lunar surface with long-term remote operation
FN-M-502 L	Reposition a limited amount of cargo (100s of kg) at distributed sites on the lunar surface

Architecture Definition Document – Unallocated Functions by Use Case

UC-U-711 L	Deployment and operation of astrophysics and fundamental physics utilization payload(s) and/or equipment on the far side of the lunar surface with long-term remote operation
FN-M-103 L	Enable crew lunar surface extravehicular activities at the lunar far side region
Architecture Definition Document – Unallocated Functions by Use Case	

UC-U-717 L	Deployment and operation of utilization payload(s) and/or equipment related to available resources on the lunar surface at the south pole region with long-term remote operation
FN-U-103 L	Conduct resource identification utilization payload and/or equipment operations on the lunar surface
Architecture Definition Document – Unallocated Functions by Use Case	

UC-U-718 L	Deployment and operation of utilization payload(s) and/or equipment related to available resources at distributed locations on the lunar surface with long-term remote operation
FN-M-303 L	Enable local unpressurized surface mobility in sunlit areas and non-PSRs at distributed sites on the lunar surface
FN-M-502 L	Reposition a limited amount of cargo (100s of kg) at distributed sites on the lunar surface
FN-U-103 L	Conduct resource identification utilization payload and/or equipment operations on the lunar surface
Architecture Definition Document – Unallocated Functions by Use Case	

UC-U-723 L	Deployment and operation of utilization payload(s) and/or equipment related to bio-regenerative oxygen and water recovery at assets in cislunar space
FN-U-601 L	Conduct bioregenerative ECLSS utilization payload and/or equipment operations in space
Architecture Definition Document – Unallocated Functions by Use Case	

UC-U-725 L	Deployment and operation of utilization payload(s) and/or equipment related to plant growth at assets in cislunar asset(s)
FN-U-602 L	Conduct plant growth utilization payload and/or equipment operations in space
Architecture Definition Document – Unallocated Functions by Use Case	

UC-U-728 L	Deployment and operation of utilization payload(s) and/or equipment related to demonstration of recovery of excess propellant from surface asset(s)
FN-U-501 L	Provide capability to access residual propellant from surface assets
FN-U-502 L	Transfer propellant between assets on the lunar surface

Architecture Definition Document – Unallocated Functions by Use Case

B.5.2.11 Human Systems

UC-X-103 L	Crew countermeasure capabilities to support the crew for mid-durations (month+) on the lunar surface
FN-X-103 L	Provide crew countermeasure system(s) to support the crew for mid-durations (month+) on the lunar surface

Architecture Definition Document – Unallocated Functions by Use Case

UC-X-104 L	Crew countermeasure capabilities to support the crew for mid- (month+) to long-durations (year+) in cislunar space
FN-X-104 L	Provide crew countermeasure system(s) to support the crew for mid-(month+) to long-durations (year+) in cislunar space

Architecture Definition Document – Unallocated Functions by Use Case

UC-X-201 L	In-situ crew training on the lunar surface
FN-X-201 L	Provide in-mission crew training on the lunar surface

Architecture Definition Document – Unallocated Functions by Use Case

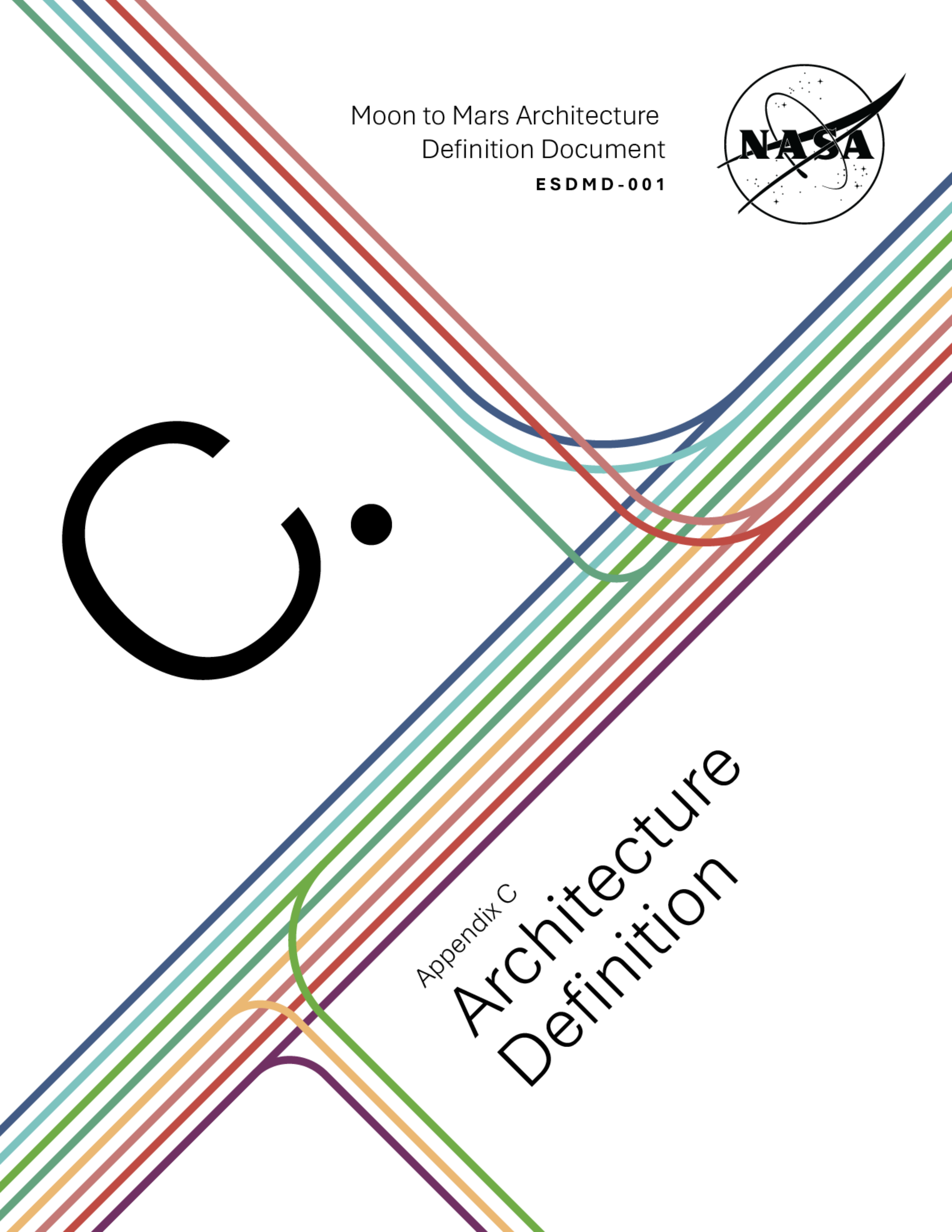
UC-X-202 L	In-situ crew training in cislunar space
FN-X-202 L	Provide in-mission crew training in cislunar space

Architecture Definition Document – Unallocated Functions by Use Case

UC-X-203 L	Provision of in-situ training to astronauts for science tasks during mission(s) on the lunar surface
FN-X-201 L	Provide in-mission crew training on the lunar surface
Architecture Definition Document – Unallocated Functions by Use Case	

Moon to Mars Architecture
Definition Document

ESDMD-001



C.

Appendix C

Architecture Definition

Appendix C: Architecture Definition

C.1 Architecture Roadmapping

NASA's architecture roadmapping process, rooted in systems engineering principles, establishes a recommended sequence for answering the many questions that make up the architecture. NASA uses the approach described in this appendix to identify, catalog, and sequence key architecture definition tasks. Section C.2 of this appendix lists these key trades and outcomes to date.

Architecture roadmapping ensures that NASA traces, assesses, and coordinates impacts of far-reaching key definition tasks. NASA uses an approach rooted in systems engineering principles to ensure that it conducts key definition tasks in an efficient way and remains a smart buyer of capabilities and services.

Architecture roadmapping also incorporates "legacy decisions" that predate the Moon to Mars Architecture approach but still influence lunar exploration.

The table below defines some key roadmapping terms.

Term	Definition
Architecture definition task	An examination of an open question or trade within the architecture.
Definition outcome	The result of a definition task, which could include a decision, down-select, ground rule, methodology, or other narrowing of the trade space.
Trade space	The range of options for a particular area of the architecture.
Key definition task	A definition task that so profoundly influences the end-to-end architecture that it warrants elevated scrutiny.
Priority key definition task	A key definition task with many flow-down impacts upon subsequent tasks and which was therefore presented and approved at the Architecture Concept Review to be made early in the architecture process.
Legacy decision	A decision made before the implementation of the architecture roadmapping process.

C.1.1 Value Proposition

Architecture roadmapping provides value in three main ways:

- **Minimizing later rework or disruption:** Architecture roadmapping prioritizes high-impact definition tasks that influence every aspect of the architecture early in the overall architecting process, minimizing implementation delays, rework, or re-litigation.
- **Defining inter-organizational critical paths:** The Moon to Mars Architecture includes many programs and projects, meaning that responsibility for conducting definition tasks crosses multiple organizations. One task may be in the critical path of a seemingly unrelated task. Architecture

roadmapping maps these relationships and ensures programs, projects, and technical authorities are aware of how their activities and outcomes affect other authorities.

- **Informing investment strategies:** Down-selects are necessary when multiple investments could meet objectives, but budget and schedule demands preclude multiple developments. Making these down-selects too early or too late can cause unwanted costs, delays, or architectural limitations. Architecture roadmapping helps authorities time their activities to optimize their development resources.

C.1.2 Roadmapping Process

C.1.2.1 Identifying and Defining Key Definition Tasks

The first step in architecture roadmapping is identifying and defining each key definition outcome that the architecture needs. Definition tasks include the question to be answered (i.e., the type of outcome needed), potential options, the NASA authority for the definition task (if known), relevant stakeholders, and architecture context.

NASA has used two methods to identify candidate key definition tasks. First, a bottom-up analysis drew initial input from decades of heritage studies; then, an ongoing top-down assessment has identified candidate key definition tasks from the objective decomposition. When NASA identifies a new candidate key definition task, it matures that task to add scope and context and then brings it forward for approval at the annual Architecture Concept Review.

C.1.1.1 Identifying Definition Task Flow-downs

After identifying candidate key definition tasks, NASA assesses how these tasks depend on one another to develop a recommended sequence for conducting them. Each candidate key definition task has dependencies on and for other key definition tasks; the dependencies are called “flow-downs.”

NASA uses a digital, SysML-based definition space model to capture the flow-down relationships between key definition tasks, visualize the impacts and importance of various key definition tasks, generate definition sequences, and trace the impact of definition outcomes.

C.1.1.2 Sequencing Key Definition Tasks

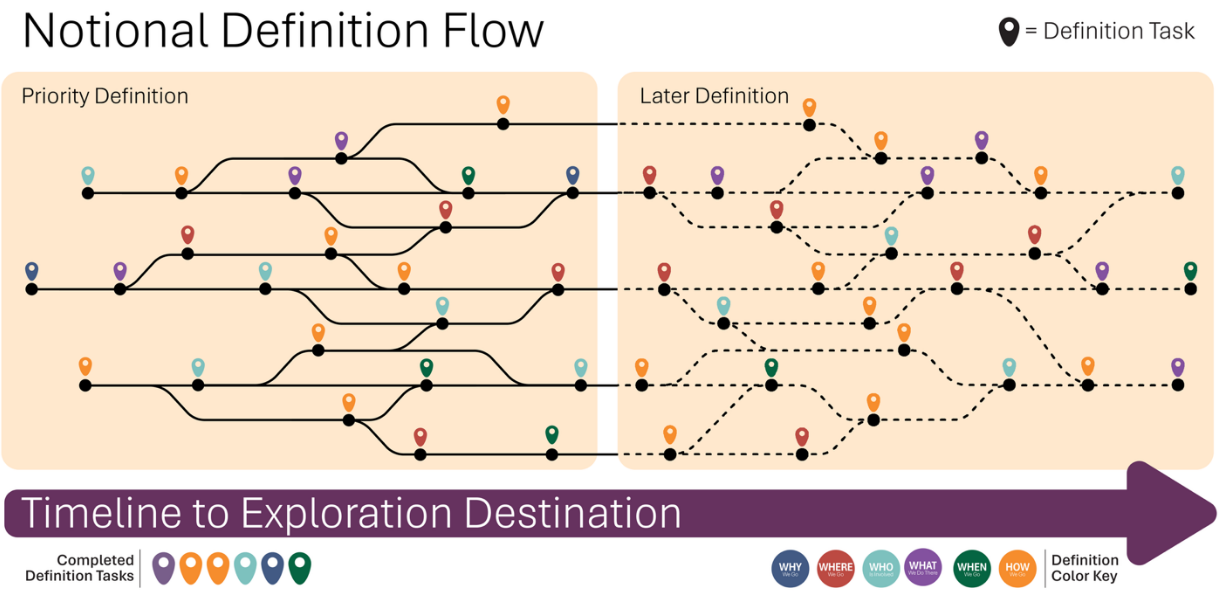
Using the dependencies captured in the definition space model, NASA performs analysis to identify options for the definition task sequence — the order in which the agency should conduct definition tasks. The initial analysis is based directly on the flow-downs and is designed to minimize violations of those flow-downs. However, this is an optimization problem in which many solutions are possible.

Many considerations are at play when comparing options for the sequence and determining what the recommended sequence should be, including the level of resources available that constrain how many definition tasks the agency could conduct in a given year, needs that inform technology development investments, the impact of a given definition outcome on the remaining trade space, and other considerations. The recommended sequence must carefully balance competing priorities and needs.

Based on these considerations, NASA establishes a partial roadmapping sequence and adds to it each year. This is represented by the “priority” key definition tasks — those with many flow-down impacts upon subsequent definition tasks and have been chosen to be conducted early in the architecture roadmapping process. Priority key definition tasks are approved at the Architecture Concept Review each year to be included in the sequence and to be addressed in the near term.

The graphic below shows a notional example, with several priority key definition tasks with many flow-down impacts preceding many later definition tasks. Separating priority key definition tasks from the later key definition tasks allows stakeholders to prioritize their resources.

The sequence represents the optimal order, but it is not strictly serial; multiple definition tasks can proceed in parallel. The sequence may evolve as priorities shift and NASA resolves feedback loops between key definition tasks.



Notional Depiction of Categorizing the Key Definition Tasks Based on Time Criticality

C.1.1.3 Documenting Outcomes

The actual process for conducting each key definition task will vary depending on the relevant authority, but in all cases, relevant internal organizations will participate in development of task scoping, analysis, and documentation. Once the agency has identified definition task options, collected data, performed analysis to evaluate the options, and developed recommendations in coordination with stakeholders, the relevant authority selects a definition outcome.

Definition outcomes can include decisions, down-selects, ground rules, methodologies, or other means of narrowing of the trade space and further defining the architecture. Definition outcomes appear in annual revisions of the Architecture Definition Document. The lists below capture all the outcomes of key definition tasks completed to date (as well as identified future key definition tasks). Resulting impacts to the architecture are reported at subsequent Architecture Concept Reviews.

C.2 Architecture Definition Tasks and Legacy Decisions

The lists below capture legacy decisions and completed and open key definition tasks. Subsequent revisions of this document will update these lists as NASA completes key definition tasks and identifies new ones.

C.2.1 Legacy Lunar Architecture Decisions

Legacy lunar architecture decisions, introduced in Section 3, are decisions that were made prior to the establishment of the Moon to Mars Architecture and its architecture roadmapping approach. The list below presents these decisions with additional detail and rationale.

C.2.1.1 LD-01-L: Enable Human Exploration on the Surface of Planetary Bodies

Although this decision predates the Moon to Mars Architecture, it lays the foundation for subsequent definition tasks spanning the entire “blueprint” for space exploration. By establishing the human component of planetary surface exploration, this decision underpins the future of human exploration of our solar system. By utilizing the moon as a testing ground for sustained deep space explorations and operations, NASA will have the tools and experience necessary to enable a sustained human presence on Mars and beyond.

The agency’s vision for deep space exploration has been highlighted in the Moon to Mars Objectives, a collection of common themes and goals across a variety of different technical disciplines. Building upon decades of studies and analyses, NASA has identified a need for humans to explore the surface of planetary bodies such as the Moon and Mars, beyond solely robotic endeavors. Accomplishing this task requires the development of technologies related to crew launch, transport, and habitation in space.

Successful and persistent human planetary surface exploration is dependent on developing an architecture to meet specific needs. Longer-duration missions, with increased exposure to radiation and varying gravity fields, will have unclear effects on the human body. Communications delays highlight the need for increased Earth independence. The human component of NASA’s exploration architecture affects the development of everything from transportation and habitation elements to risk mitigation strategies and Earth-independent operational guidelines.

C.2.1.2 LD-02-L: Deep Space Element(s) in Microgravity for Long-duration, Crewed Exploration

NASA will deploy a persistent crewed platform in deep space to address the needs of the Moon to Mars Architecture and enable long-duration crewed exploration of deep space. To meet this decision, the agency will deploy the Gateway station in lunar orbit (see also LD-04-L). Gateway will serve as an aggregation location for crewed vehicles and logistics payloads, and as a deep space laboratory with various capabilities to conduct experiments.

The decision to deploy Gateway has downstream impacts across the lunar architecture. The Gateway decision, alongside the decision to utilize NRHO, constrains surface operations and crew size. Lunar surface access is partially dictated by the orbit of Gateway, and the crew size capability of both Gateway and Orion constrain how many crew will operate on the lunar surface. Gateway also has its own requirements that will constrain how much cargo it can hold, what science and utilization it can support, and what resources are needed to enable sustained operation in cislunar space.

In addition, the technologies and techniques developed for Gateway will address essential requirements for Mars exploration by informing and shaping architectures for habitation, propulsion, and communications. Gateway will also serve as a testing platform for Mars-focused operations, mission planning, and adaptations to different gravity environments, while offering a rapid return capability to Earth if unforeseen issues related to Mars-forward analog testing arise.

C.2.1.3 LD-03-L: Lunar Landing Region Selection

Following the decision to pursue lunar surface exploration (see LD-01-L), NASA chose the lunar South Pole region as the initial landing area for crewed missions. Key factors informing this decision include access to areas of both near-continuous sunlight and continuous darkness, access to ancient terrain, and access to completely unexplored areas.

Near-continuous sunlight areas, found in the polar regions, are more thermally stable than areas with a more typical day-night cycle. Hardware in these areas will experience constant thermal conditions and have a steady source of solar power. Systems developed for use in a near-continuous solar environment will not need excess capability designed to survive lunar night, decreasing complexity and power requirements.

Scientifically, permanently shadowed regions have been found to preserve volatiles, due to constant low temperature. Sampling volatiles in the South Pole region will lead to discoveries about the history of our solar system and have potential for ISRU. In addition, the South Pole is also home to the South Pole-Aitken Basin, the oldest impact basin in the solar system. Having direct access to some of the oldest parts of the Moon will provide insight into the interactions between the Sun and our solar system across billions of years. Studying lunar surface volatiles builds technical and scientific competence, which is useful when envisioning future missions to Mars. The Martian poles contain ice, meaning work completed on the lunar surface will directly inform how Mars science objectives are completed.

C.2.1.4 LD-04-L: Crewed Lunar Orbit

Following the decision to deploy Gateway in deep space (see LD-02-L), NASA selected NRHO for crewed lunar orbital operations. This decision links Gateway with other aspects of the Artemis architecture, such as landing site selection and usage of elements such as Orion.

NRHO's Earth-facing orientation allows for continuous communications, while also providing line of sight and coverage to the lunar South Pole for communications and operations. Compared to orbits closer to the lunar surface, NRHO is relatively easy to sustain, and is also able to facilitate the demonstration and testing of Mars-forward technologies, such as large-scale solar electric propulsion systems.

Alongside these benefits, NRHO's repeatability allows for consistent access to both vehicles needing to reach NRHO from Earth and landers needing to reach the lunar South Pole. This decision defines the location for Gateway and drives downstream design requirements for Gateway, HLS, and lunar communication systems.

C.2.1.5 LD-05-L: Integrated Crewed Lunar Mission Cadence

NASA is planning integrated crewed missions to the Moon for an annual basis, combining both orbital and lunar surface operations, as a result of this decision. This decision originates from early requirements in the Constellation Program, specifically targeting a minimum mission rate of two crewed lunar missions per year. After the cancellation of Constellation in 2011, program elements were evaluated for use in other architectures and evolved into Orion, and overall production capability was rescoped to provide for a yearly launch cadence, with the potential for surges of up to two missions each year.

While LD-05-L does not directly affect the Moon to Mars Architecture, it characterizes the frequency of operations on the lunar surface, which will affect how certain future objectives are satisfied. And while this is not a driver of the decision, an annual launch cadence will also serve as an analog for future Mars missions, which can only depart every 26 months. This will allow NASA and its partners to pursue iterative processes to better understand the downstream impacts of the 26-month cadence on future Mars missions, while offering a rapid return capability to Earth if unforeseen issues related to Mars-forward analog testing arise (see also LD-02-L).

C.2.1.6 LD-06-L: Number of Crew to Cislunar Space

Similar to LD-01-L, the decision to have a crew complement of four predates the Moon to Mars Architecture. This decision can be traced back to the Constellation Program, specifically the 2005 Exploration Systems Architecture Study (ESAS). The ESAS was conducted to define the top-level architecture of George W. Bush's Vision for Space Exploration, including the definition for a new Crew Exploration Vehicle (CEV) as well as lunar exploration concepts. NASA baselined the CEV for up to four crew for lunar missions, stemming from a variety of studies, constraints, guidance, and design practices. After Constellation was cancelled in 2011, the CEV eventually became what is now known as Orion, maintaining the baseline of up to four crew.

This decision impacts several parts of the current Moon to Mars Architecture, including lunar crew configuration, element design, and surface operations. With elements such as Gateway currently being planned, a crew complement of up to four can be divided between crew operating on the lunar surface and crew staying aboard the station. The crew complement is also divided between astronauts from the United States and international partners. Depending on the number of crew on the surface, mobility assets such as rovers will be sized to match architecture needs. Benefits of four crew split between orbit and surface include safety, risk management, expanded operational capabilities with surface monitoring, more efficient use of resources, support for longer surface missions, and refining techniques and lessons learned for future Mars missions.

C.2.1.7 LD-07-L: Crewed Lunar Surface Stay Duration Capability

Crewed lunar surface missions will build on initial capabilities to enable crewed surface durations of up to 33 consecutive days for initial campaign segments. This decision highlights a build in capability between shorter initial sorties and longer missions as NASA builds up surface assets.

Surface stay duration has many downstream architecture impacts, including effects on designs for habitability, mobility, and logistics, among others. It also is heavily linked to lunar orbit operations, specifically with the NRHO decision (see also LD-04-L). For early lunar surface missions, crew will complete a sortie of around 6 days. This aligns with the NRHO orbit of around 6.5 days, ensuring reliable surface arrival and departure. As NASA gathers further foundational data and deploys more capable surface assets are deployed, surface functions can increase up to 33-day durations, as defined in this decision.

The incremental increase in surface stay duration will provide data and lessons learned that can inform later segments of the Moon to Mars Architecture. A 33-day lunar surface stay can also provide lessons learned for Mars exploration, because it closely matches the minimum Mars surface stay duration of 30 sols.

C.2.2 Completed Key Definition Tasks

C.2.2.1 LD-101: Lunar External Power Augmentation

The agency decided to pursue trades to balance element design, aggregate power demand, total surface landed mass, mission to mission flexibility, and architecture robustness to utilize power augmentation methods on the lunar surface.

The Foundational Exploration segment is constrained by the amount of energy available to power crew life support systems, provide keep-alive support to surface elements, utilization payloads and equipment, and to make, move, or environmentally maintain critical infrastructure. This strategic decision focused on how to balance delivered mass and volume, accessible areas, power generation, energy storage, and aggregate user power demand across the architecture in an efficient manner. The Foundational Exploration segment's goals require augmenting surface elements with power generation and/or energy storage capabilities and developing a strategy for integrating external power assets Foundational Exploration and beyond. This outcome does not down-select between technologies, sizing, or concepts; future studies will address these topics.

C.2.2.2 LD-102: Lunar Logistics Strategy

The agency decided to pursue a hybrid strategy for delivering required logistics to elements on the lunar surface using a variety of solutions, ranging from small portable carriers to large mated carriers.

During the Foundational Exploration segment of our lunar human exploration missions, providing items such as food, water, air, spare parts, and other similar products required to sustain life, maintain systems, and allow for productive science and utilization activities (i.e., logistics items) is critical. The estimated total amount of logistics items required to keep the crew alive and healthy, to maintain systems, and to perform productive science and utilization can be relatively large. A hybrid strategy that uses smaller crew portable carriers as well as larger mated logistics carriers enables the agency to maintain flexible and robust means to support these missions.

C.2.2.3 LD-103: Lunar Surface Communications Strategy

In 2025, the agency formally adopted a combination of three foundational technologies for the agency's lunar surface network. They are Space-to-Space Communications Systems, an Ultra High Frequency Time-Division-Multiple Access system designed to provide voice, commands, telemetry and data services in close proximity to the International Space Station; WiFi 6, an Institute of Electrical and Electronics Engineers networking standard from the nonprofit WiFi Alliance; and 3GPP — 3rd Generation Partnership Project — (5G), a technical specification for mobile networks. This decision will offer a scalable approach to communications capabilities that enables high-bandwidth, high-availability communications to support long-term science, exploration, and industry needs.

C.2.2.4 MD-07: Mars Primary Surface Power Generation Technology

At the 2024 Architecture Concept Review, the agency selected nuclear power technology (specifically, fission power) over non-nuclear power technology (in particular, photovoltaic arrays with energy storage) to be baselined as the primary surface power generation technology in the initial Humans to Mars architecture segment. Mitigating loss-of-mission risk was the primary driver for this selection: although solar power may have a lower per unit cost, fission power is more robust to Martian environmental and atmospheric conditions, providing consistent power generation across a wide range of potential landing sites, around the clock, and during global dust storms, and a landed mass and volume advantage at the power levels needed for human Mars exploration.

C.2.2.5 MD-02: Initial Human Mars Segment Target State

At the 2025 Architecture Concept Review, the agency completed a down-select for the initial Humans to Mars segment target state that outlines a vision for the segment and will guide future architecture definition tasks. The architecture options for the Mars target state at this stage included various combinations of three primary parameters: number of crewed surface missions, surface mission duration, and number of sites visited. Based on various factors of benefit, risk, and cost, a trade space down-select removed all single-mission scenarios and the most expensive scenario, leaving three remaining target state options: multiple short-duration missions that return to the same site, multiple long-duration missions that return to the same site, and multiple short-duration missions to different sites.

C.2.2.6 MD-04: Mars Architecture Loss of Crew Risk Methodology

At the 2025 Architecture Concept Review, the agency approved a risk methodology that leverages agency experience with risk assessments and mission modeling to ensure risk-informed decision-making is incorporated in architecture definition tasks. The risk methodology outlines a combination of both quantitative and qualitative assessment to evaluate loss-of-crew risk at the architecture level. The risk assessment methodology is expected to be applied to future key definition tasks, architecture trade studies, and an annual architecture risk assessment update. This methodology is expected to be continually improved over time, in particular with the subsequent MD-08: Mars Architecture Loss of Mission Risk Methodology definition task.

C.2.2.7 MD-05: Number of Crew to Mars Surface

At 2025 Architecture Concept Review, the agency decided that the initial Humans to Mars segment will send a range of four to six crew members to the Martian surface. Stakeholders across the agency explored the implications of number of crew to potential architecture approaches, as well as operations, mission safety, crew health and performance (CHP), technology development priorities, cost, and loss of crew risk. There is consensus within the stakeholder community that fewer than four crew introduces significantly more crew risk, and more than six crew offers diminishing return on reduction of mission and crew risk while taking on a substantial increase in cost and system complexity. The integrated data and analyses indicated that the main drivers are CHP and mission risk, as well as opportunities to accomplish mission objectives. In particular, the (unavoidable) long communication delay between Earth and Mars forces a shift in operational tasking, workload, and how crew members respond to off-nominal and unforeseen events. The range of four to six crew members to the Martian surface best balances these factors.

C.2.3 Open Architecture Key Definition Tasks

Note: *Key definition tasks captured here exist in various states of maturity. Through the roadmapping process, NASA identified certain key definition tasks to work in the near term and therefore prioritized the maturation of those tasks. As NASA has begun work on these priority key definition tasks in the near term, they have been assigned an identification number and appear at the top of the list in the table below. The remaining identified tasks that do not yet have a number are grouped by category and alphabetically. The order does not imply prioritization. NASA may add, remove, or modify key definition tasks in future updates to the Architecture Definition Document. Completed tasks are listed in Section C.2.2 and indicated in the table below.*

ID	Key Definition Task Title	Category		Result
MD-01	Initial Human Mars Segment Science Objectives Priorities	01	Science	
MD-02	Initial Human Mars Segment Target State	02	Overall Strategy	ACR25 *Down-Select*
MD-03	Initial Human Mars Segment Mission Cadence	02	Overall Strategy	
MD-04	Mars Architecture Loss of Crew Risk Methodology	03	Overall Risk Posture	ACR25 *Methodology*
MD-05	Number of Crew to Mars Surface	04	Human Systems & Habitation	ACR25 *Decision*
MD-06	Number of Crew to Mars Vicinity Per Mission	05	Human Systems & Habitation	
MD-07	Primary Mars Surface Power Generation Technology	05	Surface Systems & Infrastructure	ACR24 *Decision*
MD-08	Mars Architecture Loss of Mission Risk Methodology	03	Overall Risk Posture	
MD-09	Maximum Mars Crew Surface Stay Duration	07	Surface Operations	
MD-10	Mars Forward Contamination Planetary Protection Risk Posture	02	Overall Strategy	
MD-11	Mars Backward Contamination Planetary Protection Risk Posture	02	Overall Strategy	
MD-12	Maximum Allowable Crewed Communications Disruption	11	C&PNT	
	Mars Sample Analysis Strategy	01	Science	
	Science Support Platform (In-Space)	01	Science	
	Science Support Platform (Mars Surface)	01	Science	
	Maximum Total Crew Mission Duration	02	Overall Strategy	
	Minimum Mars Surface Element Design Lifetime	02	Overall Strategy	

ID	Key Definition Task Title	Category		Result
	Architecture Level Contingency Protection Posture	03	Overall Risk Posture	
	ECLSS Strategy (In Space)	04	Human Systems & Habitation	
	ECLSS Strategy (Mars Surface)	04	Human Systems & Habitation	
	Food Refrigeration and Growth	04	Human Systems & Habitation	
	Safe Haven Strategy (In Space)	04	Human Systems & Habitation	
	Safe Haven Strategy (Mars Surface)	04	Human Systems & Habitation	
	Waste and Trash Disposal Strategy (In Space)	04	Human Systems & Habitation	
	Waste and Trash Disposal Strategy (Mars Surface)	04	Human Systems & Habitation	
	Crew Surface Mobility Strategy	05	Surface Systems & Infrastructure	
	Mars Landing Support Infrastructure	05	Surface Systems & Infrastructure	
	Surface Ingress/Egress Strategy	05	Surface Systems & Infrastructure	
	Source of Mars Crew Consumables	05	Surface Systems & Infrastructure	
	Surface Construction Priorities	05	Surface Systems & Infrastructure	
	Surface Servicing Capability Strategy	05	Surface Systems & Infrastructure	
	Surface Habitation Mobility Strategy	06	Surface Infrastructure Deployment Strategy	
	Small Cargo Delivery, Stowage, and Return Strategy	06	Surface Infrastructure Deployment Strategy	
	Logistics Carrier and Interface Strategy	06	Surface Infrastructure Deployment Strategy	
	Logistics Deployment Timing (Mars Orbit)	06	Surface Infrastructure Deployment Strategy	
	Logistics Deployment Timing (Mars Surface)	06	Surface Infrastructure Deployment Strategy	
	Site Planning Schema	06	Surface Infrastructure Deployment Strategy	
	Crew Landing Region	07	Surface Operations	

ID	Key Definition Task Title	Category		Result
	Exploration EVA Schema	07	Surface Operations	
	Surface EVA Capability Strategy	07	Surface Operations	
	Number of Crew on Surface EVA	07	Surface Operations	
	In-Space Refurbishment Capability Between Missions	08	In-Space Systems & Infrastructure	
	In-Space Servicing Capability Strategy	08	In-Space Systems & Infrastructure	
	Primary Mars In-Space Power Generation Technology	08	In-Space Systems & Infrastructure	
	Cargo In-Space Propulsion Type	09	In-Space Transportation	
	Cargo Mars Orbit Capture Strategy	09	In-Space Transportation	
	Crew Earth Capture Strategy	09	In-Space Transportation	
	Crew In-Space Propulsion Type	09	In-Space Transportation	
	Crew In-Space Return Propellant Strategy	09	In-Space Transportation	
	Crew Mars Orbit Capture Strategy	09	In-Space Transportation	
	Crew Mars Parking Orbit	09	In-Space Transportation	
	Entry, Descent, Landing, Ascent and In-Space Transportation Systems Functional Split	09	In-Space Transportation	
	Element Delivery Strategy	09	In-Space Transportation	
	In-Space Transportation Systems Reuse Strategy	09	In-Space Transportation	
	Cargo Mars Entry, Descent, and Landing Technology	10	Entry, Descent, Landing, Ascent	
	Crew Earth Ascent Vehicle Strategy	10	Entry, Descent, Landing, Ascent	
	Crew Earth Descent Vehicle Strategy	10	Entry, Descent, Landing, Ascent	
	Crew Mars Ascent Availability	10	Entry, Descent, Landing, Ascent	
	Crew Mars Ascent Propulsion Type	10	Entry, Descent, Landing, Ascent	

ID	Key Definition Task Title	Category		Result
	Crew Mars Ascent Propellant Strategy	10	Entry, Descent, Landing, Ascent	
	Crew Mars Descent Availability	10	Entry, Descent, Landing, Ascent	
	Crew Mars Entry, Descent, and Landing Technology	10	Entry, Descent, Landing, Ascent	
	Entry, Descent, Landing, Ascent Systems Reuse Strategy	10	Entry, Descent, Landing, Ascent	
	Surface PNT Strategy	11	C&PNT	
	Critical Events Communications Strategy	11	C&PNT	
	Crew Communications Architecture	11	C&PNT	
	Minimum Crew Communications Capability	11	C&PNT	
	Minimum Sustained Communications Capability	11	C&PNT	
	Priorities for Crew vs. Robotic Tasks Strategy	12	Robotics & Autonomy	
	Priorities for Earth Independent Crew Tasks	12	Robotics & Autonomy	
	Inspiration Priorities	13	Inspiration	

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D.

Appendix D

Architecture-Driven Technology Gaps

Appendix D: Architecture-Driven Technology Gaps

This appendix contains a set of gap detail summary tables for each of the architecture-driven technology gaps, which are described in Section 3. These summaries describe the gap, identify the target capability or performance expected based upon the current architecture documentation, and track how the gap traces to the architecture and objective decomposition.

D.1 Technology Gap Components

Each technology gap contains the following information.

Gap Title	Summary of the needed capability in the Moon to Mars Architecture
Gap ID No.	A four-digit unique identifier; the first two digits are determined by the gap's most relevant sub-architecture
Priority Bin	Distinct groupings of architecture preference of gap closure based upon prioritized list to show relative priority
Overall Prioritization Rating	The gap's location in the prioritized list of gaps, indicating architecture preference of gap closure based upon the weighting and combination of the four priority metrics
Gap Description	Description of the gap between the current state of the art and the Moon to Mars Architecture's needed capabilities/performance targets
Architecture-Driven Child Gaps	List of the titles of the child gaps related to this technology gap, which are also architecture-driven; the * symbol denotes a child gap with multiple parents
Architecture Impact and Benefits	High-level summary of positive benefits to the Moon to Mars Architecture if the gap is closed or negative impacts to the Moon to Mars Architecture if the gap is not closed
Architecture Traceability: Use Cases & Functions	List of the use cases and functions from which the needed Moon to Mars Architecture capability was derived
Architecture Traceability: Key Definition Tasks	List of key architecture definition tasks with strong relevance to the gap; to be considered relevant, the task affects the degree of need for the gap directly
Metrics: Current State of the Art	Description of the current state-of-the-art capabilities
Metrics: Performance Target	Description of the Moon to Mars Architecture's needed capabilities/performance targets
Segments	The Moon to Mars Architecture segment(s) for which the capability is needed
Sub-Architectures	List of the Moon to Mars sub-architecture(s) with strong relevance to the gap's content and scope

Note: *For additional current state-of-the-art details, refer to the NASA Tech Port at the link below: https://techport.nasa.gov/*

D.2 Prioritized List of Technology Gaps

This list below captures the architecture-driven technology gaps in priority order. The technology gaps fall into priority bins based on similar level of preference. This list includes gap identification number, title, rating, and priority bin. For the full details for any given technology gap, refer to Appendix D.3.

ID	Gap Title	Priority Ranking	Priority Bin
0801	Lunar Dust-Tolerant Systems and Dust Mitigation	1	1
0201	Extreme Environment Avionics	2	
0301	Systems to Survive and Operate through Extended Periods of Lunar Shadow	3	
1107	Cryogenic Fluid Transfer	4	
0103	High-bandwidth, High-reliability Surface-to-Surface Communications	5	
1104	Mars Transportation Propulsion	6	
0806	Payload Offloading, Handling, and Manipulation for Surface Assets	7	2
0805	Autonomous Surface Mobility and Navigation	8	
0305	Food and Nutrition Capabilities for Long-Duration Missions	9	
1103	Mars Entry, Descent, and Landing for Human Exploration	10	
0304	Habitat Environmental Monitors and Capabilities to Support Deep Space Missions	11	
1105	Mars Ascent Propulsion for Human Exploration	12	
0901	Scalable Lunar Surface Power Generation	13	
1001	High-performance Actuators, Sensors, and Interfaces	14	
0807	Docking and Berthing between Surface Elements on the Moon and Mars	15	
0303	Dormancy Recovery for Habitat Water Storage, Distribution, and Reclamation	16	3

ID	Gap Title	Priority Ranking	Priority Bin
0307	Radiation Monitoring and Forecasting	17	
1003	Integrated System Fault/Anomaly Diagnosis, Decision Support, and Response	18	
0804	Robotic and Mobility Systems in Extreme Cold Environments on the Lunar Surface	19	
0101	Positioning, Navigation, and Timing for Lunar Surface Extreme Environments	20	
0702	Waste Management	21	
0302	Fire Safety Upgrades for Surviving Exploration Mission Environments	22	
0701	Packing, Transport, and Use of Conditioned Supplies and Commodities	23	
0903	Power Management and Distribution between Surface Elements	24	
0808	Relocation of Large Assets on the Lunar Surface	25	
0202	High-Performance Onboard Computing	26	
1101	Lunar Precision Landing and Hazard Avoidance for Human Exploration	27	
1005	Safe Human-Robot Interaction and Teaming	28	
0505	In-Situ Additive/Subtractive Construction on the Lunar Surface	29	
0504	Autonomous Lunar Surface Structure Assembly and Construction	30	
0803	Extravehicular Activity (EVA) and Intravehicular Activity (IVA) Suit System and Capabilities for Mars Missions	31	4
1106	Cryogenic Fluid Storage	32	
1004	Trustworthy Autonomy for Planning and Decision-making	33	
1002	Autonomous Monitoring for Exploration Missions	34	
0802	Mars Dust-Tolerant Systems and Dust Mitigation	35	
0501	Robotic Inspection, Maintenance, and Repair	36	
1102	Mars Precision Landing and Hazard Avoidance for Human Exploration	37	5
1201	In-Situ Sample Storage and Processing	38	
0402	Sensorimotor Countermeasures to Support Extended Habitation in Space	39	
0401	Crew Exercise Countermeasures to Support Extended Habitation in Space	40	

ID	Gap Title	Priority Ranking	Priority Bin
0403	Physiological Countermeasures for Extended Habitation in Space	41	
0404	Behavioral Countermeasures for Extended Habitation in Space	42	
0406	Spacesuit Physiology for Deep Space Missions	43	
1202	Planetary Protection Technologies for Human Exploration	44	
0902	Scalable Mars Surface Power Generation	45	
0405	Exploration Medical Capabilities for Deep Space Missions	46	
0308	Radiation Countermeasures	47	
0104	Earth-Independent Surface Positioning, Navigation, and Timing for Deep Space Missions	48	
0306	Advanced Structures and Materials to Enable Mass-Efficient Habitats	49	6
0503	In-Space & Surface Transfer of Earth-Storable Propellants	50	
0102	High-bandwidth, High-reliability Deep Space Communications	51	
0606	Mars ISRU to Support Human Exploration	52	
0605	Lunar Regolith Excavation, Manipulation, and Transportation	53	
0601	Oxygen Extraction from Lunar Regolith	54	
0603	Water Recovery from Lunar Regolith/Ice	55	
0604	Metal Extraction from Lunar Regolith	56	
0502	In-situ Manufacturing of Spares, Repairs, and New Parts	57	

Note: *Technology Gap #0602 (In-Situ Resource Identification, Characterization, and Mapping) has been replaced by Architecture-Driven Data Gaps: DN-006 L, DN-007 L, DN-008 L, DN-010 L, DN-013 L in Appendix E.*

D.3 Catalog of Technology Gaps

This section contains the full list of technology gaps, including all of the details described in Appendix D.1. The technology gaps appear in numerical order, not priority order.

Positioning, Navigation, and Timing for Lunar Surface Extreme Environments

ID No.	**0101**
Rating	**20**
Bin	**6 of 6**

Gap Description

Current positioning, navigation, and timing (PNT) systems for exploration assets and crew provide relative position but lack the ability to precisely determine their absolute location. The state of the art is insufficient for long traverses across the lunar surface that will require absolute localization to facilitate path planning and execution. The state of the art is also insufficient for the expected extreme environments at the lunar surface over the mission durations. There is a need for absolute and relative PNT systems and technologies that accurately track crew and mobile surface assets and that are tolerant to radiation, extreme temperatures, and dust. For example, solar wind plasma and ultraviolet radiation can electrically charge lunar regolith to increase the electrostatic properties and amplify the regolith on the lunar surface. These charged particles introduce an electric field on the surface that can impact navigation and timing systems and science instruments.

Architecture Impacts and Benefits

Without gap closure, the impacts may include reduced positioning, navigation, and timing systems accuracy. Additionally, due to the environment, there is a risk of PNT systems being compromised and unable to operate and perform at expected levels.

Architecture-Driven Child Gaps

0101-01	Positioning and navigation systems for lunar surface applications
0101-02	Accurate and stable timing systems for surface exploration assets on the lunar surface
0101-03	Robust positioning, navigation, and timing systems for the extreme lunar surface environment

Architecture Traceability

Key Definition Tasks

"✓" indicates completed definition task

Use Cases & Functions	
UC-M-601 L	FN-C-201 L
UC-C-202 L	FN-C-201 L
UC-C-203 L	FN-C-201 L

Metrics

Current State of the Art

Current Mars rovers possess state-of-the-art PNT capabilities for mobile assets on another planetary surface, primarily utilizing onboard sensors for relative navigation with minimal onboarding processing. However, lunar rovers will have an increased pace of exploration and operational range, which as a result will require technology advancement and the gap results from requirements for absolute navigation, real-time accuracy, and increased onboard processing of sensor data, especially for crew manual control. Additionally, Mars rovers differ from lunar rovers due to variations in the environmental conditions, lighting, and signal latency. The VIPER project developed high fidelity navigation tools for future use on an exploration rover at the lunar South Pole region.

Performance Targets

Moon

Achieve absolute real-time localization of crew, mobile, and in-place assets to within 10m, 3 sigma enabled by a navigation infrastructure (such as an orbital constellation) defined by a geometric dilution of precision (GDOP) of less than six with at least four broadcast PNT signals. Given the line-of-sight and current infrastructure coverage requirements, systems on the lunar surface can determine their location within a short period of time. Once initialized, the systems can maintain this level of accuracy given a combination of navigation infrastructure signals, local sensors and onboard processing. Initial navigation infrastructure capability for the FE segment is planned for 40% of 24 hours for the lunar South Pole region with slightly degraded performance during the remainder of the day. The navigation infrastructure for the SLE segment can include expanded coverage and availability both in terms of surface area and percent time available. In addition to absolute localization, mobile assets may need to leverage relative measurements to meet a minimum close approach to distance.

Degraded performance: When C&PNT infrastructure is not available or inadequate, Artemis navigation systems can determine absolute location (within 3 sigma of targeted accuracy) for crew within 150m and vehicles within 100m, both 3-sigma.

Future performance: Surface capabilities utilizing multiple fixed and mobile assets will require greater local and relative navigation accuracy, especially during coordinated operations in close proximity.

Segments

Foundational Exploration

Sustained Lunar Evolution

Sub-Architectures

C&PNT

High-bandwidth, High-reliability Deep Space Communications

ID No.	**0102**
Rating	**51**
Bin	**6 of 6**

Gap Description

Communication from another planetary body back to Earth is a complex challenge. Deep space communication is currently accomplished via ground-based methods using the Deep Space Network or, for Mars, a limited relay system of orbiters (with secondary objectives to relay data). To achieve constant, reliable communications for deep space missions, communication systems should be disruption-tolerant and capable of transmitting voice and data at a high bandwidth with little to no interruption. Communication systems also need to be able to operate within the spectrum allocated for use. Additionally, there are timing challenges that require highly stable timing systems capable of achieving low drift rates. Reliable communication and timing strategies for deep space missions are needed to prevent interrupted communications and/or loss of mission-critical data.

Architecture Impacts and Benefits

Without gap closure, there would be increased difficulty in supporting consistent crew communications in deep space, as well as potential increased risk for loss of mission-critical data. For timing systems, there may be impacts reducing size, weight and power.

Architecture-Driven Child Gaps

0102-01	High-bandwidth, high-availability forward link from Earth to Mars
0102-02	High-bandwidth, high-availability return link from Mars to Earth
0102-03	High-efficiency, high-power optical communications
0102-04	High-efficiency, high-power radio frequency communications
0102-05	High-stability timing systems for Mars related applications

Architecture Traceability

Key Definition Tasks	Use Cases & Functions	
● MD-12 Maximum Allowable Crewed Communications Disruption	UC-C-101 M	FN-C-102 M
● Crew Communications Architecture	UC-C-103 M	FN-C-103 M
● Minimum Crew Communications Capability	UC-C-104 M	FN-C-104 M
● Minimum Sustained Communications Capability	UC-C-105 M	FN-C-107M
	UC-C-108 M	FN-D-102 M

"✓" indicates completed definition task

Metrics

Current State of the Art	Performance Targets	
Ground-based methods through the Deep Space Network or Mars orbiters.	● Mars	Enable reliable uplink and downlink solutions that prevent or mitigate data disruptions (e.g., terrain blockages, momentary loss of surface or relay coverage). Additionally, human landers will need high definition (HD) or better quality streaming and still imagery.

Segments	Sub-Architectures
Humans to Mars	C&PNT

High-bandwidth, High-reliability Surface-to-Surface Communications

ID No. **0103**
Rating **5**
Bin **1 of 6**

Gap Description

Surface communication technologies and systems for Moon and Mars need to provide reliable and secure communication and transmit/receive voice, video, and data through multiple surface assets (e.g., crew, autonomous robotics, habitable systems, fixed infrastructure, relays, and mobility systems) at a high bandwidth, over exploration distances. Solutions must be interoperable for multiple providers and users across NASA, international, and commercial assets. There are several trade studies being pursued for more advanced surface-to-surface communications technologies and systems to meet the exploration objectives and requirements.

Architecture Impacts and Benefits

If advancements are not made toward gap closure, there will be a lack of reliable, high-bandwidth lunar and Martian surface communication systems for crew and other surface assets. Additionally, the communication infrastructure will not be robust, sustainable, and capable of scaling to support multiple users, service providers, and assets.

Architecture-Driven Child Gaps

0103-01	Scalable wireless surface-to-surface communication systems
0103-02	High-rate proximity communications between surface assets
0103-03	Characterization of the lunar surface environment for reliable surface-to-surface communication

Architecture Traceability

Key Definition Tasks		Use Cases & Functions	
LD-103 Surface Communications Strategy	✓	UC-C-102 L	FN-C-107 L
Crew Communications Architecture		UC-C-102 M	FN-C-101 M
Minimum Crew Communications Capability			
Minimum Sustained Communications Capability			

"✓" indicates completed definition task

Metrics

Current State of the Art	Performance Targets	
Ultra high frequency (UHF) systems from Shuttle that can support audio for a maximum of 5 users over a distance of 1.0 km. WiFi has been demonstrated on the ISS supporting high data rates but is limited to non-critical applications. Neither technology has yet to be enabled on the lunar surface and there are some concerns towards multipath being difficult for UHF space-to-space communication systems that may reduce the useable distance.	Moon	Advanced 3rd Generation Partnership Project (3GPP) cellular (e.g. 4G, 5G), Wi-Fi, and RF technology that supports video as well as mission critical voice, data, and other applications. Scalable, secure, and interoperable Communications technologies (e.g., rad-hard systems base stations, and user equipment) that provide a surface network throughput of 25 to 50 Mbps within 10 km, which is needed to simultaneously support multiple lunar users with voice, video, navigation, and data transfer services.
	Mars	Scalable, secure, and interoperable communications technologies to support multiple Martian users with voice, video, navigation, and data transfer services. Surface network throughput and range may differ from lunar performance due to differences in Martian regolith and atmospheric characteristics.

Segments

Foundational Exploration
Sustained Lunar Evolution
Humans to Mars

Sub-Architectures

C&PNT

Earth-Independent Surface Positioning, Navigation, and Timing for Deep Space Missions

ID No. **0104**
Rating **48**
Bin **5 of 6**

Gap Description

Crewed missions and complex robotic missions are not operationally efficient or safe without constant and accurate positioning, navigation, and timing of crew, mobility, and transportation systems. Similar to lunar surface operations, long traverses across the Mars surface will require absolute localization to facilitate path planning and execution. There are challenges that prevent reliable surface positioning, navigation, and timing such as communication delays, disruptions, and blackout periods. To mitigate, there should be Earth-independent solutions available that can provide high-availability surface positioning, navigation, and timing for deep space surface missions.

Architecture Impacts and Benefits

Without gap closure, the impacts are increased risk of not being able to accurately and reliably track crew, autonomous and robotic systems, and mobility assets, as well as continued reliance on Earth-based positioning, navigation, and timing support for deep space surface missions.

Architecture-Driven Child Gaps

0104-01	Earth-independent tracking systems for deep space missions
0104-02	Earth-independent navigation systems for deep space missions
0104-03	Earth-independent timing systems for deep space missions

Architecture Traceability

Key Definition Tasks

- ● MD-12 Maximum Allowable Crewed Communications Disruption
- ● Surface PNT Strategy

"✓" indicates completed definition task

Use Cases & Functions

UC-C-202 M	FN-C-201 M
UC-C-203 M	FN-C-202 M

Metrics

Current State of the Art	Performance Targets	
There have been several robotic missions to Mars (e.g., Curiosity and Perseverance rovers). The current robotic EDL and surface navigation capabilities represent a starting point from which equivalent human-rated systems will evolve. For timing systems, the current state of the art is the Deep Space Atomic Clock (DSAC-1), which conducted its first mission in 2019.	Mars	Enable high availability position, navigation, and timing (PNT) services to support spacecraft operations with disruptions and blackout considerations.

Segments	Sub-Architectures
Humans to Mars	C&PNT

Extreme Environment Avionics

ID No.	**0201**
Rating	**2**
Bin	**1 of 6**

Gap Description

Exploration missions in deep space and planetary environments will expose systems to extreme environment, defined here as those with hazardous effects on crew health/safety and asset operation. The state of the art is insufficient for the expected environments over the mission durations. There is a need for avionics systems that are tolerant to one or more of the following list: large aggregate radiation doses, extreme temperatures, dust, and vacuum. Heat rejection in vacuum is a particular challenge. At a minimum, the system should survive the extreme environment and in some cases, the system may need to operate in the extreme environment.

Architecture Impacts and Benefits

Without gap closure, there would be a need for increased shielding/insulation across multiple systems/subsystems, need for active thermal control, increased failures and required maintenance, inability to reliably leverage high-performance processing applications, and capability reductions for autonomy.

Architecture-Driven Child Gaps

0201-01	Thermal management for electronics in extreme environments and temperatures
0201-02	Cold- and dust-tolerant electronics interfaces and connectors
0201-03*	Radiation-tolerant exploration computing systems
0202-02*	Radiation-hardened data storage to enable autonomous operations

Architecture Traceability

Key Definition Tasks

"✓" indicates completed definition task

Use Cases & Functions	
UC-A-101 L	FN-A-202 L
UC-A-201 L	FN-A-202 L
UC-C-107 M	All FN
UC-D-201 M	All FN
UC-A-403 M	FN-G-401 M
UC-A-403 M	FN-G-407 M
UC-A-404 M	FN-G-407 M

Metrics

Current State of the Art

Existing spacecraft subsystems operate between -180 and 130 deg C. TBR radiation tolerance with degraded functionality. A limited number of vacuum-tolerant systems exist.

Performance Targets

Moon/Mars	Enable avionics' tolerance of and survival in extreme environments (temperature, radiation, dust, vacuum, etc.).
Moon	In addition, increased dust tolerance compared to the Martian performance target.
Mars	In addition, increased reliability and decreased maintenance needs compared to the lunar performance target.

Segments

Foundational Exploration

Sustained Lunar Evolution

Humans to Mars

Sub-Architectures

Data Systems and Management

High-Performance Onboard Computing

ID No.	**0202**
Rating	**26**
Bin	**3 of 6**

Gap Description

Advanced onboard computing systems are needed both in space and on surfaces to offer increased processing performance, input/output (I/O) bandwidth, and data storage, and radiation-tolerant operation to support autonomy and prognostics. Flexibility is also needed to adapt power, fault tolerance, processing bandwidth, I/O bandwidth, and on-premise edge computing performance to execute specified critical functions to meet mission needs, such as fault management algorithms and telemetry, tracking, and commands. Future computing systems should support open system avionics architectures that provide interoperability between modules sourced from different vendors.

Architecture Impacts and Benefits

With gap closure, these systems will enable increased autonomy for crewed and robotic science missions, as well as onboard data reduction where sensor bandwidth exceeds downlink bandwidth.

Architecture-Driven Child Gaps

0202-01	High-performance processors for deep space missions
0202-02*	Radiation-hardened data storage to enable autonomous operations
0201-03*	Radiation-tolerant exploration computing systems

Architecture Traceability

Key Definition Tasks

- Priorities for Crew vs. Robotic Tasks Strategy

"✓" indicates completed definition task

Use Cases & Functions

UC-D-201 L	All FN
UC-A-403 M	FN-A-402 M
UC-A-404 M	FN-A-402 M

Metrics

Current State of the Art

Redundant commercial off-the-shelf processors are used but incur the cost of increased size, weight, power, and complexity.

Performance Targets

Moon/Mars	Enable high-performance onboard computing operations to support autonomy, navigation, and other use cases in relevant environments.
Mars	In addition, increased autonomy and reliability compared to the lunar performance target.

Segments

- Foundational Exploration
- Sustained Lunar Evolution
- Humans to Mars

Sub-Architectures

- Data Systems and Management

Architecture Definition Document - Architecture-Driven Technology Gaps

Systems to Survive and Operate through Extended Periods of Lunar Shadow

ID No. **0301**
Rating **3**
Bin **1 of 6**

Gap Description

Assets on the surface of the Moon will be subjected to large variations in natural and induced environments. The ability to survive and operate through these extreme variations is required to enable long-duration surface operations. New or improved power, thermal management, and actuation technologies are required and will need to work together to accomplish this goal for science experiments, mobility assets, habitats, and more.

Architecture Impacts and Benefits

Without gap closure, the inability to survive extended periods of lunar shadow will impact the operating lifespan of surface assets. There may also be an inability to reuse surface assets if systems cannot survive shadowed periods.

Architecture-Driven Child Gaps

0301-01	Freeze-tolerant thermal components
0301-02	Extreme temperature-tolerant mechanisms and electronics
0301-03	Energy storage for extreme temperatures
0301-04	Heat rejection systems for the lunar thermal environment

Architecture Traceability

Key Definition Tasks		Use Cases & Functions	
LD-03-L Lunar Landing Region Selection	✓	UC-H-105 L	FN-H-201 L

"✓" indicates completed definition task

Metrics

Current State of the Art	Performance Targets
Small spacecraft have survived extended periods of lunar shadow with damage to subsystems and degraded capability. There is currently no state of the art for any human-scale elements successfully functioning through extended lunar shadow periods.	Moon Survive continuous shadow for 350 hours or more several times a year for 10 years.

Segments

- Foundational Exploration
- Sustained Lunar Evolution

Sub-Architectures

- Habitation Systems
- Mobility Systems
- Autonomous Systems & Robotics

Fire Safety Upgrades for Surviving Exploration Mission Environments

ID No. **0302**
Rating **22**
Bin **3 of 6**

Gap Description

Low-pressure, high-oxygen environments with partial gravity on the lunar and Martian surfaces and/or vehicles with limited abort or resupply are new, more challenging flammability environments. These environments drive the need for reduced material flammability and enhanced fire detection, suppression, response and cleanup and fire spread modeling compatible with future vehicles operating in these environments. New and upgraded fire safety capabilities targeted for low-pressure, high-oxygen environments are needed for worst-case fire scenarios for habitable volumes. These capabilities are required to mitigate the impacts and likelihood of fire eruption/spread and to enable crew to survive fire breakouts in future missions.

Architecture Impacts and Benefits

If advances are not made in fire safety, exploration missions will have an increased probability of loss of crew, loss of mission/element, or result in significant mission constraints or operational constraints. Existing capabilities may not be applicable or compatible with future vehicles or missions. Flammability and safety tests may not be passed for adequate mission safety.

Architecture-Driven Child Gaps

0302-01	Material flammability and fire propagation in reduced and microgravity environments, and at exploration atmospheres
0302-02	Non-flammable materials, additives, coatings for habitable volumes
0302-03	Fire detection, fire suppression, and post-fire monitoring and clean-up
0302-04	Fire emergency breathing mask

Architecture Traceability

Key Definition Tasks

"✓" indicates completed definition task

Use Cases & Functions

UC-T-501 L	
UC-H-101 M	All FN
UC-X-101 M	All FN
UC-X-102 M	All FN
UC-X-103 M	All FN
UC-X-104 M	All FN

Metrics

Current State of the Art

ISS and Orion subsystems, materials, and operating paradigms. Very limited small-scale analog experiments to date have demonstrated flammability and fire propagation phenomena in low gravity, reduced pressure, and elevated O2 percentage, which may be worst-case environment. Current state of the art hardware for surviving an event includes the Emergency Breathing Apparatus and Smoke-Eater, both in service on ISS.

Performance Targets

Moon/Mars	Materials capable of meeting flammability test standards in low- and partial-gravity environments at reduced pressures (8.2 psia) and higher oxygen levels. Fire detection, suppression, monitoring, and clean-up technologies that perform based on the worst-case fire scenario. Enable sufficiently greater capacity by volume of smoke/soot/water droplets.
Mars	In addition, increased reliability compared to the lunar performance target.

Segments

Foundational Exploration

Sustained Lunar Evolution

Humans to Mars

Sub-Architectures

Habitation Systems

Dormancy Recovery for Habitat Water Storage, Distribution, and Reclamation

ID No. **0303**
Rating **16**
Bin **3 of 6**

Gap Description

Moon and Mars systems with periods of dormancy have an increased risk of microbial growth and contamination in water systems. Long-life surface habitats also require technology developments to address additional contaminants from surface dust. Capabilities are needed to address these risks and handle other challenges associated with periods of dormancy, including possible logistics water bags/tanks that might spend long periods of time in transit and/or sitting on the lunar/Mars surface as pre-positioned cargo awaiting use by the crew.

Architecture Impacts and Benefits

If this gap is not closed, water systems would not support habitation requirements pertaining to dormancy and microbial risk. Insufficient and/or compromised water systems could result in the termination of missions and/or compromised mission operations and/or loss of crew. Water systems may require component replacement after dormancy, resulting in increased delivered mass.

Architecture-Driven Child Gaps

0303-01	Water recovery system with dormancy recovery
0303-02	Robust water recovery systems for long-duration missions
0303-03	Microbial control and mitigation during nominal and uncrewed operations

Architecture Traceability

Key Definition Tasks

- ● Minimum Mars Surface Element Design Lifetime
- ● ECLSS Strategy (In Space)
- ● ECLSS Strategy (Mars Surface)

"✓" indicates completed definition task

Use Cases & Functions

Use Cases & Functions	
UC-H-102 L	FN-H-102 L
UC-H-103 L	FN-H-104 L
UC-H-104 L	FN-H-105 L
UC-U-723 L	FN-U-601 L
UC-H-102 M	FN-H-104 M
UC-H-103 M	FN-H-104 M
UC-H-103 M	FN-H-108 M

Metrics

Current State of the Art

ISS water system has never been dormant, which would require replacement of most major components. Existing biocides support water recovery processing, not dormancy recovery.

Performance Targets

Moon/Mars	Safe and effective long-term (TBR years) maintenance and recovery (during crewed and uncrewed operations) of water systems that meet the chemical and microbial potable water requirements.
Mars	In addition, increased reliability compared to the lunar performance target.

Segments

Foundational Exploration

Sustained Lunar Evolution

Humans to Mars

Sub-Architectures

Habitation Systems

Habitat Environmental Monitors and Capabilities to Support Deep Space Missions

ID No.	**0304**
Rating	**11**
Bin	**2 of 6**

Gap Description

Long-duration or long-lifetime habitable elements without access to Earth-based analysis will require in-situ environmental monitoring to understand water quality, atmospheric particulate and contaminant content, microbial growth, and other measures to inform crew safety and crew response to off-nominal subsystem or mission events. The state of the art is mostly sample return for detailed analysis at Earth, with limited monitoring in space. Existing capabilities have either insufficient in-space capability or performance life for Moon and Mars mission durations.

Architecture Impacts and Benefits

Without gap closure, cislunar missions will have to return some samples for analysis with crew, which will delay hardware troubleshooting and increases crew exposure risks. Mars missions will lack detailed data for crew health, equipment monitoring, and troubleshooting. Increases detrimental health effects and decreases ability to effectively use limited spares to recover system upsets.

Architecture-Driven Child Gaps

0304-01	In-flight water quality monitors for quantification and identification
0304-02*	In-flight identification and characterization of microbes in air, in water, and on surfaces in habitable volumes
0304-03	Onboard particulate monitors to measure crew respiratory hazards, survive dormancy, and work in low pressures
0304-04	Major constituent and trace contaminant gas monitoring for cabin air
0304-05	Acoustic monitoring and control

Architecture Traceability

Key Definition Tasks

- ● MD-10 Mars Forward Contamination Planetary Protection Risk Posture
- ● MD-11 Mars Backward Contamination Planetary Protection Risk Posture

“✓” indicates completed definition task

Use Cases & Functions

UC-H-201 L	
UC-H-202 L	
UC-H-106 M	**FN-H-118 M**
UC-H-107 M	**FN-H-119 M**

Metrics

Current State of the Art	Performance Targets	
The ISS TOCA for in-flight water quality monitoring. For surfaces, collecting samples with a swab and the microbial profiles are obtained directly through sequencing. For water and air, samples are collected and cultured onboard and returned to Earth for identification analysis. NASA has supported work for bio regenerative life support systems. ISS flight demonstration of the Airborne Particulate Monitor. ISS Major Constituent Analyzer. ISS handheld acoustic monitors.	Moon/Mars	Water quality, microbial, airborne particulate, trace contaminant, and acoustic monitoring capable of informing response to off-nominal events caused by natural and induced environmental characteristics. Prevent undesirable outcomes for crew health and habitable assets. Internal and external habitation monitoring should be operable without Earth return of samples and with minimal consumables and crew time.
	Mars	In addition, increased reliability compared to the lunar performance target.

Segments

Sustained Lunar Evolution

Humans to Mars

Sub-Architectures

Habitation Systems

Food and Nutrition Capabilities for Long-Duration Missions

ID No. **0305**
Rating **9**
Bin **2 of 6**

Gap Description

Food system shelf life and production for nutritional stability and current range of foods for sufficient variety (to ensure adequate consumption) do not meet Mars-duration mission needs and present challenges to accomplishing long-duration lunar missions. On ISS, the crew has access to 200 standard foods supplemented with a wide variety of food preference items, which are regularly resupplied to meet nutritional needs. Exploration missions will not support this type of variety, and nutritional content and acceptability will not be maintained for exploration durations (including aggregation). A safe food system that provides adequate variety, food safety (microbial), palatability, and nutrition is needed to prevent menu fatigue/inadequate caloric intake and to support crew health and performance throughout increasingly Earth-independent, resource-constrained, extreme environmental (temperature, pressure, humidity), and long-duration mission operations. Exploration food systems may include a combination of storage and production.

Architecture Impacts and Benefits

Without gap closure, the crew may have insufficient nutrition to carry out their tasks and/or crew performance may decrease. Lack of gap closure may result in loss of mission objectives and contribute to increased potential loss of crew. Nutritional value must be met with the food system. Lunar missions may require logistics to be delivered with each crewed mission, reducing delivery mass capability across other areas.

Architecture-Driven Child Gaps

0305-01	Food and nutrition impact modeling for crew health and performance
0305-02	Safe, acceptable, efficient, and nutritious food system
0305-03	Earth-independent food intake tracking
0305-04	Food preservation and storage for long-duration deep space missions
0305-05	Food production for long-duration deep space missions

Architecture Traceability

Key Definition Tasks

- ● Maximum Total Crew Mission Duration
- ● ECLSS Strategy (In Space)
- ● Food Refrigeration and Growth

"✓" indicates completed definition task

Use Cases & Functions

UC-U-725 L	FN-U-602 L
UC-H-104 M	FN-X-104 M
UC-H-105 M	FN-X-106 M
UC-X-105 M	FN-X-101 M
UC-X-106 M	FN-X-102 M

Metrics

Current State of the Art

The ISS is regularly resupplied with a wide variety of shelf stable foods for the crew to choose from with a minimum of 18 months shelf life. Ambient temperature storage limits shelf life. No cold stowage capability is currently available. Ambient pressure maintains packing integrity against oxygen, humidity, and microbes. There have been food storage and nutrition studies conducted on the ISS. There have also been studies and small scale demonstrations on the ISS for crop plant production and propagation, such as the Vegetable Production System (VEGGIE) and the Advanced Plant Habitat (APH), but technology development is needed to scale up crop plant production and agriculture for long-duration missions.

Performance Targets

Moon/Mars	Food system to provide nutritional shelf life, variety, safety, and acceptability for sustained Moon and Mars mission durations and life support closure levels.
Mars	In addition, increased shelf life compared to the lunar performance target.

Segments

- Foundational Exploration
- Sustained Lunar Evolution
- Humans to Mars

Sub-Architectures

- Habitation Systems

Advanced Structures and Materials to Enable Mass-Efficient Habitats

ID No.	**0306**
Rating	**49**
Bin	**6 of 6**

Gap Description

More mass-efficient structures are needed to achieve habitation scalability and sustainability goals. Examples include softgood inflatables, composites, and advanced lightweight metallic structures.

Architecture Impacts and Benefits

Without gap closure, mass and/or volume of habitation elements may exceed launch/landing capability. Architecture may be constrained to shorter-duration missions to accommodate limits of habitat capability. Architecture may require modular habitation, increasing mass and launches.

Architecture-Driven Child Gaps

0306-01	Inflatable softgoods for long-duration missions in extreme surface environments
0306-02	Hard structure integration with inflatable softgoods
0306-03	Lightweight metallic structures for habitation applications
0306-04	Predictive models for long-term behavior of highly loaded inflatables

Architecture Traceability

Key Definition Tasks

"✓" indicates completed definition task

Use Cases & Functions

UC-H-102 L	FN-H-102 L
UC-H-103 M	FN-H-109 M
UC-H-110 M	FN-H-109 M

Metrics

Current State of the Art

Multiple options for mass and volume savings such as inflatable softgoods, composites, and lightweight metallics.

Performance Targets

Moon/Mars	Solutions that allow habitation structures to meet TBR performance thresholds while complying with TBR mass and volume constraints.
Mars	In addition, increased efficiency compared to the lunar performance target.

Segments

Sustained Lunar Evolution

Humans to Mars

Sub-Architectures

Habitation Systems

Radiation Monitoring and Forecasting

ID No. **0307**
Rating **17**
Bin **3 of 6**

Gap Description

Moon and Mars missions will encounter space radiation from multiple sources. Radiation must be monitored to determine exposure of hardware (sensitive electronics, materials) and assess health impacts to crew. Current state-of-the-art radiation monitoring can detect incoming solar particle events (SPEs) but cannot reliably forecast them. Current models provide unreliable prediction of event onset and poor predictions of duration, intensity, energy spectrum, and the intensity-time profile of the entire event. Monitors and dosimeters, new models, predictive algorithms, and new measurements/observations are needed to provide early warning of SPEs hazardous to astronauts and mission operations with low false alarms. Forecasting models for predicting GCR intensity from one solar cycle to the next are also needed.

Architecture Impacts and Benefits

Gap closure enables increased warning times and accuracy of real-time operational forecasting that can inform mission and crew operations of radiation hazards following development of an SPE event, as well as the prediction of all-clear periods.

Architecture-Driven Child Gaps

0307-01	Forecasting and radiation models for solar particle events
0307-02	Space radiation detectors for long-duration missions
0307-03	Earth-independent space weather forecasting

Architecture Traceability

Key Definition Tasks	Use Cases & Functions	
● Maximum Total Crew Mission Duration	UC-U-719 l	
	UC-U-720 L	
	UC-U-721 L	
	UC-U-722 L	
	UC-H-102 M	FN-H-106 M
	UC-H-103 M	FN-H-110 M
"✓" indicates completed definition task		

Metrics

Current State of the Art	Performance Targets	
Current space weather forecasting consists of monitoring the state of the Sun and altering the mission activities to account for any radiation events once detected. Existing charged particle detectors accurately measure the charged particle environment inside spacecraft, but long life, radiation hard detectors with an increased sensitivity to electrons are needed for SPE warning systems external to the spacecraft. Existing neutron monitors can measure the neutron spectrum up to 15 MeV, but higher energy neutron measurements are limited by large uncertainties and measurement systems with excessive mass/volume/power. Current models do not accurately forecast the duration, intensity or how the event will change over time and struggle to predict the most intense and hazardous events.	Moon/Mars	Accurately characterize, forecast the onset of, and predict the duration, intensity, energy spectrum, and intensity-time profile of SPE events with low false alarm rates and hours of early warning for EVA planning. Monitor and forecast the GCR environment. Prediction should warn for electrons as well as protons.
	Mars	In addition, increased reliability compared to the lunar performance target.

Segments

Foundational Exploration
Sustained Lunar Evolution
Humans to Mars

Sub-Architectures

Habitation Systems
Human Systems

Radiation Countermeasures

ID No. **0308**
Rating **47**
Bin **5 of 6**

Gap Description

Solar Particle Event (SPE) radiation shielding is relatively well understood and passive shielding can be applied to small volumes of habitat. Galactic Cosmic Radiation (GCR) is very difficult to mitigate. Passive shielding is mass-prohibitive, while active methods are very low maturity and utilize substantial vehicle mass and power. New shielding techniques as well as other potential mass-efficient countermeasures for ionizing and non-ionizing radiation are needed to reduce the risk of adverse medical impacts on crew. GCR shielding will also help shield for SPE radiation.

Architecture Impacts and Benefits

With gap closure, the benefits are reduction in crew lifetime radiation dose and reduction of detrimental crew health effects from radiation exposure during long-duration exploration missions. Using lunar proving ground to prove out Mars.

Architecture-Driven Child Gaps

0308-01	Solar Particle Event (SPE) radiation effects mitigation and shielding
0308-02	Radiation risk models for crew health and performance
0308-03	Biomedical countermeasures to mitigate health effects from exposure to space radiation
0308-04	Galactic Cosmic Radiation (GCR) effects mitigation

Architecture Traceability

Key Definition Tasks

● Maximum Total Crew Mission Duration

"✓" indicates completed definition task

Use Cases & Functions

UC-H-102 M	FN-H-106 M
UC-H-103 M	FN-H-110 M
UC-X-105 M	
UC-X-106 M	
UC-X-109 M	

Metrics

Current State of the Art

Operational and physical mitigation strategies are used to reduce crew doses on the ISS. Current ionizing radiation mitigation strategies are based on the application of the As Low As Reasonably Achievable (ALARA) principle to protect the crew from severe long-term effects from radiation exposure (NASA-STD-3001-Vol 2) but there have been minimal medical radiation countermeasures that have been identified/validated to fully protect crew against long-term health effects from radiation exposure. Additionally, current radiation analysis tools closely align with predicted space measurements, but are less accurate for thick shielding which would be found in long duration mission vehicles and habitats. GCRs cannot be effectively mitigated against with the SOA.

Performance Targets

Moon/Mars	Develop long-duration, mass-efficient passive and active shielding, time, and distance countermeasures to mitigate adverse crew health outcomes to ionizing and non-ionizing radiation including SPE and GCR conditions (reference NASA-STD-3001 V1 4030, 4031).
Mars	In addition, increase in performance target for longer duration missions.

Segments

Sustained Lunar Evolution
Humans to Mars

Sub-Architectures

Habitation Systems
Human Systems

Crew Exercise Countermeasures to Support Extended Habitation in Space

ID No. **0401**
Rating **40**
Bin **5 of 6**

Gap Description

ISS crew rely on exercise countermeasures to mitigate health effects associated with long-duration exposure to microgravity. However, current systems are mass-, power-, and volume-intensive and are sufficient for microgravity extravehicular activities (EVA) but not completely effective for crew egress or immediate surface EVA after a long period in deep space. Mass efficient and effective exercise is needed for preventing injury and providing muscle/cardio fitness in preparation for crew activities, including surface EVA. For long-duration missions, effective exploration-compatible exercise countermeasures and assessment tools are needed for crew to accurately maintain and monitor physical health and performance during exploration missions.

Architecture Impacts and Benefits

Without gap closure, the impacts are large mass/volume exercise equipment and/or potential crew health decrements from inadequate countermeasures. Use of current systems may be incompatible with future vehicles. Potential impacts to spares and maintenance. (TBR)

Architecture-Driven Child Gaps

0401-01	Crew health and performance countermeasure modeling
0401-02	Exercise countermeasures for microgravity and reduced-gravity environments
0401-03	Bone countermeasures for long-duration exploration missions
0401-04	Cardiovascular countermeasures for microgravity and reduced-gravity environments

Architecture Traceability

Key Definition Tasks

- MD-09 Maximum Mars Crew Surface Stay Duration
- Maximum Total Crew Mission Duration

"✓" indicates completed definition task

Use Cases & Functions

UC-X-103 L	FN-X-103 L
UC-X-104 L	FN-X-104 L
UC-X-101 M	FN-X-101 M
UC-X-102 M	FN-X-102 M

Metrics

Current State of the Art

ISS exercise countermeasures address aerobic, muscle, and bone loss risk. Ongoing work on exploration solutions (TBR). Currently, ground support provides exercise data interpretation. Use of multiple on-orbit devices and the efficacy to support high-frequency lunar and Martian surface EVA unassisted is still being researched. As we move to exploration missions, the communication delay will introduce new issues, and will force crew to be more self-reliant.

Performance Targets

Moon/Mars	Hardware and software that 1) are sufficient to meet crew health and performance standards for aerobic fitness, muscle strength, bone health for extraterrestrial surface injury risk minimization; 2) require planned maintenance of no more than (TBD); and 3) are applicable for in-transit and surface mission phases.
Moon	In addition, support mission durations up to 365 days in space.
Mars	In addition, hardware and software that are compatible with Mars mission, systems, and operations. Support mission durations on the order of 2-3 years.

Segments		Sub-Architectures
Sustained Lunar Evolution	Humans to Mars	Human Systems

Sensorimotor Countermeasures to Support Extended Habitation in Space

ID No. **0402**
Rating **39**
Bin **5 of 6**

Gap Description

Exercise on its own will not prevent issues with gravity adaptation due to impacts on the neurovestibular system, and crew readaptation to the gravity environment is highly variable. Many crew returning from ISS with state-of-the-art countermeasures are unable to egress the vehicle after reintroduction of gravity without ground assistance. For long-duration missions, effective exploration-compatible sensorimotor countermeasures and assessment tools are needed for crew to accurately maintain and monitor physical health and performance during exploration missions.

Architecture Impacts and Benefits

Without gap closure, there is an increased risk of injury from insufficient sensorimotor adaptation.

Architecture-Driven Child Gaps

0402-01	Sensorimotor and disorientation countermeasures and mitigation
0402-02	Sensorimotor adaptation assessment tools

Architecture Traceability

Key Definition Tasks	Use Cases & Functions	
● MD-09 Maximum Mars Crew Surface Stay Duration	UC-X-103 L	FN-X-103 L
● Maximum Total Crew Mission Duration	UC-X-104 L	FN-X-104 L
	UC-X-101 M	FN-X-101 L
	UC-X-102 M	FN-X-102 M
"✓" indicates completed definition task		

Metrics

Current State of the Art	Performance Targets	
There are no effective sensorimotor countermeasures. Exercise is an inadequate sensorimotor countermeasure. (Current ISS return is example of ineffectiveness).	Moon/Mars	Hardware and software that are sufficient to meet crew health and performance standards for sensorimotor health to safe completion of assessment within (TBD) of preflight baseline.
	Moon	In addition, support mission durations up to 365 days in space.
	Mars	In addition, support mission durations on the order of 2-3 years.

Segments		Sub-Architectures
Sustained Lunar Evolution	Humans to Mars	Human Systems

Physiological Countermeasures for Extended Habitation in Space

ID No.	**0403**
Rating	**41**
Bin	**5 of 6**

Gap Description

Long mission durations do not yet have complete countermeasures in this area (e.g., spaceflight-associated neuro-ocular syndrome, reduction in immune function, and infectious and allergenic diseases), which need improvements due to increased isolation, resource constraints, and communications delay. As missions increase in duration and become more Earth-independent, the crew's on-board equipment and tools need to be adequate to maintain crew health and be compatible with future missions/systems. Physiological countermeasures and assessment tools in low-gravity and microgravity environments need to be improved for long duration crewed missions to accurately maintain and monitor physical health and performance during exploration missions.

Architecture Impacts and Benefits

Impacts require closer investigation, but non-closure of the gap may result in increased clinical risks to crewmembers during prolonged deep space missions. Decremented crew performance may also affect mission in other aspects beyond risk.

Architecture-Driven Child Gaps

0403-01	Neuro-ocular countermeasures and mitigation
0403-02	Microbially-induced disease countermeasures
0403-03	Immune system dysregulation countermeasures

Architecture Traceability

Key Definition Tasks	Use Cases & Functions	
● Maximum Total Crew Mission Duration	UC-X-103 L	FN-X-103 L
	UC-X-104 L	FN-X-104 L
	UC-X-101 M	FN-X-101 L
	UC-X-102 M	FN-X-102 M
"✓" indicates completed definition task		

Metrics

Current State of the Art

Countermeasures on ISS currently include neuro-ocular monitoring, Crew Health Stabilization Program, stringent environmental and food monitoring, and the use of disinfectants and biocides. There is no validated immune countermeasure protocol compatible with operations in deep space. Countermeasures already deployed to ISS seem to benefit immunity but are largely incompatible with deep space missions.

Performance Targets

Moon/Mars	Long-duration exploration mission-compatible physiological countermeasures performing adequately to reduce adverse crew health outcomes with communication delay and without resupply
Moon	In addition, support mission durations up to 365 days in space.
Mars	In addition, support mission durations on the order of 2-3 years.

Segments

Sustained Lunar Evolution

Humans to Mars

Sub-Architectures

Human Systems

Behavioral Countermeasures for Extended Habitation in Space

ID No.	**0404**
Rating	**42**
Bin	**5 of 6**

Gap Description

Long mission durations do not yet have complete countermeasures in this area, which need improvements due to increased isolation, resource constraints, and communications delay. As missions increase in duration and become more Earth-independent, the crew's on-board equipment and tools need to be adequate to maintain crew health and be compatible with future missions/systems. Behavioral countermeasures and assessment tools need to be improved for crew to accurately maintain and monitor health and performance during exploration missions.

Architecture-Driven Child Gaps

0404-01	Behavioral health and performance countermeasures
0404-02	Behavioral health and performance assessment tools

Architecture Impacts and Benefits

Impacts require closer investigation, but non-closure of the gap may result in increased clinical risks to crewmembers during prolonged deep space missions. Failure to close this gap may also increase the risk to crew behavioral health and performance, which may increase loss of crew and loss of mission risk. Decremented crew performance may also affect mission in other aspects beyond risk.

Architecture Traceability

Key Definition Tasks

● Maximum Total Crew Mission Duration

"✓" indicates completed definition task

Use Cases & Functions

UC-X-103 L	FN-X-103 L
UC-X-104 L	FN-X-104 L
UC-X-101 M	FN-X-101 L
UC-X-102 M	FN-X-102 M

Metrics

Current State of the Art

Current countermeasures for behavioral health and performance rely on real-time support and resupply from the ground team via private family conferences, care packages, etc. These will not be an adequate approach for exploration missions with communication delays and limited to no resupply.

Performance Targets

Moon/Mars	Long-duration exploration mission-compatible behavioral countermeasures performing adequately to reduce adverse crew health outcomes with communication delays and without resupply.
Moon	In addition, support mission durations up to 365 days in space.
Mars	In addition, support mission durations on the order of 2-3 years.

Segments

Sustained Lunar Evolution

Humans to Mars

Sub-Architectures

Human Systems

Exploration Medical Capabilities for Deep Space Missions

ID No. **0405**
Rating **46**
Bin **5 of 6**

Gap Description

As missions become more Earth-independent (increased duration, communications delays, limited abort or resupply), improvements are required across the spectrum of medical capabilities to enable deep space human habitability. There is a need for improved capabilities to allow for prevention, early diagnosis, and treatment options for a wider range of medical conditions as well as long-duration storage of medical supplies. In addition, we cannot fully rely on ground support to address time-critical treatments, increasing the need for crew autonomy in initial diagnostic decision support and guidance in the use of treatments for medical care.

Architecture Impacts and Benefits

Failure to close this gap increases the risk to crew of adverse medical outcomes impacting risk of loss of crew/mission or risk of decremented crew performance. Some medical scenarios or emergencies requiring advanced medical treatment may be unsuccessful due to limited or absent real-time ground support. In addition, crews will need to be increasingly autonomous and less reliant on ground support to address time-critical diagnoses and treatments.

Architecture-Driven Child Gaps

0405-01	Medical treatment for high-risk and/or high-likelihood medical ailments
0405-02	High-pressure oxygen generation for medical response
0405-03	Probabilistic risk models and simulations for crew health
0405-04	In-situ medical sample storage, processing, and analysis
0405-05	Medical imaging, diagnostics, and decision support
0405-06	Crew health & performance integrated data architecture

Architecture Traceability

Key Definition Tasks

● Maximum Total Crew Mission Duration

"✓" indicates completed definition task

Use Cases & Functions

UC-X-101 L	FN-X-101 L
UC-X-101 L	FN-D-105 L
UC-X-102 L	FN-X-102 L
UC-X-102 L	FN-D-106 L
UC-X-103 L	FN-X-103 L
UC-X-104 L	FN-X-104 L
UC-X-105 M	FN-X-101 M
UC-X-106 M	FN-X-102 M

Current State of the Art

The scope of ISS medical capabilities is predicated on real-time communication and ground support, evacuation for definitive care of significant medical events, frequent and reliable resupply, and mission durations less than one year.

Performance Targets

Moon	Same as Mars target, except with less communication delay and some additional abort capability.
Mars	Dependent upon future integrated risk assessment trades. Medical systems and ConOps to reduce risk of adverse crew health outcomes with communication delay, limited abort capability, and limited diagnostic and treatment resources.

Segments

Sustained Lunar Evolution
Humans to Mars

Sub-Architectures

Human Systems

Spacesuit Physiology for Deep Space Missions

ID No. **0406**
Rating **43**
Bin **5 of 6**

Gap Description

Currently there is not a fully validated pre-breathe, injury modeling, and self-health monitoring capability. There is a reasonable risk of reduced science or activities supporting mission objectives if injury occurs. As missions increase in duration, EVA frequency significantly increases due to reduced recovery time. Providing the crew time-critical health data & contingency con-ops information for crew risk decisions is important for even short time delays or loss of communication. Capabilities advancement is required for spacesuit physiology, especially as it pertains to conducting surface EVA and ingress/egress from habitable assets.

Architecture-Driven Child Gaps

0406-01	Earth-independent health monitoring and decision support during exploration EVAs
0406-02	Suited injury prevention and mitigation
0406-03	Decompression stress prediction and mitigation

Architecture Impacts and Benefits

Failure to close this gap will result in EVA planning, operations, training, system design, and/or decision support systems that have a risk of being inconsistent or incompatible with crewmember capabilities and constraints. This will also preclude crew health and performance assessment and decision-making during exploration EVAs with intermittent or delayed space-ground communications. High likelihood of multiple mission-impacting injuries during exploration missions involving high-frequency EVA.

Architecture Traceability

Key Definition Tasks

- ● Maximum Total Crew Mission Duration
- ● Surface Ingress/Egress Strategy
- ● Surface EVA Capability Strategy

"✓" indicates completed definition task

Use Cases & Functions	
UC-M-101 L	All FN
UC-M-102 L	All FN
UC-X-102 M	FN-H-124 M

Current State of the Art

Real-time Crew Health and Performance decision support during ISS EVA operations is provided by ground-based flight controllers with high bandwidth and near-zero latency space-ground communications. Suit-to-crew fit is well understood in microgravity but not lunar gravity for a walking or sitting suit configuration. Prebreathe protocol for lower pressure higher oxygen habitats is only partially validated.

Performance Targets

Moon/Mars	Dependent upon future integrated risk assessment trades, improved spacesuit physiology capabilities, such as tools to predict, monitor, and mitigate EVA crewmember injuries. Solutions capable of supporting Moon and Mars mission EVA strategy with acceptable risk of adverse outcomes.

Segments

Sustained Lunar Evolution

Humans to Mars

Sub-Architectures

Human Systems

Robotic Inspection, Maintenance, and Repair

ID No. **0501**
Rating **36**
Bin **4 of 6**

Gap Description

As in-space and surface systems and infrastructure are deployed, there is a need to develop technologies and capabilities that enable inspection, maintenance, and repair (IM&R) activities without undue reliance on crew time or the built-in assumption of crew presence and availability. Robotic systems are needed that can perform IM&R activities in the absence of crew to maximize available time for crew science and exploration priorities. This includes the maturation of robotic systems with the necessary manipulation capabilities and the design and integration of interfaces suited for robotic IM&R. Aspects of task performance include procedures; the equipment, tools, and materials needed to restore functional integrity; troubleshooting; gaining access; replacement; reservicing/retesting; and system closeout.

Architecture Impacts and Benefits

Closing this gap helps assure in-space and surface assets remain available to achieve mission objectives.

Architecture-Driven Child Gaps

0806-01*	Affordance recognition, grasp planning, and execution for autonomous object and interface manipulation
1001-01*	Robust robotic sensors
1001-02*	Adaptable robotic end effectors for fine grasping and manipulation
1001-03*	Efficient autonomous object detection, classification, and pose estimation

Architecture Traceability

Key Definition Tasks

- ● Priorities for Crew vs. Robotic Tasks Strategy

“✓” indicates completed definition task

Use Cases & Functions

UC-A-105 L	FN-A-201 L
UC-G-401 M	All FN
UC-G-402 M	All FN
UC-A-104 M	FN-A-106 M
UC-A-107 M	All FN

Current State of the Art	Performance Targets	
IM&R tasks performed manually by crew on Shuttle and ISS. Autonomous robotic IM&R has been performed on four Mars rovers utilizing cameras and perception software. Ingenuity helicopter performed autonomous aerial photography inspection of Perseverance rover, as well as terrain and landing spot inspection.	Moon/Mars	Improved system availability (reliability, maintainability, supportability) as well as safety.
	Mars	In addition, increased autonomy and reliability compared to the lunar performance target.

Segments

Foundational Exploration
Sustained Lunar Evolution
Humans to Mars

Sub-Architectures

Infrastructure Support
Autonomous Systems & Robotics

In-situ Manufacturing of Spares, Repairs, and New Parts

ID No. **0502**
Rating **57**
Bin **6 of 6**

Gap Description

An on-demand and in-situ approach to manufacturing, maintenance, repair, and logistics can support a sustainable presence on the Moon and Mars. Spare electronic parts include sensors, such as those used for environmental control and life support systems (ECLSS), small electronic devices, and supporting components for energy and power applications. Metal and polymer parts include structural components for the construction, outfitting, and repair of infrastructure; basic tools, materials for daily crew use, and custom-designed parts for mission-critical needs.

Architecture Impacts and Benefits

Closing this gap enables flexibility to manufacture parts on demand for missions with limited resupply options and the inability to fully predict mission needs.

Architecture-Driven Child Gaps

0502-01	On-demand manufacturing of metals, electronic components, and tools in-situ
0502-02*	In-situ evaluation, verification, and validation of manufactured components
0502-03	Reuse/recycling of materials and components into usable manufacturing feedstock
0502-04*	Manufacturing of materials and components from ISRU-derived feedstock

Architecture Traceability

Key Definition Tasks	Use Cases & Functions	
Surface Servicing Capability Strategy	**UC-I-203 L**	**FN-I-207 L**
	UC-I-204 L	**FN-I-206 L**
	UC-I-201 M	**All FN**

"✓" indicates completed definition task

Current State of the Art	Performance Targets	
Capability to manufacture new products, spare parts, replacement units, or specialty tools in-situ does not exist beyond small demonstration components fabricated from polymers.	Moon/Mars	Enable space-based manufacturing techniques allowing repairs and replacement of hardware components in-situ.

Segments

Sustained Lunar Evolution
Humans to Mars

Sub-Architectures

Infrastructure Support
In-Situ Resource Utilization Systems
Logistics Systems

In-Space & Surface Transfer of Earth-Storable Propellants

ID No. **0503**
Rating **50**
Bin **6 of 6**

Gap Description

Planned Moon and Mars exploration missions benefit from propellant transfer of hypergolic and electric propulsion propellants, including both in-space and Moon and Mars surface operations. This gap captures the required activities to enable efficient propellant transfer with acceptable risk posture.

Architecture Impacts and Benefits

Without gap closure, the architecture will be unable to transfer storable propellant between elements.

Architecture-Driven Child Gaps

0503-01	Cold- and dust-tolerant seals to enable surface transfer of high-pressure fluids
0503-02	Compressors and pumps for filling or venting of high-pressure fluids in reduced gravity and microgravity
0503-03	Autonomous commodity transfer and recovery
1104-06*	In-space transfer of electric propulsion (EP) propellant

Architecture Traceability

Key Definition Tasks

- Crew In-Space Propulsion Type
- Cargo In-Space Propulsion Type
- Crew In-Space Return Propellant Strategy

"✓" indicates completed definition task

Use Cases & Functions

UC-U-501 L	FN-U-507 L
UC-U-502 L	FN-U-508 L
UC-T-108 M	FN-T-210 M
UC-T-108 M	FN-T-211 M
UC-T-108 M	FN-T-212 M
UC-U-501 M	All FN

Current State of the Art

Hypergolic propellant transfer has been demonstrated in space and is common for ground operations. Subsystems at scale are TRL 2-3.

Performance Targets

Moon/Mars	Enable the thermal conditioning and reliable and safe transfer of storable propellant and high pressure gases between exploration assets in space and on the surface of the Moon and Mars.

Segments

Sustained Lunar Evolution

Humans to Mars

Sub-Architectures

Infrastructure Support

Autonomous Lunar Surface Structure Assembly and Construction

ID No. **0504**
Rating **30**
Bin **3 of 6**

Gap Description

Autonomous assembly and construction has been identified as a potential target to support sustained presence on the lunar surface. This new technology needs to be demonstrated in situ before it can be relied upon to construct infrastructure that can be used by surface exploration assets. Systems for robotic assembly, inspection, outfitting, repair, and site preparation will be needed to enable autonomous assembly and construction on the lunar surface. Potential scalable applications include, but are not limited to, the assembly and construction of tall towers, walls/barriers (e.g., PSI ejecta mitigation and FSP radiation attenuation), and shelters.

Architecture Impacts and Benefits

With gap closure, this infrastructure can provide a variety of services to surface assets such as communications, power, dust and PSI ejecta mitigation, and protection from the harsh thermal and radiation environments.

Architecture-Driven Child Gaps

0806-01*	Affordance recognition, grasp planning, and execution for autonomous object and interface manipulation
1001-01*	Robust robotic sensors
1001-02*	Adaptable robotic end effectors for fine grasping and manipulation
1001-03*	Efficient autonomous object detection, classification, and pose estimation
0504-01	Structural joining methods for surface construction and assembly

Architecture Traceability

Key Definition Tasks	Use Cases & Functions	
	UC-I-201 L	FN-I-205 L

"✓" indicates completed definition task

Current State of the Art	Performance Targets
In-space assembly and construction is at subscale and low TRL. Examples include the Automated Reconfigurable Mission Adaptive Digital Assembly Systems (ARMADAS) modular structural assembly system and the Tall Lunar Tower (TLT) autonomous robotic tower assembly system, both at TRL 4.	Moon: Enable the assembly and construction of structures on the lunar surface using autonomous/semi-autonomous robotic technologies.

Segments

Foundational Exploration

Sustained Lunar Evolution

Sub-Architectures

Infrastructure Support

Autonomous Systems & Robotics

In-Situ Additive/Subtractive Construction on the Lunar Surface

ID No.	**0505**
Rating	**29**
Bin	**3 of 6**

Gap Description

In situ additive and subtractive construction has been identified as a key capability target to enable the development of scalable technologies. Additive and subtractive construction is common in terrestrial industry but new technology is needed to adapt to the lunar surface environment and use feedstock derived from in-situ materials (regolith). Significant challenges include material deposition in low gravity, in-situ inspection, in-situ structure outfitting, material characterization, and scaling up to structural applications. Potential scalable applications include, but are not limited to, the construction of pathways, launch/landing pads, walls, and shelters.

Architecture Impacts and Benefits

With gap closure, this infrastructure can provide a variety of services to surface assets such as easily traversable pathways, dust and blast ejecta mitigation, and protection from the harsh thermal and radiation environments.

Architecture-Driven Child Gaps

0502-02*	In-situ evaluation, verification, and validation of manufactured components
0502-04*	Manufacturing of materials and components from ISRU-derived feedstock
0806-01*	Affordance recognition, grasp planning, and execution for autonomous object and interface manipulation
0505-01	Deposition of materials in low-pressure and low-gravity environment
0505-02	Non-destructive in-situ verification and validation of constructed products and structures

Architecture Traceability

Key Definition Tasks	Use Cases & Functions	
	UC-I-202 L	**FN-I-205 L**

"✓" indicates completed definition task

Current State of the Art	Performance Targets
Subscale technology testing in thermal vacuum chambers using regolith simulant.	Moon: Enable in-situ additive/subtractive construction technologies on the lunar surface.

Segments

Foundational Exploration

Sustained Lunar Evolution

Sub-Architectures

Infrastructure Support

In-Situ Resource Utilization Systems

Oxygen Extraction from Lunar Regolith

ID No.	**0601**
Rating	**54**
Bin	**6 of 6**

Gap Description

Oxygen from lunar regolith has been identified as a potential target to support sustained lunar presence through ISRU. Long-term operation of these systems has not been enabled.

Architecture Impacts and Benefits

Without gap closure, oxygen extraction demonstrations may not be able to use scalable techniques to promote potential growth of ISRU in future campaign segments. With gap closure, in-situ sourced O2 would benefit future missions through reduction of delivered mass.

Architecture-Driven Child Gaps

0601-01*	Preprocessing of granular regolith for ISRU
0601-02	Sensors for monitoring of ISRU processes for oxygen extraction
0601-03*	Regolith-tolerant components for long-duration ISRU processes
0601-04	ISRU system modeling for oxygen extraction

Architecture Traceability

Key Definition Tasks	Use Cases & Functions	
	UC-I-102 L	All FN

"✓" indicates completed definition task

Current State of the Art

Days of operation with highland simulants and Thermal Vacuum Chamber (TVAC) conditions around TRL 5/6, including the Carbothermal Reduction Demonstration (CaRD) project.

Performance Targets

Moon

Enable the acquisition, processing, storage and transfer of usable ISRU-generated products at the Moon in a scalable manner. Produce on the order of 250kg oxygen per year to meet Sustained Lunar Exploration habitation target state consumption rates, assuming 4 crew to the surface for 28 days.

Segments

Foundational Exploration

Sustained Lunar Evolution

Sub-Architectures

In-Situ Resource Utilization Systems

Water Recovery from Lunar Regolith/Ice

ID No. **0603**
Rating **55**
Bin **6 of 6**

Gap Description

Water has been identified as a potential target to support sustained lunar presence through ISRU. Techniques to mine or acquire the water such that they are not volatilized (lost) to the environment in the process is a challenge, as is hardware operation in harsh water-bearing environments (lunar permanently shadowed regions (PSRs)).

Architecture Impacts and Benefits

Without gap closure, water collection demonstrations may not be able to use scalable techniques needed for potential growth of resource utilization and frequent operations inside PSRs. With gap closure, in-situ sourced water would benefit future missions through reduction of delivered mass.

Architecture-Driven Child Gaps

0603-01	Preprocessing of hard/icy regolith for ISRU
0603-02	Sensors for monitoring of ISRU processes for water extraction
0603-03	Regolith- and thermal-tolerant components for long-duration ISRU processes
0603-04	ISRU system modeling for water extraction
0603-05	In-situ resource extraction in Lunar PSRs

Architecture Traceability

Key Definition Tasks

"✓" indicates completed definition task

Use Cases & Functions	
UC-I-103 L	All FN

Current State of the Art

Various methods and low TRL technologies tested with simulant at subscale.

Performance Targets

Moon

Enable the acquisition, processing, storage, and transfer of usable ISRU generated products at the Moon in a scalable manner. Produce on the order of 700kg water per year to meet Sustained Lunar Exploration habitation target state consumption rates, assuming 4 crew to the surface for 28 days.

Segments

Foundational Exploration

Sustained Lunar Evolution

Sub-Architectures

In-Situ Resource Utilization Systems

Metal Extraction from Lunar Regolith

ID No. **0604**
Rating **56**
Bin **6 of 6**

Gap Description

Metals for manufacturing feedstock have been identified as a potential target to support sustained lunar presence through in-situ resource utilization (ISRU). Technologies for lunar demo of extraction of metals from regolith require maturation to enable the lunar demo. Experience gained from the demonstration should feed into manufacturing of articles/equipment/spare parts from the feedstock.

Architecture Impacts and Benefits

Without gap closure, metal extraction demonstrations may not be able to use scalable techniques for potential growth of ISRU in future campaign segments. With gap closure, in-situ sourced metals could benefit future missions through reduction of delivered mass.

Architecture-Driven Child Gaps

0604-01	Sensors for monitoring of ISRU processes for metal extraction
0604-02	ISRU system modeling for metal extraction
0601-01*	Preprocessing of granular regolith for ISRU
0601-03*	Regolith-tolerant components for long-duration ISRU processes

Architecture Traceability

Key Definition Tasks	Use Cases & Functions	
	UC-I-106 L	All FN
"✓" indicates completed definition task		

Current State of the Art	Performance Targets	
Proof of concept type lab operations (TRL 4); short durations and small quantities.	Moon	Enable the acquisition, processing, storage and transfer of usable ISRU-generated products in the TBR kg class at the Moon in a scalable manner.

Segments

Foundational Exploration

Sustained Lunar Evolution

Sub-Architectures

In-Situ Resource Utilization Systems

Lunar Regolith Excavation, Manipulation, and Transportation

ID No. **0605**
Rating **53**
Bin **6 of 6**

Gap Description

Robust and scalable technologies are needed to collect and deliver different types of regolith to support the variety of resources targeted for in-situ resource utilization (ISRU) activities such as oxygen, water ice, metals, and feedstock. Developing systems to provide the forces required for digging, extraction, and relocation of material in lunar gravity is a challenging obstacle to closing this gap. Site preparation requires manipulation of regolith, rocks, and other surface obstacles. Novel implements are needed to provide these capabilities and to enable routine operations at landing zones, habitation zones, and pathways.

Architecture Impacts and Benefits

Without gap closure, the impact is an inability to acquire, manipulate, and deliver enough regolith to support lunar surface ISRU activities, surface site needs, and industry. Surface operations on unprepared lunar terrain will contend with dusty, unlit, and uneven conditions that may increase operational time and risk.

Architecture-Driven Child Gaps

0605-01	Excavation of granular regolith for ISRU
0605-02	Excavation of hard/icy regolith for ISRU
0605-03	Robotic regolith manipulation and transportation for ISRU and site preparation

Architecture Traceability

Key Definition Tasks

"✓" indicates completed definition task

Use Cases & Functions

UC-I-202 L	All FN

Current State of the Art

Regolith manipulation has been demonstrated in situ with scientific instruments and scoops at small <10 kg scale. Current ongoing efforts, including the development of the ISRU Pilot Excavator (IPEx) (TRL 5), are being designed with the goal of reliability and efficiency to excavate 10 metric tons of lunar regolith over 14 days.

Performance Targets

Moon	Demand for regolith excavation, manipulation, and transportation will depend on the scale of ISRU operations and site preparation. The scale of regolith manipulation to also minimize lofted dust will depend on the scale of site preparation and surface infrastructure support.

Segments

Sustained Lunar Evolution

Sub-Architectures

- In-Situ Resource Utilization Systems
- Autonomous Systems & Robotics
- Mobility Systems

Architecture Definition Document - Architecture-Driven Technology Gaps

Mars ISRU to Support Human Exploration

ID No.	**0606**
Rating	**52**
Bin	**6 of 6**

Gap Description

Although Mars in-situ resource utilization (ISRU) strategies have yet to be defined, several decision options and reference missions rely on ISRU-derived materials and/or propellants to minimize mission mass. This gap represents the end-to-end ISRU processes for multiple potential Mars commodities (oxygen, carbon, etc. extraction from Mars atmosphere or collection of surface/subsurface water) that may need to be developed to support human exploration.

Architecture Impacts and Benefits

Without gap closure, Mars mission architectures will be confined to Earth-delivered resources.

Architecture-Driven Child Gaps

0606-01	Mars atmosphere collection and processing for ISRU
0606-02	Mars surface and/or subsurface ice acquisition and processing for water
0606-03	Methane production with ISRU
0606-04	Carbon dioxide conversion to oxygen with ISRU
0606-05	Long-duration water electrolysis for ISRU applications

Architecture Traceability

Key Definition Tasks

- Surface Construction Priorities
- Crew In-Space Return Propellant Strategy
- Crew Mars Ascent Propellant Strategy
- Source of Mars Crew Consumables

"✓" indicates completed definition task

Use Cases & Functions

UC-I-101 M	All FN
UC-I-102 M	All FN
UC-I-201 M	All FN

Current State of the Art	Performance Targets
Various technologies at TRL 3/4. MOXIE CO2 to O2 demonstration on Mars at subscale with challenges that must be addressed for scaling operations.	Mars: Enable the production of commodities, propellant, and other usable materials to support human Mars missions.

Segments

Humans to Mars

Sub-Architectures

In-Situ Resource Utilization Systems

Packing, Transport, and Use of Conditioned Supplies and Commodities

ID No.	**0701**
Rating	**23**
Bin	**3 of 6**

Gap Description

Capability to package and maintain environmentally conditioned supplies and commodities is lacking. Logistics systems for supplies and commodities should be low overhead mass, interoperable with surface elements, human-robotic compatible, transportable by robotic assets and/or crew, thermally and pressure stable, recyclable, and reusable. An efficient system solution may include soft-sided and rigid carriers, crew portable and other mated carriers, pallets, power systems, automated asset tracking, etc.

Architecture-Driven Child Gaps

0701-01	Payload handling, manipulation, and transport
0701-02	Large payload/logistics transfer into pressurized volume
0701-03	Uncrewed robotic logistics management

Architecture Impacts and Benefits

With gap closure, the benefit is the more reliable and efficient point-to-point delivery of supplies and commodities. Maximize survivability of supplies and commodities with ability to expand coverage and flexibility to improve supportability and achievement of overall mission objectives.

Architecture Traceability

Key Definition Tasks		Use Cases & Functions	
LD-102 Lunar Logistics Strategy	✓	**UC-L-201 L**	**FN-L-201 L**
Logistics Carrier and Interface Strategy		**UC-H-102 M**	**FN-H-104 M**
		UC-H-103 M	**FN-H-108 M**

"✓" indicates completed definition task

Current State of the Art	Performance Targets	
Apollo equipment carriers. ISS extravehicular robotics experience (e.g., SPDM). ISS systems for pressurized cargo (e.g., CTB, ZSR, fluid bags).	Moon/Mars	Minimize logistics footprint, system mass, crew handling, and delivery time. Maximize reuse and interoperability.
	Mars	In addition, increased efficiency compared to the lunar performance target.

Segments

Foundational Exploration

Sustained Lunar Evolution

Humans to Mars

Sub-Architectures

Logistics Systems

Waste Management

ID No. **0702**
Rating **21**
Bin **3 of 6**

Gap Description

A comprehensive ability to manage waste streams is lacking. Trash disposal can release viable and non-viable microorganisms, water, and other volatiles and can contaminate the local environment. Additionally, a variety of resources and residuals are available from elements at end-of-life (e.g., landers) and in trash/waste including plastics, metals, water, and gases among others. If recovered, these resources may be recycled (water, oxygen, etc.) or repurposed (plastics, metals) for new applications. This includes technologies such as trash to gas, material sorting, trash material separation/extraction, in-space manufacturing, liquid/gas recovery, trash compaction, biological processing of waste, resource scavenging, long-term storage, etc.

Architecture Impacts and Benefits

Closing this gap may reduce amount of delivered logistics and volume of waste. Improved waste disposal technologies may mitigate the release of microorganisms and volatiles preventing contamination of science samples and complying with planetary protection protocols.

Architecture-Driven Child Gaps

0702-01	Non-metabolic solid waste processes that reduce volume, stabilize, and recover water
0702-02	Resource recovery and repurposing from trash
0702-03	Compact low-logistics commode for exploration

Architecture Traceability

Key Definition Tasks

- MD-10 Mars Forward Contamination Planetary Protection Risk Posture
- Waste and Trash Disposal Strategy (In Space)
- Waste and Trash Disposal Strategy (Mars Surface)

"✓" indicates completed definition task

Use Cases & Functions

UC-L-201 L	FN-L-301 L
UC-L-202 L	FN-L-302 L
UC-H-102 M	FN-L-301 M
UC-H-103 M	FN-L-302 M

Current State of the Art	Performance Targets	
Abandoning all waste on the surface or in designated orbit.	Moon/Mars	Solutions that maximize reuse, reduce logistics needs from Earth, encourage in-situ recycling, minimize logistics footprint, and prevent microbial and volatile releases that contaminate the vehicle and planetary surface.

Segments

Foundational Exploration

Sustained Lunar Evolution

Humans to Mars

Sub-Architectures

Logistics Systems

Lunar Dust-Tolerant Systems and Dust Mitigation

ID No. **0801**
Rating **1**
Bin **1 of 6**

Gap Description

Lunar dust has been established as a concern for EVA, mobility, and surface assets. Lunar dust particles are jagged and electrostatically charged, causing potential problems for systems regardless of mission or surface destination. Long-life lunar systems require solutions to ensure subsystems are operable and tolerant to dusty environments. Examples of affected subsystems include surface heat rejection, surface solar power, EVA, rovers, mechanisms, seals, and surface habitats. Additionally, dust mitigation technologies can be leveraged to reduce the impact of dust on systems/subsystems.

Architecture Impacts and Benefits

Without gap closure, systems may be damaged by dust particles and unable to perform at expected reliabilities or for expected durations.

Architecture-Driven Child Gaps

0801-01	Lunar dust tolerant thermal systems
0801-02	Mitigation of lunar dust transfer between surface vehicles/elements
0801-03	Lunar surface EVA suit dust mitigation tools and systems
0801-04	Lunar dust mitigation via surface coatings, treatments, and/or topography modifications of hardware
0801-05	Lunar dust mitigation via active methods
0801-06	Filtration and mitigation of lunar dust in habitable cabin volumes

Architecture Traceability

Key Definition Tasks

"✓" indicates completed definition task

Use Cases & Functions

UC-U-804 L	
UC-M-101 L	FN-M-101 L

Current State of the Art

Dust-tolerant systems used during Apollo missions. Terrestrial-based applications, such as flange couplings used in the oil and gas industry. These applications would need to be tested in the applicable environment first before being ready for use on a mission.

Performance Targets

Moon	Systems should be capable of operating efficiently for expected durations or longer, as well as preventing extreme wear and tear to the system or mechanisms from lunar dust. Prevention and/or removal of dust accumulation/adhesion is desired for external systems and for internal habitable spaces to allow for operational capability.

Segments

- Foundational Exploration
- Sustained Lunar Evolution

Sub-Architectures

- Mobility Systems
- Habitation Systems
- Logistics Systems
- Power Systems

Mars Dust-Tolerant Systems and Dust Mitigation

ID No. **0802**
Rating **35**
Bin **4 of 6**

Gap Description

Mars dust has the potential to serve as a challenge for Mars extravehicular activities (EVAs) and surface assets. There is a potential health risk to the crew if excessive Martian dust is inhaled over extended timeframes. Additionally, Mars has dust storms that last for days or months, which can be highly destructive to seals and bearings. Systems that will be exposed to the Martian dust should have solutions to ensure they are operable in and tolerant to the hazardous Martian environments. Examples include EVA, rovers, mechanisms, seals, connectors, and surface habitats. Additionally, dust mitigation technologies that can be leveraged to reduce the impact of dust on systems/subsystems are needed.

Architecture Impacts and Benefits

Without gap closure, systems may be damaged by dust particles and unable to perform at expected reliabilities or for expected durations. Additionally, there is a potential health risk to the crew if excessive Martian dust is inhaled over extended timeframes.

Architecture-Driven Child Gaps

0802-01	Mars dust-tolerant thermal systems
0802-02	Mitigation of Mars dust transfer between surface vehicles/elements
0802-03	Mars dust mitigation via surface coatings, treatments, and/or topography modifications of hardware
0802-04	Mars dust mitigation via active methods
0802-05	Filtration and mitigation of Mars dust in habitable cabin volumes

Architecture Traceability

Key Definition Tasks	Use Cases & Functions	
● Surface Ingress/Egress Strategy	UC-H-103 M	FN-H-110 M

"✓" indicates completed definition task

Current State of the Art	Performance Targets	
Dust-tolerant systems and mechanisms on the Mars Perseverance rover.	Mars	Systems should be capable of operating efficiently for expected durations or longer, as well as prevent extreme wear and tear to systems or mechanisms from Martian dust. Prevention and/or removal of dust accumulation/adhesion is desired for external systems and for internal habitable spaces to allow for operational capability.

Segments	Sub-Architectures			
Humans to Mars	Mobility Systems	Habitation Systems	Logistics Systems	Power Systems

Extravehicular Activity (EVA) and Intravehicular Activity (IVA) Suit System and Capabilities for Mars Missions

ID No. **0803**
Rating **31**
Bin **4 of 6**

Gap Description

Many new roles for humans performing EVAs, upgrades in EVA suits, and tools are an essential part of achieving mission success. While there are multiple options for Mars, human missions may require radical changes in the approach to EVA suit design and mass to ensure crew can operate effectively in the Mars gravity and atmosphere. Furthermore, there is unknown material degradation due to radiation beyond LEO that future suits must account for.

Architecture Impacts and Benefits

Without gap closure, Mars EVA will not be possible without new suits. Furthermore, the high EVA system mass will limit crew's abilities on Mars surface and could further exacerbate crew injury risk. Degraded performance will limit EVA time or restrict crew activity, increase system mass, and/or increase logistics transfer, etc. In addition, science objectives will not be met without adequate tool availability.

Architecture-Driven Child Gaps

0803-01	Continuous CO2 removal systems for Mars surface EVA suit in Martian atmosphere
0803-02	Thermal control systems for Mars surface EVA suit in non-vacuum
0803-03	Mars surface EVA suit dust mitigation tools and systems
0803-04	Earth-independent maintenance, reuse, and repair of Mars surface EVA suit

Architecture Traceability

Key Definition Tasks	Use Cases & Functions	
● MD-10 Mars Forward Contamination Planetary Protection Risk Posture	**UC-M101 M**	**All FN**
● Crew Surface Mobility Strategy		
● Surface EVA Capability Strategy		
● Exploration EVA Schema		

"✓" indicates completed definition task

Current State of the Art	Performance Targets	
The xEMU heat rejection and CO2 removal systems are dependent on operating in a vacuum environment as opposed to the Martian atmosphere. The xEMU system mass is also incompatible with a Mars surface gravity environment due to the too-large workload for the astronaut.	Mars	Mars spacesuits must be compatible with the surface gravity environment and the presence of an atmosphere. Mars spacesuits will require a different CO2 removal technology and thermal management technology than a lunar surface suit. Further, Mars spacesuits must be capable of supporting TBD concepts of operation with respect to EVA dwell time, EVA frequency, and use life.

Segments	Sub-Architectures	
Humans to Mars	Mobility Systems	Human Systems

Robotic and Mobility Systems in Extreme Cold Environments on the Lunar Surface

ID No. **0804**
Rating **19**
Bin **3 of 6**

Gap Description

Access to extreme cold surface environments including permanently shadowed regions (PSRs) presents several technology challenges. Extreme cold temperature robotic and mobility components such as actuators, wheels, electrical and electronic systems, and other subsystems including robust perception in low or no lighting are critical to enabling access to PSRs. Lunar regolith poses a significant challenge for the durability of mobility systems. Regolith mitigation technologies and strategies are vital to limit degradation to mobility systems, including actuators, wheel components, and power transmission systems.

Architecture Impacts and Benefits

Without gap closure, robotic and mobility assets may not be able to survive/operate for required duration inside PSRs (TBR) or while transiting shadowed regions. With gap closure, robotic and mobility assets may enhance remote access to areas of scientific interest, and improve robotic reconnaissance (e.g., scouting, surveying, mapping, collecting samples).

Architecture-Driven Child Gaps

0804-01*	Perception and navigation sensors for extended operation in the lunar environment and dynamic lunar lighting conditions
0804-02	Robotic actuation for extreme cold access
0804-03	Rover wheels/tires for extended-duration surface missions in extreme lunar environments
0804-04	Robotic mobility for robust, repeatable access to and through extreme terrain, surface topography, and harsh environmental conditions
0804-05	Extreme-temperature electronics for exploration missions
0805-01*	Software for robust perception in dynamic, suboptimal lunar lighting conditions

Architecture Traceability

Key Definition Tasks

"✓" indicates completed definition task

Use Cases & Functions

UC-A-101 L	FN-A-202 L
UC-A-106 L	FN-A-202 L

Current State of the Art

Non-integrated subsystems tested independently between 220 K and 130 K, with limited operational lifetimes.

Performance Targets

Moon

Enable use cases for surveying and accessing PSRs for sample retrieval. Enable robotic operations in PSRs with minimum temperatures of ~20–30 K for a maximum duration of [TBR] hours. Enable robotic exploration of regions where landing or crew entry are not feasible or advisable (e.g., areas of darkness colder than TBD degrees Kelvin, slope greater than TBD degrees, or other difficult terrain).

Segments

Foundational Exploration

Sustained Lunar Evolution

Sub-Architectures

Mobility Systems

Autonomous Systems & Robotics

Autonomous Surface Mobility and Navigation

ID No. **0805**
Rating **8**
Bin **2 of 6**

Gap Description

Mobility assets' autonomous and semi-autonomous surface mobility and navigation capabilities are valuable to enable a sustained lunar presence and Mars missions. Challenging environmental characteristics (e.g., harsh lighting effects, feature-sparse terrain) require advanced perception sensing and new algorithms and control paradigms for autonomous mobility. Current human-in-the-loop teleoperation for navigation and pathfinding may be insufficient for the level of support that robotic assets will be expected to provide for exploration missions. Advances in human-in-the-loop operation, supervised autonomy, onboard autonomy, and autonomous and semi-autonomous operations are desired to achieve a faster cadence of continued operation over previously unmapped terrain, over an order of magnitude greater range, and in the presence of communication delays and data latency.

Architecture Impacts and Benefits

Without gap closure, robotic assets will rely on heritage teleoperation from Earth that has challenges navigating difficult and/or unmapped terrain in a timely manner.

Architecture-Driven Child Gaps

0804-01*	Perception and navigation sensors for extended operation in the lunar environment and dynamic lunar lighting conditions
0805-01*	Software for robust perception in dynamic, suboptimal lunar lighting conditions
0805-02	High-performance processors for deep space missions
0805-03	Software for onboard localization, hazard detection, and path planning for surface mobility systems

Architecture Traceability

Key Definition Tasks

- Crew Surface Mobility Strategy
- Surface PNT Strategy
- Priorities for Crew vs. Robotic Tasks Strategy

"✓" indicates completed definition task

Use Cases & Functions

UC-A-201 L	FN-A-201 L
UC-C-202 M	FN-C-201 M
UC-A-101 M	All FN
UC-A-403 M	FN-A-401 M

Current State of the Art	Performance Targets
Human-in-the-loop ground control solutions navigating at slow pace over communications delays and data latency. The VIPER project developed sensors for determining position and identifying hazards for future use on an exploration rover at the lunar South Pole region. Terrestrial autonomous navigation systems rely on high performance computing. Mars 2020 Rover Perseverance uses human-in-the-loop goal setting augmented by onboard autonomous navigation with hazard avoidance which enables typical traverse distances of ~250m/sol or ~700m per multi-sol command cycle.	Moon/Mars: Capability for autonomous surface mobility and navigation to enable accurate location estimation and repositioning of surface assets while uncrewed. Moon: In addition, the uncrewed surface mobility range target for FE segment is 1050 km/year at the lunar South Pole region. Mars: In addition, increased autonomy and reliability compared to the lunar performance target.

Segments

Foundational Exploration
Sustained Lunar Evolution
Humans to Mars

Sub-Architectures

Mobility Systems
Autonomous Systems & Robotics

Payload Offloading, Handling, and Manipulation for Surface Assets

ID No. **0806**
Rating **7**
Bin **2 of 6**

Gap Description

Human-scale robotic manipulation can enable a broad set of crew support, infrastructure support, and utilization tasks during crewed and uncrewed periods. As the surface architecture evolves and stay times increase, current offloading practices will no longer be sufficient to manage large amounts of logistics and utilization cargo without technology development. Greater multi-purpose material handling capabilities will be desired to manage the large amounts of cargo. This includes technologies such as those for larger-scale off- and on-loading, transfer, elevated access, robotic manipulators/end effectors, construction, assembly (including industrial scale power), and disassembly capabilities.

Architecture Impacts and Benefits

Without gap closure, crew would be required to manually move all payloads from landers, which will reduce crew time for other mission critical activities and extravehicular activities.

Architecture-Driven Child Gaps

0806-01*	Affordance recognition, grasp planning, and execution for autonomous object and interface manipulation
0806-02	Payload maneuvering tools for offloading, positioning, and delivery
1001-01*	Robust robotic sensors
1001-02*	Adaptable robotic end effectors for fine grasping and manipulation
1001-03*	Efficient autonomous object detection, classification, and pose estimation

Architecture Traceability

Key Definition Tasks		Use Cases & Functions	
LD-102 Lunar Logistics Strategy	✓	**UC-A-103 L**	**All FN**
Small Cargo Delivery, Stowage, and Return Strategy		**UC-A-105 M**	**All FN**
Priorities for Crew vs. Robotic Tasks Strategy			

"✓" indicates completed definition task

Current State of the Art	Performance Targets	
Crew manual labor to manipulate logistics cargo and payloads that do not provide their own mobility systems. Small mechanical assist with pullies and crew carry. Surface level access and lightweight ladders.	Moon/Mars	Uncrewed logistics transfer methodologies. 100s to 1000s of kgs robotic load handling/transfer capacities. Expand from crew portable to large element-scale volumes. Access from surface level to elevated heights up to 10s of meters.
	Mars	In addition, increased autonomy and reliability compared to the lunar performance target.

Segments

Foundational Exploration
Sustained Lunar Evolution
Humans to Mars

Sub-Architectures

Mobility Systems
Autonomous Systems & Robotics
Logistics Systems

Docking and Berthing between Surface Elements on the Moon and Mars

ID No. **0807**
Rating **15**
Bin **2 of 6**

Gap Description

The ability for surface elements to share services and transfer commodities, cargo, and/or crew by establishing a pressurized environment and intravehicular activities (IVA) without performing extravehicular activities (EVA) has been identified for enabling sustained lunar operations. No existing dust-tolerant berthing/docking fills the need.

Architecture Impacts and Benefits

Closing this docking and berthing gap will reduce the need to use EVA for crew and cargo transfer. This increases EVA time for exploration, reduces time moving carriers in tight quarters, reduces number of required EVAs, etc.

Architecture-Driven Child Gaps

0807-01	Surface element docking sensors
0807-02	Tools for aligning surface assets
0807-03	Cold- and dust-tolerant interface seals to enable pressurized surface transfers and EVAs
0807-04	Surface umbilicals to enable commodity transfer

Architecture Traceability

Key Definition Tasks

- Crew Surface Mobility Strategy
- Surface Ingress/Egress Strategy
- Small Cargo Delivery, Stowage, and Return Strategy

"✓" indicates completed definition task

Use Cases & Functions

UC-L-201 L	FN-L-101 L
UC-L-201 L	FN-L-205 L
UC-M-101 L	FN-M-203 L

Current State of the Art

Heritage ISS docking systems. Surface docking/mating systems for dusty surface environments do not currently exist.

Performance Targets

Moon/Mars	Dust-tolerant mating system and utilities/logistics connections that can facilitate the transfer of commodities and/or crew and cargo between elements in a shirtsleeve environment while maintaining pressure integrity for up to a decade of surface operations.
Mars	In addition, increased reliability compared to the lunar performance target.

Segments

Foundational Exploration
Sustained Lunar Evolution
Humans to Mars

Sub-Architectures

Mobility Systems
Logistics Systems
Habitation Systems

Relocation of Large Assets on the Lunar Surface

ID No.	**0808**
Rating	**25**
Bin	**3 of 6**

Gap Description

The capability to manipulate and transport large assets (>6 metric tons) on the lunar surface can enable a wider range of exploration and science. Relocated assets can be reused by subsequent missions to visit diverse sites. Payload and cargo manipulation systems currently in development do not address the need for a system capable of repeatedly moving large, human-rated assets across short to long distances on the lunar surface.

Architecture Impacts and Benefits

Without gap closure, challenges relocating assets may limit the science and exploration value of repeated visits to the same location or require new assets to be launched and landed. With gap closure, benefits include increased exploration range reusing previously landed assets.

Architecture-Driven Child Gaps

0808-01	Robotic offloading and relocation for large-scale payloads

Architecture Traceability

Key Definition Tasks

“✓” indicates completed definition task

Use Cases & Functions

UC-M-401 L	FN-M-403 L
UC-M-601 L	FN-M-601 L

Current State of the Art

Cargo and payload manipulation and transportation options that may not scale or be capable of transporting a high-mass asset over a long distance.

Performance Targets

Moon	Capability to manipulate and transport >6-metric ton asset over TBR distance.

Segments

Foundational Exploration

Sustained Lunar Evolution

Sub-Architectures

Mobility Systems

Autonomous Systems & Robotics

Scalable Lunar Surface Power Generation

ID No. **0901**
Rating **13**
Bin **2 of 6**

Gap Description

There is a need for scalable lunar surface power generation capabilities to provide continuous electrical energy for large assets and crew safety-critical (i.e., contingency) operations during both shadowed and illuminated operations, including energy storage, as applicable. There is a desire for evolvable technologies that can support continuous robotic/human operation and are capable of scaling to global power utilization and industrial power levels. Technology development is needed to ensure high reliability and power availability at the lunar South Pole region.

Architecture Impacts and Benefits

Without gap closure, state-of-the-art power generation capabilities (and energy storage as applicable) will be leveraged without scalability for achieving power infrastructure and in-situ resource utilization production objectives.

Architecture-Driven Child Gaps

0901-01	Nuclear power generation for the lunar surface
0901-02	Solar power generation for the lunar surface
0901-03	Fuel cell power for the lunar surface
0901-04	Energy storage to enable robust and long-duration operations on Moon

Architecture Traceability

Key Definition Tasks

“✓” indicates completed definition task

Use Cases & Functions	
UC-P-101 L	All FN
UC-P-102 L	All FN
UC-P-501 L	
UC-P-502 L	

Current State of the Art

ISS has ~200 kW of solar arrays with battery energy storage for ~30-minute LEO eclipse. NASA experience with long-duration Moon and Mars surface power is limited to <1 kW robotic missions (e.g., ALSEP, InSight, Curiosity). There has been one brief ground test of a kW-scale fission power system intended for space ("KRUSTY" in 2018).

Performance Targets

Moon

Scalable multi-kWe-scale power generation (and energy storage, as applicable) capable of supporting crew safety and exploration activities in lunar temperatures, dust, and solar availability conditions to extend crewed operation during lunar shadowed periods.

Segments

Foundational Exploration

Sustained Lunar Evolution

Sub-Architectures

Power Systems

Scalable Mars Surface Power Generation

ID No. **0902**
Rating **45**
Bin **5 of 6**

Gap Description

There is a need for scalable Mars surface power generation capabilities to provide electrical energy for the majority of large assets and crew safety-critical operations planned for initial crewed missions to Mars. Technology development is needed to ensure high reliability and power availability in the Martian environment, including during potential hazardous environmental events. Technologies developed for the Moon may be applicable but insufficient due to differences in surface conditions: Mars surface solar flux is <40% of the Moon and exacerbated by month-long dust storms.

Architecture Impacts and Benefits

Without gap closure, the impact is the inability to support more than minimal missions to the Martian surface. Inability to enable in-situ resource utilization described in objective MI-04.

Architecture-Driven Child Gaps

0902-01	Nuclear power generation for the Martian surface
0902-02	Solar power generation for the Martian surface
0902-03	Fuel cell power for the Martian surface
0902-04	Energy storage to enable robust and long-duration operations on Mars

Architecture Traceability

Key Definition Tasks		Use Cases & Functions	
● MD-07 Primary Mars Surface Power Generation Technology	✓	UC-P-101 M	All FN
		UC-P-102 M	All FN
		UC-P-103 M	
		UC-P-501 M	

"✓" indicates completed definition task

Current State of the Art	Performance Targets
NASA experience with long-duration Moon and Mars surface power is limited to <1 kW robotic missions (e.g., ALSEP, InSight, Curiosity). There has been one brief ground test of a kW-scale fission power system intended for space ("KRUSTY" in 2018).	Mars: Scalable multi-kWe-scale power generation (and energy storage, as applicable) capable of supporting crew safety and exploration activities in Mars temperatures, dust, and solar availability conditions.

Segments	Sub-Architectures
Humans to Mars	Power Systems

Power Management and Distribution between Surface Elements

ID No. **0903**
Rating **24**
Bin **3 of 6**

Gap Description

Traditional surface power infrastructure is limited to systems that could be packaged and deployed with surface assets in a single launch. Given the increased power requirements and larger distribution of surface assets, there is value in an independent power management and distribution (PMAD) infrastructure that can efficiently manage power transfers between assets at a variety of distances from each other while minimizing overall mass and power loss. It is desirable to have PMAD solutions that focus on reducing overall system mass and power loss while providing high reliability and long-duration operating lifetimes in extreme environments.

Architecture Impacts and Benefits

Without gap closure, power systems would be required to run independently of each other and would need to carry their own energy storage/power generation/power support systems, which can cause penalties to the estimated launch and landing mass for all elements. With gap closure and the ability to interchange power, total system robustness and resiliency of elements can be increased, and risk decreased.

Architecture-Driven Child Gaps

0903-01	Power management systems for long-duration lunar and Martian missions
0903-02	Reliable, rad-hard electronic power converters
0903-03	High-power energy transmission and distribution between surface assets
0903-04	Power transfer in dusty surface environments

Architecture Traceability

Key Definition Tasks

"✓" indicates completed definition task

Use Cases & Functions

UC-P-301 L	All FN
UC-P-302 L	All FN
UC-P-301 M	FN-P-303 M
UC-P-302 M	FN-P-303 M

Current State of the Art

ISS produces ~200 kW and distributes power at 120-160 Vdc across distances of 10s of meters. There are no current PMAD options capable of distributing multi-kW power at high voltage over km-scale distances in harsh surface environments.

Performance Targets

Moon/Mars	Robust power management and distribution solutions for long-duration operations in extreme environments. Consistent design guidelines for PMAD interfacing between surface power and surface assets, allowing for modularity and resiliency to off-nominal scenarios. Design to minimize system mass for PMAD transfer infrastructure (from power source to user).
Moon	In addition, the target surface power available between elements for FE segment is 20 kW.
Mars	In addition, increased reliability compared to the lunar performance target.

Segments

- Foundational Exploration
- Sustained Lunar Evolution
- Humans to Mars

Sub-Architectures

- Power Systems

High-performance Actuators, Sensors, and Interfaces

ID No. **1001**
Rating **14**
Bin **2 of 6**

Gap Description

Human exploration would benefit from robotic elements and other exploration elements with robust actuators, cameras, sensors, and interfaces for autonomous and tele-operated functions such as capture, berthing, assembly, inspection, repair, and manufacturing with high reliability and the ability to be verified and validated in space. Technology advancements are needed in the robotic subsystems' survivability of extreme temperature, radiation, and dust conditions.

Architecture Impacts and Benefits

Without gap closure, robotic operations would be limited for exploration and science operations. Additionally, robotic solutions would be unavailable to extend the useful life of high-value assets via inspection, repair, maintenance, and upgrade, assuming that high-value assets can be recertified and reused for multiple round-trip exploration missions.

Architecture-Driven Child Gaps

1001-01*	Robust robotic sensors
1001-02*	Adaptable robotic end effectors for fine grasping and manipulation
1001-03*	Efficient autonomous object detection, classification, and pose estimation

Architecture Traceability

Key Definition Tasks

- In-Space Refurbishment Capability Between Missions
- In-Space Servicing Capability Strategy
- Priorities for Crew vs. Robotic Tasks Strategy

"✓" indicates completed definition task

Use Cases & Functions

UC-L-202 L	FN-T-106 L
UC-A-107 L	FN-A-204 L
UC-A-101 M	All FN
UC-A-102 M	All FN
UC-A-103 M	All FN
UC-A-104 M	All FN

Current State of the Art

Heritage robotic missions to Mars have tele-operated actuators, cameras, sensors for limited capture functions.

Performance Targets

Moon/Mars	Need motor drivers to meet corresponding performance metrics. Provide environmentally robust components and/or operationally robust components with TBD reliability, TBD accuracy, and TBD mean-time-between-failure, dependent on application.
Mars	In addition, increased autonomy, reliability, and communication delays compared to the lunar performance target.

Segments

- Sustained Lunar Evolution
- Humans to Mars

Sub-Architectures

- Autonomous Systems & Robotics
- Mobility Systems

Autonomous Monitoring for Exploration Missions

ID No. **1002**
Rating **34**
Bin **4 of 6**

Gap Description

Improvement is needed in software capability for remote and autonomous monitoring to provide situational awareness and inform follow-on decision-making in increasingly Earth-independent operations. Applications include monitoring crew health, crew system health, and vehicle system health, and enabling safe, effective autonomous operations.

Architecture Impacts and Benefits

Without gap closure, health and performance assessment will be limited or poorly informed, and the probability of loss of an entire system would increase, which would represent a risk to crew and mission.

Architecture-Driven Child Gaps

1002-01	Autonomous monitoring software
1002-02	High-performance processors for deep space missions

Architecture Traceability

Key Definition Tasks

- ● MD-12 Maximum Allowable Crewed Communications Disruption
- ● Priorities for Crew vs. Robotic Tasks Strategy

"✓" indicates completed definition task

Use Cases & Functions	
UC-A-201 L	FN-A-301 L
UC-A-301 L	FN-A-302 L
UC-A-403 M	FN-G-401 M
UC-A-404 M	All FN

Current State of the Art	Performance Targets	
ISS crew largely relies on ground support for remote monitoring with max ~8-second time delay. Autonomous monitoring requires large and heavy processors and extensively pre-programmed decision algorithms.	Moon/Mars	Enable autonomous monitoring of systems and crew that support human exploration, progressing toward Mars-distance communication delays and blackouts.
	Mars	In addition, increased autonomy, reliability, and communication delays compared to the lunar performance target.

Segments

- Foundational Exploration
- Sustained Lunar Evolution
- Humans to Mars

Sub-Architectures

- Autonomous Systems & Robotics
- Data Systems and Management

Integrated System Fault/Anomaly Diagnosis, Decision Support, and Response

ID No. **1003**
Rating **18**
Bin **3 of 6**

Gap Description

Fault management provides detection, diagnosis, decision, response, and adjustment to off-nominal conditions to maintain mission objectives. Future missions with long element lifetimes, periods of dormancy, and potential communication delay may require improved software and hardware capability to enable system fault/anomaly detection, diagnosis, prognostics, decision support, automated safing/recovery, and response. Existing strategies and algorithms currently detect faults/anomalies through physics/statistical models, empirical knowledge, and sensor data diagnostics through expected coverage levels, false-positive/false-negative targets, and telemetry, tracking, and command (TTC) allocations per fault class.

Architecture Impacts and Benefits

Without gap closure, missions will have to rely on ground (on a limited basis due to communication delays in deep space) or crew onboard to detect and diagnose faults and anomalies correctly and in a timely manner.

Architecture-Driven Child Gaps

1003-01	Fault detection and diagnosis
1003-02	Streamline sources of information for autonomous or semi-autonomous anomaly resolution
1003-03	Automated control and safing sequences from system monitoring

Architecture Traceability

Key Definition Tasks

- MD-12 Maximum Allowable Crewed Communications Disruption
- Priorities for Crew vs. Robotic Tasks Strategy

"✓" indicates completed definition task

Use Cases & Functions

UC-H-201 L	
UC-H-202 L	
UC-G-501 M	FN-D-201 M

Current State of the Art

ISS crew largely relies on ground support for off-nominal diagnosis and decision-making. Ad-hoc integrations are complex, costly, and difficult-to-maintain one-time implementations specific to a particular system.

Performance Targets

Moon/Mars	Safe, reliable, autonomous control of systems; autonomous detection and diagnosis of off-nominal conditions and events; automated control and safing sequences.
Mars	In addition, increased autonomy, reliability, and communication delays compared to the lunar performance target.

Segments

- Foundational Exploration
- Sustained Lunar Evolution
- Humans to Mars

Sub-Architectures

- Autonomous Systems & Robotics
- Data Systems and Management

Trustworthy Autonomy for Planning and Decision-making

ID No.	**1004**
Rating	**33**
Bin	**4 of 6**

Gap Description

Moon and Mars missions would benefit from capabilities (hardware, software, firmware, "cloud," etc.) to enable autonomous crew planning, forecasting, and decision-making with simple-to-use, low-cost, and replicable solutions at a level of accuracy that supports human exploration. Robust systems would be capable of combining multiple data sources and dynamic decision-making as information updates. Autonomous decision-making with existing technology cannot be done in a way that is trusted to meet performance objectives.

Architecture Impacts and Benefits

Without gap closure, planned and future missions may not be viable or may have reduced value due to lack of trust in autonomous systems.

Architecture-Driven Child Gaps

1004-01	High-performance processors for deep space missions
1004-02	Data fusion tools to merge complex and disparate data for real-time autonomous decision-making
1004-03	Earth-independent decision support tools
1004-04	Capability to integrate planning resources into commanding tasks

Architecture Traceability

Key Definition Tasks

- MD-12 Maximum Allowable Crewed Communications Disruption
- Priorities for Crew vs. Robotic Tasks Strategy

"✓" indicates completed definition task

Use Cases & Functions

UC-A-301 L	FN-A-302 L
UC-A-403 M	FN-A-401 M
UC-A-404 M	FN-A-402 M

Current State of the Art

ISS crew largely relies on ground support for planning and nominal decision-making. There are insufficient ontologies and languages to facilitate implementation of autonomous capabilities.

Performance Targets

Moon/Mars	Software platforms to enable analysis and decision-making without humans in the loop and can explain their decision-making (or have it inspected) to build trust.
Mars	In addition, increased autonomy, reliability, and communication delays compared to the lunar performance target.

Segments

- Sustained Lunar Evolution
- Humans to Mars

Sub-Architectures

- Autonomous Systems & Robotics
- Data Systems and Management
- Human Systems

Safe Human-Robot Interaction and Teaming

ID No. **1005**
Rating **28**
Bin **3 of 6**

Gap Description

Integrated human and robotic systems are desired to enable maximum science and exploration during future missions. Technology advancements are needed in robust, reliable, safe, and efficient methods of human-robot interaction, communication, and task coordination. Human-robot interaction could describe crew operating in the same area as one or many autonomous/semi-autonomous robotic systems, ground-based operators supervising semi-autonomous robots in space, crew inside a surface habitat controlling remote robots external to the habitat, or other permutations. Human-robot teaming could describe joint crew-robot teams operating in parallel or collaboratively.

Architecture Impacts and Benefits

Without gap closure, robotic operations would be limited for exploration and science operations. Planned and future missions may not be viable or may have reduced value due to actual or perceived lack of safety in human-robot interactions.

Architecture-Driven Child Gaps

1005-01	Situational awareness and safety controls for human-robot interaction
1005-02	Task planning and execution software for autonomous systems
1005-03	In-situ command and control of multiple robotic assets

Architecture Traceability

Key Definition Tasks	Use Cases & Functions	
● Priorities for Crew vs. Robotic Tasks Strategy	UC-A-101 L	FN-A-102 L
	UC-A-104 L	FN-A-101 L
	UC-A-301 L	FN-A-302 L
	UC-A-301 M	FN-A-301 M
"✓" indicates completed definition task		

Current State of the Art	Performance Targets	
Increasing commercial use of human-scale robots working alongside humans to move cargo in warehouses.	Moon/Mars	Safe human-robot interactions at level of efficiency that supports human exploration; safe command and control across high-latency and bandwidth-limited networks; built-in or automated safing sequences.
	Mars	In addition, increased autonomy, reliability, and communication delays compared to the lunar performance target.

Segments

- Foundational Exploration
- Sustained Lunar Evolution
- Humans to Mars

Sub-Architectures

- Autonomous Systems & Robotics
- Human Systems

Lunar Precision Landing and Hazard Avoidance for Human Exploration

ID No. **1101**
Rating **27**
Bin **3 of 6**

Gap Description

Advancement in precision landing and hazard avoidance (PL&HA) is needed to safely and reliably aggregate surface elements at lunar South Pole region explorations sites. PL&HA technologies should enable safe and accurate landings in all visibility conditions (induced plume surface interaction effects, darkness, etc.) for safe delivery of crew and cargo to lunar exploration sites.

Architecture-Driven Child Gaps

1101-01	Real-time mapping technologies for precision landing and hazard detection during lunar descent
1101-02	Characterization and mitigation of plume surface interaction on lunar surface
1101-03	Navigation sensors for lunar precision landing
1101-04	Algorithms and onboard computing to enable lunar precision landing and hazard avoidance

Architecture Impacts and Benefits

Without gap closure, the ability to land crew and cargo in close proximity to other surface elements and in low-visibility conditions is reduced.

Architecture Traceability

Key Definition Tasks		Use Cases & Functions	
LD-03-L Lunar Landing Region Selection	✓	UC-T-401 L	All FN
		UC-T-401 L	All FN

"✓" indicates completed definition task

Current State of the Art	Performance Targets
Systems capable of soft-touchdowns on illuminated landing sites at the lunar South Pole region.	Moon: Enable crew and cargo to be landed at lunar South Pole region exploration sites in various illumination conditions with 50m landing accuracy for FE segment with <10 minute initialization time to confirm position within 25m.

Segments

Foundational Exploration

Sustained Lunar Evolution

Sub-Architectures

Transportation Systems

Mars Precision Landing and Hazard Avoidance for Human Exploration

ID No.	**1102**
Rating	**37**
Bin	**5 of 6**

Gap Description

Lunar landing systems will be insufficient to achieve precision landing on Mars. Technologies developed for the Moon may be applicable but insufficient due to differences in entry, descent, and landing (EDL) on Mars, primarily due to the presence of the Martian atmosphere. Precision landing and hazard avoidance systems used for robotic Mars landers will not scale to human-class vehicles.

Architecture Impacts and Benefits

Without gap closure, the ability to land in close proximity to science targets and surface assets is reduced. With gap closure, the ability to land in low-visibility conditions (e.g., dust storms) could significantly lower loss of mission risk.

Architecture-Driven Child Gaps

1102-01	Real-time mapping technologies for precision landing and hazard detection during Mars descent
1102-02	Characterization and mitigation of plume surface interaction on Mars surface
1102-03	Navigation sensors for Mars precision landing
1102-04	Algorithms and onboard computing to enable Mars precision landing and hazard avoidance
1102-05	Atmospheric entry modeling and simulation to enable precision landing at Mars

Architecture Traceability

Key Definition Tasks

- ● Crew Mars Descent Availability
- ● Cargo Mars EDL Technology
- ● Crew Mars EDL Technology
- ● EDLA Systems Reuse Strategy

"✓" indicates completed definition task

Use Cases & Functions	
UC-C-204 M	FN-C-207 M

Current State of the Art

Perseverance had a landing ellipse of 7.7 km x 6.6 km. This EDL architecture does not scale to human-class vehicles. The Perseverance Terrain Relative Navigation system enabled landing accuracy to within 5 m of the final designated landing target.

Performance Targets

Mars	Landing accuracy on order of 100 m. Detect and avoid obstacles on order of 1 m in diameter/depth.

Segments

Humans to Mars

Sub-Architectures

Transportation Systems

Mars Entry, Descent, and Landing for Human Exploration

ID No. **1103**
Rating **10**
Bin **2 of 6**

Gap Description

The landed mass required for a human Mars mission exceeds the practical limits of heritage robotic mission entry, descent, and landing (EDL) systems. New and scalable EDL technologies are needed to enable Mars human exploration. Child gaps represent a non-exhaustive list of technology options in the architecture trade space.

Architecture Impacts and Benefits

Without gap closure, the impact is the inability to land human-class payloads on Mars surface to support exploration missions. Heaviest indivisible landed payload may be significantly constrained and threaten architecture viability.

Architecture-Driven Child Gaps

1103-01	Supersonic retropropulsion engines for Mars descent
1103-02	Low-L/D systems for Mars atmospheric entry and/or aerocapture
1103-03	Mid-L/D systems for Mars atmospheric entry and/or aerocapture
1103-04	Robust modeling and simulation for high-mass Mars atmospheric entry

Architecture Traceability

Key Definition Tasks

- Crew Mars Descent Availability
- Cargo Mars EDL Technology
- Crew Mars EDL Technology
- EDLA Systems Reuse Strategy
- EDLA and In-Space Transportation Systems Functional Split

"✓" indicates completed definition task

Use Cases & Functions

UC-T-102 M	All FN
UC-T-207 M	All FN

Current State of the Art

Perseverance landed approximately 1 metric ton on Mars surface with EDL architecture that does not scale to human-class elements. LOFTID successfully demonstrated a 6 m inflatable aeroshell with peak deceleration of 9g returning 1100kg from Earth orbit.

Performance Targets

Mars

Enable the safe, reliable, and precise landing of payloads between 25 and 75+ metric tons.

Segments

Humans to Mars

Sub-Architectures

Transportation Systems

Mars Transportation Propulsion

ID No. **1104**
Rating **6**
Bin **1 of 6**

Gap Description

To support crewed missions to Mars, there is a need for propulsion systems capable of transporting large, human-class systems to Mars vicinity. There are several technology options being considered for the Mars transportation propulsion system. Nuclear systems, non-nuclear systems, high-thrust ballistic systems, low-thrust systems, and hybrid high-/low-thrust systems are just a few of the options currently in the propulsion technology trade space. The decision will be informed by a plethora of other decisions, including total mission duration, transit habitation strategy, mission mode operation, and others.

Architecture Impacts and Benefits

Without gap closure, propulsion system trade space may become constrained to few options, substantially increasing cost of Mars missions or threatening viability.

Architecture-Driven Child Gaps

1104-01	Nuclear thermal propulsion (NTP) for Mars transportation
1104-02	Nuclear electric propulsion (NEP) for Mars transportation
1104-03	Main stage chemical propulsion systems for Mars transportation
1104-04	Solar electric propulsion (SEP) systems for in-space Mars transportation
1104-05	Dynamic power conversion and management systems for exploration-class electric propulsion systems
1104-06*	In-space transfer of electric propulsion (EP) propellant
1107-04*	Hardware components for repeated reuse for low-loss cryogenic fluid transfer in space

Architecture Traceability

Key Definition Tasks	Use Cases & Functions	
● Crew In-Space Propulsion Type	UC-T-105 M	All FN
● Cargo In-Space Propulsion Type	UC-T-108 M	All FN
● In-Space Transportation Systems Reuse Strategy	UC-T-203 M	All FN
● Crew Mars Parking Orbit		

"✓" indicates completed definition task

Current State of the Art	Performance Targets	
Chemical combustion solutions are current state of the art, but aggregation of chemical propellant has not been demonstrated on orbit. NTP and NEP are at low TRL at human exploration scale. SEP for Gateway is at TRL 6. All of the above may need a larger-scale propulsion system for Mars than has been tested/built.	Mars	Enable the transfer of crew and cargo between Earth and Mars. Desired propulsion system performance will be informed by ongoing and future key decisions.

Segments	Sub-Architectures
Humans to Mars	Transportation Systems

Mars Ascent Propulsion for Human Exploration

ID No. **1105**
Rating **12**
Bin **2 of 6**

Gap Description

Mars atmosphere and gravity make ascent a high "gear ratio" operation, meaning several kilograms of ascent propulsion mass are required for every kilogram lofted back to orbit. At a minimum, ascending just two crew members—even without any return cargo—is estimated to require more than 30 tons of propellant to a 5-sol Earth transportation vehicle parking orbit with current technology. New technologies are required to return crew and cargo to Mars orbit.

Architecture Impacts and Benefits

Ascent stage performance has significant impact throughout the architecture. Without gap closure, architecture may require large amounts of ascent propellant to be delivered from Earth or produced in-situ and stored for long durations, which may threaten architecture viability.

Architecture-Driven Child Gaps

1105-01	High-efficiency, high-thrust liquid rocket engine with storable propellant for Mars ascent propulsion
1105-02	Robust liquid rocket engine with cryogenic propellant for Mars ascent propulsion
1105-03	Reliable and human-rated solid propellant rocket engine for Mars ascent propulsion
1105-04	High-efficiency, high-thrust rocket engine with hybrid propellant system for Mars ascent propulsion

Architecture Traceability

Key Definition Tasks

- ● Crew Mars Parking Orbit
- ● Crew Mars Ascent Availability
- ● Crew Mars Ascent Propulsion Type
- ● Crew Mars Ascent Propellant Strategy
- ● EDLA Systems Reuse Strategy

"✓" indicates completed definition task

Use Cases & Functions

UC-T-101 M	FN-T-102 M
UC-T-208 M	All FN

Current State of the Art

Ascent from Mars surface has never been attempted. Current solutions are conventional storable propellant liquid rocket engines.

Performance Targets

Mars	Enable crew and cargo to ascend to Mars orbit. Desired performance will be informed by ongoing and future key decisions.

Segments

Humans to Mars

Sub-Architectures

Transportation Systems

Cryogenic Fluid Storage

ID No. **1106**
Rating **32**
Bin **4 of 6**

Gap Description

There is a need to store certain fluids, such as propellants for propulsion assets, at cryogenic temperatures during long-duration missions and to quantify the amount of propellant remaining within a tank at any time. This capability would enable long-duration missions with minimal loss of cryogenic fluids and reduce the need for additional elements carrying propellant that compensates for loss to boil-off, leakage, and uncertainties of usage. Additionally, propellant gauging will be critical to determine the remaining propellant and track any additional losses that occur from boil-off, leakage, or inefficiencies from venting and pressurization.

Architecture-Driven Child Gaps

1106-01	Thermal management for long-duration cryogenic fluid storage
1106-02	Fluid management for long-duration cryogenic fluid storage
1106-03*	High-efficiency cryo-coolers at 20K and 90K temperature class

Architecture Impacts and Benefits

Closing this gap enables long-duration missions using cryogenic propellant systems with minimal unintended propellant losses and the ability to quantify remaining propellant in tank.

Architecture Traceability

Key Definition Tasks

- Crew In-Space Return Propellant Strategy
- Crew Mars Ascent Propellant Strategy
- Crew In-Space Propulsion Type
- Cargo In-Space Propulsion Type

"✓" indicates completed definition task

Use Cases & Functions

UC-U-503 L	FN-U-504 L
UC-U-504 L	FN-U-503 L
UC-I-102 L	FN-I-105 L
UC-T-108 M	FN-T-211 M
UC-T-108 M	FN-T-212 M
UC-U-501 M	FN-U-504 M
UC-I-102 M	FN-I-104 M

Current State of the Art

Boil-off rate in current storage solutions necessitates additional propellant mass margin of 15%-20%. A zero boil-off tank experiment series has been conducted aboard ISS.

Performance Targets

Moon/Mars	System that can efficiently store propellant for long-durations in microgravity and partial gravity environments while minimizing boil-off.
Mars	In addition, increased autonomy and reliability compared to the lunar performance target.

Segments

- Foundational Exploration
- Sustained Lunar Evolution
- Humans to Mars

Sub-Architectures

- Transportation Systems
- Infrastructure Support

Cryogenic Fluid Transfer

ID No. **1107**
Rating **4**
Bin **1 of 6**

Gap Description

There is a need to transfer cryogenic fluids in cislunar space, deep-space and surface applications with minimal leakage. This capability would enable and enhance transportation vehicle performance involving cryogenic propellants, as it would reduce the amount of propellant that must be budgeted for leak margin.

Architecture Impacts and Benefits

Closing this gap enables regular transfer of cryogenic fluids across tanks and other interfaces with minimal propellant losses and transfer inefficiencies (such as residual propellant, which is not transferable), and reduces risks associated with fluid leakage.

Architecture-Driven Child Gaps

1107-01	Dust-tolerant hardware components for low-loss cryogenic fluid transfer on the lunar and Martian surface
1107-02	Thermal management to maintain low boil-off rates during transfer
1107-03	Fluid management to enable efficient transfer of cryogenic fluid
1107-04*	Hardware components for repeated reuse for low-loss cryogenic fluid transfer in space

Architecture Traceability

Key Definition Tasks	Use Cases & Functions	
● Crew In-Space Return Propellant Strategy	**UC-U-501 L**	**FN-U-507 L**
● Crew Mars Ascent Propellant Strategy	**UC-U-502 L**	**FN-U-508 L**
	UC-U-728 L	**FN-U-502 L**
	UC-I-102 L	**FN-I-107 L**
	UC-T-108 M	**FN-T-210 M**
	UC-U-501 M	**FN-U-501 M**
	UC-I-102 M	**FN-I-105 M**
"✓" indicates completed definition task		

Current State of the Art

Boil-off rate in current storage solutions necessitates additional propellant mass margin of 15%-20%. In-space transfer of cryogenic fluids has not been demonstrated at scale. Fluid transfer and capillary flow experiments have been conducted aboard ISS.

Performance Targets

Moon/Mars	System that can enable low-loss cryogenic fluid transfer between spacecraft in microgravity and partial gravity environments.
Mars	In addition, increased autonomy and reliability compared to the lunar performance target.

Segments

Foundational Exploration

Sustained Lunar Evolution

Humans to Mars

Sub-Architectures

Transportation Systems

Infrastructure Support

In-Situ Sample Storage and Processing

ID No. **1201**
Rating **38**
Bin **5 of 6**

Gap Description

In-situ samples collected on the Moon and Mars will call for storage at refrigerated, frozen, and cryogenic temperatures to preserve critical science samples. Currently, a combination of active and passive cold storage is used to return samples back to Earth from the International Space Station for short durations, but Orion, for example, has no active cold storage capabilities. There is a need for long-duration storage methods and technologies to enable successful storage and return of in-situ samples.

Architecture Impacts and Benefits

Without gap closure, the impact is potential loss or degradation of critical samples. Also, depending on how the samples are preserved, this could lead to insufficient use of crew time if the samples are not stored and processed properly.

Architecture-Driven Child Gaps

1201-01	Conditioned surface sample storage and return
1201-02	High-capacity and high-efficiency cryocoolers for sample conditioning applications
1106-03*	High-efficiency cryo-coolers at 20K and 90K temperature class

Architecture Traceability

Key Definition Tasks

- MD-01 Initial Human Mars Segment Science Objective Priorities
- Science Support Platform (Mars Surface)
- Mars Sample Analysis Strategy

"✓" indicates completed definition task

Use Cases & Functions

UC-T-303 L	All FN
UC-T-304 L	All FN
UC-T-305 L	All FN
UC-T-306 L	All FN
UC-T-307 L	All FN
UC-T-302 M	All FN
UC-T-303 M	All FN

Current State of the Art	Performance Targets	
Active cold storage systems on the ISS (e.g., MERLIN, MELFI, Glacier) and active and passive cold stowage.	Moon/Mars	Enable storage of geological and biological samples at TBR temperature range for TBR duration. Refrigerated and frozen storage will be needed before cryogenic storage.
	Moon	In addition, lower end of temperature range is expected to be lower at the Moon than at Mars.
	Mars	In addition, duration of storage is expected to be longer for Martian samples compared to lunar samples.

Segments

Foundational Exploration
Sustained Lunar Evolution
Humans to Mars

Sub-Architectures

Utilization Systems

Planetary Protection Technologies for Human Exploration

ID No. **1202**
Rating **44**
Bin **5 of 6**

Gap Description

Current robotic spacecraft are assembled in various levels of clean facilities, cleaned to prevent contaminants and to meet applicable bioburden control requirements, and sterilized using heat. Once humans enter exploration systems, preventing contamination at exploration destinations at Mars becomes much more complex. Bioburden management, sample handling, and sensing/monitoring will be key components of effective planetary protection measures. In-situ technologies that can minimize crew effort and operational complexity to keep contamination prevention realistic and cost-effective will be an effective part of a successful scientific exploration campaign.

Architecture Impacts and Benefits

Without gap closure, the impacts are possible constraints on human traverse paths and destinations, which could drive design requirements necessary for compliance with applicable planetary protection protocols. Uncontrolled and unquantified release of bioburden from vehicles, space suits, and items deposited on surface could potentially pose significant contamination threats to geological and life science objectives. Planetary protection countermeasures that prevent venting may significantly impact vehicle life, spacesuit support performance, and vehicle mass.

Architecture-Driven Child Gaps

0304-02*	In-flight identification and characterization of microbes in air, in water, and on surfaces in habitable volumes
1202-01	Methods to minimize forward contamination of Mars environment at crewed exploration sites
1202-02	Mitigation of microbial growth and biofilms in spacecraft systems for planetary protection and crew health
1202-03	Onboard systems to protect crew from backward contamination of potential bioactive molecules

Architecture Traceability

Key Definition Tasks

● MD-10 Mars Forward Contamination Planetary Protection Risk Posture

● MD-11 Mars Backward Contamination Planetary Protection Risk Posture

"✓" indicates completed definition task

Use Cases & Functions

UC-M-202 M	FN-G-501 M

Current State of the Art

Pre-launch cleaning methods that enable compliance with planetary protection guidelines and protocols for robotic spacecraft provided in NPR 8715.24, NASA-STD-8719.27 and NASA-HDBK-20240016475. Life support systems and airlocks vent unfiltered gas to environment, no ability to disinfect equipment or spacesuits exiting vehicle.

Performance Targets

Mars	Ability to quantify and identify bioburden and chemicals released to environment and introduced from exterior into vehicle. Technologies to enable compliance with spacecraft protocols and guidelines.

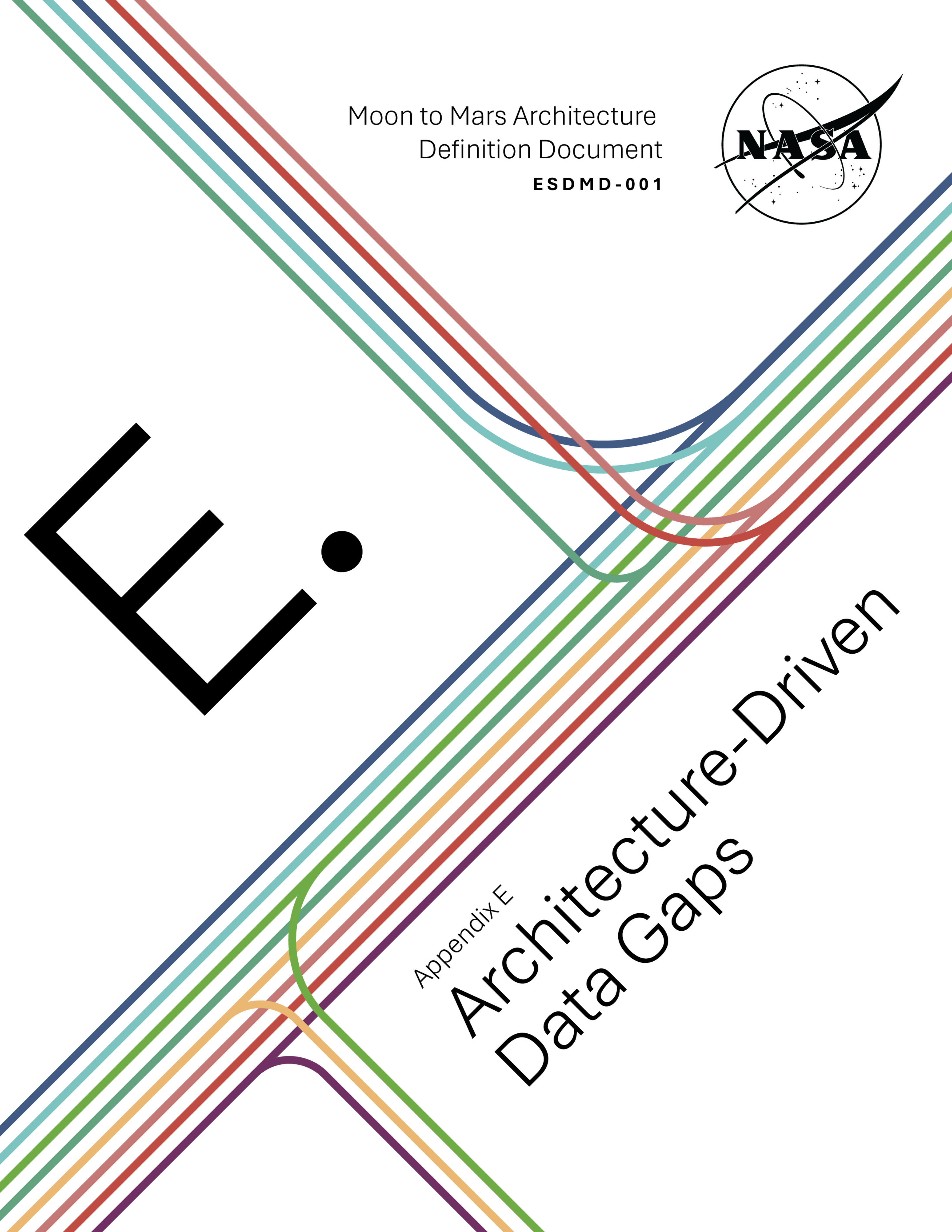
Segments

Humans to Mars

Sub-Architectures

Utilization Systems

Moon to Mars Architecture
Definition Document
ESDMD-001



E.

Appendix E

Architecture-Driven Data Gaps

Appendix E: Architecture-Driven Data Gaps

This appendix contains a set of architecture-driven data gap summary tables that capture key information, such as a description of the data gap, traceability and timing needs from the architecture, existing available data and solutions and risks, and the impact if the data is unavailable versus the benefits the data would bring. The table below defines each field.

Data Gaps listed here represent types of information desired by NASA to enable and enhance the agency's Moon to Mars Architecture. Section 3.3 provides additional details.

Data Gap Field	Definition
ID	A unique three-digit identifier
Title	Brief description of the Data Gap, including keywords/terms
Description	Clear statement of need
Need Driver	Area(s) where the data gap has the highest impact
Data Type	Category of data (e.g., orbit-to-surface imagery, in-situ measurement, etc.)
Segment	The segment during which the data is needed, but not necessarily when it is collected
Objective	Mapping of the data gap to the Moon to Mars Objectives
Target Measurement Parameters	A set of measurable goals/metrics to define the criteria for the data gap being successfully fulfilled
Current State of Data	A summary of existing data sets and capabilities, with associated risks and insufficiencies
Impacts and Benefits	A description of the architectural risk that the absence of this data incurs, as well as the benefits that the data offers

E.1 List of Data Gaps

The current list of data gaps represents a snapshot in time. Future revisions of this document will update the list as gaps close and new gaps are identified. The current list is a representative sample — it is neither comprehensive nor complete. While the current data gaps are not listed in priority order, they all represent near-term, high-priority needs.

ID	Data Gap Title
DN-001 L	Sustained, site-specific sub-meter scale imaging of lunar south pole exploration zones and sites
DN-002 L	Comprehensive, high-fidelity digital elevation map (DEM) coverage of lunar south pole exploration zones and sites
DN-003 L	High-resolution, time-resolved thermal mapping of lunar south pole exploration regions and sites
DN-004 L	Collection of imagery over lunar surface exploration sites to monitor impacts of human exploration
DN-005 L	Optical images from lunar surface at the lunar south pole
DN-006 L	Orbital observations of water ice deposits in the south polar region
DN-007 L	In situ measurements of the horizontal and vertical distribution, abundance, and physical makeup of shallow bulk water ice
DN-008 L	Geotechnical properties of highland regolith at the lunar south pole
DN-009 L	Electrostatic properties of highland regolith at the lunar south pole
DN-010 L	South polar lunar regolith elemental and mineral composition
DN-011 L	In situ lunar surface plasma environment characterization
DN-012 L	In situ lunar surface radiation environment measurements and space weather monitoring
DN-013 L	In situ measurements of the composition, distribution, and abundance of volatiles in the near-surface lunar south pole
DN-014 L	High resolution lunar rock size distribution and morphology at the lunar south pole

ID	Data Gap Title
DN-015 L	Flux and size measurements of lunar meteoroid ejecta
DN-016 L	Lunar surface seismic activity characterization and monitoring
DN-017 L	In situ measurement of particle velocity during lunar plume surface interaction (PSI) phenomena
DN-018 L	In situ measurement of landing site alteration imaging at small scale on the lunar surface
DN-019 L	In situ measurement of lunar regolith (dust) particle flux and charge
DN-001 M	Geotechnical properties of Mars regolith, rocks, and bedrock at diverse geographic locations
DN-002 M	Surface and subsurface water content at surface exploration sites
DN-003 M	Localized and predictive Mars surface weather characterization
DN-004 M	Human-scale EDL atmospheric entry environment characterization
DN-005 M	In situ measurement of particle velocity during Martian plume surface interaction (PSI) phenomena
DN-006 M	In situ measurement of landing site alteration imaging at small scale on Mars

E.2 Catalog of Data Gaps

Sustained, site-specific sub-meter scale imaging of lunar south pole exploration zones and sites

ID No.	**DN-001 L**
Objective	**LPS-01 LM, SE-05 LM, LI-03 L**
Data Type	**Orbit-to-Surface Imagery**

Gap Description

Produce optical maps or a set of optical images of the lunar south pole region that can be used to identify surface features, obstacles, and hazards across all Artemis landing regions. These maps and images should be capable of supporting landing site/ellipse design, element placement, and surface traverse planning. Multiple images of the same site should be captured at varying lighting conditions and be higher resolution than currently available.

Need Driver

Lunar Exploration Surface Site Characterization

Segment

Human Lunar Return

Target Measurement Parameters

Ensure sustained availability of high spatial resolution (<0.5 m/pixel preferred) optical imaging of lunar south pole exploration regions. Additionally, the system should have sufficiently high temporal resolution to collect imagery under varying lighting conditions enabling hazard avoidance, precision landing, and traverse planning. Images should be taken in at least 1-week intervals (every 48 hours preferred) over the course of an entire year.

Impacts and Benefits

Impacts if Data is Unavailable

Additional orbital imagery is not required to land and conduct a nominal surface mission at the lunar south pole. High resolution data collected by LROC NAC over the last 15 years is the primary data set being used to plan missions in the HLR and initial FE segment. However, additional optical imagery is desirable to inform surface element design, such as power systems, energy storage and user operating power especially for winter hibernation. Lack of continued high-resolution data could lead to Element loss due to power failure in winter, unsafe landings, or mission-ending mobility hazards. Overcompensating for uncertainty adds prohibitive mass, while underestimating risks threatens survival and operational success.

Benefits if Data is Available

Enables longer planning safer landings, optimized surface operations, and more accurate traverse planning. Improves situational awareness and hazard avoidance, increasing confidence in mission success.

Current State of Data

No additional orbital imagery is necessary to land and conduct a nominal Artemis surface mission. Data collected by the Lunar Reconnaissance Orbiter (LRO) Lunar Reconnaissance Orbiter Camera (LROC) Narrow Angle Camera (NAC) over the last 15 years is the primary data set being used to plan missions in the HLR and initial FE segment. The highest resolution panchromatic imagery of Artemis landing regions from LROC NAC is ~.5 m/pixel. NASA has the ShadowCam instrument on board the Korean Pathfinder Lunar Orbiter (KPLO) which is designed to collect high resolution images of Permanently Shadow Regions (PSRs) poles, as high as 1.7 m/pixel. However, this is only in low light locations and thus would not provide optimal imagery of a lander or surface operations in illuminated lunar regions. Additionally, JAXA Kaguya orbiter has scanned the lunar surface ~8-10m/pixel. Currently in orbit, is the Indian Space Research Organization's (ISRO) Chandrayaan-2 Orbiter High Resolution Camera (OHRC) which images the lunar surface at ~.3 m/pixel at select areas of the lunar south pole region.

Comprehensive, high-fidelity digital elevation map (DEM) coverage of lunar south pole exploration zones and sites

ID No.	**DN-002 L**
Objective	**SE-05 LM, LI-03 L, TH-03 L**
Data Type	**Remote Sensing**

Gap Description

Provide complete, higher resolution (<1m/pixel, <0.1 vertical error) DEM coverage of lunar south pole regions (84°S-90°S), with sufficient spatial and temporal resolution to support hazard avoidance, illumination modeling, landing ellipse definition, and traverse planning.

Need Driver

Lunar Exploration Surface Site Characterization

Segment

Human Lunar Return

Target Measurement Parameters

The topographic products should be gridded at < 1m/pixel with less than 0.1 height error.

Impacts and Benefits

Impacts if Data is Unavailable

Additional elevation map coverage is not required to land and conduct a nominal surface mission at the lunar south pole. High resolution data collected by LRO over the last 15 years is the primary data set being used to plan missions in the HLR and initial FE segment. However, additional elevation map coverage is desirable to inform surface element design, such as power systems, energy storage and user operating power especially for winter hibernation. Lack of accurate data could lead to Element loss due to power failure in winter, unsafe landings, or mission-ending mobility hazards. Overcompensating for uncertainty adds prohibitive mass, while underestimating risks threatens survival and operational success. While south pole new crater impacts are not a concern, continued altimeter measurements to guarantee no changes that could impact safe landing and traverse planning. The concern increases as go equatorial.

Benefits if Data is Available

Enables safer landings, optimized surface operations, and more accurate traverse planning. Improves situational awareness and hazard avoidance, increasing confidence in mission success. With the proposed DEM resolutions, we will gain significant situational awareness, reduce risk by enabling navigation and hazard avoidance with respect to known DEMs, can plan more optimal landing and EVA scenarios, and increase confidence in ability to meet mission objectives. A prior acquisition of high resolution, low height error surface elevation data enables the ability to predict the illumination over challenging winter periods of the year which will put the Element energy storage to its limit. Underestimating the energy storage required duration could result in Element loss.

Current State of Data

Lunar topographic data comes predominantly from LRO's Lunar Orbiter Laser Altimeter (LOLA). LOLA DEMs have been generated at multiple resolutions and have been used in the development of Terrain Referenced Navigation (TRN) algorithms. LOLA-derived DEMs are limited to some extent by the frequency of individual altimeter measurements, which when gridded require interpolation, and contain a level of uncertainty. For mission planning purposes at select locations, higher resolution LOLA DEMs are supplemented by other topographic products such as Stereo and Shape from Shading models which range from ~1 – 2 m/pixel in spatial resolution. Such image-based topographic products generally have denser coverage than the LOLA products. However, such products may contain interpolation in shadowed areas when there isn't a corresponding altimeter observation. As LRO's orbit altitude continues to increase and its inclination decreases, additional NAC imagery of polar sites will be increasingly difficult. Topographic products from KPLO ShadowCam images are expected to be released publicly in the near-future and will provide independent topographic data in permanently shadowed regions.

High-resolution, time-resolved thermal mapping of lunar south pole exploration regions and sites

ID No. **DN-003 L**
Objective **SE-05 LM, AS-01 LM, TH-03 L**
Data Type **Remote Sensing**

Gap Description

Capture multispectral thermal imagery to determine surface temperature profiles of lunar south pole areas of interest. Areas should be imaged multiple times to track how surface temperature changes with time and illumination conditions. Resolution should be improved compared to currently available data. High resolution thermal maps are needed over all Artemis regions for design of element thermal control systems and power systems (including power cables).

Need Driver

Lunar Exploration Surface Site Characterization

Segment

Human Lunar Return

Target Measurement Parameters

Acquire higher resolution (<50m, <30m preferred) thermal imaging of lunar south pole exploration regions to resolve PSR temperatures, diurnal/seasonal cycles, and surface heat fluxes at the scale needed for element thermal design and traverse planning.

Impacts and Benefits

Impacts if Data is Unavailable

Present model surface and temporal resolution could be enhanced to mitigate risks to long term emplacements required to survive yearly thermal cycles.

Benefits if Data is Available

A prior acquisition of higher-resolution thermal maps (surface heat fluxes and temperatures) and the ability to predict the required thermal design requirements over the entire year's summer and winter cycles. Such information will permit proper thermal and power system design to assure continuity of services. Such data can be used in selection of hibernation sites, lander sites/ellipses and mobility traverses.

Current State of Data

Currently available thermal imagery is sourced from the LRO Diviner Lunar Radiometer Experiment. Diviner data has been used to create a variety of temperature maps including maximum temperature anomaly (global), minimum temperature anomaly (global), south polar thermal maps, and north polar thermal maps. Cylindrical maps are provided at resolutions of 128, 64, 16, 4, and 1 pixel/degree (PPD) and polar stereographic maps are provided at a single resolution of 126.347 PPD (map scale of 240 m/pixel). Data is constrained to brightness temperature values between 10 to 450 K (anything outside that range is considered "bad" data). LRO has the state of the art of data in terms of thermal maps. This data is limited due to 240m/pixel and a coarse temporal frequency of 2 hour for some locations to 2 weeks.

Collection of imagery over lunar surface exploration sites to monitor impacts of human exploration

ID No.	**DN-004 L**
Objective	**SE-05 LM, TH-03 L**
Data Type	**Orbit-to-Surface Monitoring**

Gap Description

Capture optical imagery of Artemis missions in progress on the surface of the lunar south pole. This imagery should be capable of monitoring surface elements and mission activities. Image resolution should be sufficient to determine the status of landed elements and observe how human activities alter the natural lunar surface environment.

Need Driver

Lunar Exploration Surface Site Characterization

Segment

Human Lunar Return

Target Measurement Parameters

Capability to quickly capture, produce, and provide optical images of specific locations on the lunar surface with a resolution of <1 m/pixel (<0.5 m/pixel preferred) sufficient to determine the status of surface elements and characterize the disruption to the natural environment caused by landers and surface traverses.

Impacts and Benefits

Impacts if Data is Unavailable

Imagery is required to demonstrate a successful landing. Without timely imagery of <1 m/pixel resolution, there may be difficulty locating a lost asset or determining a cause of failure. Potential inability to image the active landing site in a contingency scenario. Lack of timely orbital imagery of Artemis missions may have national posture implications.

Benefits if Data is Available

Increased understanding and situational awareness of in-mission risk and status of elements for subsequent operations. Increased understanding of anthropogenic impacts/disruptions on lunar environments, allowing for informed considerations on site preservation. Orbital imagery during the mission provides additional situational awareness and enables contingency capability in off-nominal scenarios. Timely and repeated orbital imagery enables contingency analysis, locating lost or non-communicating assets and determination of position and orientation, evidence of soft landing, and the capability to evaluate how exploration activities alter the lunar surface.

Current State of Data

No existing available data as the missions are not in operation yet. However, LRO may be able to capture optical imagery of the Artemis missions with sufficient resolution to monitor large scale surface elements and mission activities at a regular cadence. While NASA has past orbital assets that have collected imagery of the lunar surface (e.g., Clementine, Lunar Orbiters 1-5), the resolution of those images is far less than that of LRO (~30 m/pixel for Clementine and ~60 m/pixel for Lunar Orbiter). Currently, NASA has the ShadowCam instrument on the Korean Pathfinder Lunar Orbiter (KPLO) which can take high resolution images of the poles, as high as 1.7 m/pixel; however, this is only in low light location and thus would not provide optimal imagery of a lander or surface operations in illuminated lunar regions.

Optical images from lunar surface at the lunar south pole

ID No. **DN-005 L**
Objective **SE-05 LM**
Data Type **Surface-to-Surface Imagery**

Gap Description

Take a series of panoramic images from the surface of the lunar south pole at potential Artemis landing regions to determine real lighting conditions. Images should be coupled with accurate positional data in order to compare with expected illumination conditions based on orbital data and enable in situ surface feature information for traverse planning, hazard identification and illumination impact predictions.

Need Driver

Lunar Exploration Surface Site Characterization

Segment

Human Lunar Return

Target Measurement Parameters

Take a number of images sufficient to ascertain surface lighting conditions/levels at different locations and times at the lunar south pole. High-resolution images should cover 360 degrees and overlap to enable 3D object information to be obtained. Need at all relevant locations, possibly many for mobility assets.

Impacts and Benefits

Impacts if Data is Unavailable

Increased uncertainty in detailed illumination conditions at particular locations at South Pole can lead to inaccurate expectations for solar-based power systems and potentially lead to insufficient power for surface systems. In addition, uncertainties in illumination profile can cause difficulties in traversing and a lack of situational awareness for astronauts on EVA reliant on vision and observable landmarks.

Benefits if Data is Available

Increased confidence in selection of site to allow for sufficient power generation. Increased confidence in expected illumination profile during surface EVAs. Help in real time traverse planning and hazard avoidance. Allow science experts to identify targets for traverse planning. Additional advantage to incapacitated crew rescue traverse planning and landmark identification.

Current State of Data

Multiple CLPS providers have taken images from the surface. NASA’s Lunar Reconnaissance Orbiter has collected, to date, over 70000 meter-scale images of the South Pole of Earth’s Moon that can be used to validate illumination models at the meter scale for specific illumination conditions.

Any previously modeled panoramic or framing camera which can be slewed on the surface can achieve these objectives at specific sites on the lunar surface. However, panoramic images from the surface have not been acquired at a potential Artemis mission location.

Orbital observations of water ice deposits in the south polar region

ID No.	**DN-006 L**
Objective	**AS-03 LM, LI-07 L, OP-03 LM**
Data Type	**Remote Sensing**

Gap Description

Measure the horizontal distribution and abundance of water ice at a regional scale at the lunar south pole. Spatial resolution should be sufficient to resolve permanently shadowed craters.

Need Driver

Lunar Resource Exploration

Segment

Foundational Exploration

Target Measurement Parameters

Water spatial resolution of <10 km (<5 km preferred) to a depth of 1 m, coverage <15° from poles, sensitivity at least 1 wt%.

Impacts and Benefits

Impacts if Data is Unavailable

Knowledge of water distribution and abundance will be constrained to limited existing data sets which do not sufficiently identify potential water ice reserve sites for potential utilization.

Benefits if Data is Available

Orbital measurements typically have larger coverage area than expected mobility ranges of landed missions and can be used with ground measurements to create a predictive model to locate potential water reserve sites.

Current State of Data

There are four existing orbital data sets that indicate the presence of shallow bulk water on the lunar surface: LCROSS, Chandrayaan-1, LRO, and Lunar Prospector. There are more data sets for surface frost detection; however, while surface frost may be a geologic indicator of deeper water, there is currently no strong correlation between the two types of data sets. Water equivalent hydrogen (WEH), inferred from neutron spectroscopy, cannot give accurate concentration or depth distribution data. Neutron flux indicates there is hydrogen somewhere between the surface layer down to about 80 cm to 100 cm. Resolutions from current data sets are insufficient to characterize bulk water ice concentrations for the purpose of resource utilization.

In situ measurements of the horizontal and vertical distribution, abundance, and physical makeup of shallow bulk water ice

ID No.	**DN-007 L**
Objective	**AS-03 LM, LI-07 L, OP-03 LM**
Data Type	**In Situ Measurement**

Gap Description

Measure the vertical and horizontal distribution and abundance of shallow bulk water as a function of depth in shadowed regions of the lunar south pole. Identify the physical makeup of the shallow water ice (i.e., granular vs. consolidated sheets). A series of direct, ground-based measurements should be taken at several different locations to support resource exploration on the lunar surface. This data gained over a limited area should be matched with orbital data to identify water-favorable sites at regional scales.

Need Driver	Segment
Lunar Resource Exploration	Foundational Exploration

Target Measurement Parameters

Water ice abundance with vertical resolution <20 cm depth intervals to 1 m depth, at least 50 m horizontal resolution (distance between sample sites), with a 1 wt% water ice abundance detection limit.

Impacts and Benefits

Impacts if Data is Unavailable

Knowledge of water ice distribution and abundance is a critical input for both ISRU system design and architecture analysis and identifying potential water reserve sites. Without data, we will be unable to understand the abundance and accessibility of bulk water ice at the south pole. Therefore, we will be unable to take advantage of in-situ water during lunar surface missions which increases uncertainty of water collection and extraction methods.

Benefits if Data is Available

With direct, ground-based data covering a sufficient area and matched to orbital measurements, a predictive 'water favorability' model can be developed, generating a map of potential water concentrations and distributions at other locations. This is critical to the selection of favorable ISRU surface sites which can inform both ISRU systems and surface exploration activities.

Current State of Data

There are no ground truth measurements that characterize shallow bulk water ice on the lunar surface.

Geotechnical properties of highland regolith at the lunar south pole

ID No.	**DN-008 L**
Objective	**AS-01 LM, LI-07 L, LI-08 L, TH-03 L, OP-05 LM**
Data Type	**In Situ Measurement/Sample Return**

Gap Description

Characterize lunar regolith physical and mechanical properties as a function of depth (min depth extent: 1 meter), area, and terrain slope/features, to understand South Pole properties and their variability. These measurements should be taken over multiple locations at the lunar south pole at locations representative of landing and exploration sites.

Need Driver

Lunar Surface Natural Environment Characterization

Segment

Human Lunar Return

Target Measurement Parameters

Particle size distribution (<10μm), particle morphology and density, other geotechnical properties including but not limited to porosity, permeability, bulk density, bearing capacity, cohesion. "Fine fraction" of particle size distribution (particles < ~50 microns), variation with depth up to ~3 m.

Impacts and Benefits

Impacts if Data is Unavailable

Limitations in in-situ regolith sampling and characterization increase uncertainty to, analyses for interactions between footpads and regolith, rocket engine blast effects (erosion and ejection of material), etc. Limited datasets of lunar samples result in uncertainty about the stability and behavior of the lunar surface. This is particularly true for the South Pole, as we have no samples from this region and properties may differ from previous equatorial mission sites (i.e., particle size, porosity). Insufficient characterization of regolith geotechnical properties can potentially lead to instability of spacecraft on the lunar surface and lack of soil integrity.

Benefits if Data is Available

Increased confidence/decreased uncertainty in landing, plume-surface interaction, and trafficability analyses, which may increase flexibility/allow more areas and terrain to be considered for mission operations. For example, better constraints on slope stability could arise from regolith strength measurements. Data can be used to predict structural behavior of lunar vehicles and structures as the architecture evolves. The geotechnical stability of landing vehicles can be better estimated/calculated, which will inform assessments regarding the structural integrity and capacity of lunar regolith when vehicles have landed on the lunar surface.

Current State of Data

Geotechnical property values in M2M Design Specification for Natural Environments (DSNE) rely on historical archive of Apollo results and estimates from analyses of orbital imagery or modelling. Variance in these values spatially, with terrain type, and with depth is not well constrained.

Electrostatic properties of highland regolith at the lunar south pole

ID No.	**DN-009 L**
Objective	**AS-01 LM, LI-07 L, LI-08 L, TH-03 L, OP-05 LM**
Data Type	**In Situ Measurement**

Gap Description

Measure the state of the electrostatic charging level of granular materials. Electrostatic properties refer to the charge state of regolith at a given instance in time which is heavily dependent on the induced environment as well as the natural environment. Note that some electrostatic properties are intrinsic to the materials while others are not. Any disturbance of the regolith greatly affects the charge state. There are several types of electrostatics properties of interest including chargeability, volume and surface resistivity, and charge decay.

Need Driver

Lunar Surface Natural Environment Characterization

Segment

Human Lunar Return

Target Measurement Parameters

Measure several electrostatic properties of regolith such as chargeability, volume and surface resistivity, charge decay.

Impacts and Benefits

Impacts if Data is Unavailable

Limitations in understanding of electrostatic properties can negatively impact effective design and employment of dust mitigation strategies and capabilities. Electrostatics is one of the primary mechanisms in which lunar dust adheres to surfaces. Without a detailed understanding of such properties and how external systems and factors may induce charge; dust can become a significant risk to surface elements and crew.

Benefits if Data is Available

Increased confidence in development and performance of dust mitigation capabilities and better understanding of expected impacts on surface operations. Can help better plan mission operations that avoid accumulation of dust. Provide better understanding of potential near-surface natural dust transport/lofting.

Current State of Data

Regolith electrical property values in M2M Design Specification for Natural Environments (DSNE) rely on limited Apollo data and estimates from analyses of orbital imagery or modelling. Variance in these values spatially and with terrain type is not well constrained.

South polar lunar regolith elemental and mineral composition

ID No.	**DN-010 L**
Objective	**LPS-01 LM, LI-07 L, LI-08 L**
Data Type	**In Situ Measurement/Sample Return**

Gap Description

Characterize site-specific and depth-resolved mineralogical and elemental composition of lunar south pole regolith and rocks to support ISRU, geotechnical assessment and contamination mitigation. A series of in situ measurements across the exploration area should be taken to support lunar environment characterization and resource exploration.

Need Driver

Lunar Surface Natural Environment Characterization

Segment

Human Lunar Return

Target Measurement Parameters

Elemental and mineral composition of bulk rocks and mineral grains where possible, as well as relative abundances of regolith constituent components (to resolution of 0.1 wt%) over various locations and with depth.

Impacts and Benefits

Impacts if Data is Unavailable

Limited in situ mineralogical composition data exists for the lunar south pole. While mineralogy is not expected to greatly vary from orbital observations and in situ Apollo samples, variation may exist that could increase uncertainty in the landing site environment. Aspects tied to mineral hardness/density could impact terrain stability, composition could impact contamination/science integrity, and metal content may impact electrostatic interactions. Further, without mineralogical surveying, effective ISRU for critical minerals/metals would be limited. Inability to accurately anticipate or predict chemical reactions between elements or compounds in the lunar regolith and surfaces or environments.

Benefits if Data is Available

A better understanding of the typical lunar surface composition at the south pole would enable tighter constraints on regolith properties and critical mineral abundances. Having a standardized dataset of regolith composition could also help minimize the effect of contamination on science sites. Will inform material selection to prevent or mitigate chemical reactivity effects between regolith and surface assets.

Current State of Data

Apollo-era returned samples and lunar meteorites are the primary in-situ data set (predominantly mare terrain and equatorial), with orbital spectral data (e.g., Clementine, LRO, Lunar Prospector, Kaguya, Chandrayaan-1) at a km-scale resolution.

In situ lunar surface plasma environment characterization

ID No.	**DN-011 L**
Objective	**HS-03 LM, AS-01 LM, TH-03 L**
Data Type	**In Situ Measurement**

Gap Description

Measure the plasma environment at the lunar south pole, including observations in the terminator region, permanently shadowed regions (PSRs), and in sunlit and shaded areas influenced by topography and spacecraft-induced wakes. Long-term measurements are needed to capture variations when the Moon is exposed to the solar wind, within Earth's magnetotail, and during dynamic space weather conditions. These observations should also include measurements of electric potential on both the spacecraft and the lunar surface.

Need Driver	Segment
Lunar Surface Natural Environment Characterization	Human Lunar Return

Target Measurement Parameters

Measure plasma electron and ion density and energy (0-30keV), secondary populations (secondary electron emission and photoemission), and spacecraft and lunar surface electric potential. Provide data in a format that allows comparison with other orbit-based plasma measurements and future measurements.

Impacts and Benefits

Impacts if Data is Unavailable

Data used to validate the environment definitions in the M2M Design Specification for Natural Environments (DSNE). Plasma environment definitions are used to assess the risk of electrostatic discharge resulting from interactions between the plasma environment and surfaces. These data also support modeling of the dust environment and triboelectric charging analyses.

Benefits if Data is Available

Validated lunar surface plasma environments ensure accurate inputs to spacecraft charging assessments, which are critical for identifying and mitigating electrostatic discharge risk. Electrostatic discharges can interfere with communications, damage avionics, and introduce shock hazards to astronauts, making reliable environment definitions critical for mission safety and success.

Current State of Data

Current estimates of the lunar plasma environment are from orbital satellite data, modeling, and limited in-situ surface measurements with temporal and spatial limitations.

In situ lunar surface radiation environment measurements and space weather monitoring

ID No.	**DN-012 L**
Objective	**HS-01 LM, AS-01 LM, TH-03 L, LI-09 L**
Data Type	**In Situ Monitoring**

Gap Description

Measure the radiation environment on the lunar surface at the south pole. Measurements should include flux and energy spectra of electrons, protons, and heavy-ions from solar particle events and galactic cosmic rays, and secondary or albedo neutrons generated by interactions of energetic particles with the lunar regolith. Neutron spectrum measurements inside a lunar lander or habitat or on the surface of the moon are needed to validate models used in the assessment crew radiation exposure. Long-term measurements are needed to capture variations when the Moon is exposed to the solar wind, within Earth's magnetotail, and during dynamic space weather conditions.

Need Driver

Lunar Surface Natural Environment Characterization

Segment

Human Lunar Return

Target Measurement Parameters

Measure neutron flux spectrum up to at least 100 MeV. Measure charged particle (electron, proton, heavy- ion) flux and energy spectra at the same time.

Impacts and Benefits

Impacts if Data is Unavailable

Data enables accurate characterization of the average and extreme radiation environments encountered by crew and surface systems. Neutrons produced in the Lunar regolith may contribute as much as ~30% of effective dose incurred by crew on surface missions, but models used to predict this environment have not been validated with surface measurements.

Benefits if Data is Available

Long-term, in-situ radiation environment monitoring will improve the fidelity of radiation exposure assessments. Measurement data will be used to quantify the uncertainty in models that predict neutron environments, an important part of the crew exposure assessment and risk prediction process. Additionally, extending the neutron spectral measurements over longer periods of time may also contribute to several Moon to Mars science objectives.

Current State of Data

Current estimates of the lunar radiation environment are from orbital satellite data, modeling, and limited in-situ surface measurements with temporal and spatial limitations. A limited number of neutron flux measurements have been made on the Lunar surface or by devices in Lunar orbit, but the energy range for these measurements did not exceed 20 MeV. Neutron flux spectrum measurements have also been made on ISS, during Mars transit, and on the surface of Mars, but the energy range for these measurements was also limited to neutrons below 20 MeV. Models that have not been validated with space measurements for neutrons greater than 20 MeV are currently used to predict crew radiation exposure. The energy region between 1 MeV – 1 GeV accounts for most of the neutron induced cancer risk, and validation of model calculations over just the low energy region provides little information on model accuracy at higher energies, because the physical processes producing higher energy particles differ from those producing lower energy particles.

In situ measurements of the composition, distribution, and abundance of volatiles in the near-surface lunar south pole

ID No. **DN-013 L**
Objective **LPS-03 LM, AS-01 LM, TH-03 L**
Data Type **In Situ Measurement**

Gap Description	Need Driver	Segment
Measure the distribution, abundance, and composition of other ices/volatiles that may exist at the lunar south pole both within and outside of permanently shadowed regions to better understand the population of gases that may become volatilized/released during Artemis activities. As concentrations are likely too low to be detected from orbit, a series of direct, ground-based measurements should be taken at several different locations. Data should be taken within and nearby PSRs as different species have variable stability temperatures.	**Lunar Surface Natural Environment Characterization**	Human Lunar Return

Target Measurement Parameters

Volatile abundance to at least 1 m depth, with a 0.1 wt% detection limit. Abundance at greater depth may have relevance to rocket landing effects.

Impacts and Benefits

Impacts if Data is Unavailable

While the Moon is typically thought of as "dry," there is evidence that volatiles (in addition to water) exist in the lunar regolith, especially at the south pole. There have been no firm detections in situ; as such, the nature and distribution of these volatiles is unknown and could potentially pose a hazard to surface operations. The release of potentially corrosive or toxic gases could occur via heating when landing or sublimation during operations (EVA/rover). Further, the presence of these volatiles could impact regolith geotechnical properties like cohesion or stability when disturbed, which poses a threat to large landers.

Benefits if Data is Available

The type, abundance, and distribution of volatiles within the near-surface environments of the lunar south pole would greatly improve our understanding of their impacts on terrain stability and contamination potential.

Current State of Data

No community agreement on concentrations of lunar volatiles at the lunar south pole just below the surface.

High resolution lunar rock size distribution and morphology at the lunar south pole

ID No.	**DN-014 L**
Objective	**SE-05 LM, LI-06 L, TH-03 L, OP-05 LM**
Data Type	**In Situ Measurement**

Gap Description	Need Driver	Segment
Constrain the size-frequency distribution and shape of lunar rocks/regolith that exist below the resolution of existing imagery (sub-meter scale) at the south pole to better understand the lunar surface environment as it pertains to lunar surface activities. Activities could include survey instruments/cameras of surrounding terrain to capture areal rock distributions as well as sampling instruments of the regolith.	**Lunar Surface Natural Environment Characterization**	Human Lunar Return

Target Measurement Parameters

Measurements of particle sizes and frequencies from length scales > 10 um to 1 m not via discrete bins or sieve sizes, but measurements capable of detecting all unique sizes, shapes, and aspect ratios in this range. Understand how these distributions change with depth/spatially.

Impacts and Benefits

Impacts if Data is Unavailable

The population of sub-meter scale rocks poses a hazard to landers and rovers, especially during landing phases which require precise navigational inputs to prevent tip-over. Incomplete datasets about morphology and size of regolith/rocks poses a risk to understanding how and where to safely operate surface assets.

Benefits if Data is Available

In-situ surveys of surface regolith/rocks would provide valuable data on the distribution and abundance of sub-meter scale rocks that would allow for refined size-frequency models. Improved models could impact landing site selection and traverse paths.

Current State of Data

Surface images from Surveyor, Apollo, Lunokhod, and Chang'e missions have been used to derive quantitative estimates of rock abundance on the surface of the Moon at multiple locations. Orbital instruments can unambiguously detect rocks of 1m or greater; depending on the height of the feature in question, submeter detection may be possible.

Flux and size measurements of lunar meteoroid ejecta

ID No.	**DN-015 L**
Objective	**AS-01 LM, LI-09 L, TH-03 L**
Data Type	**In Situ Measurement**

Gap Description

Measure the mass and velocity range of particles ejected via impact processes from primary meteoroids on the lunar surface. Continuous measurements should be taken at the lunar south pole to evaluate the risk these particles pose to human exploration activities.

Need Driver

Lunar Surface Natural Environment Characterization

Segment

Human Lunar Return

Target Measurement Parameters

Measure ejecta particle speed (from 0.1-4.8 km/s), mass (10-6 - 102 g), direction, and frequency.

Impacts and Benefits

Impacts if Data is Unavailable

Potential damage to landers, rovers, habitats, suits, etc. from unaccounted for ejecta fluxes. Primary meteoroids may directly damage surfaces assets, but the associated ejected material will be more abundant (though at lower velocities).

Benefits if Data is Available

While this data has been modelled, in-situ measurements will help constraint the actual ejecta environment to better assess the risk these projectiles pose to surface assets. The mass/speed distribution may also differ at the South Pole compared to the equator due to different impactor populations, so having datasets for the lunar south pole would be invaluable.

Current State of Data

An Apollo-era detector (LEAM) was flown to measure this for very small particles but did not conclusively detect impacts.

Lunar surface seismic activity characterization and monitoring

ID No.	**DN-016 L**
Objective	**AS-01 LM, LI-09 L, TH-03 L**
Data Type	**In Situ Measurement**

Gap Description

Establish a baseline of seismic events in the polar region for design of structural elements, EVA operations, and lander systems. While this includes continuous monitoring of moonquakes, it also includes events such as incoming meteoroids and spent stages of rockets. These types of event monitoring provide real time feedback to Artemis Elements to enable emergency and survival operations of Elements and crew.

Need Driver	Segment
Lunar Surface Natural Environment Characterization	Human Lunar Return

Target Measurement Parameters

Measure magnitude and frequency of seismic events at multiple locations in the lunar south pole region.

Impacts and Benefits

Impacts if Data is Unavailable

Lack of this seismic data means risk due to seismic events must be accepted. The south polar region has young, active thrust faults. One of the strongest shallow moonquakes ever recorded by the Apollo network was a magnitude 5.5 moonquake in the south polar region. This is equivalent to moderate to strong ground shaking over 40 kilometers.

Benefits if Data is Available

Acquisition of this data prior to Element design help to create more resilient and robust designs to last long lifetimes. Real-time data can be used to enhance Element survivability and crew safety.

Current State of Data

The Apollo Passive Seismic Network of 5 experiments set up across the lunar surface operated from 1969-1977 to gather seismic data. Re-analysis of data has shown over 35,000 moonquakes.

In situ measurement of particle velocity during lunar plume surface interaction (PSI) phenomena

ID No.	**DN-017 L**
Objective	**SE-07 LM, LI-05 L, TH-03 L**
Data Type	**In Situ Measurement**

Gap Description

Characterize the lunar regolith ejected by rocket exhaust plumes interacting with the lunar surface at different sites and under different plume conditions (i.e. lander types). During final descent and landing, material may be lofted toward the landing vehicle and/or ejected away. As material leaves the influence of the exhaust plume, and given the lack of a substantial lunar atmosphere, it will travel on a trajectory dictated by those initial conditions.

Need Driver

Lunar Surface Induced Environment Characterization

Segment

Human Lunar Return

Target Measurement Parameters

Regolith particle sizes, speeds, and angles of ejection caused by rocket exhaust interacting with the lunar regolith.

Impacts and Benefits

Impacts if Data is Unavailable

Increased uncertainty in risk to landing vehicle and surrounding assets caused by debris strike or the "sandblasting", abrasive effects of ejected material. Increased uncertainty to scientific operations near the landing site, as the probability of surface alteration caused by ejected material may not be well constrained. Inability to determine PSI effects during landing and ascent events, including vehicle and hardware lunar dust loading. Inability to predict visibility expectations for spacecraft during ascent and landing. Inability to determine effectiveness of radar and range finding hardware, particularly those used during landing and ascent events.

Benefits if Data is Available

Understanding and characterization of this will translate to vehicle hardware which is better designed to withstand the effects of PSI during ascent and landing events and mitigate the risk of damage to this hardware. Increased confidence in ejecta hazard analyses that affect the landing vehicle and nearby assets. Tighter design constraints for protection from hazards/operating conditions. Better understanding of induce landing environment to inform lunar surface science goals.

Current State of Data

Modeling reports for preliminary site comparisons have been generated using regolith data gathered during Apollo coupled with engine performance data. Plume surface interaction is a complex phenomenon, and current estimates are insufficient to accurately predict the behavior of regolith and its effects on vehicle performance.

SCALPSS instrument suite successfully captured stereo imagery during Blue Ghost's final descent and soft landing. Similar imaging suites could be used to provide comparative data for different lander configurations and lunar terrain types.

In situ measurement of landing site alteration imaging at small scale on the lunar surface

ID No. **DN-018 L**
Objective **SE-07 LM, LI-05 L, TH-03 L**
Data Type **In Situ Measurement**

Gap Description	Need Driver	Segment
Characterize the landing site alteration caused by rocket exhaust plumes interacting with the lunar surface at different sites and under different plume conditions (i.e. lander types). During final descent and landing, rocket exhaust may erode material which changes surface topography or alters surface properties. This has the potential to create a hazardous landing environment or affect scientific outcomes.	**Lunar Surface Induced Environment Characterization**	Human Lunar Return

Target Measurement Parameters

Measurement of landing site topography before, during, and after vehicle plume-surface interactions at the cm-m scale. Measurement of regolith geotechnical properties in the affected area. Measurement of chemical contamination of the affected area.

Impacts and Benefits

Impacts if Data is Unavailable

Increased uncertainty in risk to landing vehicle caused by surface alteration. Increased uncertainty to scientific operations near the landing site if regolith alteration or contamination is not well understood. Inability to level the spacecraft properly due to lack of understanding of the terrain could lead to loss of crew, loss of vehicle and loss of mission (or combinations thereof). Inability to properly account for terrain topography in ascent and descent scenarios can potentially complicate abort response, potentially leading to loss of crew, loss of mission and loss of vehicle.

Benefits if Data is Available

Increased confidence in analyses of surface alteration during final descent and landing. Informs vehicle design and operational mitigations. Informs scientific community regarding experiment placement and operations. Enhancement of vehicle preparedness for ascent and landing, increased ability of lunar rovers to traverse varied lunar terrain, determination of abort scenarios during ascent and landing. Understanding of the terrain also contributes to better response to terrain conditions through modifications to leveling hardware for lunar landers.

Current State of Data

Modeling reports for preliminary site comparisons have been generated using regolith data gathered during Apollo coupled with engine performance data. Plume surface interaction is a complex phenomenon, and current estimates are insufficient to accurately predict the behavior of regolith and its effects on vehicle performance. Currently available topographic data comes predominantly from LRO's LOLA instrument. Localized mosaic DEMs are available at as low as 5 m/pixel ins resolution. Higher resolution DEMs can be made using shape-from-shading (SfS, or photoclinometry) image processing, where several high-resolution NAC images taken at various times lighting conditions) are used to create higher resolution DEMs over smaller areas. The resolution of these DEMs is dependent on the resolution of the available NAC images.

Alternative solutions include cameras on landing and return vehicles, which can monitor landing site alterations induced by PSI during descent/ascent. Orbital imagery may be able to achieve desired resolution with high performance instrumentation and appropriate orbital configuration on a new mission.

In situ measurement of lunar regolith (dust) particle flux and charge

ID No.	**DN-019 L**
Objective	**AS-01 LM, TH-03 L**
Data Type	**In Situ Measurement**

Gap Description	Need Driver	Segment
Measure the electric charge and flux of regolith (dust) particles impacting spacecraft surfaces in the lunar south pole region. Measurements over long durations and during dynamic events, such as PSI, are needed to characterize the variability of lunar dust accumulation and electrostatic charging on vehicles and assets, including EVA suits.	**Lunar Surface Induced Environment Characterization**	Human Lunar Return

Target Measurement Parameters

Measure electric charge of individual regolith particles upon impact and the flux of dust particles over time with a temporal resolution sufficient to capture transient events such as PSI.

Impacts and Benefits

Impacts if Data is Unavailable

The absence of in-situ measurements introduces uncertainty in predicting dust accumulation and its effects on spacecraft systems, including its contribution to spacecraft charging and electrostatic discharge. This uncertainty limits the effectiveness of dust mitigation strategies and increases the risk to crewed and robotic assets operating in dusty environments.

Benefits if Data is Available

Measurements enable the development and validation of models for dust charging, transport, and surface accumulation. These models will inform the design of spacecraft materials and systems that are more resilient to dust-related effects. Additionally, the data will support the refinement of operational procedures and risk assessments for surface missions, enhancing mission safety and longevity.

Current State of Data

Current estimates are from modeling, ground testing, and limited in-situ surface measurements with temporal and spatial limitations.

Geotechnical properties of Mars regolith, rocks, and bedrock at diverse geographic locations

ID No.	**DN-001 M**
Objective	**MI-04 M, TH-06 M, TH-07 M, OP-05 LM**
Data Type	**In Situ Measurement**

Gap Description	Need Driver	Segment
Characterize Martian regolith physical and mechanical properties as a function of depth (min depth extent: 1 meter), area, and terrain slope/features, to understand regolith properties and their variability across distinct regions. Characterize the rock and bedrock physical and mechanical properties, fracturing, and suitability for landing across distinct regions.	**Mars Surface Natural Environment Characterization**	Humans to Mars

Target Measurement Parameters

Particle and rock size distribution, particle morphology and density, bulk rock density, bedrock spatial fracture frequency, size, and depth, other geotechnical properties including but not limited to porosity, permeability, bulk density, bearing capacity, cohesion. "Fine fraction" of particle size distribution (particles < ~50 microns), variation with depth up to ~3 m. These properties may differ from location to location.

Impacts and Benefits

Impacts if Data is Unavailable

Limitations in in-situ regolith sampling and characterization increase uncertainty to, for example, analyses for interactions between footpads and regolith, rocket engine blast effects (erosion and ejection of material), etc. Limited datasets and lack of Mars regolith samples result in uncertainty about the stability and behavior of the Martian surface when interacting with a rocket plume. Uncertainty in environmental parameters leads to needing increased robustness, and thus mass, for surface assets.

Benefits if Data is Available

Increased confidence in landing, plume-surface interaction, and trafficability analyses, which may increase flexibility and allow more areas and terrain to be considered for mission operations. Constraining the geotechnical characteristics of Martian surface materials, will decrease uncertainty in the landed environment, influencing both the robustness of the landers and areas available for exploration. For example, better constraints on slope stability could arise from regolith strength measurements.

Current State of Data

Rock, regolith and dust properties, as well as rock abrasion data sets, gathered from on-board rover tools and scientific instruments. Rock and regolith properties were estimated from thermal emission spectroscopy data aboard Mars Reconnaissance Orbiter. Potential data from images of rover tracks to determine bearing capacity and compaction properties. Limited data exists on particle size distribution on the surface of Mars. Dust properties from lander observations.

Surface and subsurface water content at surface exploration sites

ID No.	**DN-002 M**
Objective	**TH-06 M, TH-07 M**
Data Type	**In Situ Measurement**

Gap Description

Characterize the spatial and depth variability of near-surface water content at geographically diverse sites – including seasonal variations to enable reliable predictions of site-specific conditions. Water sources could include ice deposits and hydrated minerals.

Need Driver

Mars Surface Natural Environment Characterization

Segment

Humans to Mars

Target Measurement Parameters

Measure the relative concentration and spatial extent of water in the form of hydrated minerals and subsurface ice at the surface and near-surface of geographically diverse sites. Measure potential seasonal variation in water concentrations at potential surface exploration sites.

Impacts and Benefits

Impacts if Data is Unavailable

Hydrated minerals or ice could vaporize during a landing event, potentially enhancing surface erosive effects. Potentially detrimental impacts to lander stability.

Benefits if Data is Available

Increased confidence in landing, plume-surface interaction, and trafficability analyses, which may increase flexibility and allow more areas and terrain to be considered for mission operations. Concentrations of hydrated material on the surface or near-subsurface may indicate the presence of usable in-situ resources. Further resource exploration activities would be needed to determine if available water concentrations are sufficient to constitute a usable reserve.

Current State of Data

Observations of water ice and frost by landers at high latitudes. Water maps based on combining available Mars orbital instrument datasets (Mars Odyssey neutron and gamma ray spectroscopy, as well as thermal emission imaging data; Mars Express visible and infrared imaging spectrometer data; and Mars Reconnaissance Orbiter shallow radar, climate sounder, imaging spectrometer, and context and high-resolution imaging data). Rover-mounted instruments have detected hydrated minerals at select sites. The Phoenix lander has directly measured and sampled Martian ice.

Localized and predictive Mars surface weather characterization

ID No. **DN-003 M**
Objective **TH-06 M, TH-07 M**
Data Type **In Situ Measurement**

Gap Description	Need Driver	Segment
Refine site-specific understanding and models of atmospheric pressure, density, winds, and dust/aerosol loading at the Martian surface, including diurnal and seasonal variability, to reduce uncertainty, plume-surface interaction, and operations planning.	**Mars Surface Natural Environment Characterization**	Humans to Mars

Target Measurement Parameters

Measurement of atmospheric pressure, wind velocity, temperature, atmospheric composition at diverse surface sites on Mars.

Impacts and Benefits

Impacts if Data is Unavailable

Increased uncertainty in modeling plume structure and resultant effects on surface erosion. Effects of Mars atmospheric conditions could impact the behavior of the Martian surface when interacting with a rocket plume. Uncertainty in environmental parameters leads to needing increased robustness, and thus mass, for surface assets. Martian wind can spread plume materials outside expected range and potentially contaminating science sites and impacting nearby exploration assets.

Benefits if Data is Available

Increasing understanding of surface atmospheric density, winds, and dust effects on Mars would result improved landing safety in potential low visibility conditions induced by PSI. Additionally, exploration operations on the Martian surface will be heavily impacted by weather conditions which can be mitigated or planned for using forecasting models.

Current State of Data

Pressure data from landers/rovers, atmospheric profiles/models. Mars global reference atmospheric model (Mars GRAM) and orbiter data for atmospheric composition. Mars GRAM is built to inform EDL and ascent simulations; uncertainties increase at surface level.

Human-scale EDL atmospheric entry environment characterization

ID No. **DN-004 M**
Objective **TH-06 M, TH-07 M**
Data Type **In Situ Measurement**

Gap Description

Refine models of vertical variability in atmospheric pressure, density, winds, temperature, and aerosol loading in the Martian atmosphere across altitudes relevant to human-class EDL. Improve temporal and spatial coverage to reduce uncertainty in descent and ascent trajectory predictions.

Need Driver

Mars Surface Natural Environment Characterization

Segment

Humans to Mars

Target Measurement Parameters

Measurement of atmospheric pressure, wind velocity, temperature, atmospheric composition at various altitudes above representative surface sites.

Impacts and Benefits

Impacts if Data is Unavailable

Without further understanding of the Martian atmosphere, operational risks for human-scale EDL may not be able to close. No human-scale descent vehicle has ever descended through the Martian atmosphere and landed safely on the surface.

Benefits if Data is Available

Mars robotic landers have consistently landed downwind of their intended targets. Increased understanding of the Martian atmosphere may lead to increased landing accuracy.

Current State of Data

Pressure data from instrumented EDL systems, atmospheric profiles/models. Mars global reference atmospheric model (Mars GRAM) and orbiter data for atmospheric composition. Mars GRAM is built to inform EDL and ascent simulations; uncertainties increase at surface level.

In situ measurement of particle velocity during Martian plume surface interaction (PSI) phenomena

ID No. **DN-005 M**
Objective **SE-07 LM, TH-06 M, TH-07 M**
Data Type **In Situ Measurement**

Gap Description

Characterize Martian regolith ejected by rocket exhaust plumes interacting with the surface. During final descent and landing, material may be lofted toward the landing vehicle and/or ejected away. As material leaves the influence of the exhaust plume, it will travel on a trajectory dictated by those initial conditions and interactions with the Martian atmosphere.

Need Driver	Segment
Mars Surface Induced Environment Characterization	Humans to Mars

Target Measurement Parameters

Regolith particle sizes, speeds, and angles of ejection caused by rocket exhaust interacting with the Martian regolith. Local atmospheric density during plume surface interaction.

Impacts and Benefits

Impacts if Data is Unavailable

Increased uncertainty in risk to landing vehicle and surrounding assets caused by debris strike or the "sandblasting", abrasive effects of ejected material. Increased uncertainty to scientific operations near the landing site, as the probability of surface alteration caused by ejected material may not be well constrained.

Benefits if Data is Available

Increased confidence in ejecta hazard analyses that affect the landing vehicle and nearby assets. Tighter design constraints for protection from hazards/operating conditions. Better understanding of induced landing environment to inform Mars surface science goals.

Current State of Data

Exhaust plume captured by engineering cameras aboard MSL and Mars2020 Sky Crane. Potentially able to estimate particle velocity from videos of descent but would not be able to characterize full descent profile of a human class lander.

In situ measurement of landing site alteration imaging at small scale on Mars

ID No. **DN-006 M**
Objective **SE-07 LM, TH-06 M, TH-07 M**
Data Type **In Situ Measurement**

Gap Description	Need Driver	Segment
Measure landing site alteration caused by rocket exhaust plumes interacting with the Martian surface. During final descent and landing, rocket exhaust may erode material which changes surface topography or alters surface properties. This has the potential to create a hazardous landing environment or affect scientific outcomes.	**Mars Surface Induced Environment Characterization**	Humans to Mars

Target Measurement Parameters

Measurement of landing site topography before, during, and after vehicle plume-surface interactions at cm scale or better. Measurement of regolith geotechnical properties in the affected area. Measurement of chemical contamination of the area affected by the exhaust plume.

Impacts and Benefits

Impacts if Data is Unavailable

Increased uncertainty in risk to landing vehicle caused by surface alteration. Increased uncertainty to scientific operations near the landing site if regolith alteration or contamination is not well understood.

Benefits if Data is Available

Increased confidence in analyses of surface alteration during final descent and landing. Informs vehicle design and operational mitigations. Informs scientific community regarding experiment placement and operations.

Current State of Data

Flight reconstructions of erosion caused by InSight and Mars Phoenix. Analysis of MSL and Mars2020 descent videos could be performed to determine surface alteration at some level of uncertainty.

Moon to Mars Architecture
Definition Document
ESDMD-001

F.

Appendix F

Terminology

Appendix F: Terminology

This appendix captures acronyms and abbreviations, defines terms used throughout the document.

F.1 Acronyms and Abbreviations

Acronym	Meaning	Usage/Context
ACR	Architecture Concept Review	
ADD	Architecture Definition Document	
APH	Advanced Plant Habitat	Technology Gaps
ALARA	As Low As Reasonably Achievable	Technology Gaps
ARMADAS	Automated Reconfigurable Mission Adaptive Digital Assembly Systems	Technology Gaps
AS	Applied Science	Objective Category
ASA	Australian Space Agency	Space Agency
ASI	Italian Space Agency *(Agenzia Spaziale Italiana)*	Space Agency
CAPSTONE	Cislunar Autonomous Positioning System Technology Operations and Navigation Experiment	Mission
CaRD	Carbothermal Reduction Demonstration	Technology Gaps
CLDP	Commercial Low Earth Orbit Development Program	Program
CLPS	Commercial Lunar Payload Services	Element
CNES	French Space Agency *(Centre National D'Etudes Spatiales)*	Space Agency
COTS	Commercial Off-The-Shelf	
C&PNT	Communication and Positioning, Navigation, and Timing	Sub-Architecture
CSA	Canadian Space Agency	Space Agency
DEM	Digital Elevation Map	Data Gaps
DLR	German Aerospace Center *(Deutsches Zentrum für Luft- und Raumfahrt)*	Space Agency
DSAC-1	Deep Space Atomic Clock	Technology Gaps
DSN	Deep Space Network	Sub-Element
DSNE	Design Specification for Natural Environments	Data Gaps
ECLSS	Environmental Control and Life Support System	
EDL	Entry, Descent, and Landing	
EGS	Exploration Ground Systems	Element
EP	Electric Propulsion	Technology Gaps
ESA	European Space Agency	Space Agency
ESM	European Service Module	Sub-Element
ESPIRIT	European System Providing Refueling Infrastructure and Telecommunication	Gateway Component

Acronym	Meaning	Usage/Context
EVA	Extravehicular Activity	
FE	Foundational Exploration	Segment
GCR	Galactic Cosmic Radiation	Technology Gaps
GDOP	Geometric Dilution of Precision	Technology Gaps
GNSS	Global Navigation Satellite System	
H2M	Humans to Mars	Segment
HALO	Habitation and Logistics Outpost	
HBS	Human and Biological Science	Objective Category
HD	High Definition	Technology Gaps
HDL	Human-class Delivery Lander	
HLR	Human Lunar Return	Segment
HLS	Human Landing System	Element
HS	Heliophysics Science	Objective Category
I/O	Input/Output	Technology Gaps
I-Hab	International Habitation Module	Gateway Component
IM&R	Inspection, Maintenance, and Repair	Technology Gaps
IPEx	ISRU Pilot Excavator	Technology Gaps
ISA	Israel Space Agency	Space Agency
ISRO	Indian Space Research Organization	Space Agency
ISRU	In-Situ Resource Utilization	
IVA	Intra-Vehicular Activities	
JAXA	Japan Aerospace Exploration Agency	Space Agency
KASA	Korean AeroSpace Agency	Space Agency
KASI	Korea Astronomy and Space Science Institute	Space Agency
KPLO	Korea Pathfinder Lunar Orbiter	Mission
LCRNS	Lunar Communication Relay and Navigation Systems	Sub-Element
LEAP	Lunar Exploration Accelerator Program	
LEO	Low Earth Orbit	
LI	Lunar Infrastructure	Objective Category
LOLA	Lunar Orbiter Laser Altimeter	Data Gaps
LPS	Lunar/Planetary Science	Objective Category
LRO	Lunar Reconnaissance Orbiter	Mission
LROC	Lunar Reconnaissance Orbiter Camera	Data Gaps
LTV	Lunar Terrain Vehicle	Element
LuPEX	Lunar Polar Exploration	Mission
GRAM	Global Reference Atmospheric Model	
MBRSC	Mohammed Bin Rashid Space Centre	Space Agency

Acronym	Meaning	Usage/Context
MEGANE	Mars-moon Exploration with GAmma rays and NEutrons	Mission
MI	Mars Infrastructure	Objective Category
NAC	Narrow Angle Camera	Data Gaps
NASA	National Aeronautics and Space Administration	Space Agency
NEP	Nuclear Electric Propulsion	Technology Gaps
NPR	NASA Procedural Requirements	
NRHO	Near Rectilinear Halo Orbit	
NSN	Near Space Network	Sub-Element
NTP	Nuclear Thermal Propulsion	Technology Gaps
NZSA	New Zealand Space Agency	Space Agency
OHRC	Chandrayaan-2 Orbiter High Resolution Camera	Data Gaps
OP	Operations	Objective Category
PL&HA	Precision Landing and Hazard Avoidance	Technology Gaps
PMAD	Power Management and Distribution	Technology Gaps
PNT	Positioning, Navigation, and Timing	
PPD	Pixel/Degree	Data Gaps
PPE	Power Propulsion Element	Gateway Component
PPS	Physics and Physical Sciences	Objective Category
PR	Pressurized Rover	Element
PRISM	Payload and Research Investigations from the Surface of the Moon	Solicitation
PSI	Plume Surface Interaction	Technology Gaps
PSR	Permanently Shadowed Region	
RT	Recurring Tenet	Objective Category
SCALPSS	Stereo Cameras for Lunar Plume-Surface Studies	Payload
SCaN	Space Communications and Navigation	NASA Program
SE	Science-Enabling	Objective Category
SEP	Solar Electric Propulsion	Technology Gaps
SfS	Shape from Shading	Data Gaps
SLE	Sustained Lunar Evolution	Segment
SLIM	Smart Lander for Investigating Moon	Mission
SLS	Space Launch System	Element
SPE	Solar Particle Event	Technology Gaps
SSA	Saudi Space Agency	Space Agency
SWaP	Size, Weight, and Power	
TLT	Tall Lunar Tower	Technology Gaps
TH	Transportation and Habitation	Objective Category
TRL	Technology Readiness Level	Technology Gaps

Acronym	Meaning	Usage/Context
TRN	Terrain Referenced Navigation	Data Gaps
TTC	Telemetry, Tracking, and Command	Technology Gaps
UHF	Ultra High Frequency	Technology Gaps
VEGGIE	Vegetable Production System	Technology Gaps
WEH	Water Equivalent Hydrogen	Data Gaps
xEVA	Exploration EVA Systems	Element
3GPP	3rd Generation Partnership Project	Technology Gaps

F.2 Glossary of Terms

Term	Description
Architecture	The high-level unifying structure that defines a system. It provides a set of rules, guidelines, and constraints that defines a cohesive and coherent structure consisting of constituent parts, relationships and connections that establish how those parts fit and work together. (Definition from NASA's System Engineering Handbook)
Architecture-driven Data Gap	Data the agency needs to advance the Moon to Mars Architecture that is not met by any existing information.
Artemis Mission	The crewed portion of an Artemis Mission Campaign, beginning at crew liftoff from Earth and ending at crew return to Earth.
Artemis Mission Campaign	A collective grouping of uncrewed missions and their associated crewed mission.
Automation	Automatically controlled operation of an apparatus, process, or system by mechanical or electronic devices that take the place of human labor (e.g., computer control of a docking operation or vehicle surface traverse). Human intervention can be available, as determined by hazard controls (e.g., breakout or transition to safe mode), but not required to complete an automated operation.
Autonomous System	A combination of elements that function together to achieve goals while operating independently of external controls. An autonomous system may involve any combination of elements (e.g., humans and machines) and is not limited to uncrewed capability.
Autonomy	The ability of a system to achieve goals while operating independently of external controls. Autonomy does not preclude external reprioritization or generation of new goals. It only requires execution of existing goals without external control.
Baseline	An agreed-to set of requirements, designs, or documents that will have changes controlled through a formal approval and monitoring process.
Campaign	A series of interrelated missions that together achieve Agency goals and objectives. (Definition from Moon to Mars Strategy and Objectives)
Cargo	Items that are transported from one location to another.
Carrier	A transport structure or container used to secure and protect logistics items that require transport to the point of use.
Characteristics	Features or activities of exploration mission implementation that are necessary to satisfy the goals and objectives.
Cislunar Space	The region of space from the Earth to the Moon. Specifically for the Moon to Mars Architecture, elements under the influence of lunar gravity, beyond Earth's geosynchronous orbit and inclusive of low lunar orbit but distinct from the lunar surface.
Co-Manifested Payload	Cargo on a transportation element utilizing excess volume and mass (e.g., cargo located inside the payload attach fitting adapter ring).
Concept of Operations	Developed early in Pre-Phase A, describes the overall high-level concept of how the system will be used to meet stakeholder expectations, usually in a time-sequenced manner. It describes the system from an operational

Term	Description
	perspective and helps facilitate an understanding of the system goals. It stimulates the development of the requirements and architecture related to the user elements of the system. It serves as the basis for subsequent definition documents and provides the foundation for the long-range operational planning activities (for nominal and contingency operations). It provides the criteria for the validation of the system. In cases where an operations concept is developed, the concept of operations feeds into the operations concept and they evolve together. The concept of operations becomes part of the concept documentation.
Consumables	Supplies (not including propellant) that are needed to support mission activities.
Continuous Presence	Steady cadence of human/robotic missions in subject orbit/surface with the desired endpoint of 24/7/365 operations. (Definition from Moon to Mars Strategy and Objectives)
Control Mass	Used to define the capability and baseline architecture of the system. It represents the controlled, not-to-exceed allocation of mass to an element.
Crew Countermeasure System(s)	Systems that enable aerobic and resistance exercise for crew inside habitable assets.
Cryogenic Samples	Samples that are typically below -153°C/120K.
Deep Space Environments	Deep space is the vast region of space that extends to interplanetary space, to Mars and beyond. It is the region of space beyond Earth’s Moon, including Lagrange 2, or L2, (274,000 miles from Earth). This environment has many defining factors, including harsh radiation (both solar particle events and galactic cosmic rays), space weather, and microgravity.
Deep Space Transport	Deep Space Transport is used to describe the assembled Mars transit vehicle stack, which will consist of a propulsion and power transportation system backbone and attached cargo. There are two Deep Space Transport variants: in the crew variant, the cargo will consist of a transit habitat that may or may not be a separate free-flyer that docks with transport; in the cargo variant, the cargo will consist of orbital assets to be delivered to Mars orbit, or surface assets mounted to Mars descent systems that will be delivered to the Mars surface.
Deep Sub-Surface Samples	Samples collected from locations 10–100m below the lunar or Martian surface.
Demonstrate	Deploy an initial capability to enable system maturation and future industry growth in alignment with architecture objectives. (Definition from Moon to Mars Strategy and Objectives)
Deploy	To move into place or bring into effective action.
Develop	Design, build, and deploy a system, ready to be operated by the user, to fully meet architectural objectives. (Definition from Moon to Mars Strategy and Objectives)
Earth Vicinity	The region of space around the Earth-Moon system, including cislunar space, low Earth orbit, and orbits around the Earth-Moon barycenter.
Effectivity	The conditions or mission for which a requirement is initially applicable.
Element	Any exploration system that enables a high-level functional allocation (e.g., crew transport, habitation, logistics delivery) that is primarily self-sufficient.

Term	Description
Excursion	The activity of moving to and/or returning from a location on the lunar surface through extravehicular operations and/or surface mobility assets.
Explore	Excursion-based expeditions focused on science and technology tasks. (Definition from Moon to Mars Strategy and Objectives)
Exploration Asset	All items that are in place and being used as part of the exploration architecture.
Exploration Strategy	Establish the scenarios, conceptual missions, and systems needed to extend humanity's reach beyond low Earth orbit, return to the Moon, and proceed on toward Mars and beyond.
Function	Actions that an architecture would perform that are necessary to complete the desired use case.
Frozen Samples	Samples that are typically around the -85°C range.
Global	Infrastructure and capabilities that support human and robotic operations and utilization across the subject planetary surface. (Definition from Moon to Mars Strategy and Objectives)
Gravity	"Gravity" refers to acceleration on Earth (~9.81 ms−2), and is expressed in the international system of units (SI) as g. A gravity level lower than 1 g is called "partial gravity" or "reduced gravity".
Habitable Environment	The environment that is necessary to sustain the life of the crew and to allow the crew to perform their functions in an efficient manner.
Human Landing System - Initial Configuration	Any crewed mission to the lunar surface executed with the initial HLS configurations as defined in the HLS Broad Agency Announcement Option A. (Effectivity for requirements unique to this configuration are noted as "HLS Initial Configuration.")
Human-Rating	A human-rated system accommodates human needs, effectively utilizes human capabilities, controls hazard with sufficient certainty to be considered safe for human operations, and provides, to the maximum extent practical, the capability to safely recover the crew from hazardous situations. Human-rating consists of three fundamental tenets: Human-rating is the process of designing, evaluating, and assuring that the total system can safely conduct the required human missions. Human-rating includes the incorporation of design features and capabilities that accommodate human interaction with the system to enhance overall safety and mission success. Human-rating includes the incorporation of design features and capabilities to enable safe recovery of the crew from hazardous situations.
Hybrid Propulsion System	A vehicle consisting of two or more unique propulsion systems, each optimized for different types of maneuvers. For the purpose of this document, two hybrid systems are considered: solar electric propulsion/chem, which combines a solar electric propulsion system with a chemical stage, and Nuclear Electric Propulsion/chem, which combines a nuclear electric propulsion system with a chemical stage.
Increment	The period of time between the end of one crew mission (i.e., crew splashdown) and the end of a second crew mission, including the uncrewed activities and operations that commence during this defined timeframe.

Term	Description
Incremental	Building compounding operational capabilities within the constraints of schedule, cost, risk, and access. (Definition from Moon to Mars Strategy and Objectives)
Integrated Element	A portfolio that comprises multiple individual assets and provides a suite of integrated capabilities, offering flexible, evolvable concepts to achieve NASA's Moon to Mars Objectives.
Interoperability	The ability of two or more systems to physically interact; exchange data, information, or consumables; or share common equipment while successfully performing intended functions.
Intravehicular Activity Facilities	Facilities inside a habitable asset, sustained across crewed and uncrewed increments, that allow the hosting and operation of dedicated utilization payloads.
Key Architecture Definition Task	An architecture definition task that influences the end-to-end architecture and warrants elevated scrutiny.
Large Cargo	Items greater than 6t in mass that are transported from one location to another.
Large Asset	For lunar, an asset that is greater than 6t in mass.
Legacy Decision	A decision made before the implementation of the architecture decision roadmapping process.
Limited Capability Mission	A mission to a polar landing site where the utilization capability of the mission is limited to the threshold capabilities of HLS and Orion, with no additional delivery or return mass available from goal capabilities or other elements. Additionally, certain missions may prioritize crew time and transportation mass to the delivery and outfitting of new elements in NRHO (e.g., Gateway elements) or the lunar surface (e.g., Pressurized Rover and initial surface habitat). For the purposes of analysis, a two-crew, 6.5-day sortie was assumed as a representative case. In such a mission, it is expected that a significant amount of crew time will be needed to ingress, setup, outfit, and checkout new elements being delivered to or operated for the first time in NRHO or on the lunar surface, leaving less time available for utilization activities. In addition to crew time, it is expected that the delivery and outfitting of these new elements will require a greater fraction of the overall logistics mass delivery capability, further reducing the utilization potential of the mission. Thus, this mission category represents a case in which only a threshold of utilization activities is expected to be performed.
Live	The ability to conduct activities beyond tasks on a schedule. Engage in hobbies, maintain contact with friends and family, and maintain healthy work-life balance. (Definition from Moon to Mars Strategy and Objectives)
Logistics	Capabilities associated with packaging, handling, storage, transportation, and tracking of logistics items and goods not initially delivered as part of an exploration element, including equipment, tools, consumables, maintenance items, spares, and subsystem components needed to support mission activities such as operations, outfitting, science, research, and utilization. Logistics also includes capabilities associated with reuse, recycling, and disposal of trash and waste.
Logistic Items	Supplies (not including propellant) that are needed to support mission activities.

Term	Description
Loss of Crew	Death of or permanently debilitating injury to one or more crew members.
Loss of Mission	Loss of or inability to complete significant/primary mission objectives, which includes loss of crew. Each mission is defined with different assumptions and mission objectives. Therefore, specific mission loss-of-mission assessments are accomplished evaluating the attainment of specific mission objectives, using methods tailored to the specific mission risk drivers and each specific program but consistent with defined NASA Probabilistic Risk Assessment standards.
Maintenance	The function of keeping items or equipment in, or restoring them to, a specified operational condition. It includes servicing, test, inspection, adjustment/alignment, removal, replacement, access, assembly/disassembly, lubrication, operation, decontamination, installation, fault location, calibration, condition determination, repair, modification, overhaul, rebuilding, and reclamation. Preventative maintenance is performed before a failure occurs, whereas corrective maintenance occurs in response to a failure.
Mechanical Assistance	Device intended to allow the crew to transport more mass than they can hand carry while walking.
Mission	A major activity required to accomplish an agency goal or to effectively pursue a scientific, technological, or engineering opportunity directly related to an Agency goal. Mission needs are independent of any particular system or technological solution. (Definition from Moon to Mars Strategy and Objectives)
Mobility	Powered surface travel that extends the exploration range beyond what is possible for astronauts to cover on foot. Spans robotic and crewed systems and can be accomplished on and above the surface. (Definition from Moon to Mars Strategy and Objectives)
Near-Surface Samples	Samples collected from locations 1–2m below the lunar or Martian surface.
Needs	A statement that drives architecture capability, is necessary to satisfy the Moon to Mars objectives, and identifies a problem to be solved, but is not the solution.
Permanently Shadowed Regions	Areas of the lunar surface that never receive direct sunlight (or have not seen direct sunlight in billions of years). These extremely cold regions, often found in craters near the lunar poles, can contain frozen volatiles of interest for lunar science and ISRU.
Planetary Protection	Approaches used to avoid harmful contamination of solar system bodies during exploration activities, as well as avoiding possible harmful extraterrestrial contamination from material that may be returned from other solar system bodies, in compliance with Outer Space Treaty constraints.
Position, Navigation, and Timing	Position, navigation, and timing (PNT) encompasses the ability to enable broad awareness of a user's location in space and time. Accomplishing PNT relies on both infrastructure and user capabilities. Infrastructure includes the critical foundations of lunar reference system components and lunar reference time, and the sources provided by a broad suite of network assets that rely on those foundations. These radionavigation sources act as distributed known reference and form the backbone for PNT services and are provided by signals and data from ground stations on Earth, satellites in orbit

Term	Description
	around the Moon, and assets on the lunar surface. User-provided sensors provide additional local observations to enable resilience to the PNT infrastructure and more accurate local relative knowledge. The user real-time solution computed in situ can be communicated to other lunar assets and back to Earth, and/or the measurements from all PNT sources and sensors can be post-processed on Earth. Together these foundational elements, radionavigation sources, and user-provided sensors enable a user, either in orbit or on the surface, to maintain awareness of their position, velocity, and time.
Powered Mobility Asset	Asset that allows the crew to travel further distances than they can walk (e.g., Lunar Terrain Vehicle or Pressurized Rover).
Priority Key Definition Task	A key definition task with many flow-down impacts upon subsequent tasks and which therefore was presented and approved at the Architecture Concept Review to be made early in the architecture roadmapping process.
Reconfiguration	If a system is required to provide a function, any time required by the crew associated with making that function available for use, including changing spaces and moving logistics to allow for use of the space for a different purpose (e.g., exercise, eating, sleeping, medical, training, working).
Reference Mission	A defined set of elements with assumed functional allocations working together in a focused mission context that serves as a common point of comparison for strategic analysis and early program formulation activities (prior to Authority to Proceed) and will be updated when necessary to remain in alignment with the overall exploration goals and objectives.
Reference System	A theoretical system of coordinates and standards sufficient to define the position and motion of objects in space and time. A reference system is composed of a specified origin, the directions of fundamental axes, and a set of conventional models, procedures, and constants used to realize the system.
Refrigerated Samples	Samples that typically need to be maintained in the +4°C to -20°C range.
Reposition/Relocate	The act of moving cargo from one location to another on the lunar or Martian surface.
Robotic Systems	Systems intended to interact with their environment and/or objects in the environment through powered motions and a controlled relationship between sensing and action. Robotic systems can perform physical tasks (e.g., manipulating or moving objects, mobility across terrain), and they may or may not exhibit some degree of autonomy. Habitation and transportation systems (as defined by those sub-architectures) and disembodied autonomous systems that lack the capacity for physical interaction are not robotic systems.
Routine	Recurring subject operations performed as part of a regular procedure rather than for a unique reason. (Definition from Moon to Mars Strategy and Objectives)
Routine Preventative Maintenance	Planned maintenance done on a regular (daily, weekly, monthly) basis that is part of the design, such as filter changes, lubrication, cleaning, etc.
Samples/Commodities/ Logistics Items	Samples, commodities, and supplies (not including propellant) that are needed to support mission activities.

Term	Description
Secondary Payloads	Additional cargo carried on a transportation element, currently on an adapter ring, after the primary and co-manifested payloads are accommodated, limited by the remaining transportation element resources (e.g., mass, volume, power).
Semi-Autonomous System	A system that operates independent of external control in the execution of a subset of its operational goals or task objectives while relying on operator control input (from crew and/or ground) for its complete end-to-end operations (i.e., a system that shares control with an external operator, exhibiting autonomy over some, but not all, of its operational goals/objectives).
Scalability	Initial systems designed such that minimal recurring DDT&E is needed to increase the scale of a design to meet end state requirements. (Definition from Moon to Mars Strategy and Objectives)
Segments	A portion of the architecture, identified by one or more notional missions or integrated use cases, illustrating the interaction, relationships, and connections of the sub-architectures through progressively increasing operational complexity and objective satisfaction.
Small Asset	For lunar other, non-utilization assets less than 6t in mass. Excludes utilization payloads, utilization equipment, and samples/commodities/logistics items.
Small Cargo	Any item less than 6t in mass that is transported from one location to another, including utilization payloads and equipment, small assets, or samples/commodities/logistics items.
Sol	Martian day, approximately 24 hours and 39 minutes long. For the purpose of this document, operational timekeeping on the surface of Mars uses Martian sols to align with the Martian day/night cycle.
Sortie Missions	A single crewed mission to a lunar surface location for a period of days supported solely by the lunar crewed lander. The main characteristics of the sortie mission are that crew habitation is provided by the crewed lander and the crew can perform all lunar surface activities using self-contained resources—although pre-deployment of resources is not necessarily precluded during a sortie mission.
Stakeholder	An organization with an interest in a particular architecture definition task because it can either affect or be affected by the definition outcome. Different architecture definition tasks may have different stakeholders who are responsible for contributing supporting data and analyses. In some cases, stakeholders are authorities for prerequisite definition tasks that feed into a particular key definition task.
Stage	Provide an area in which participants and logistics are brought together and readied for an activity.
Stow	Provide physical space for the storage of items, usually samples that have been collected and placed in containers.
Sub-Architecture	A group of tightly coupled elements, functions, and capabilities that perform together to accomplish architecture objectives.
Sub-Surface Samples	Samples collected from locations 2–10m below the lunar or Martian surface.

Term	Description
System	The combination of elements that function together to produce the capability required to meet a need. The elements include all hardware, software, equipment, facilities, personnel, processes, and procedures needed for this purpose. (Refer to NPR 7120.5.)
Definition Task	An examination of a question within the architecture, typically to shape or reduce the trade space.
Definition Outcome	The result of an architecture definition task, which could include a decision, down-select, ground rule, methodology, or other narrowing of the trade space.
Trade Space	An exploratory part of the systems engineering process that identifies and analyzes potential solutions for an architectural concept, function, or component. The trade space includes assessments of state-of-the-art and anticipated future capabilities applied as part of a range of solutions, and assessments of impacts that each solution could have across a system's development lifecycle or the architecture as a whole.
Transit	The carrying of people, goods, or materials from one place to another in space.
Transport	The act of moving crew or cargo from one location to another in space.
Traverse	To travel across or over the surface.
To Be Determined (TBD)	Used when the value to be placed in a requirement is not known and there is open work to determine what it should be.
To Be Resolved (TBR)	Used when a value for a requirement is presented but it is to be resolved or refined as to whether it is the right number.
Use Case	Operations that would be executed to produce the desired needs and/or characteristics.
User Burden	The demands imposed on exploration elements or assets seeking to access a service or capability (e.g., for missions or systems accessing C&PNT sub-architecture services)
Utilization	Use of the platform, campaign, and/or mission to conduct science, research, test and evaluation, public outreach, education, and industrialization. (Definition from Moon to Mars Strategy and Objectives)
Utilization Mass	The mass of utilization payloads.
Utilization Payloads and Equipment	Any item that is primarily in support of and attributed to utilization objectives. Utilization payloads include science/research payloads and technology demonstrations. Equipment includes other internal and external hardware, supporting tools, supplies, etc.
Validate	Confirming that a system satisfies its intended use in the intended environment (i.e., did we build the right system?). (Definition from Moon to Mars Strategy and Objectives)
Verification (of a product)	Proof of compliance with a requirement. Verification may be determined by testing, analysis, demonstration or inspection.
Volatiles	Elements, molecules, and compounds that readily vaporize, converting to their gaseous form (e.g., water and carbon dioxide). To preserve the scientific integrity of these materials, sample return efforts require preservation of their native environmental conditions (e.g., cold conditioning).

Term	Description
Work Time	Non-personal time. Time during which the crew is in a duty status (e.g., typically 8–8.5 hours, but could be 11.5 hours for an EVA day or other mission-specific extension).

F.3 Quantity Descriptors

The following descriptors define terms used in the objective decomposition; they capture approximate quantities for terms like *small*, *medium*, and *large*, etc.

Transport of cargo to the lunar surface	
Term	Description
Limited Amount	100s of kg
Moderate Amount	1000s of kg
Large Exploration Assets	Assets greater than 6t in mass

Transport of cargo from the lunar surface	
Term	**Description**
Small Amount	10s of kg
Large Amount	100s of kg

Unloading of cargo	
Term	**Description**
Limited Amount	100s of kg
Moderate Amount	1000s of kg
Large Exploration Assets	Assets greater than 6t in mass

Repositioning of cargo	
Term	**Description**
Limited Amount	100s of kg
Moderate Amount	1000s of kg
Exploration Assets	Assets greater than 6t in mass

Repositioning of samples and containers	
Term	**Description**
Small Amount	10s of kg
Large Amount	100s of kg