National Aeronautics and
Space Administration

NASA's

Moon to Mars Architecture

Architecture Definition Document

ESDMD-001 Revision B

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Exploration Systems Development Mission Directorate

Moon to Mars Architecture Definition Document (ESDMD-001) – Revision B

National Aeronautics and
Space Administration

Mary W. Jackson Headquarters
Washington, D.C.

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EXECUTIVE SUMMARY

The National Aeronautics and Space Administration (NASA) explores the unknown in air and space, innovates for the benefit of humanity, and inspires the world through discovery. Extending the reach of humanity through the human exploration of the Moon, Mars, and beyond is key to that mission. NASA's Moon to Mars Strategy and Objectives document establishes long-term goals and objectives for crewed deep space exploration; however, satisfying NASA's Moon to Mars Objectives requires an innovative approach to the definition, management, and execution of NASA's Moon to Mars Architecture. An architecture offers a high-level unifying structure and defines a system. It provides rules, guidelines, and constraints that define a cohesive and coherent framework that identifies constituent parts, relationships, and connections and establishes how those parts fit and work together. This Architecture Definition Document (ADD) establishes the process for the decomposition of objectives empowers the agency's success in achieving human exploration of the cosmos. NASA updates this document annually to reflect the maturation of the architecture and the progress NASA and partners make toward achieving exploration objectives.

The ADD is not a manifest or requirements document. Instead, it serves as a tool for the programs, projects, and engineers who will implement and execute NASA's bold ambitions for crewed exploration of deep space.

As established in the Moon to Mars Strategy and Objectives, "Why" we explore encompasses three pillars: Science, Inspiration, and National Posture. Ensuring success in all three areas requires an architectural approach that incorporates innovation, collaboration, and partnerships that can be sustained across a multi-decadal effort. This second revision (Rev-B) of the ADD, developed to support NASA's 2024 Architecture Concept Review (ACR), incorporates several key updates to support the continued evolution of the architecture.

Since the last revision of the ADD, NASA has significantly improved the clarity of the objective decomposition, which distills exploration objectives into the characteristics and needs and use cases and functions needed to achieve them. The updated decomposition incorporates findings from internal studies and diverse stakeholder feedback. A model-based systems engineering approach ensures coherence and consistency, removing inconsistency and repetition.

Revision B also incorporates advancements to NASA's Mars architecture, including insight into initial capabilities, systems, and operations necessary to support the Humans to Mars segment. Updates to objective decomposition for Mars add significant detail to the ADD and hint at areas of forward work and future study. An appendix adds greater depth in the future decisions needed for Mars that will drive lunar needs. They are not the only decisions to be made, but they will have huge effects on subsequent decisions.

NASA continues to introduce new exploration systems into the architecture. Two new elements — initial surface habitat and lunar surface cargo lander — successfully passed mission concept review in 2024 as a result of extensive analysis, concept refinement, and studies. These elements and their respective reference missions appear in this revision.

NASA also continues to apply architecture processes to cross-agency efforts and coordination with external stakeholders by including definitions of architecture technology gaps — essential areas for engagement across and beyond the agency. The technology gaps appendix identifies areas that need attention and innovation to enable future exploration. In publishing this information, NASA communicates the technologies and capabilities that may benefit from partnership with industry, academia, other U.S. government agencies, and international space agencies.

Ultimately, NASA established the Moon to Mars Architecture approach to communicate and facilitate humanity's journey into the universe according to the principles and recurring tenets of NASA's Moon to Mars Strategy and Objectives. The NASA architecture team thanks their many stakeholders, participants, and partners for their efforts to review and provide feedback. Their support has been critical to the success of this approach.

REVISION AND HISTORY

The NASA Office of Primary Responsibility for this document is the Exploration Systems Development Mission Directorate Architecture Development Office. Please visit https://www.nasa.gov/MoonToMarsArchitecture for the latest version and updates to the Moon to Mars Architecture and exploration campaign.

Revision Identification	Description	Release Date
Initial	Initial Release (Reference NASA/TP-20230002706)	04/18/2023
Revision A	Updates for 2023 Architecture Concept Review • Refined sub-architectures and added the following: Data Systems and Management, Infrastructure, ISRU, Robotics (Section 1.3.2.1) • Refined and expanded objective decomposition into the characteristics and needs (Section 2.4 and Appendix A) • Added and updated use cases & functions (Appendix A) • Updated Human Lunar Return segment (Section 3.1) • Updated Foundational Exploration segment (Section 3.2) • Added the following elements with use cases & functions mapping: Gateway Expanded Capability Configuration, which includes Gateway External Robotic System (GERS), ESPRIT Refueling Module (ERM), and the Gateway airlock; Human-class Delivery Lander (HDL); Lunar Terrain Vehicle (LTV), and Pressurized Rover (PR) (Section 3.2) • Updated Humans to Mars segment (Section 3.4) • Added and updated assessments for all recurring tenets (Section 4.0)	01/22/2024
Revision A, Management Directive 1	Corrections of minor errata • Addition of FN-060-L and FN-062-L mapping to HLS in HLR and FE segments (Tables 3-10 and 3-23, respectively) • Updated definition of “cargo” • Updated definition of “consumables” • Removed “large cargo” from glossary	03/27/2024

Revision B	Updates for 2024 Architecture Concept Review • Refined and expanded objective decomposition (Section 2.6 and Appendix A) • Added Mars characteristics, needs, use cases, and functions for Transportation and Habitation, Mars Infrastructure, and Operations Objectives (Appendix A) • Updated Human Lunar Return segment (Section 3.1) • Updated Foundational Exploration segment (Section 3.2) • Added the following elements with use cases and functions mapping: initial surface habitat and lunar surface cargo lander (Section 3.2) • Updated Humans to Mars segment (Section 3.4) • Updated assessments for recurring tenets (Section 4.0) • Added and expanded on Moon to Mars Architecture Decisions (Section 2.4 and Appendix B) • Added Architecture Technology Gaps (Section 2.5 and Appendix C)	12/13/2024

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1.0 INTRODUCTION

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. This definition, as found in the National Aeronautics and Space Administration (NASA) Systems Engineering Handbook,[1] is essential to capture the broad range of systems, programs, and projects supporting the human exploration of the Moon, Mars, and beyond. Although this definition is typically used for a single program construct rather than a multidecadal Moon to Mars human exploration architecture, the need for a unifying structure to address the magnitude of the endeavor remains. These goals represent the most complex systems engineering effort conducted by NASA to date. Ultimately, the programs, projects, and contributing systems will span decades, agencies, countries, cultures, and a variety of commercial, academic, and other types of contributors. Establishing a common architectural language, framework, and integration process to communicate and document the Moon to Mars system-of-systems is necessary, and this document is the first step in that process.

1.1 PURPOSE

An integrated architecture creates many opportunities to execute the ambitious Moon to Mars efforts. Many of these opportunities involve establishing a systems engineering framework that can support the breadth of necessary program and system contributions. By applying these needs to nearer-term lunar development, NASA will be instituting the process, procedures, and techniques needed to enable longer-term Mars goals and more. Some of the challenges being addressed in the Moon to Mars Strategy are associated with the architecture definition, including broad/changing goals, funding, and external pressures/influences. This document and the methodology outlined for architecture definition have been crafted to contend with these challenges using an iterative and adaptable framework.

The primary purpose of the Architecture Definition Document (ADD) is to capture the methodology, organization, and decomposition necessary to translate the broad objectives outlined in the Moon to Mars Strategy into functions and use cases that can be allocated to implementable programs and projects. Inherent in this process is the need to communicate the long-term vision, maintain traceability to responsible parties, and iterate on the architectural implementation as innovations and solutions develop. This document is updated and improved in conjunction with the Architecture Concept Review (ACR), which is held annually to get buy-in and input from across the agency on the human exploration architecture. The annual nature of the process provides the opportunity to continually incorporate new developments in technologies and new partnerships, whether they are with industry, the U.S. government, international entities, or academia.

1.2 SCOPE

The scope of this document is to capture the programs, projects, systems, and contributions that enable the human exploration of the Moon, Mars, and beyond. The agency-level Moon to Mars Strategy encompasses the combined objectives that may be satisfied through human, robotic, or other efforts conducted across all agency directorates. NASA's Exploration Systems Development Mission Directorate (ESDMD) has established this ADD, the methodology, and the

[1] NASA System Engineering Handbook, SP-20170001761.

decomposition of the objectives for the efforts applicable to the human exploration architecture and robotic systems interfacing with or supporting it. Agency blueprint goals and objectives will, in many cases, also decompose or be supported by independent robotic or other non-NASA systems that, in combination with the human architecture, contribute to objective satisfaction. Objective decompositions in the ADD identify objectives derived to support human exploration architecture and systems. They may also have other functions, features, or uses beyond those presented here. The Moon to Mars Architecture process will coordinate objective decomposition in conjunction with all NASA mission directorates.

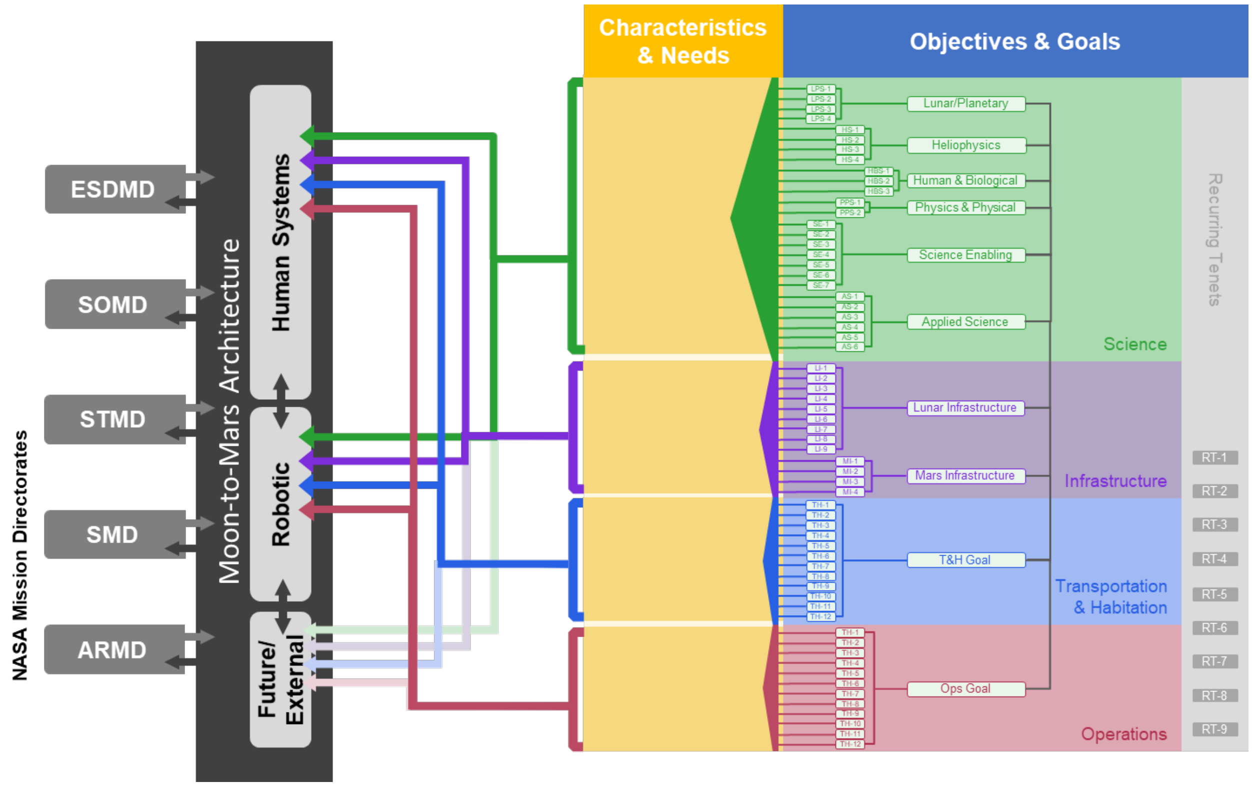

Figure 1-1. Human Exploration Moon to Mars Architecture Scope

1.2.1 ADD Content Structure

This ADD has been structured to reflect the architecture process and will be iterated on over time through subsequent analysis and integration efforts with partners. Section 1.0 describes the methodology and framework of the decomposition. This description includes definitions of the segments and sub-architectures used to describe the architecture and the process NASA will use to organize the decomposition through iterative cycles.

Section 2.0 Architecture Decomposition includes the rationale for the lunar architecture as viewed through a systems engineering lens. This describes the key drivers and questions that must be answered to arrive at the implemented architecture. Unique considerations for the Moon are also included. This section introduces the relationships between the architectural questions and how the order in which they are answered drives the Mars architecture. In subsequent iterations of this document, this content will eventually be replaced by the Mars architecture description as decisions are made and implemented. This section concludes with the decomposition of the objectives to the characteristics and needs the architecture must possess to support the Moon to Mars Strategy and Objectives.

Section 3.0 Moon to Mars Architecture describes the relationship of the characteristics and needs to assigned use cases and functions as applied to supporting architecture elements. These elements are organized by the architecture framework introduced in Section 1.0. In the scope of the ADD, one of the key drivers is to delineate between committed and funded elements and avoid premature inclusion of concept solutions. This approach is necessary to ensure the Moon to Mars Architecture reflects the open and evolutionary opportunities to support innovation, technology enhancements, and potential partnerships. As concepts are refined, the pre-formulation process develops elements into potential program/projects for implementation. These concepts are reviewed at NASA project management decision gates per the NASA Procedural Requirement 7120.5 NASA Space Flight Program and Project Management Requirements process. Following a successful NASA Mission Concept Review (MCR), an element will be approved as a candidate for inclusion into the architecture through the ACR process. NASA's project management decision gates, in combination with program/projects milestone reviews, will formally allocate architecture use cases and functions, key driving performance needs, and initial program/project concepts to the element. Additionally, following the successful completion of an MCR, the element concept also transitions to an implementing program/project phase. Through the ACR process, the ADD will be updated to capture the formal allocation of use cases and functions to the defined element in the appropriate segment. With respect to international partnerships, proposed cooperation will be included in the Moon to Mars Architecture and be reflected in the ADD upon the completion of internal NASA and partner reviews and conclusion of an appropriate international agreement. Section 3.0 also identifies open or unanswered questions in the architecture and the unallocated functions that are yet to be addressed by future systems or supporting elements. This section also includes descriptions of open trades or considerations for future architecture development are included, with an emphasis on the Mars Architecture.

Section 4.0 Assessment to the Recurring Tenets provides qualitative assessments of the architecture and reflects on the degree to which the architecture is adhering to the cross-cutting tenets of the strategy and objectives. These assessments are qualitative in nature to consider the state of the architecture and identify opportunities for revision. These will be living assessments updated on a recurring basis as the architecture adapts and develops. With respect to potential international partnerships, study agreements are developed to frame efforts. The ability to efficiently address gaps and needs in the architecture can be explored through strategic analysis, assessments of alternatives, and technology infusion studies. Results from these studies inform pre-formulation activities. Subsequent ADD revisions will be updated to reflect these efforts and potential areas of collaboration in the Section 4.0 Recurring Tenet 1 (RT-1): International Collaboration assessment.

The document content is followed by extensive decomposition and traceability tables in Appendix A. This appendix provides the complete traces from lunar objectives to the implementing element lunar use case and functions. Appendix B provides narratives of the priority Key Mars Architecture Decisions and a full list of candidate key decisions. The architecture-driven technology gaps list found in Appendix C identifies areas that need attention and innovation to enable future exploration. Lastly, Appendix D provides a list of acronyms and abbreviations and a glossary of terms for reference.

1.2.2 Content Outside of ADD Scope

During iteration of the ADD and communication of the architecture, it is important to note what the ADD includes and intentionally excludes. This is necessary to capture the content that is within the scope of the architecture effort and delineate it from the existing process or other implementing organization areas of responsibility. To this end, the ADD is not…

… a replacement for existing processes or agreements.

Existing documented NASA mechanisms and processes for partnerships, procurements, etc., are unchanged and existing formal governmental processes remain in effect. The architecture approach is to engage and communicate in support of these processes and architecture products will be updated to reflect decisions from the formal processes.

… procurement direction.

As with existing processes and agreements, the NASA procurement process is a formally documented and highly managed activity. Architecture products, including the ADD, white papers, and other materials, are to communicate needs and not to presuppose solutions. Any indications of the procurement timing, requirements definition, and contract methods are defined within the procurement process. The ADD informs the procurement process by articulating the relationships for new elements in the context of the wider architecture.

… a manifest.

Actual flight manifests, sequences, or specific mission content or design are the responsibility of the Moon to Mars Program(s), partner planning, and contract mechanisms. Manifests are subject to the development, budget, schedule, and other pressures that are beyond the scope of the ADD. The architecture products reflect the content necessary to achieve the Moon to Mars goals and objectives and their effectiveness at doing so. The actual manifesting of flights or schedule to achieve the objectives are subject to the procurement, development, and implementation processes managed by the implementing programs.

… a budget request.

Decisions related to the creation of programs and elements occur in the context of the budget planning process and are not presupposed in the architecture documentation of needs. Ultimately, those needs may be fulfilled through various means coordinated through the existing processes and procedures, including the budget analysis associated with them. Architecture products will inform those processes and reflect progress toward the objectives as decisions and content are approved, funded, or contributed.

1.3 ARCHITECTURE METHODOLOGY

The Moon to Mars Strategy has developed two complementary principles to address the complex framework: architect from the right and execute from the left. Architecting from the right means beginning with the long-term goal (farthest to the right on a timeline) and working backwards from that goal to establish the complete set of elements that will be required for success. Derived from the decomposed plan, systems and elements execute from the left in a regular development process, integrating as systems move left to right within the architecture.

NASA developed an applied systems engineering method to facilitate applying these principles to the architecture definition. The first part of this method is an ordered process of objective decomposition to complete the process of architecting from the right. The purpose of objective decomposition is to define the actionable capabilities the human exploration architecture needs to satisfy the agency's exploration objectives. In this process, the characteristics and needs are identified to ensure objective satisfaction. These characteristics and needs are then traced to the functions and use cases that must be accomplished by elements and systems. The second supporting method is establishing an architectural framework to organize, integrate, and track the allocation of functions and use cases to the executing programs and projects. This structure will enable the integration of the system-of-systems development, identify gaps in the architecture, and adjust the architecture as left-to-right execution occurs, technologies mature, or objectives are satisfied. The architectural framework is managed using sub-architectures and segments, which are discussed in Sections 1.3.2.1 and 1.3.2.2, respectively.

1.3.1 Objective Decomposition Process

As documented in the Moon to Mars Strategy, the broad top-level objectives of the Moon to Mars campaign have been identified with the help of stakeholders. These objectives establish desired results for NASA's exploration activities, with each objective defining a desired outcome of the Moon to Mars Architecture. Objectives were purposely drafted to be agnostic with respect to implementation, and thus do not specify architectural or operational solutions. Rather, they provide the goals to facilitate the development of an architecture and the means to measure progress.

To facilitate the objective decomposition process, several terms are defined as follows:

Table 1-1. Key Architecture Process Terms and Definitions

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.[2]
Needs	Statements that drive architecture capability, are necessary to satisfy the Moon to Mars objectives, and identify a problem to be solved, but are not solutions.
Characteristics	Features or activities of exploration mission implementation necessary to satisfy the goals and objectives.
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.
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.

[2] Definition from NASA System Engineering Handbook. SP-20170001761.

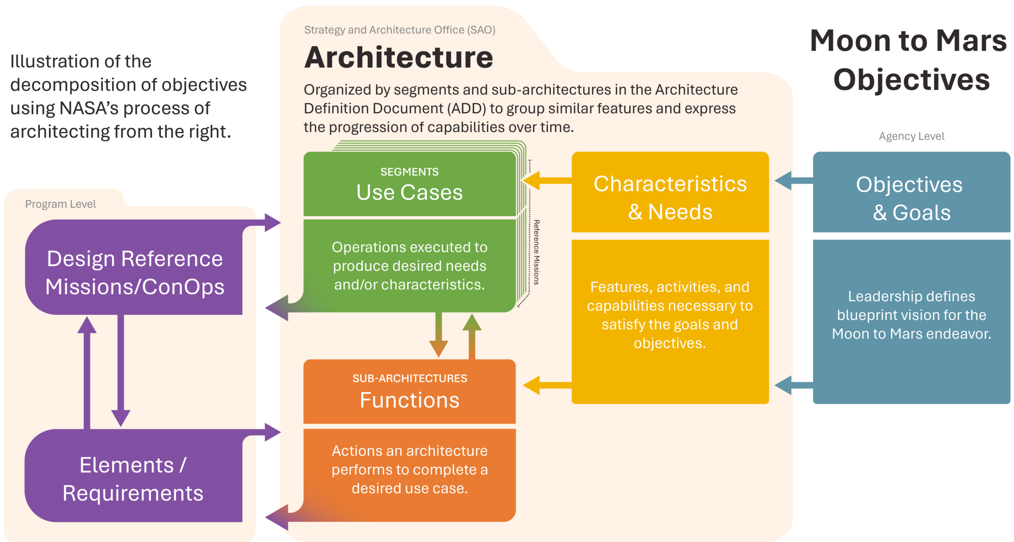

Figure 1-2. Objective Decomposition Process

The process that NASA will apply to define the exploration architecture, described in Figure 1-2, is rooted in the defined set of top-level objectives within the Moon to Mars Strategy. The process includes a series of discrete steps, each of which results in the progressive definition of needs with reduced abstraction in the architecture and increasing fidelity.

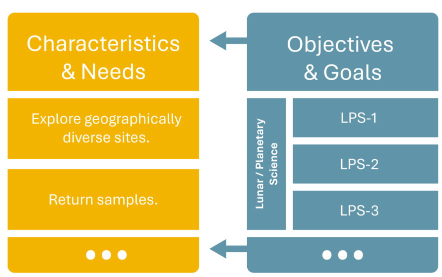

Figure 1-3. Notional Example Mapping of an Objective to Characteristics and Needs

The first step in this process is to define the characteristics and needs required to satisfy an objective or a group of objectives. While the 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. Characteristics and needs are defined in a form that is still neutral regarding architectural implementation, not specifying a particular solution to produce the desired results, but rather focusing on what the architecture produces or accomplishes. This step of the process is critical for converting generalized objectives into actionable exploration activities. Goal owners and stakeholders who are familiar with and helped to define the Moon to Mars Strategy's top-level objectives contribute to the definition of the characteristics and needs, adding the detail needed to define the features and products. Figure 1-3 shows a partial and notional example of how one representative objective could be decomposed into a set of characteristics and needs.

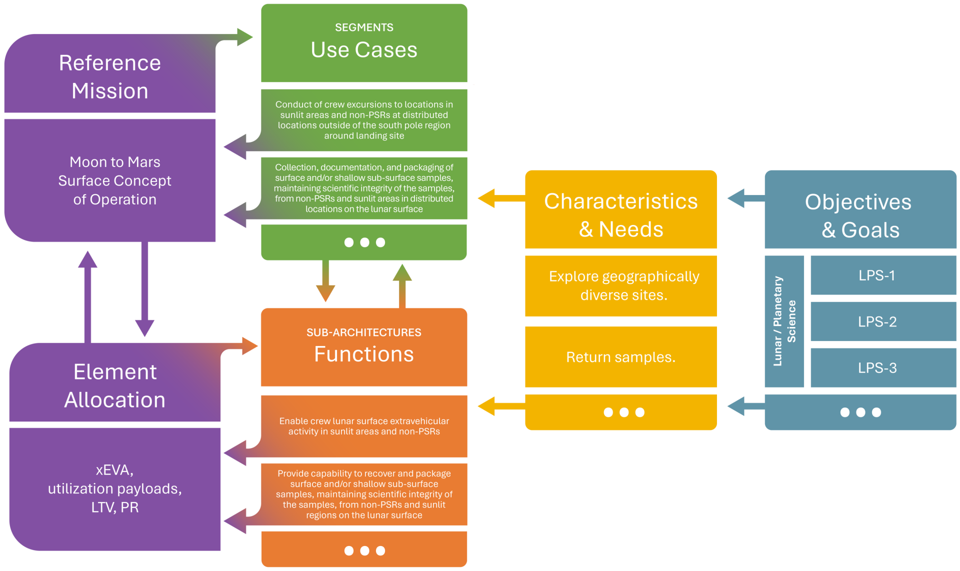

Figure 1-4. Notional Example Mapping of Characteristics and Needs to Functions and Use Cases

Once the characteristics and needs are defined, the next step in the process is to translate those statements into a more specific definition of implementable functions and use cases. This step adds further definition to the architectural needs and begins to define actionable features that could be included in the exploration architecture. Functions are the services or actions that the exploration architecture would have to produce to provide the desired characteristics and needs. Use cases describe how those functions are operationally employed to produce the desired characteristics and needs. Architecture teams formally decompose the characteristics and needs into functions and use cases, working with stakeholders to ensure that the defined functions and use cases would result in the desired outcomes.

In the last step in the decomposition process, the defined use cases and functions are organized to group similar features into representative reference missions, concepts of operations, and reference elements. Architecture teams, through trade studies and assessments, develop reference elements that can most effectively provide a subset, or group, of the desired functions within defined constraints. Similarly, teams develop reference missions and concepts of operations that employ those elements to fulfill the defined use cases. This step in the process is the first phase in the development of architectural solutions; it demonstrates the viability of the reference elements, reference missions, and concepts of operations in delivering the defined functions and use cases, providing the desired characteristics and needs, and satisfying the blueprint objectives.

Figure 1-4 shows an example of how the notional characteristics and needs could be further decomposed into notional functions and use cases. The decomposition of blueprint objectives is provided in Appendix A and will continue to be refined during future process cycles.

The definitions of reference missions, concepts of operations, and system requirements can be traced from the use cases and functions. The allocated use cases and functions will be used throughout the program or project formulation process to address feasibility, definition, and scope. Programmatic assessments will identify the existence of feasible solutions to meet the assigned functions and use cases as requirements are instantiated. If adjustments are needed in formulation, functions/use cases may be descoped for allocation to a different system later in the architecture process. During design and development, assessments will be conducted to ensure the system is achieving the expected architectural functions or adjustments are made as needed. Groupings and definitions may change as designs progress and/or are better understood; however, the mapping of objectives to reference missions, concepts of operations, and systems should be continually revisited to ensure objective satisfaction as intended.

1.3.2 Architecture Framework

Given the scale of the Moon to Mars Architecture, it is necessary to establish a framework for partitioning the effort into portions that are executable by NASA and its partners. Instituting a systems engineering process that empowers incremental advancements and the ability to infuse innovations in technologies and solutions provides the opportunity for economic benefit and the incorporation of partnerships while ensuring that objectives are systematically accomplished. In a typical systems engineering process, the architecture would be fully established up front, the requirements and concept of operations would be defined, and the programs would begin execution. This traditional method, if applied to the scale of Moon to Mars Architecture, would therefore have to "pick" the mission profile, technologies, and development schedule for an enormous number of projects up front and would be biased toward mature solutions and capabilities that exist today. This traditional "single pass through" architecture definition has been attempted for Moon and Mars systems many times in the past with limited success, as discussed in the Moon to Mars Strategy document.

To contend with this architecture breadth, NASA established an iterative framework process using two types of integration categories. The first type is to group tightly coupled systems, needs, and capabilities that function together to accomplish objectives as sub-architectures, similar to a system-to-sub-system relationship. More detail on the sub-architectures can be found in Table 1-2.

The second type is to establish segments defined as 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. The specific segments are discussed in Section 2.6.1 and Table 3-1. Segments reflect the integration reference missions established to ensure elements can function together. Actual missions and segments operations may overlap; it is not necessary to complete one mission or segment before functions and projects in the next begin operations. Together, these provide horizontal (sub-architecture) and vertical (segment) integration to provide traceability in the Moon to Mars Architecture definition as illustrated in Figure 1.

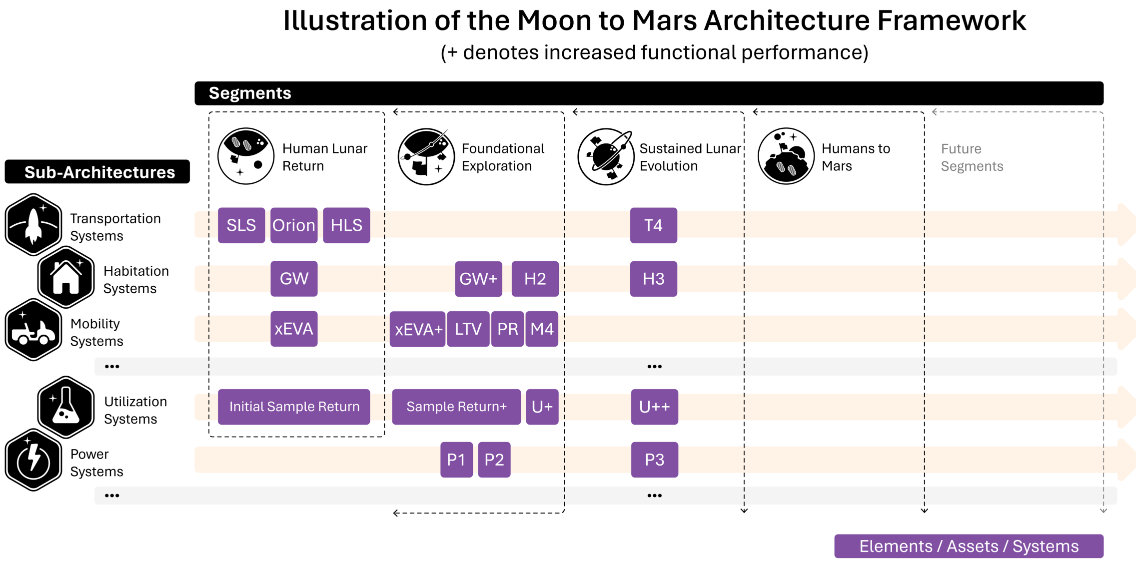

Figure 1-5. Illustration of the Moon to Mars Architecture Framework

In the Architecture Framework, the sub-architectures and segments will be used to ensure coherence in the elements, which may include various programs, projects, or systems, as represented by the lettered and numbered boxes. These programs and projects will be expanded or added to over time, plus additional elements with which they will need to interface within a sub-architecture. Segments will describe the relationship and cooperation across these elements. As systems mature, functions may be added or reassigned to reflect capabilities or implementations through the design or evolution of systems.

1.3.2.1 Sub-Architecture Definitions

The use of sub-architectures addresses the complexity of programs, projects, systems, and operations that span multiple sources or elements but must interact in a tightly coupled manner. By sub-dividing the architecture, functions and use cases can be assessed for consistency, gaps, or improvements. These sub-architectures will then evolve through the ADD iterations as functions and use cases are assigned to associated elements and systems to facilitate increasing capabilities toward the accomplishment of objectives. As shown in Figure 1Figure 1-5. Illustration of the Moon to Mars Architecture Framework, sub-architectures will add elements and systems through the progression of segments to achieve the associated characteristics and needs. These sub-architectures can facilitate and identify the areas where common standards and interoperability of associated elements are beneficial to ensure consistency in functions and allocations. Once identified, architecture-level interconnections can also be included in respective sub-architectures (e.g., Data Systems and Management) to ensure interoperability and application of common standards.

Table 1-2. Sub-Architecture Definitions

	Sub-Architecture	Definition
	Communication and Positioning, Navigation, and Timing Systems	A group of services that enable the transmission and reception of end-to-end data flows such as commands, telemetry, video, files, and voice across all elements and all missions, the ability to accurately and precisely determine location and orientation, the capability to determine current and desired position, and the ability to acquire and maintain accurate and precise time from a standard.
	Data Systems and Management	The group of avionics and software capabilities that works together to manage, compute, store, translate, and ensure integrity and interoperability of data for use throughout the architecture. Responsibilities of this sub-architecture include identifying and analyzing data handling (e.g., commands, files, telemetry, imagery, audio, and biomedical) across communications or computational systems to ensure architectural robustness, effective use of bandwidth, and interoperability between current and future technologies (e.g., encryption, servers, cloud computing, internet of things (IoT))
	Habitation Systems	A group of capabilities that provide controlled environments to ensure crew health and performance.
	Human Systems	The overall capabilities of the crew, ground personnel, and the supporting systems required to develop and execute safe and successful crewed and uncrewed missions.
	Infrastructure Support	The group of support capabilities including facilities (e.g., structures, site improvements, manufacturing/fabrication shops, and other labs), systems (e.g., environmental monitoring, contamination control, food/crop management), operations planning and control, equipment (e.g., access, construction, heavy equipment & common tools), and services (e.g., commodity storage & handling; inspection, maintenance, and repair) needed across all domains (i.e., Earth, in space, and surfaces).

	Sub-Architecture	Definition
	In-Situ Resource Utilization Systems	The group of capabilities dealing with estimating resource reserves and harvesting these resources to generate products (e.g., consumables, feedstocks for manufacturing and construction) on other planetary bodies (the Moon, Mars, etc.) or environments to further the goals of a project or mission while reducing the reliance on Earth-based resources and make space missions more sustainable and cost-effective.
	Logistics Systems	Systems and capabilities needed for packaging, handling, transport, staging, storage, tracking, and transfer of logistics items and cargo, including equipment, spares required for anticipated repairs, materials, supplies, and consumables including capabilities for disposal.
	Mobility Systems	A group of capabilities and functions that enable mobility of crew and/or cargo on and around the surface of the destination, including extravehicular activity systems.
	Power Systems	Capabilities that support the function of providing electrical energy to architectural elements. These capabilities include components and hardware for power generation, power conditioning and distribution, and energy storage.
	Autonomous Systems & Robotics	A group of capabilities which are accomplished with the use of software and hardware devices that can assist the crew and operate during uncrewed periods, either autonomously and/or via remote operator control (tele-robotics).

	Sub-Architecture	Definition
	Transportation Systems	Capabilities that provide the transportation functions for all phases of the Moon and Mars missions for both crew and cargo, including in-space; entry, descent, and landing (EDL); and ascent for all Earth, Moon, and Mars phases.
	Utilization Systems	A group of capabilities whose primary function is to accomplish utilization which enables science and technology demonstrations.

The initial set of identified sub-architectures reflects the current state of program and project development and current integration challenges. While the sub-architectures are defined independently, they will have interfaces and dependencies with other sub-architectures and will all work together to perform utilization activities supported by the architecture. The current sub-architectures will be refined and new sub-architectures will be identified during future ACR cycles. Table 1-2 identifies and provides rationale for the initial sub-architectures.

1.3.2.1.1 Communication and Positioning, Navigation, and Timing Systems

The Communication and Positioning, Navigation, and Timing (C&PNT) sub-architecture is a group of services that enable the transmission and reception of end-to-end data flows such as commands, telemetry, video, files, and voice across all elements and provides all missions with the ability to accurately and precisely determine location and orientation, the capability to determine current and desired position, and the ability to acquire and maintain accurate and precise time from a coordinated lunar time standard that is traceable to Earth's Coordinated Universal Time (UTC). The regions in which service is available, the delivery mechanisms for those services to those areas, and the evolution of each aspect throughout the lifetime of the architecture are all key factors that will affect C&PNT implementation. Another key consideration for a strong foundation is maximizing the interoperability of C&PNT assets throughout an evolving architecture with many different providers and users (e.g., government, commercial, scientific, international). As the architecture evolves, the C&PNT sub-architecture and concept of operations will scale based on the developing user needs and will evolve by collecting ground truth data as the campaign progresses. Services may expand (for example, with high-throughput optical links), and service regions may expand to include larger volumes of data on the South Pole and Far Side. Position, navigation, and timing services may expand to more Global Navigation Satellite System (GNSS)–like capabilities by providing services on a global or regional basis. Accurate position, velocity, and time knowledge are essential for applications like safe navigation, tracking, surveying, geolocation-based services, and precision temporal and spatial science. The evolution of lunar communications and navigation capabilities will close knowledge gaps to enable NASA and its partners to develop communications and navigation capabilities and concepts of operations for Mars missions.

1.3.2.1.2 Data Systems and Management

The Data Systems and Management (DS&M) sub-architecture includes capabilities that work together to move, manage, 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 to ensure data is shared and made useful across the architecture. Future capabilities may include data fusion, internet of things (IoT), cloud computing, and servers. The implementation of this sub-architecture spans Earth systems, space, and planetary surfaces. Not all capabilities are expected to reside in-situ; each domain will include a mixture of assets.

Data systems and management play a pivotal role in modern information-driven landscapes. This area encompasses the intricate framework 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 Moon to Mars Architecture ensures that valuable insights can be derived from raw data, driving informed decision making and providing broad access as allowed.

The DS&M sub-architecture provides architecture definition for logical and conceptual data models using element-level physical data specifications. This data architecture includes analysis of relationships among elements to ensure robustness throughout the evolution of NASA missions. These systems can consist of databases, their management systems, data warehouses, and data lakes that collectively organize and maintain data integrity. With the advent of big data, cloud computing, and advanced analytics, modern data systems not only handle structured information, but also embrace unstructured and semi-structured data formats. A robust data management strategy considers data availability, quality, interoperability, security, privacy, compliance policy, and access to ensure that we can harness the full potential of the expansive amount of lunar data, fostering innovation across the architecture. The architecture considers cybersecurity as a key aspect of the design given the many government, commercial, and international elements that are part of a common architecture. Given the diversity of these interfaces, cybersecurity architecture design is critical in minimizing impacts from threats of these various elements and works to reduce overall risk to the system.

1.3.2.1.3 Habitation Systems

The Habitation sub-architecture is a group of capabilities that provide controlled environments to ensure crew health and performance over the course of missions. This functionality extends across multiple applications throughout the architecture and is tailored to suit the location and environment (e.g., deep space, lunar surface, Martian surface). Common habitation functions include environmental control and life support (ECLS), thermal control, extravehicular activity (EVA) support (e.g., ingress/egress, suit services, worksite accommodations), crew habitability (e.g., hygiene, food and nutrition, waste management, sleep, crew exercise), crew health (e.g., health and medical care, human performance, psychological support), and crew survival (e.g., pressurized suits, safe haven), among others. These functions may scale in size and complexity based upon crew size, mission duration, operational environment, and the ability to share functionality through interfaces with other elements (e.g., consumables and power transfer). As such, the volume and structure supporting habitation can vary drastically and potentially include modular, connected, pressurized volumes of various materials (e.g., inflatable soft goods, metallic structure, in-situ constructed elements). While crew size and mission duration are primary factors in scaling the appropriate habitable volumes, other factors such as gravity environment, crew tasks, and required motions (e.g., supportability of on-board equipment; accommodation of science and technology utilization; and logistical stowage and resupply that require controlled, pressurized environments) also factor into overall volume. Some key trades to help scope such habitation elements include EVA ingress/egress methods, logistics resupply needs, and use of regenerable ECLS systems (ECLSS). To maximize the availability of crew time to perform science and technology utilization activities and to maintain nominal operation in each operational environment while uncrewed, habitation elements must use system autonomy (e.g., vehicle/element control and operation, including planning/scheduling/execution and fault management; identification/recovery; robotic assistance) while also enabling crew control (i.e., manual operations, software override) for critical functions and troubleshooting during unforeseen contingencies.

1.3.2.1.4 Human Systems

The Human Systems sub-architecture covers the collective capabilities of the flight crew, ground/mission teams, mission systems, and enabling architecture required to develop and execute safe and successful crewed and uncrewed missions that are not covered by sub-architectures like Habitation Systems, Mobility Systems, Logistics Systems, and others. However, the Human Systems sub-architecture is tightly coupled with all the other sub-architectures. Human Systems is unique from the other hardware sub-architectures; it significantly expands exploration beyond uncrewed mission capabilities. These systems ensure the safety and success of the mission and the well-being of the crew. They require a multidisciplinary approach, involving expertise in engineering, medicine, space science, human factors, safety and mission assurance, and operations. These systems are crucial for monitoring and maintaining crew health, enabling crew to accomplish the jobs required across the architecture, supporting the crew’s physical and mental performance, and keeping the crew safe and comfortable during the mission.

The humans who embark on the exploration missions are the most critical component of the campaign to get humans to the Moon and, ultimately, to Mars. Vehicles, systems, training, and operations must be designed around the “human system.” The success of ambitious lunar and Mars crewed missions will largely be determined by the degree to which the human system is strategically considered and integrated into the architecture. The architecture and implementation should allow the crew to move and operate seamlessly across elements to execute the mission. The Artemis Flight Control Team, consisting of the Mission Control Center – Houston (MCC-H) and other NASA/partner control centers, will monitor and control the crewed and uncrewed Artemis elements. This distributed operations model leverages decades of experience from International Space Station collaboration with international and commercial partners while advancing partner roles for Artemis. Standards for human-rated systems, design and construction, safety and mission assurance, crew health and performance, flight operations, crew and ground personnel training and certification, and system interoperability are necessary to conduct safe and successful missions. Mars missions will require NASA and its partners to fill key knowledge gaps and establish standards related to human performance after extended deconditioning beyond the International Space Station 6-to-12-month mission timeframe, with crew-Earth communication delays beyond a few seconds, and/or with total Earth autonomy for up to two weeks. Human capabilities and limitations within the context of mission-induced environments will drive the enabling architecture for element robustness, integrated capabilities, interoperable/consistent interfaces, human system integration, and crew health and performance.

1.3.2.1.5 Infrastructure Support

The Infrastructure Support sub-architecture describes the infrastructure associated with the operations of the Moon to Mars endeavor across the Earth (ground), in space, and in extraterrestrial surface domains. Several of the sub-architectures will have facilities, systems, equipment, and services in these domains that require supporting infrastructure. For example, ground processing of spaceflight elements and logistics items supports the transportation sub-architecture. Other examples include landing and recovery infrastructure on the ground for returning transportation vehicles and curation facilities for samples returned from the Moon and Mars. An in-space example is landers that require adapters to transfer stages. Surface examples include equipment needed for handling, accessing, and transferring dry goods and fluid commodities and common and portable lighting support equipment, both of which are likely to be shared across sub-architectures. Surface examples may also include prepared regolith surfaces or structures to minimize lofted dust, facilitate transfer of materials, and maximize crew mobility.

1.3.2.1.6 In-Situ Resource Utilization (ISRU) Systems

In-situ resource utilization (ISRU) is the concept of locating, mapping, and estimating extraterrestrial resource reserves and extracting and processing these local resources to generate products instead of delivering the products from Earth. As humans stay longer and go farther into space and the focus turns to more sustainable commercial operations and Earth independence, missions will incorporate ISRU practices. ISRU starts with identifying, characterizing, and mapping the resources at potential sites of exploration. ISRU identifies products that can significantly reduce mission cost and risk or enable new mission options, such as utilizing local resources (both natural resources, such as regolith, water, atmosphere, etc., as well as crew trash, waste, discarded hardware, etc.) to produce water, propellant, and other supplies, and capabilities to excavate and construct structures on an extraterrestrial body. ISRU pathways include commercial-scale water, oxygen, and metals; consumables for humans and food production; feedstock for construction, manufacturing, and energy; and commodities for reusable in-space and surface transportation and depots.

For successful implementation, ISRU systems and capabilities must obtain products and services from other lunar systems and infrastructure, and ISRU systems and operations require customers/users to utilize the products/commodities they produce. Lunar support services and infrastructure for ISRU systems include material transfer and asset movement between ISRU resource extraction, processing, waste tailing, product storage sites, handling and manipulation of resources and bulk regolith, local navigational aids, communications to/from and within ISRU operational sites, power transmission and management, crew and robotic logistics management, maintenance, and repair capabilities, and construction of roads and infrastructure to/from and on the ISRU operation sites. To achieve the full benefits of using in-situ derived products and to meet the intent of Moon to Mars Objective OP-11, customer/users need to design their systems and concepts of operation around the availability and location of these products and how they can be provided. To minimize the risk to the Artemis campaign and ISRU product customers, NASA and its partners must plan a transition of Earth-delivered to ISRU-derived products, along with adequate resource mapping and demonstration of the ISRU processes and product quality.

1.3.2.1.7 Logistics Systems

The Logistics Systems sub-architecture includes the systems and capabilities needed for packaging, handling, staging, and transferring logistics goods, including equipment, materials, supplies, and consumables needed to support use cases and meet architecture functional needs. This sub-architecture also includes approaches and capabilities for addressing trash and waste management. During the initial part of the campaign, the capability for logistics goods and consumables will be limited to those that arrive with the crew. As time advances, additional functions are introduced into the architecture. The logistics needs will broaden as the sub-architectures mature. Over time, the architecture will require solutions for increasing Mars mission duration. The need to deliver elements, payloads, cargo, experiments, and larger quantities of logistics and to better address inventory management, trash, and waste disposal functions necessary to support the missions and meet planetary protection requirements will increase. As the sub-architecture matures, the capabilities can continue to grow to take advantage of increased automation and/or in-situ resource sourcing of logistics to support increased mission durations.

1.3.2.1.8 Mobility Systems

The Mobility Systems sub-architecture is a group of capabilities and functions that enable the mobility of crew and/or cargo on and around the destination, including EVA systems. This sub-architecture extends the range of exploration and external operations in support of science. It spans robotic and crewed systems with both pressurized and unpressurized capabilities. Mobility systems will likely need to interface with other sub-architecture capabilities like power, C&PNT, habitation, and logistics to accomplish the desired outcomes.

1.3.2.1.9 Power Systems

The Power Systems sub-architecture is a group of capabilities that support the function of providing electrical energy to architectural elements. These capabilities include components and hardware for power generation (e.g., solar arrays, fission surface power [FSP]), power distribution (e.g., electrical cables, induction), and energy storage (e.g., batteries, regenerative fuel cells). A primary aspect of the power sub-architecture is interoperability, including standardized power interfaces (either hard or inductive connections) and compatible power quality standards. The power sub-architecture will include the coordination of missions where elements are expected to provide their own power with the development of energy infrastructure to support future needs.

1.3.2.1.10 Autonomous Systems and Robotics Systems

The Autonomous Systems and Robotics (AS&R) sub-architecture aims to integrate the unique and complementary capabilities of humans and robotic systems to maximize the crew's efficiency, provide needed capabilities during uncrewed mission phases, and expand the range of possible exploration, science, and utilization activities 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 the crew to focus on higher-priority activities while at the destination and improves safety without sacrificing operational effectiveness or mission reach. Robotics capable of efficient and effective mobility and manipulation improve remote access to areas of scientific interest; asset handling, repositioning, and utilization; logistics management; and infrastructure assembly, outfitting, and maintenance during crewed operations (and enable them in the absence of crew) and robotic reconnaissance (e.g., scouting, surveying, mapping, collecting samples). During both crewed and uncrewed periods, robotic operations will be performed remotely via teleoperations of robotic systems or with increasing levels of autonomy, requiring minimal human interaction. The AS&R sub-architecture includes capabilities and systems that can 1) assist the crew (working in tandem or collaboratively with them), 2) perform operations at a distance from crew under their control or supervision, 3) operate remotely in the absence of crew, and 4) perform tasks in parallel to crew independent of crew timelines and requiring no oversight or intervention by the crew. The sub-architecture also includes support systems and equipment on Earth, such as simulations, planning and scheduling tools, and ground analog test beds. The sub-architecture spans the Earth (ground), cislunar space, and lunar surface environments, and eventually includes Mars.

1.3.2.1.11 Transportation Systems

The Transportation sub-architecture is the collection of capabilities that provide the transportation functions for all phases of the Moon and Mars missions for both crew and cargo, including in space; entry, descent, and landing (EDL); and ascent for all Earth, Moon, and Mars phases. The transportation systems will need to interface with or be incorporated into a variety of systems and payloads, including habitation and other human support systems, as well as refueling or recharging systems, all in diverse environments, including in-space and surface conditions. 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 surface, ascent of crew and limited cargo to cislunar space, and return to Earth. As the architecture expands toward Mars, the transportation sub-architecture will evolve to include Mars transit, EDL, and ascent systems for cargo and crew.

1.3.2.1.12 Utilization Systems

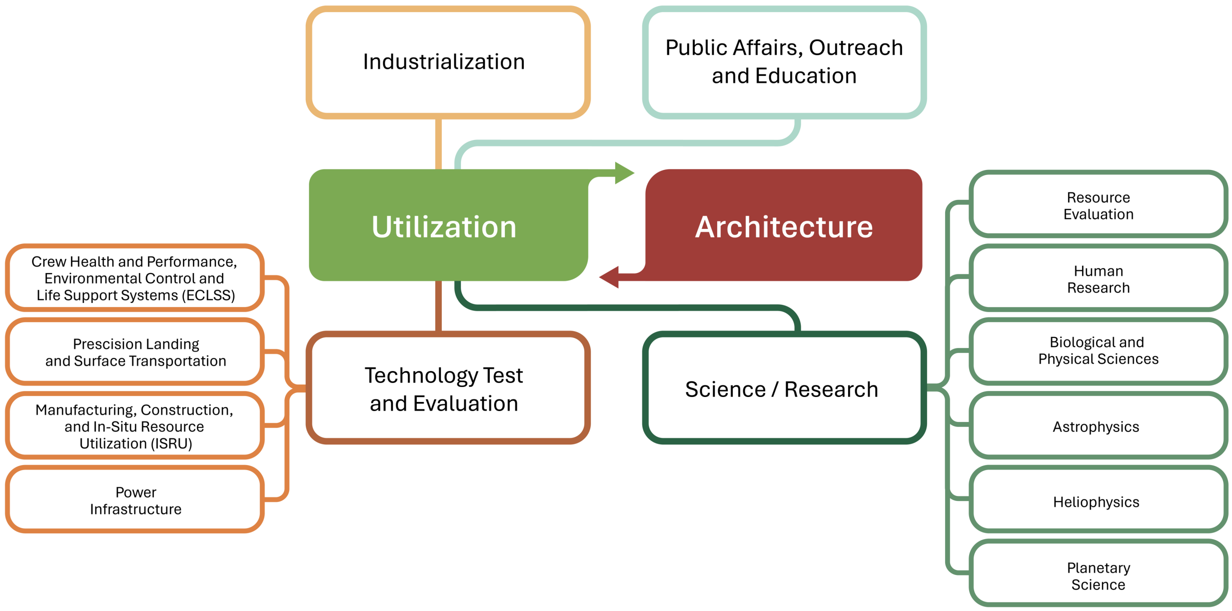

Figure 1-6. Visualization of Utilization Areas

The Moon to Mars Strategy document[3] defines *utilization* as the "use of the platform, campaign and/or mission to conduct science, research, test and evaluation, public outreach, education, and industrialization." In this document, the term *utilization* is used generically to encompass all areas of utilization; specific terms, such as "science or technology demonstration," are used where the meaning is more specific. The Utilization Systems sub-architecture is a group of capabilities whose primary function is to accomplish these science, technology, and other activities, including sample and utilization cargo return to Earth. In this sense, the Moon to Mars Architecture provides a platform of functions to a broad set of organizations in support of their needs. Inherent in the Moon to Mars Architecture is that all the sub-architectures ultimately support utilization; utilization systems will levy functions and use cases on all other sub-architectures. The major utilization areas of emphasis for the Moon to Mars Architecture are depicted in Figure 1-6.

Utilization is achieved through not just the capabilities in the Utilization Systems sub-architecture, but the entire architecture. For instance, a technology may be demonstrated under the umbrella of utilization on one mission and, through technology maturation, provide essential services as part of the exploration platform on subsequent missions. Similarly, some items may serve multiple functions (e.g., multi-purpose cameras used for both science and operations, equipment shared between human research and medical operations). However, systems whose primary purpose is to achieve utilization, and not just enable the mission, will be included in the utilization sub-architecture.

1.3.2.1.13 Future Sub-Architecture Development

As the focus of the Architecture Framework is to establish the process for recurrent architecture definition and refinement, the sub-architectures will continue to evolve. The current sub-architectures were initially established based on knowledge gained from driving system

[3] NASA's Moon to Mars Strategy and Objectives Development, NP-2023-03-3115-HQ.

requirements and included updates based on the revised use cases and functions. Future revisions will likely include additional sub-architectures.

1.3.2.2 Campaign Segment Definition

Segments capture the interaction, relationships, and connections of the sub-architectures at a specific phase. These would most commonly be typified by reference missions or operations use cases of the systems to illustrate how systems will work together to satisfy objectives. These examples provide the context for the allocation of functions to elements and systems in the sub-architectures, rather than prescriptive solutions. These segments will grow increasingly complex as systems are developed and added to the sub-architectures. The segments are crafted in a manner such that the knowledge gathered earlier in the campaign informs implementation later in the campaign. The segments integrate the exploration, utilization, and sustained development of the Moon, with preparation for the exploration of Mars. The segments integrate needs and capabilities over time but are not a defined launch manifest, as systems from a later segment may begin to appear as available. Further, in representing the context of the sub-architecture interactions, segments do not limit the types of missions that may be designed and flown. As systems are built, novel operations and uses are expected.

The segments, described in detail in Section 3, reflect the current Moon to Mars effort and provide open opportunities to refine and include use cases in the architecture as systems and technologies mature. The segments and their content will evolve through the annual ACR cycles to reflect the inputs, capabilities, and needs identified across the partners to achieve the Moon to Mars Strategy.

1.3.3 Architecture Definition Process

Having established the necessary components to decompose objectives (“architecting from the right”) and the framework to correlate the systems (“executing from the left”), the process by which these components and systems will be integrated remains. NASA and its partners established the process to enable an iterative allocation to programs and projects and infusion of solutions, technologies, and capabilities that emerge over time to address the strategy objectives. This process is managed by NASA’s ESDMD through the coordination of Strategic Analysis Cycles (SAC). These cycles will occur annually to prioritize the work and studies needed to address open questions, identify potential architectural drivers to buy down mission risk, coordinate with partners, and identify and resolve gaps in the architecture. The cycles will conclude with study findings and/or updates and iteration to the ADD and supporting products, which are reviewed at the annual ACR.

These iterative cycles will need to both enable the definition of new elements or systems as they are added to the architecture by defining the allocated functions and needs and update and modify the architecture as existing elements and programs mature. The SAC process will also need to include assessments or studies of how emerging technologies or new solutions, whether from within NASA or from partners, could address architecture needs or modify the future segments. This complex analysis process will reflect a diversity of viewpoints, perspectives, and ideas from stakeholders and partners.

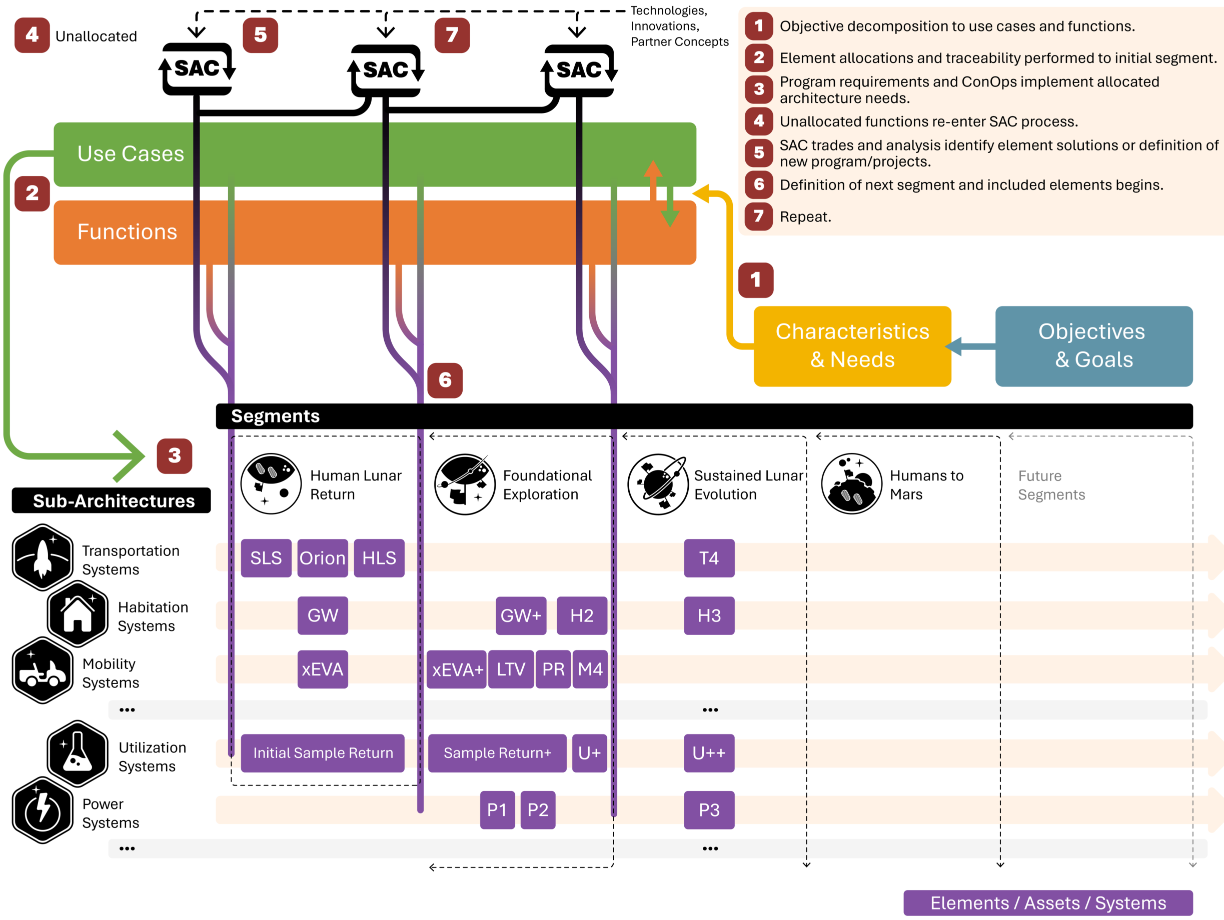

Figure 1-7. Illustration of the Architecture Definition Process

Table 1-3. Iterative Architecture Process Steps

#	Iterative Architecture Process Step
1	Objectives decomposed to use cases and functions
2	Element allocations and traceability performed to segments
3	Program requirements and concepts of operation implementation allocated to architecture needs
4	Unallocated functions (gaps) re-enter SAC process w/ partner inputs/concepts

#	Iterative Architecture Process Step
5	SAC trades and analysis identify element solutions or definition of new program/projects, including sub-architecture allocation and/or alignment
6	Definition of next segment and included elements begins
7	Repeat

Figure 1 shows the architecture definition process, which reflects the intersection of the architect from the right and execute from the left principles outlined in the Moon to Mars Strategy. Examples and representative systems using known sub-architectures, segments (discussed further in Section 3), and elements are used to illustrate this iterative process. This process reflects the reality the systems, functions, and needs of the most immediate segments are known and that significantly fewer allocations are made as the segments process to the right. Systems reflected in the current programs and projects are already executing their development and, in some cases, have conducted their first flights, such as the Space Launch System and Orion. Modifications to these existing systems should be limited or carefully traded in future segments. The SAC process will need to consider the programmatic trades in any allocation, whether existing or new systems are used, for cost, schedule, technical, and risk factors. The process steps are highlighted in Figure 1 are outlined in Table 1-3. Iterative Architecture Process Steps.

The SAC trade studies will continue to evaluate concepts and analysis to identify possible solutions to address unallocated functions and potential alternatives. Coordination with both internal NASA partners and external partner communities will be a key enabler to identify solutions that can most effectively satisfy objectives. Inputs of technological advancements, alternate concepts, and other innovations can be assessed for satisfaction to meet the integrated architecture needs during the SACs. These assessments will mature and refine allocations in partnership with the executing element or partner leadership to ensure traceability from the use cases and functions into the requirements and concepts of operations that formally establish the design process for execution. The SAC process will also consider technology advancements, alternative solutions, and different concepts to identify efficiencies or priorities for development in future segments. As program execution matures and actual missions are flown, the architecture will account for realized system performance and science discovery. These efforts will inform how future systems and elements are instantiated and developed as systems mature.

2.0 ARCHITECTURE DECOMPOSITION

A similar systems engineering process to the one applied at the strategic level in Section 1.0 can be used as a framework for the architecture by addressing the six key questions: Who, What, Where, When, How, and Why? (Figure 2-1.) Different stakeholders may find the answers to some of these questions more compelling than others: for example, engineers tend to focus on “How?,” whereas technology developers may be more interested in “When?”; partners want to know “Who?,” and scientists may be keen to discuss “Where?” and “What?” To reach consensus and move forward, an exploration architecture must address all six questions, but reiteration and negotiation may be required. The answer to any one question is less important than ensuring that the answers to all six fit together as an integrated whole.

Figure 2-1. Elements of a Compelling Architecture Story

2.1 Exploration Strategy: "Why Explore?"

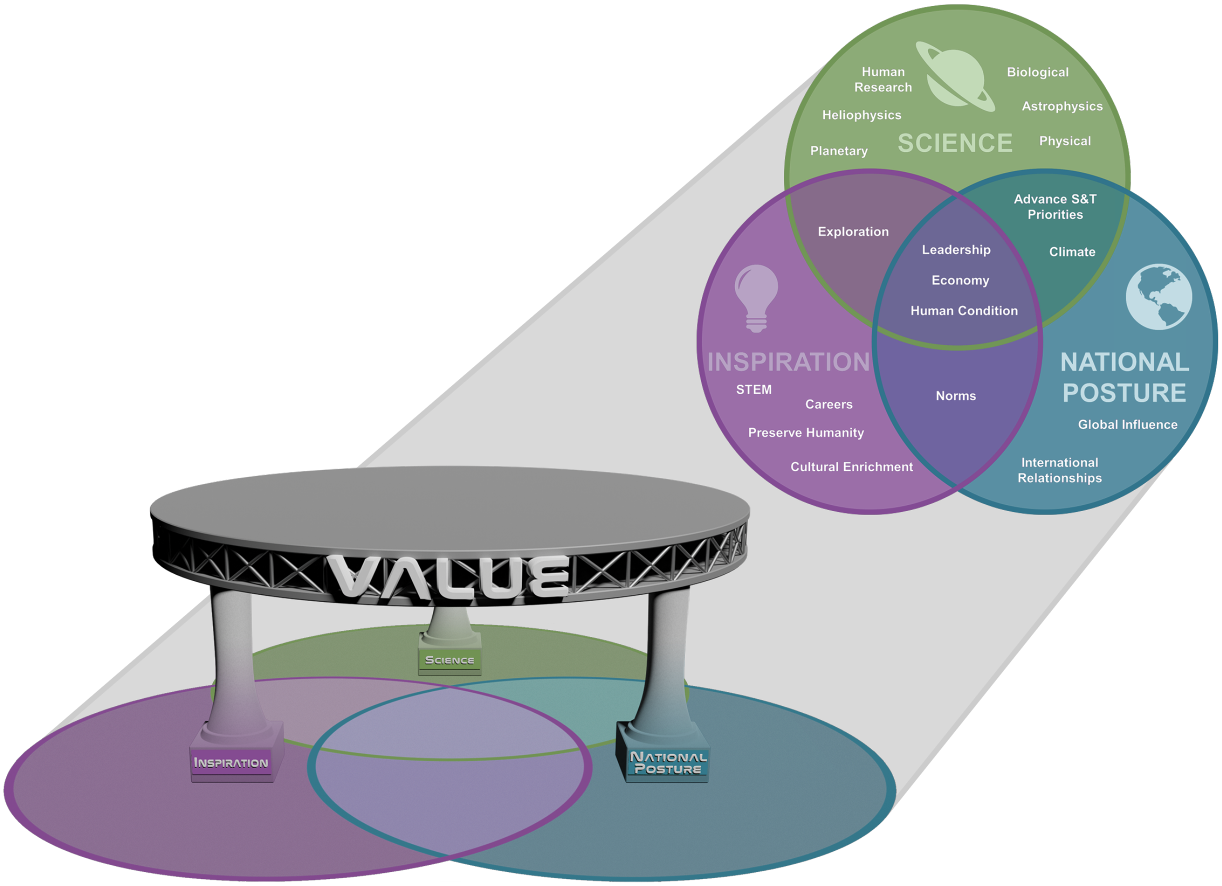

Figure 2-2. Three Pillars of Exploration from NASA's Moon to Mars Strategy and Objectives Development Document[4]

Systems engineering is predicated on the motivation, which is the fundamental goal. Why do this? For the blueprint vision and Moon to Mars endeavor, along with its goals, objectives, and subsequent architectural wireframe, the question is: Why send humans into space? Creating a blueprint for sustained human presence and exploration throughout the solar system provides a value proposition for humanity that is rooted across three balanced pillars: science, inspiration, and national posture. Each pillar contains both unique and intersecting stakeholder values that together form the value proposition for the blueprint vision, starting with the Moon to Mars endeavor (shown in Figure 2-2). While different individuals identify with different values, it is NASA's responsibility as a steward of taxpayer dollars to consider the entire landscape of motivating factors that underscore our society's answer to Why Go? Uniquely, by balancing all the factors, NASA positions the Moon to Mars strategy for longevity and success: it is not subject to whims or leadership overhauls. Instead, it is rooted deeply in a broadly relevant, largely unchanging value system. So, Why Go? These combined and intersecting three pillars, as illustrated in Figure 2-2, are why humans go into space.

[4] NASA's Moon to Mars Strategy and Objectives Development, NP-2023-03-3115-HQ.

2.1.1 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 engagement with and visitation of other bodies in the solar system ultimately reap more data more effectively.

2.1.2 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. Specifically, 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 United States companies. Commercial space activity impacts other industries, such as agriculture, maritime, energy, and homeland security, producing ripple effects throughout the economy. Additionally, 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.

2.1.3 Inspiration

The "Moonshots" of the Apollo Program became a metaphor for how we as a 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 — the Artemis 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.

2.2 LUNAR ARCHITECTURE STRATEGIC ASSESSMENTS

The effort to return humans to the Moon has been addressed at a strategic level first by answering the "Why," as documented in NASA's Moon to Mars Strategy and Objectives Development document. This strategic plan ensures that the lunar architecture must consider a range of stakeholder needs, including the long-term goal of enabling Mars and other deep space exploration. Definition of the architecture and the methodology to achieve it is fundamental to the leadership needs reflected in the "Why." By implementing an architecture that can respond to innovation and developments and includes partners, the endeavor will enable benefits reflected in terms of both the economy and the human condition. Working from both the blueprint objectives and the array of available Mars studies, NASA has derived several key characteristics of the lunar architecture. Throughout all of these decisions, the Responsible Use (RT-6) Tenet is applied to ensure consistent application of policy, legal, and ethical frameworks. Areas of uncertainty about how policy or standards should be applied to the objectives or architecture are elevated to agency leadership for resolution.

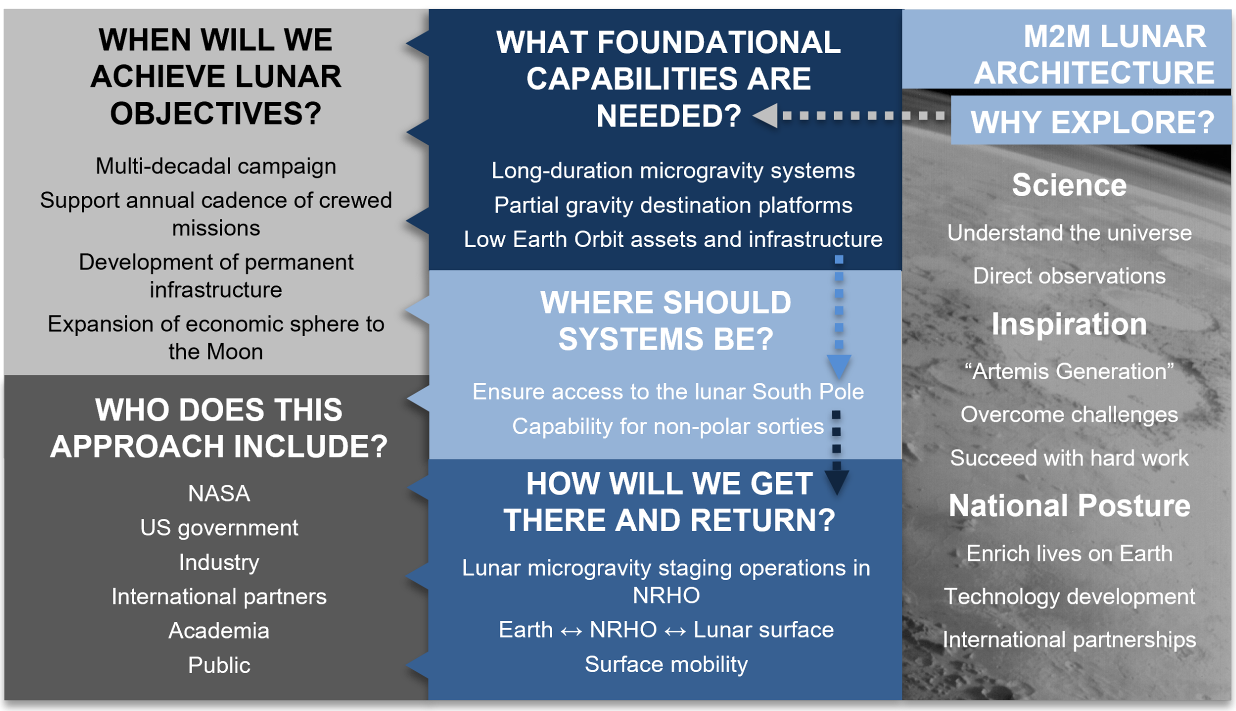

Figure 2-3. Lunar Architecture Decision Flow Starting with "Why?"

As illustrated in Figure 2-3, answering the "Why" for lunar exploration is only the first step in the decision process. Answering (or exploring the option space for) other big architecture questions ("Where," "What," "Who," "How," and "When") helps define the key characteristics of the lunar exploration campaign.

There are other questions that will be answered while developing programmatic solutions for architecture implementation, including "how much?," "how safe?," etc., that take the form of constraints as conditions to be met. These constraints inform an iterative design loop driven by the set of stakeholder expectations where an architecture, the associated concepts of operations, and the derived requirements and design solutions are developed and programmatic constraints such as cost and schedule are applied. The associated implementing organization works this iterative loop (sometimes referred to as “closure”), which is informed by the architecture in this document.

2.2.1 Key Lunar Decision Drivers

2.2.1.1 “What” Foundational Capabilities are Needed?

As decomposition of the objectives — captured in the Strategy and Objectives document — indicates, several technological, scientific, or human condition insights are needed to inform Mars architectural decisions. These multi-dimensional objectives across the science, technology, and infrastructure development goals will need to be supported by foundational platforms from which the crew will operate. These systems will enable the crew to retrieve and return samples, deploy instrumentation or technology demonstration, research in-situ resource utilization, understand the human condition in long-term deep space exploration, and much more. The ability to support these activities and the decomposition of the capabilities needed to accomplish science and infrastructure objectives will be key characteristics for cislunar and surface destination systems. Common across all architectural studies to date is the need to provide demonstration and test environments across dynamic space weather conditions, deep space microgravity, partial gravity, and the transitions between them. These environmental drivers must be paired with increasing operational durations to establish sufficient design, engineering, and demonstration drivers in the architectural approach.

From these assessments, two key destination systems and the ability to transition between them are derived as platforms for this development. First is the ability to stage long-duration microgravity systems in deep space or near–deep space–equivalent environmental conditions that analogues to the transit conditions to and from Mars. This platform will necessarily need to accommodate a human crew and function with reductions in the crew-managed reliability, maintenance, and ground intervention associated with near-Earth systems (RT-5 Maintainability and Reuse). Other characteristics beneficial for any microgravity platform include the ability to aggregate elements autonomously and to support incremental build-up to prepare for the eventual accumulation of systems necessary for Mars transit.

Second, the destination platform must provide human systems deployment and aggregation in partial gravity with what can be considered “hostile” atmospheric conditions (in the case of Mars) or no atmospheric environment (in the case of the Moon). This surface platform as an aggregation of elements will also provide the opportunity to demonstrate the necessary components for achieving Mars-forward systems for human-conducted surface exploration. These systems will need to support increasingly long crewed exploration periods and be expandable to accommodate the breadth of the objectives laid out towards the Mars goal.

The architectural approach will also leverage available low Earth orbit (LEO) assets and infrastructure to accomplish lunar and Mars objectives. In this regard, exercising objective capabilities at the lowest energy state (whereas performance demand can be considered proportional to the resources and/or programmatic needs) will be applied throughout (RT-8 Leverage Low Earth Orbit).

2.2.1.2 “Where” Should the Systems Be?

From the definition of the “What,” it is necessary to support the architectural approach in the microgravity and surface platforms; “Where,” in relation to the Moon, became the next systems engineering driver. To ensure the platforms’ support of long-term objectives and the balanced-systems approach of the “Why,” NASA and other organizations have conducted numerous studies of lunar system locations. The primary consideration of "Where” is to ensure surface access to and optimization for the lunar South Pole; however, this approach ensures access to non-polar locations as well.

The lunar South Pole has several key driving characteristics to enable systems development for the Moon to Mars Architecture. First, from a flight performance perspective, the lunar South Pole provides a bounding condition for vehicle translation or delta-velocity costs. These performance drivers are one of the most significant conditions for transportation system design. Vehicles and reference missions designed to achieve landing at the South Pole can provide future flexibility to reach global locations through planning and certification. This approach differs from the Apollo vehicles and systems, which, when directed to reach the Moon at essentially the earliest possible time (answering the “When” question first), necessarily selected the “easiest” lunar landing sites on Earth-facing, near-equatorial regions and lacked the performance and systems capabilities for global and/or polar landings.

Second, lunar poles support multiple scientific and engineering values, and the South Pole provides more opportunity for these conditions in designing systems to ensure extensibility to other lunar locations and future Mars needs. One key enabling characteristic of the South Pole is the lighting conditions. At the lunar equator, solar illumination occurs in 14 days of continuous daylight and 14 days of continuous darkness (these are the lunar cycles we are so familiar with as viewed from Earth). However, at the South Pole, the Sun is seen very low on the horizon, as during the extreme summer nights at Earth’s poles. Unlike Earth, the extreme terrain on the lunar South Pole provides significant variation, resulting in “peaks” of light that can provide lit conditions for much of the year and “valleys” of darkness that never see the Sun. These peaks or ridges along craters provide advantageous locations to stage systems for longer-duration operations. However, while advantageous for illumination, the peaks and ridges are more challenging for navigation and placement of elements. These factors must be considered in the architectural approach and element designs. This lighting environment will be an enabling feature of the polar region to represent Mars-forward precursor missions and aggregation of surface elements for longer-duration test and demonstration.

Finally, the lighting conditions in the South Pole region also contribute to unique scientific opportunities. Although the lunar surface was found to be void of volatiles, as they are stripped away by the solar wind, sites of permanent darkness in the polar regions could preserve volatiles collected throughout the Moon’s past. This region is among the oldest parts of the Moon—older than any explored during Apollo. The volatiles, likely trapped as ice, could reveal valuable knowledge about the history of the inner solar system, including when life gained a foothold on Earth. Just as ancient ices hold scientific value, lunar samples from this area will increase our knowledge of the history of the Moon itself. These ices could also serve as valuable resources for use during future exploration. Finally, the peaks of light at the South Pole are an enabling characteristic to support extended durations of human-tended surface operations to provide the infrastructure capabilities for sustainable and lasting development and research.

The lunar South Pole environment results in several architectural drivers. The power and thermal systems to operate in environmental extremes, provide surface mobility, and allow the aggregation of infrastructure are possible at the lunar South Pole. Given the necessary development of platforms and systems at these locations over time, the application of interoperability and commonality will be a key enabling characteristic (RT-7). The ability to deploy, upgrade, and develop systems across the platforms will be critical to the evolution and continued operations of the integrated architecture. These reasons ensure that the South Pole is a significant feature in the Moon to Mars Architecture definition, while also maintaining and supporting the ability to visit diverse non-polar sites.

2.2.1.3 "How" Will We Get There and Return?

The driving surface of the South Pole destination for long-term infrastructure, the need for global periodic access, and the development of a long-duration cislunar platform inform the architectural driver of "How" to place the lunar microgravity staging operations. Based on a variety of studies and alternatives, the Lunar Architecture will use the near-rectilinear halo orbit (NRHO). This orbit meets several key needs, including the long-duration staging through minimal propellent demand for orbit maintenance, accessibility to the lunar South Pole and other global access on a frequent and recurring basis, and consistent access for crew and cargo to and from Earth while still providing near–deep space environmental conditions with near-continuous illumination and limited lunar albedo (i.e., reflectivity of light and heat) to the orbiting platform.

Having established the NRHO architectural orbit, the ability to transport crew, cargo, and support systems to and from the destinations can be decomposed. These systems are driven by the sizing performance splits across the architectural destinations to traverse the regions from Earth to cislunar space and to the surface. Crewed transportation systems will be driven by the need to launch, transport, and safely mitigate potential contingencies and risks in two key transportation regimes: first, crew accessibility to and from Earth to NRHO platforms, and second, to and from NRHO to the surface destinations to support either South Pole or non-polar mission selection. The crew transportation access, in conjunction with destination systems, will necessarily need to ensure the safety and responsive planning for crew return (RT-3) for potential contingency scenarios.

Transportation objectives are some of the earliest objectives in the architecture and most established systems, given that they are necessary first steps for the human return to the Moon, enabling subsequent objectives. These systems are developed with several key characteristics applied, including the ability to achieve missions with sufficient frequency and opportunity. With the scope of objectives and the tightly coupled architectural aggregation approach, the ability to ensure timely and consistent launch and mission opportunities is a key characteristic. In addition to crew transportation, systems will also need to support the launch and delivery of cargo across a range of masses and volumes to support the element aggregation, logistics, and maintainability across the architectural lifetime and destinations (RT-5 Maintainability and Reuse). Systems capable of reuse offer significant benefits, reducing the number of launches required and continuing to enable long-term objectives across the architecture. Given the significant considerations in transportation objectives, the ability to support docking, deployment, and disposal — with minimal crew intervention when necessary — will be key. Increased crew time to support routine operations, maintenance, and services would compromise crew time (RT-4) to achieve utilization and other objectives.

Although the largest and most recognizable transportation systems are those that carry the crew through space, the ability to support mobile operations on the lunar surface is a key characteristic of many of the blueprint objectives. Mobility systems on the lunar surface are necessary to enable the myriad objectives that must be accomplished at points across the surface that would be impractical to reach or inaccessible to crew traveling on foot from the landing location. The ability to transport crew members safely and efficiently between surface locations is essential for maximizing crew time (RT-4) applied to the utilization objectives. This capability is also necessary for future Mars exploration and is essential to the exploration plans to enable the crew to travel to increasingly far points from the landing sites, explore regions where landing is not feasible, and carry and transport samples or utilization payloads.

A robust, secure communication and position, navigation, and timing system will also be critical to these complex operations. The volume of data required to safely monitor, command, and control active vehicles, both crewed and uncrewed, will be a key characteristic of the integrated architecture. The number of systems in both cislunar and surface operations will also generate the need to handle multiple simultaneous streams of data and telemetry. Management of these systems and functions across the distributed architecture through interoperable and expandable systems will be a key characteristic to accomplish lunar objectives.

2.2.1.4 "When" Will We Achieve Lunar Objectives?

As the lunar campaign has already begun, the key characteristics to address the "When" question are more appropriately addressed as the time frequency, or "how often". Driving the systems to support an annual cadence of crewed lunar missions is a need that flows throughout the system development, from ground processing and launch facilities, to development and assembly timelines, to the assets necessary to support those missions. Turnaround and processing times will also be key characteristics for any system reuse driven by the transportation objectives. Further, the demand for logistics supply, repurposing, and disposal will be key considerations in the architecture's opportunity frequency. Logistics demand is a significant derived capability necessary to support increasing mission durations to accomplish the blueprint objectives at both cislunar and surface platforms. Periods between crew flights will drive characteristics for the assets to provide ongoing value and benefit during tele-robotic or autonomous operations.

This diverse suite of frequent crewed and uncrewed operations using permanent infrastructure, will provide significant opportunity for commercial and space development. The agency objectives can be addressed through a variety of approaches, innovations, and partners. One of the key recurring tenets applicable to addressing "When" is RT-9 Commerce and Space Development. NASA plans to foster the innovation among industry partners, expanding the economic sphere to the Moon, following the example of the commercial development of LEO. Creative solutions to meet multi-user needs, responsiveness to opportunities, and the shared support of lunar exploration across industry and partners will be necessary to keep the architecture durable and sustainable.

The planned campaign will spend several decades establishing permanent footholds in cislunar space and on the lunar surface, developing and deploying major human-rated transportation systems to the Moon and Mars, and developing and deploying lunar and Martian surface infrastructure to enable humans to live and explore once they arrive. The term "sustainable" can have different meanings, depending on the context. For the exploration campaign, several definitions apply. *Financial sustainability* is the ability to execute a program of work within spending levels that are realistic, managed effectively, and likely to be available. *Technical sustainability* requires that operations be conducted repeatedly at acceptable levels of risk. Proper management of the inherent risks of deep space exploration is the key to making those risks "acceptable." Finally, *policy sustainability* means that the program's financial and technical factors are supportive of long-term national interests, broadly and consistently, over time.

2.2.1.5 "Who" Does This Approach Include?

Having established all the component parts of the architecture, sizing for systems is designated to include up to four crew during an integrated mission. These crew members will thus be enabled to conduct the scientific, technological, and developmental objectives for which the human mind is most suited. Again, maximizing the time of the crew members to support these objectives is a recurring tenet (RT-4) in the architectural selection and decomposition. The ability to support four crew members provides the opportunity to assign various tasks ranging from piloting to utilization and operations. The crew operations will provide a gradual build-up approach to demonstrate the technologies and operations necessary to live and work on planetary surfaces and in extended deep space microgravity environments, including a safe return to Earth. Risk is inherent in any type of spaceflight, but it is an especially important consideration in the context of human spaceflight. As one of the recurring tenets, RT-3 Crew Return is a key characteristic across all architectural domains. The application of risk management, fault tolerance, and integrated human-rating certification is necessary at the architectural level. Contingency capability, abort performance, and risk management are treated as an applied characteristic across the architecture.

The most critical components of the campaign to get humans to the Moon, and ultimately Mars, are the humans themselves. Vehicles, systems, training, and operations must be designed, developed, and certified to be safe and reliable for, compatible with, and in support of the “human system” as an integrated system to accomplish the mission with an acceptable level of human risk. Human-rating is the process of designing, evaluating, and ensuring that the total system can safely conduct the required human missions, as well as incorporating design features and capabilities that both accommodate human interaction with the system to enhance overall safety and mission success and enable safe recovery of the crew from hazardous situations. Human-rating applies standards for design and construction, safety and mission assurance, health and medical concerns, flight operations, and system interoperability. Human-rating is an integral part of all program activities throughout the life cycle of the system, including (but not limited to) design and development; test and verification; program management and control; flight readiness certification; mission operations; sustaining engineering; and maintenance, upgrades, disposal, and ground processing. NASA will lead/integrate the distributed team of government, commercial, and international partners that develop and implement hardware, software, and operations supporting exploration. Both nominal and contingency scenarios must be part of the overall development of the mission, hardware, software, and operations to arrive at a reasonable level of risk. The crew will require many years of Earth training across numerous vehicles and systems in a compressed timeframe to prepare for the mission.

In addition to the crew themselves, the development of the myriad systems, operations, and capabilities to meet objectives will require the support of international and industry collaborations (RT-1 and RT-2). The Moon to Mars Architecture approach enables a variety of support mechanisms and contributions to enable innovation, economic development, and the inspiration foundation to address Why We Explore (Section 2.1). Characteristics include architectural robustness to infuse innovative solutions and technological advancements over time. The iterative methodology, flexibility in design solutions, and ability to perform responsive mission planning for future developments will be key considerations.

NASA has a long, successful history of working with a diverse community of international partners to advance common space exploration and science objectives. The agency is committed to building on and broadening these global partnerships as part of the Moon to Mars Objectives. NASA has numerous international partnerships already in place and is engaging in ongoing bilateral and multilateral dialogues with international space agencies to identify new, mutually beneficial opportunities for collaboration.

Building upon more than two decades of experience with the International Space Station in LEO, NASA and its partners will need operational flexibility to demonstrate the capability to integrate the multi-party contributions, aggregations of systems over time, and increasing complexity to address long-term Mars-forward development. The coordination of integrated ground, launch, and flight systems for both crewed and uncrewed regimes and multiple planetary bodies will require a significant leap forward in the complexity of mission operations.

2.2.2 Unique Considerations for the Moon

Although NASA has previously conducted human exploration on the lunar surface with the Apollo Program, there are still unique aspects to consider for the current lunar architecture. With the desire to seamlessly expand to long-term, sustainable exploration while preparing for human Mars exploration, the Moon to Mars Architecture must remain flexible to plan for the future campaign with current programs and elements in development, adjust to the actual flight systems as the elements mature and are deployed, and accommodate new contributions. This allows for an incremental increase in capabilities for lunar exploration, gradually building up functionality to achieve the agency's objectives.

The most recent human spaceflight exploration and the majority of hours of human spaceflight experience have been conducted in LEO. There are several major differences in concepts of operations between LEO and cislunar missions. For one example, abort capabilities back to Earth vary in duration. With exploration interest in lunar South Pole locations and a cislunar platform in NRHO, aborts back to Earth are more complex and take days rather than hours (as is the case from the International Space Station). These durations significantly complicate or eliminate crew rescue options that may be available in LEO. In another example, crew will transition between micro- and partial-gravity environments, eventually doing so after extended durations in microgravity without the support that crew members experience upon their return to Earth after long missions on the International Space Station. Testing out the concept of operations for surface exploration with deconditioned crew will also help NASA prepare for Mars exploration. Further, the unique aspects of the South Pole, in term of lighting, terrain, and other environmental considerations, present unique challenges to the missions and strategic planning. These include the relatively constrained area of the South Pole, which is advantageous not only to NASA, but also to other commercial, scientific, international, or other lunar exploration plans.

2.3 Mars Architecture Strategic Assessments

In the five decades since Dr. Wernher von Braun proposed NASA's first human Mars architecture, NASA has pivoted from one exploration point design concept to another, many optimized around heritage programs or emerging technologies of particular interest. Indeed, half a century of architecture studies have filled our libraries with myriad architecture concepts that have maintained interest in Mars and contributed some progress toward the current Moon to Mars effort. However, none of these concepts found traction with stakeholders, many of whom had competing perspectives or needs. The agency's Moon to Mars Objectives provide a comprehensive framework to ensure that human Mars architectures will meet — or can evolve to meet — more stakeholder needs. After mapping objectives to the required functional capabilities, the architecture team will coordinate with technology and element concept developers and identify the key architecture decisions that must be made. Because decisions in one part of the architecture will ripple through other parts of the architecture, it is critical that decision-makers understand the effect of each decision on the integrated architecture, including differences that depend on the order in which decisions are made. The strategic assessment and campaign segment description described in this document form the foundation for this Mars decision road-mapping process. Later revisions will document Mars Architecture decisions as they are made.

To build a compelling architecture that will gain traction with stakeholders, a similar systems engineering process applied at the strategic level can be used as a framework for the architecture by addressing the six key questions: "Who," "What," "Where," "When," "Why," and "How"? To reach consensus and move forward, an exploration architecture must address all six questions, but reiteration and negotiation may be required. The answer to any one question is less important than ensuring that the answers to all six fit together as an integrated whole.

2.3.1 Key Mars Decision Drivers

As noted in at the beginning of this section, the human Mars exploration architecture can be described as a six-sided trade space, shaped by the answers to six key questions: "Who," "What," "Where," "When," "How," and "Why"? (s shown in Figure 2-1). In laying out the agency's architecture decision roadmap, it is critical for decision-makers to understand how these key drivers relate to each other and how the architecture can vary depending on the order in which these decisions are made.

Figure 2-4. Mars Architecture Decision Flow Starting with "When?"

The Apollo Program was famously characterized by the mandate of "landing a man on the Moon and returning him safely to Earth before the end of the decade". This prioritized "When?" (within the decade) over other considerations. NASA successfully achieved this goal, but because the resulting architecture was optimized to meet a tight implementation schedule, it was not particularly extensible, with implications for sustained human exploration of the Moon.

The Apollo Program serves as a cautionary tale for Mars exploration: if decision-makers focus on "When?" as an anchoring decision (Figure 2-4), and the answer is a date that does not give us enough time to develop new technologies, then the answer to "How?" would default to heritage or heritage-derived systems. If the specified date is too soon to develop and certify new transportation, descent, ascent, and surface systems, then the schedule compromise may be an orbital-only or fly-by first mission, followed by surface missions in later years. This affects not just "How?" but cascades to "What?" and "Why?" If, instead of a particular date, "When?" is indexed to another event — for example, the timeline of a particular technology development or an agency funding profile — then certain technologies or assets from other programs may be prescribed, again influencing both "How?" and "What?" If the answer to "When?" specifies both a "boots on Mars" date and a "boots back on Earth" date (in other words, a total crewed mission duration), that restriction will define whether we require new high-tech, high-energy transportation systems capable of shorter mission durations. As shown in Figure 2-4, starting with "When?" can cause the answers to "Why?," "Where?," and "Who?" to rely on the answers to "How?" and "What?".

Figure 2-5. Mars Architecture Decision Flow Starting with "Why?"

With few architecture decisions mandated thus far, human Mars exploration offers a unique opportunity to take an objectives-based approach to exploration architecture development. NASA's Moon to Mars Strategy provides such a framework. In contrast to a capabilities-based approach, an objectives-based approach focuses on the big picture, establishing the "What?" and "Why?" of deep space exploration before prescribing the "When?" or "How?"

As shown in Figure 2-5, NASA's blueprint identifies the answers to the question of "Why?" Any single answer is unlikely to satisfy all stakeholders, but each answer is important to one or more stakeholders. Starting with "Why?" will help anchor the development process, but architecture choices may still vary widely depending on how the many different answers to "Why?" are prioritized. Must the first human Mars mission check off *every* item in the "Why?" Venn diagram, or is it sufficient to establish a first-mission architecture that meets the highest-priority items, and is extensible to meet lower priorities during subsequent missions?

For example, prioritizing science on the first human Mars mission will influence "Where" we land if the specific science objective of interest requires access to a particular region or feature and may require other mission elements tailored to that particular science discipline. If that priority science location is difficult to reach or lacks the resources for sustained human presence, NASA could desire a lighter exploration footprint for the first mission, and crew selection may be heavily influenced by science expertise. Conversely, if inspiration, in the form of sustained human presence, is the priority goal, then NASA may desire a landing site offering abundant resources or ease of access, with the first mission elements laying the groundwork for a heavier, permanent infrastructure at a single location that is able to support a larger number of crew, possibly selected for their engineering expertise. As shown in Figure 2-5, different priorities within "Why?" will cascade through the other questions.

These sample decision structures illustrate an important point: the Mars architecture will heavily depend on the decisions that are prioritized. In practice, the Mars architecture decision flow is likely to be iterative rather than linear. To minimize disruption, rework, and cost or schedule changes, understanding the minimum goals and priorities for the first mission, as well as the longer-term goals for subsequent missions, can aid in establishing a flexible and sustainable architecture. The answer to any one of these questions is less important than whether the answers to all six complement one another as a set and can be balanced to establish an architecture that is achievable, affordable, and adaptable.

2.3.2 Unique Considerations for Mars

2.3.2.1 Mars Architecture Frame of Reference

In Mars Architecture discussions, it is helpful to keep in mind that mission distances traveled will be at a scale far beyond the entirety of human spaceflight experience to date (Figure 2-6). A single round-trip journey between Earth and Mars will put about 1.8 to 2 billion kilometers on a Mars transportation system's odometer, regardless of departure opportunity or trajectory traveled—that is roughly equivalent to 950 round trips to the Moon. The distance between the Moon and Earth only varies by about 43,000 kilometers over time, so it always takes about the same amount of energy to travel to the Moon and back, no matter when we go. By contrast, the distance between Earth and Mars can vary by as much as 340 million kilometers as the two planets orbit the Sun. The closest Mars ever approaches Earth is 54.6 million kilometers; at their farthest, over 400 million kilometers of deep space separates the two planets. This means that much of the operational experience and many of the paradigms — such as mission control, sparing/resupply strategy, crew rescue, and mission abort contingency planning — will require a different approach than previously used on heritage programs (such as the International Space Station).

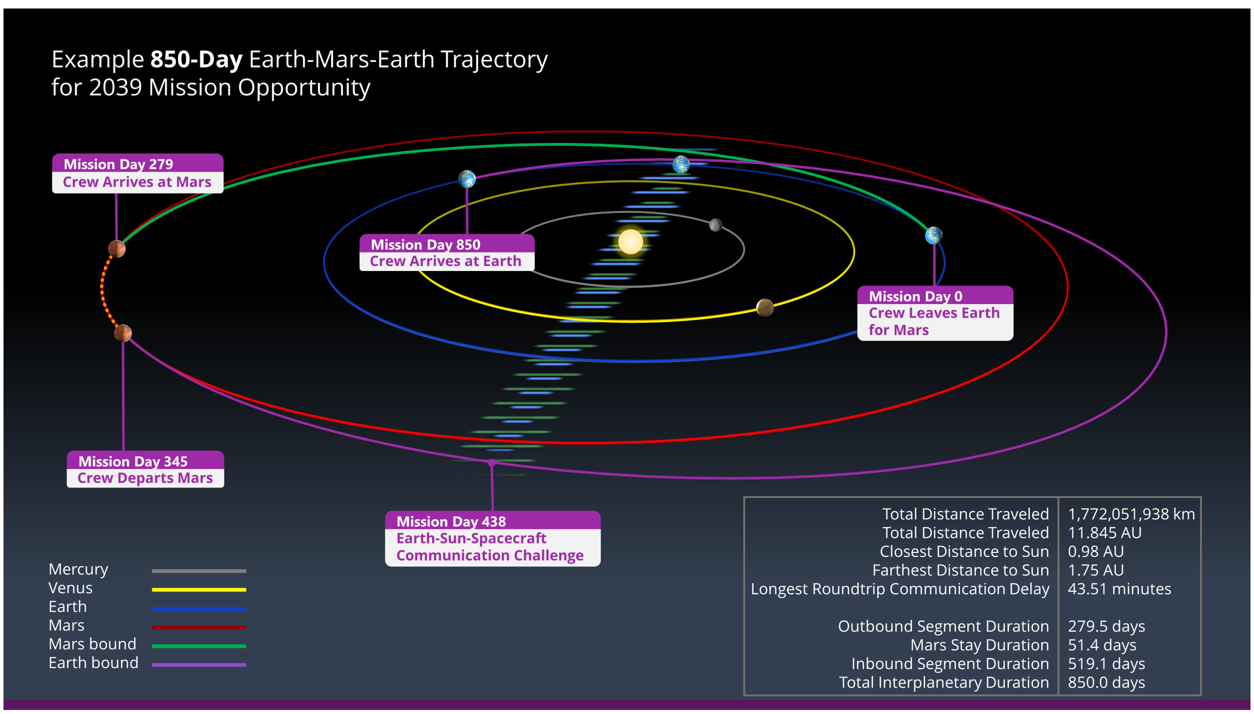

Figure 2-6. Roundtrip Mars Mission Distance in Perspective (AU, Astronomical Unit)

The energy required to achieve the roundtrip journey from Earth to Mars and back depends heavily on the timing. Because both planets orbit the Sun, both the distance and the relative velocity of the planets are constantly changing, cycling on a roughly 15- to 20-year cycle. It always takes about the same amount of energy to reach the Moon from Earth, but the amount of energy required to reach Mars varies considerably over this cycle. As part of the "When?" decision, a determination must be made on whether to optimize the transportation system for the easiest opportunities (more affordable, but limits us to one mission every 15 to 20 years), optimize for the most difficult opportunities (less affordable, but allows missions every 2 years), or aim for something in the middle.

Traditionally, to minimize the total energy required to achieve the roundtrip mission, mission planning has selected optimal planetary departure and arrival timing to maximize the benefit of the natural relative positions and velocity between the planets. This results in what is typically known as conjunction-class long-stay missions, where both the Earth-to-Mars and Mars-to-Earth trajectories are minimum-energy in nature, typically 180–300 days in duration (each way), depending on the mission opportunity. This approach requires a Mars stay time of 300–500 days to wait for the proper planetary alignment for the return trip and results in a roundtrip total mission duration of around three years.

Shorter duration roundtrip missions to Mars require less energy-efficient trajectories. The energy versus time tradeoff for a roundtrip mission to Mars is a continuum, but the relationship is exponential in nature: as the mission duration is shortened, the energy required to achieve the roundtrip mission increases exponentially. This translates to an exponential increase in the vehicle mass required, in terms of both propellant and propulsion system. The total energy required is also highly dependent on the Mars stay time. Unlike the minimum-energy conjunction-class mission, where the Mars stay time is dictated by the waiting period for the optimal return trajectory, shorter roundtrip missions do not have built-in constraints for Mars stay time. This design parameter becomes a key driving factor in interplanetary mission planning. Shorter mission duration also results in shorter stay time at Mars.

An example of these shorter roundtrip missions to Mars is an opposition-class short-stay mission. This class of roundtrip mission to Mars is optimized with one minimum-energy transit (either Earth-to-Mars or Mars-to-Earth), like the conjunction-class missions, and one high-energy transit that is timed to take advantage of a gravity assist swing-by of Venus during opportunities where Venus is in the correct location. This trajectory has typical transit time of 180–300 days each way, with a very short Mars stay time between 10 and 50 days, to achieve a roundtrip total mission duration as short as two years.

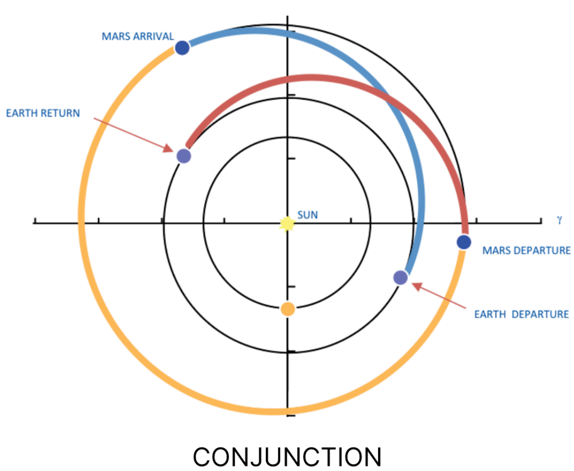

Figure 2-7. Illustration of Conjunction- and Opposition-Class Mars Trajectories

These two classes of mission have traditionally been the focus of Mars mission design and planning, but it is important to note that roundtrip missions to Mars are not limited to these two options, as evinced by the example trajectory shown in Figure 2-6. Mars mission design should not be a contest of "conjunction" versus "opposition," but rather an integrated, thoughtful analysis of all parameters of interest. Roundtrip transit time, Mars stay time, and departure dates are all important factors in determining the total energy required to achieve roundtrip missions. Analyzing the implications of each factor on all relevant systems will help us better understand the overall design trade space to support more informed decisions.

2.3.2.2 Aggregate Mars Mission Risk

Throughout the entire 60-year history of human spaceflight, astronauts have never been more than a few days (and rarely more than a few hours) from Earth. For missions to the International Space Station, or even to the Moon, aborting the mission and returning home is a relatively straightforward option. But on the transit to Mars, mission abort is complicated because of the sheer distance between Earth and Mars. Depending on when abort is initiated in the mission timeline, the heliocentric nature of the transit may require *months* to return to Earth, regardless of the transportation system selected. For transportation architectures that rely on Mars vicinity return fueling strategies, mission abort during the outbound transit leg may not be possible. In many cases, transit abort will not be a practical response to an emergency because the time to effect crew return will exceed the amount of time within which the crew must resolve the emergency. Early human Mars missions will also have limited Mars ascent/descent abort options. Mars's atmosphere and gravity make it difficult to carry sufficient on-board propellant to initiate human-scale payload descent and abort back to orbit during Mars descent, and Mars will initially lack the specialized infrastructure and staffing needed to aid crew after an ascent abort back to the Mars surface — even a successful abort to the surface may very well leave crew stranded away from assets necessary for a safe return to Mars orbit. These challenges will require an entirely new contingency operations paradigm for initial human Mars missions relative to NASA's Earth-centric flight experience. Given that crew survival has been key in meeting human-rating certification loss-of-crew requirements (as derived from Administrator-established safety risk thresholds), additional emphasis will need to be placed on hazard mitigation via other measures (e.g., incorporation of additional reliability and maintainability of hardware/software and a heavier reliance upon autonomy) to do the same for a Mars architecture. Such measures will need to account for various other factors, including longer Earth-based communication delays and blackout periods, negative mental health and physiological impacts of transit and surface operations, and impacts upon human reliability.

The farther that humans travel from Earth, the more risk we must accept to achieve the goals of exploration. Mission durations, travel distances, and mass constraints increase the probabilities of something not performing as expected and decrease NASA's ability to respond in a timely manner to emergencies. Crew health, safety, and survival techniques will necessarily change as we move into Mars exploration. The definition of and acceptance of reasonable levels of risk will be a driving factor in determining architecture capabilities and use cases. The definition of acceptable risk is influenced heavily by both internal and external environments and, thus, must be explicitly defined and understood within the architecture so that it can influence decisions throughout the design and implementation process.

2.3.2.3 The Human System in the Mars Architecture

Mars architecture discussions must consider the human system as part of the integrated mission architecture. Historically, emphasis on conjunction-class Mars missions on the order of three or more years duration was driven by a desire to lower Earth-launched transit propellant mass. While this may result in a "better" architecture from a transportation system point of view — with total stack mass serving as the measuring stick for "better" — the three-or-more-year conjunction-class mission duration is not necessarily better from a crew health and performance perspective. From a purely medical point of view, it would seem intuitively obvious that the two-year opposition-class mission should be “better” for the crew than the longer-duration conjunction-class mission because of the shorter time spent in the deep space environment, but that conclusion is premature without more insight into the integrated vehicle risks that will be layered on top of the medical risks, as well as considerations for crew performance. Beyond the transportation and habitation systems, crew support elements, such as a long-duration food system, remote medical care, laundry/clothing, on-demand training aids, communications, physical and psychological support, and utilization systems, must be included as part of the end-to-end human Mars architecture.

To ensure the human system is well integrated into the overall architecture, NASA is exercising a process to develop more robust spaceflight systems and build a culture of interplanetary human exploration, guided by the agency’s new blueprint objectives for exploration. This process incorporates iterative steps building on lessons learned from NASA assets and operations — such as Earth analogs, International Space Station and commercial LEO missions, and the development of plans for Artemis — to mature plans for future human Mars missions and to use these plans to inform activities for the International Space Station and future platforms in LEO, as well as Gateway and lunar surface mission analogs during upcoming Artemis missions. The knowledge gained from these will reduce uncertainty and risk for Mars.

2.3.2.4 Mars Architecture Development Approach

The light-footprint initial mission architecture that has been developed over the past several analysis cycles will serve as a starting point to define one corner of the trade space. This modest architecture concept, described in more detail below, will be expanded through a methodical process to develop the initial human Mars segment. The decomposition of the agency objectives drives the specific functions and use cases that inform Mars architecture strategy. NASA will coordinate with stakeholders to explore integrated architecture impacts, such as how infrastructure or science objectives influence mass, volume, power, and overall transportation and habitation design. This will be an iterative process, resulting in a catalog of key Mars architecture decisions. Where additional research is required to inform a decision, NASA will coordinate activities across the agency, which may include testing, analysis, or analog investigations on Earth, orbiting platforms, or the lunar surface. Objectives will be prioritized to align with anticipated resource availability timelines, opportunities, and partner agreements. As a roadmap of key architecture decisions emerges and the trade space is narrowed, this document will be updated to reflect the evolving Mars architecture.

Since the Mars architecture will be built up over time, interoperability is a vital aspect to ensure compatibility between elements and systems. With limited ground support, on-board autonomy (crew and systems) and interoperability in the Mars campaign will be crucial for crew safety and mission success. Lunar interoperability lessons will guide the development of interoperability for Mars architecture systems. Compatible systems envisioned include deep space vehicles, surface vehicles, utilization/science, and logistics operations. The Mars architecture team will work with lunar programs to evaluate best practices learned from the lunar campaign and define the future needs for specific system compatibility.

2.4 MOON TO MARS ARCHITECTURE DECISION ROADMAPPING

Developing a new exploration architecture will depend on hundreds of individual decisions made by dozens of decision authorities across NASA. Every decision is important, but there is a class of decisions (i.e., "key" decisions) that can so significantly influence the end-to-end architecture that they warrant a much higher level of scrutiny. For example, the decision about whether to launch round-trip propellant from Earth versus pre-deploying or manufacturing return propellant at the destination will significantly impact the surface infrastructure and ascent elements, which in turn will influence the number, cadence, and payload capacity of landers, which will in turn will influence transportation system cadence and capacity — all of which will influence the number, capacity, and cadence of rockets that must be launched from Earth. Though return propellant acquisition strategy might appear at first blush to be a straightforward engineering decision solely under the purview of the transportation element implementation authority, there are other, less obvious considerations: manufacturing propellant from in-situ Mars resources may involve forward or backward planetary protection constraints, for which planetary protection and health and medical decision authorities must be involved. Establishing the infrastructure necessary for in-situ manufacturing has technology benefit implications that will be traded against development cost and schedule. Although a human spaceflight program office might prefer that subsequent missions return to the same landing site to take advantage of existing infrastructure (thus lowering total architecture costs), constraining exploration to a single landing site might preclude the agency's ability to achieve important science objectives elsewhere on the planet. Either approach may target addressing different mission objectives for different stakeholders, but careful consideration is needed for weighting different objective priorities and infrastructure demands.

The architecture decision roadmapping process was designed to identify "key" decisions for the Moon to Mars Architecture and to carefully track and assess the impact of these highly influential decisions. The process also includes assessing how the key decisions might impact the agency's exploration objectives and RTs. By definition, the architecture key decision roadmapping will only include "key" decisions whose outcomes significantly influence the architecture and/or that require collaboration between multiple lower-level decision authorities, meaning that the decision authority for these key decisions resides with agency leadership.

2.4.1 Architecture Key Decision Roadmapping Approach

The architecture decision roadmapping process was designed to ensure the impacts of these far-reaching decisions are carefully traced, assessed, and coordinated with those affected. The process defines a common terminology, establishes roles and responsibilities, and provides guidance on how to identify decisions to be included in the roadmapping, trace linkages between these decisions, and develop new tools to manage all the relevant information as decisions are made and the architecture trade space narrows over time.

Although the premise of architecture decision roadmapping applies to lunar and Mars architecture development, there will be differences, given that some lunar architecture decisions have already been made. The human Mars architecture, on the other hand, is being developed with no existing decisions made prior to the creation of the decision roadmapping process ("clean slate"). NASA is therefore using the *Initial Humans to Mars segment* as a decision roadmap pathfinder, while the process is still being tailored to determine and manage the remaining lunar architecture decisions in the context of legacy lunar decisions that have already been made. This approach also establishes a process baseline that could be applied to future exploration destinations beyond Mars.

As with all new processes, refinements and improvements will be made over time, so the process and the architecture decision roadmapping will continue to be updated. It is called "roadmapping" because it not only provides a path to follow for decision-making, but also is iterative work with annual updates anticipated. Note that architecture key decisions and overall decision roadmapping is an internal agency process, though in many cases external input will be factored into decision making.

2.4.1.1 Value Proposition

As noted here and in ACR 2022 White Paper "Systems Analysis of Architecture Drivers," making one key decision before fully understanding the cascading effects of that decision across the end-to-end architecture can limit the flexibility or utility of an architecture, rendering the enterprise unsustainable. At its core, architecture decision roadmapping is a path to orient the recommended of decision-making. The essential question is: of all the important decisions to be made, which should be decided first?

The practical utility of architecture decision roadmapping is to understand which decisions lay in the critical path of other decisions. Architecture decision roadmapping developed early in an exploration campaign provides value in three ways:

1. **Minimizes later rework or disruption**
Decomposing exploration objectives into characteristics and needs and their associated use cases and functions will identify architecture key decisions. To enhance the traceability and utility of this process, identifying linkages between those decisions — in particular, the effect that one decision has on others (if/then relationships and decision prerequisites) — will aid in identifying high-impact decisions that influence every aspect of the architecture. Architecture decision roadmapping that prioritizes these high-impact decisions early in the overall decision flow will minimize implementation delays, rework, or relitigating decisions.

2. **Defines inter-organizational critical paths**
Most decision authority will reside within programs or projects, but because exploration architectures typically represent a collection of programs and projects, architecture decision authority will necessarily cross multiple organizational boundaries. A decision under one decision authority may be in the critical path of what might seem at first glance to be an unrelated decision under a different decision authority. By mapping out how decisions relate to each other — and under whose purview these decisions fall — programs, projects, or technical authorities will be aware of whose critical path they are in or who may be in their critical path.

3. **Informs investment strategies**
Where two or more investments could meet objectives, but budget or schedule realities cannot support multiple developments, a down-select decision must be made with input from all affected internal organizations. Making the decision too late will likely result in unwanted program/project consequences, including increased costs or schedule delays associated with development and testing schedules. However, as noted above, making the decision too early — such as before flow-down impacts are fully understood — may result in an architecture that is unable to meet exploration objectives. As an example, integrating important technology down-select decisions into the architecture decision roadmapping will help technologists time their decision gates to optimize development resources.

2.4.1.2 Terminology

New terms used in the decision roadmapping process include the following:

Decision outcome – A formal judgement of the options as a result of deliberation, culminating in an approved forward path on which option(s) to implement.

Decision definition – Before a decision outcome is determined, there is a fully scoped decision definition. The decision definition is the set of inputs required to reach a decision outcome, which includes a question, options, context, dependencies, and a recommendation on which a decision authority will deliberate.

Key decision – Defined as a decision (i.e., decision definitions and, when available, decision outcomes) that so profoundly influences the end-to-end architecture that it warrants elevated scrutiny. At one end of the spectrum, deciding how many crew members an architecture must accommodate is obviously a "key" decision because it influences virtually every aspect of the architecture and will involve collaboration between multiple decision authorities. At the other end of the spectrum, deciding handrail color or style — even though it will affect many elements — is best categorized as an engineering decision that does *not* rise to the same level of management scrutiny. But where to draw the line? For the purpose of sorting through thousands of decisions to determine which have a profound enough impact to be labeled as "key," NASA employs two criteria: high connectivity to other decisions, programs, and projects and high sensitivity of architecture-level and agency values (such as cost, schedule, or risk) to the decision options. This sorting process is subjective but errs on the side of caution: if in doubt, a decision is considered key; it may be reclassified later if further analysis indicates — or a decision authority decides — that the decision could be made at a lower level or does not have a significant technical, cost, schedule, or risk impact.

Decision authority – Defined as the highest-ranking official or body (such as a control board or executive council) that will sign a formal decision outcome, thus indicating responsibility for — *and commitment to implementing* — that decision outcome. The instrument used to document each decision outcome — such as formal reports, executive summaries, or approval memos — will vary depending on the internal processes used by each decision authority. In the hierarchy of decision authorities, some decision outcomes will be determined by programs or projects, while other decision outcomes may be determined by agency technical authorities. Where the needs of multiple projects, programs, or technical authorities must be balanced, a key decision may necessitate elevation to the applicable mission directorate's associate administrator. Where the needs of multiple mission directorates must be balanced, a key decision may necessitate elevation to the NASA administrator. In some cases, the decision authority may reside outside of NASA, such as with another government agency. For any given architecture decision definition, there may be multiple stakeholders, *but there can only be one decision authority*.

Stakeholders – In the context of architecture decision roadmapping, stakeholders are defined as those internal NASA organizations with an interest in a particular key decision because they can either affect or be affected by the decision outcome. For example, the stakeholder may affect the decision outcome by providing critical data, technical analyses, risk assessments, cost estimates, or other supporting data and analyses to the decision package. On the other hand, the stakeholder may be affected by the decision if that decision results in a change to their implementation requirements, schedules, or resource requirements. Different architecture key decisions may have different stakeholders. In some cases, stakeholders are decision authorities for prerequisite decisions that feed into another architecture key decision.

2.4.1.3 Identifying and Defining Key Decisions Needed for the Architecture

The first step of architecture decision roadmapping is to identify and define each key decision outcome that is needed for the architecture. Decision definitions include the question that needs to be answered (i.e., the type of decision *outcome* needed), potential decision options, the decision authority (if known), relevant stakeholders, architecture context, and dependencies (both prerequisites and flow-down impacts of the decision on other decisions). Collecting all of this information in the first step before analyses or decision package development begin is crucial. NASA has used two methods to identify candidate key decisions: first, a bottom-up analysis drew input from decades of heritage studies. Then, a top-down assessment was used to decompose NASA's exploration objectives into use cases and functions, and the entire objective decomposition was used as a guide to identify candidate key decisions. This top-down approach is key to NASA's "architecting from the right" strategy for human exploration and is still ongoing as the list of key decisions continues to be iterated on each year. The two approaches together provide a more thorough identification process. The identified key decisions are "candidates" for the roadmapping until they are approved at the annual ACR.

2.4.1.4 Developing Decision Linkages

Once candidate key decisions are identified, the next step is to assess how these key decisions are "linked" to each other so that a recommended sequence of decision-making may be developed in the next phase of the roadmapping process. For each candidate key decision identified in the previous step, the dependencies on and for other key decisions are cataloged.

In some cases, the dependencies can be defined as "prerequisites" when a given decision depends on the outcome of other, earlier decisions. For example, a landing site selection decision may be highly dependent on the prioritization of utilization (technology demonstration or science) objectives, making that prioritization decision a prerequisite to the landing site decision. Additionally, there may be other types of prerequisites to a given decision, such as capability or knowledge gaps that must be filled before a decision can be made.

It is important to note that prerequisites and flow-downs are fundamentally the same type of precedence relationship, just viewed from either the downstream (prerequisite) or upstream (flow-down) perspective. Also, the specification itself of prerequisite versus flow-down is a strategic choice that is likely to impact the outcome of the architecture, so this should be done carefully. For this step of the process, teams simply begin identifying decision dependencies *for the purpose of initiating stakeholder collaboration and input for further decision definition.* Finally, if these decision dependencies are predicated on specific assumptions (for example, that a partner provides a given capability or that a new high-temperature material will be developed) or constraints (for example, a particular payload shroud's diameter), those assumptions and/or constraints are also documented, particularly if changing the assumption or constraint would make that decision obsolete or change the comparison of the decision options.

Linkages between decisions are captured in a digital decision space model. An architecture decision space model catalogs key decisions, records decision definition data, and maps the dependencies between each key decision to visualize the impacts and importance of various decisions. The model also supports the creation of decision-making sequences as inputs to the deliberations by stakeholders about the recommended sequence (i.e., the "roadmap"). Finally, the decision space model also records decision outcomes, when available, and tracks any revisions to decision outcomes, if needed.

Crucial to the model is an ontology that sets the model's foundation and defines how data is structured — and input is captured — within the model. NASA developed a decision space modeling ontology for the Moon to Mars Architecture to respond to the inadequacy of a traditional databasing approach at capturing the complex dependencies and impacts between key architecture decisions. For this model, candidate key decisions are instantiated as nodes, categorized as either an "architecture characteristic decision" or an "architecture constraint decision." Note that these terms are used in the modeling environment for the purpose of linking decisions to one another.

> ***Architecture characteristic decision* –** Decisions that define an architecture feature or characteristic, where the selection of an alternative option would be considered a different architecture. Options for these types of decisions fundamentally change the architecture trade space. Examples include number of crew to the surface or power generation or propulsion technology selections.

> ***Architecture constraint decision* –** Decisions that apply across all possible architecture variants but do not directly define an architecture characteristic. Options for these types of decisions do not narrow or expand the feasible architecture trade space; for example, establishing a loss-of-crew threshold or payload allocations to meet "inspiration" goals.

The ontology also defines types of decision options—including simple and compound options — and how each decision's set of options are captured in the model along with constraints, bounds, and units. Figure 2-8 depicts notionally how the decision ontology is used to build the decision space model, including nodes that are either decisions or decision options. Next, the dependencies for each decision are modeled as relationships (or edges) between the nodes. It is at this time that dependencies may be characterized as either prerequisites or flow-downs, but this may still be re-evaluated later during the process as the position of decisions on the architecture roadmap is assessed. The decision model is built in a modeling tool that supports team collaboration and is configuration controlled.

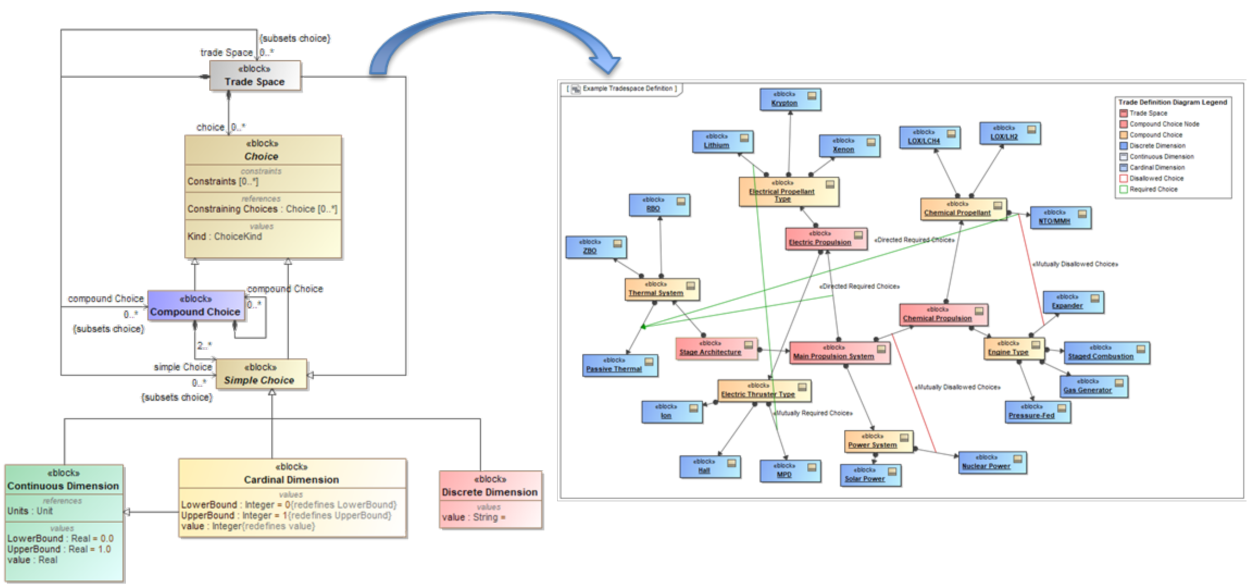

Figure 2-8. The Decision Space Ontology is Used to Build the Decision Space Model

Although the intent of the decision roadmapping is to define a recommended sequence of decision making, the reality is that — for various unforeseen reasons — key architecture decisions may not always be made in the recommended order. Therefore, the model is designed to accommodate updates.

2.4.1.5 Perform Roadmappping to Sequence Architecture Decisions

The decision space model described in Section 2.4.1.4 is being developed to capture all the needed key decisions that have been identified. The decisions, dependence relationships between decisions, decision options, and compatibilities between decision options contained in the model form a graph through which a decision-making path must be planned or "roadmapped." However, there are many possible paths through the decision space, and so a method is needed for identifying "good" paths and then down-selecting to a recommended path.

To be effective, the dependencies between decisions must be understood before placing decisions on the roadmap. For example, if the number of crew is decided *before* factoring in the top science and technology demonstration priorities, the crew complement decision may have to be changed later if the workload to meet mission priorities is greater than the selected number of crew can accomplish. If this disconnect does not surface until *after* crewed elements are well into development, either the architecture will be unable to meet mission objectives or there will be significant cost and schedule penalties for redesign or replanning. Precise timing and schedules cannot be determined without detailed decision package development, but having a sense of the *relative* timing criticality of one decision versus others will help answer the question, "where to begin?"

In an effort to identify where to initially focus analysis resources, key decisions are bucketed into two broad categories: "priority" and "later." Priority and later decisions are sub-categories of the broader class of key decisions, representing broad "time criticality" in the decision roadmapping process. Key decisions with many identified flow-downs need to be located near the beginning of the roadmap; therefore, they can be categorized as "priority" decisions. Decisions that need more prerequisites can be placed farther down the road and are categorized as "later" decisions. This does *not* imply that one category is more important than the other or that "later" decisions are optional; this is simply an acknowledgement that even critical decisions may not be practical, or even possible, until other decision outcomes are known first. Having an initial sense of the *relative* time criticality of one key decision versus others will help answer the question, "where to begin?"

In addition to decisions that have significant flow-down impacts, the "priority" category may also include decisions with few or no prerequisites. If there is sufficient available information to make a decision sooner rather than later — even if that decision is not in the critical path of another key decision — and there is relatively little flow-down risk to making an early decision, it should be considered for near-term resolution because the sooner architecture decision outcomes are determined, the sooner investments can be focused and implementation can begin. One caution is that making a decision too early may mean that flow-down impacts are not yet fully understood, which presents a risk of cost or schedule impacts, or even invalidation of certain architecture decision options later. Therefore, the agency should assess the potential impacts to cost, schedule, and risk for both waiting until later to make the decision or making this decision in the near term.

An artistic representation of bucketing "priority" and "later" key decisions is provided in Figure 2-9. In this figure, there are many key decision outcomes needed before NASA can get to the exploration destination (represented by the far-right circle). Priority key decisions are separated from the later key decisions, allowing stakeholders to prioritize their resources on developing the decision packages for the priority key decisions first and the rest later. After this initial bucketing, the priority key decisions are assigned to a specific place in the recommended order of decision-making. All architecture decisions will eventually get placed in the recommended order as the roadmapping work is refined over time. Over time, as decision outcomes are completed, they can be tracked separately and also passed on to implementation organizations, when appropriate — in Figure 2-9, these completed decisions are “pinned” along the bottom of the notional timeline.

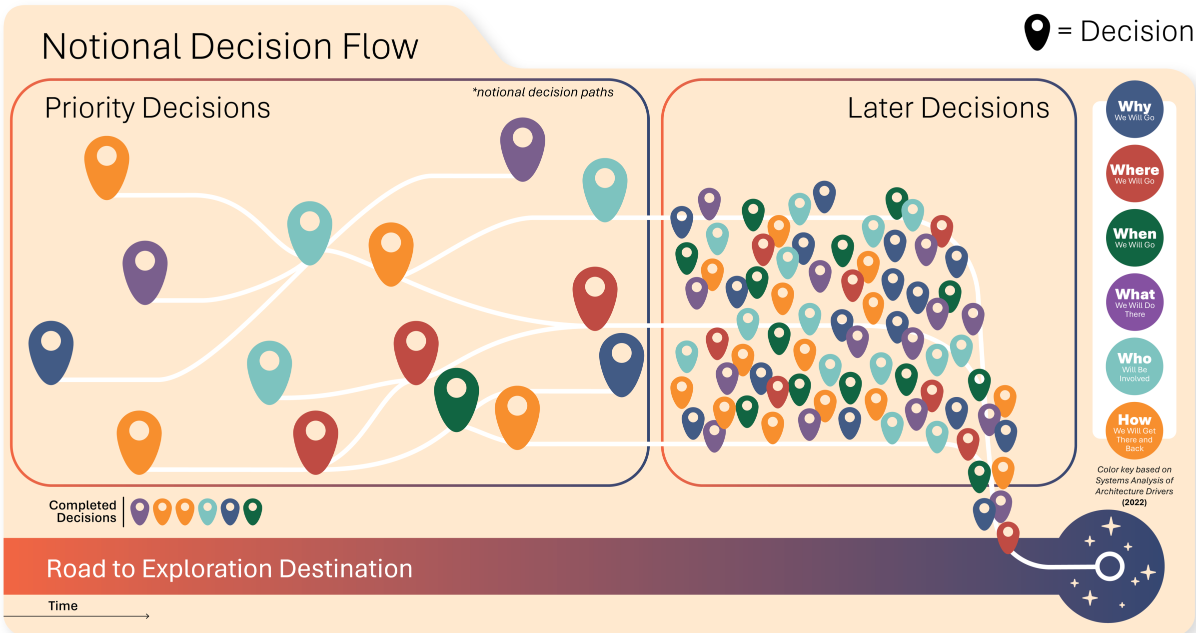

Figure 2-9. Notional Depiction of Categorizing the Key Decisions Based on Time Criticality

After this initial categorization of the key decisions, the potential decision sequence is considered in additional detail. The graph contained in the architecture decision model yields many alternative decision sequences when analyzed. One source of alternative sequences comes from the presence of decision subsets that are only loosely connected, or even entirely disconnected, from other subsets of decisions based on the dependence relationships. The freedom to sequence loosely connected subsets independently means there is not just one feasible decision sequence. The other source of alternative sequences is a more complicated one, stemming from the presence of feedback loops in the dependence relationships between decisions. For example, if the architecture teams initially determine that Decision A is a prerequisite for Decision B, which is a prerequisite for Decision C, which is a prerequisite for Decision A, then there is a feedback loop that must be addressed. The team must choose which prerequisite to violate, or whether to process interdependent decisions simultaneously; this choice also results in multiple alternative decision sequences.

Roadmapping requires down-selection from among these multiple alternative decision sequences, and down-selection necessitates considering the alternatives in the context of some form of preference or prioritization. This process is straightforward if a single objective can be defined for scoring the alternatives; however, Mars architecture decision roadmapping is a multi-objective problem. To elaborate on this, consider the following potential objectives for decision roadmapping:

1. Shortest Path: desire to select the decision sequence that results in the shortest time to completion of all architecture decisions.

2. Preservation of Architecture Flexibility: desire to defer decisions that prune large portions of the trade space to later in the decision sequence, preserving the flexibility in the architecting process for as long as possible.
3. Sustainable Decision-Making Tempo: desire to maintain a steady rate of working through decisions, understanding that the capacity of the organization to process decisions rigorously would not support something like a bell-shaped curve of decision package development activities.

Given many alternative decision sequences and multiple objectives for decision roadmapping, a critical first step towards enabling a down-selection is to identify the Pareto front of dominant architecture decision sequences — that is, the set of decision sequences among which improving any one objective can only be achieved at the cost of another objective. Because the number of alternative sequences may be very large, finding the Pareto front necessitates execution of a multi-objective optimization. The nature of this decision sequencing optimization is mathematically described as a binary integer programming problem, which is solved efficiently by modern optimization packages.

With the Pareto front of nondominated decision sequences identified, the second step in the roadmapping process can proceed. The Pareto front presents the tradeoffs to be considered between the decision roadmapping objectives; every alternative that appears on the Pareto front provides a different balance between the objectives, and final down-selection is fundamentally a subjective one that must be made by the roadmapping team with input from stakeholders.

It should also be noted that, although a sequence of decision-making is recommended, that does not necessarily mean that the decision-making process is serial. It may take time to address individual decisions, and there is no reason that certain decisions cannot be addressed in parallel for many decisions and then finalized as prerequisite decision outcomes become available. This approach may compress the overall architecture decision timeline, although the decision timeline will be highly dependent on resource availability, coordination with stakeholders, and proceeding to the relevant decision authority.

2.4.1.6 Initiating Key Architecture Decisions

Once a candidate architecture decision has been identified, defined, modeled, and pre-coordinated with internal NASA organizations and relevant decision authorities, it is presented at ACR for consensus for agency workload prioritization. This step provides rationale for relevant organizations to allocate resources for their individual contributions to decision package development, which may include research, analysis, integration.

2.4.1.7 Documenting Architecture Decision Outcomes

The actual decision-making process for each key decision will vary depending on the decision authority, but in all cases, relevant internal organizations will participate in decision package development. Once supporting data has been collected and analyzed, input has been collected, options have been identified, flow-down impacts for each option have been traced, and recommendations have been developed, a decision package is presented to the relevant authority to determine the decision outcome. If an internal NASA organization does not concur with the decision outcome, an appeals process is invoked, in accordance with NASA Procedural Requirements (NPR) 7120.5F, NASA Space Flight Program and Project Management Requirements. Different decision authorities will have different technical courts of appeal and resolution processes, but in all cases, appeals and resolutions will be captured in the decision outcome documentation, which will also summarize all options considered, supporting data, rationale for the decision, flow-down impacts to the architecture and remaining decisions in the decision roadmapping, and a high-level overview of the proposed implementation plan, including descope and fallback options.

Once an architecture decision outcome has been released, the resulting impacts to the architecture are documented and reported at the next ACR and the internal decision roadmapping is updated.

2.4.2 Lunar Architecture Key Decision Outcomes

Lunar key decisions include both legacy decisions (those made prior to publication of the ADD) and priority decisions.

2.4.2.1 Legacy Key Decision Outcomes

Legacy key decision outcomes refer to the major architectural decisions that were made prior to development of the agency Moon to Mars Objectives and associated strategy described here in the ADD and development of the Architecture Decision Roadmap. The overarching rationale for these legacy key decisions can primarily be found in Section 2.2.1 Key Lunar Decision Drivers.

2.4.2.1.1 Enable Human Exploration on the Surface of Planetary Bodies

A fundamental decision was made that the agency would pursue human exploration — not just robotic exploration — on the surface of planetary bodies. This will be accomplished by launching and transporting crew to lunar orbit with the Space Launch System and Orion and landing the crew and surface element(s) on the Moon. Future campaign segments will send the crew to Mars and look beyond to other exploration sites.

2.4.2.1.2 Deep Space Element(s) in Microgravity in Preparation for Long-duration, Crewed Exploration

This will be accomplished by deployment of the Gateway station in lunar orbit. This allows for preparation for Mars exploration with crew in cislunar space.

2.4.2.1.3 Lunar Landing Region Selection

The lunar South Pole has been chosen for the initial lunar landing region for crewed missions. This does not preclude non-polar sortie missions, but the primary exploration region for initial crewed surface missions will be the lunar South Pole.

2.4.2.1.4 Crewed Lunar Orbit

The Moon to Mars Architecture will use the NRHO for crewed lunar orbital operations.

2.4.2.1.5 Integrated Crewed Lunar Mission Cadence

Integrated crewed missions, combined orbital plus surface mission segments, are being planned for an annual mission cadence to the Moon.

2.4.2.1.6 Number of Crew to Cislunar Space

The decision has been made to include up to four crew members during an integrated mission (orbital plus surface operations) for initial architecture campaign segments, namely Human Lunar Return and Foundational Exploration.

2.4.2.1.7 Lunar Crewed Surface Stay Duration Capability

Crewed lunar surface missions will build on initial capabilities in the Human Lunar Return architecture campaign segment to enable crewed surface durations of up to 33 consecutive days for the Foundational Exploration campaign segment.

2.4.2.2 Priority Key Decision Outcomes

Ongoing and future decisions will be either directed and/or made in accordance with the architecture decision roadmapping process and will be denoted as priority key decisions. Priority key decisions align with current Moon to Mars Objectives and associated strategy. Two initial directed decisions are included. This section will be updated as more decision outcomes are available.

2.4.2.2.1 Lunar External Power Augmentation

A decision was made that the agency would 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 of our lunar human exploration will be 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. Augmenting surface elements with power generation and/or energy storage capabilities and acknowledging that integrating external power assets as a strategy in Foundational Exploration and beyond is needed to achieve segment goals. This does not down-select between technologies, sizing, or concepts which will be established in future studies.

2.4.2.2.2 Lunar Logistics Strategy

A decision was made that the agency would 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, it is critical to provide 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 — logistics items. As the exploration architecture is conceptualized and planned, 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. The architecture must assess suitable logistics sub-architectures to deliver those needs and the need to have flexible and robust means to support these missions requires a hybrid strategy using smaller crew portable carriers as well as larger mated logistics carriers.

2.4.3 Mars Architecture Key Decision Outcomes

2.4.3.1 Mars Primary Surface Power Generation Technology

Nuclear power technology (specifically, fission power) was selected at ACR24 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. This decision was driven primarily to mitigate loss of mission risk: 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.

2.5 TECHNOLOGY GAP ASSESSMENTS

As use cases and functions are identified for future lunar and Mars missions, NASA also identifies gaps between currently 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.

Technology gaps are identified through an assessment of architecture documentation, including use cases and functions decomposed from NASA's exploration objectives, key architecture decisions, and historical data. The state of the art for a technology is then compared to 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. These gaps are iterated with the architecture teams to ensure 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 C.1 of this document lists the initial set of identified architecture-driven technology gaps and contains descriptive data about each gap and its relationships to the architecture (e.g., campaign segments in which the gap is needed, use cases and functions it addresses, and relevant key decisions and sub-architectures).

2.5.1 Technology Gap Prioritization

To inform technology investment strategies and investments both internally and externally to NASA, the architecture-driven technology gaps are prioritized from an architectural perspective using a set of priority metrics. A priority metric is a gap attribute that captures an aspect of architecture preference and can be evaluated for every gap. Four priority metrics were identified: criticality, urgency, breadth, and depth.

- **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 decisions. Gaps were scored based upon mapping to decisions, along with an assessment of how much those decisions affect the need for the gap's closure.

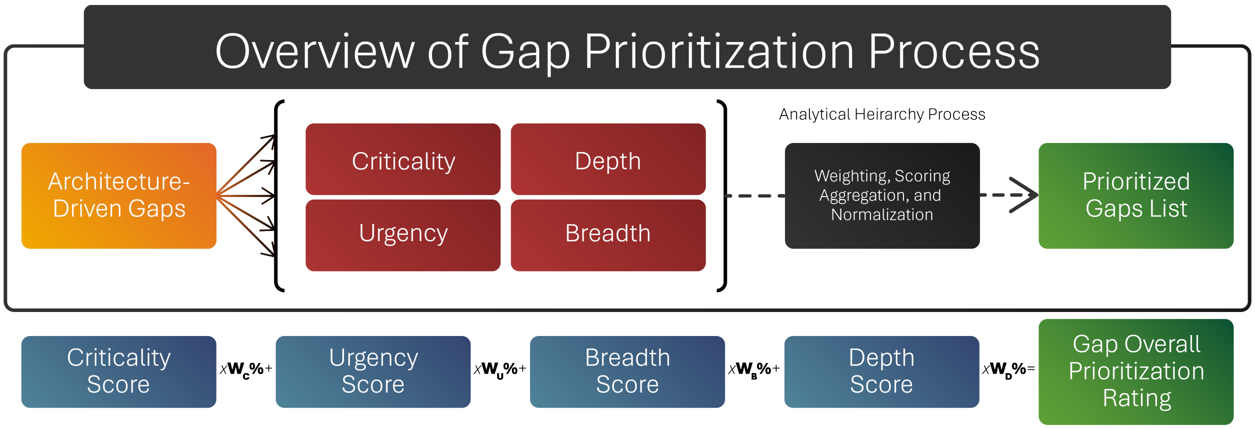

Figure 2-10. Architecture-Driven Technology Gap Prioritization Process Flow and Weighted Prioritization Rating Formula

The four priority metrics were weighted and combined to determine an overall prioritization rating as shown in Figure 2-10. 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 C.2. Note that implementation-specific metrics, such as cost, are not considered in the gap prioritization process as 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 C.1 and C.2. Note that all of these gaps, even those in the lowest priority bin shown, 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.

2.5.2 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 campaign 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/or Humans to Mars.

2.6 Decomposition of Objectives

2.6.1 Lunar Goals, Objectives, and Characteristics and Needs

Lunar Goals, Objectives, and Characteristics and Needs				
Characteristics and Needs	**ID**	**Objectives**	**ID**	**Goal**
Visit diverse sites of key scientific interest on the lunar surface, including polar and non-polar destinations to address high priority science goals.	**CN-T-108 L**	Uncover the record of solar system origin and early history, by determining how and when planetary bodies formed and differentiated, characterizing the impact chronology of the inner solar system as recorded on the Moon and Mars, and characterize how impact rates in the inner solar system have changed over time as recorded on the Moon and Mars.	**LPS-01 LM**	**Lunar/Planetary Science (LPS)**
Transfer, return, and curate a small amount (10s of kg) or a large amount (100s of kg) of unconditioned samples and containers from key destinations across the lunar surface and back to Earth, while maintaining scientific integrity of the samples.	**CN-T-302 L**			
Provide the ability for the Science Team to directly or indirectly communicate in real-time via either written or verbal means with the crew for EVA and IVA activities.	**CN-C-106 L**			
Identify, collect, and document surface and shallow subsurface samples from key destinations in non-PSRs and other sunlit areas on the lunar surface, while maintaining scientific integrity of the samples.	**CN-U-303 L**			
Deploy and operate utilization payload(s) and equipment, related to understanding impact chronology, at distributed sites on the lunar surface for a minimum of a short-duration (days to weeks).	**CN-U-713 L**			
Visit diverse sites of key scientific interest on the lunar surface, including polar and non-polar destinations to address high priority science goals.	**CN-T-108 L**	Advance understanding of the geologic processes that affect planetary bodies by determining the interior structures, characterizing the magmatic histories, characterizing ancient, modern, and evolution of atmospheres/exospheres, and investigating how active processes modify the surfaces of the Moon and Mars.	**LPS-02 LM**	
Transfer, return, and curate a small amount (10s of kg) or a large amount (100s of kg) of unconditioned samples and containers from key destinations across the lunar surface and back to Earth, while maintaining scientific integrity of the samples.	**CN-T-302 L**			
Provide the ability for the Science Team to directly or indirectly communicate in real-time via either written or verbal means with the crew for EVA and IVA activities.	**CN-C-106 L**			
Identify, collect, and document surface and shallow subsurface samples from key destinations in non-PSRs and other sunlit areas on the lunar surface, while maintaining scientific integrity of the samples.	**CN-U-303 L**			
Deploy and operate utilization payload(s) and equipment, related to geologic processes, at distributed sites on the lunar surface, for mid-durations (month+) to long-durations (year+).	**CN-U-714 L**			
Visit diverse sites of key scientific interest on the lunar surface, including polar and non-polar destinations to address high priority science goals.	**CN-T-108 L**	Reveal inner solar system volatile origin and delivery processes by determining the age, origin, distribution, abundance, composition, transport, and sequestration of lunar and Martian volatiles.	**LPS-03 LM**	
Transfer, return and curate a small amount (10s of kg) or a large amount (100s of kg) of frozen sample(s), containers, and freezers from key destinations across the lunar surface to Earth while maintaining scientific integrity of the samples.	**CN-T-304 L**			
Transfer, return, and curate a large amount (100s of kg) of cryogenic samples, containers, and freezers from key destinations across the lunar surface back to Earth while maintaining scientific integrity of the samples.	**CN-T-305 L**			
Provide the ability for the Science Team to directly or indirectly communicate in real-time via either written or verbal means with the crew for EVA and IVA activities.	**CN-C-106 L**			

Lunar Goals, Objectives, and Characteristics and Needs				
Characteristics and Needs	**ID**	**Objectives**	**ID**	**Goal**
Identify, collect, and document deep subsurface samples from key destinations in non-PSRs and other sunlit areas on the lunar surface, while maintaining scientific integrity of the samples.	**CN-U-301 L**			
Identify, collect, and document deep-surface samples from key destinations in PSRs on the lunar surface, while maintaining scientific integrity of the samples.	**CN-U-302 L**			
Identify, collect, and document surface and shallow subsurface samples from key destinations in non-PSRs and other sunlit areas on the lunar surface, while maintaining scientific integrity of the samples.	**CN-U-303 L**			
Identify, collect, and document surface and shallow subsurface samples from key destinations in PSRs on the lunar surface, while maintaining scientific integrity of the samples.	**CN-U-304 L**			
Deploy and operate utilization payload(s) and equipment, related to Solar System volatiles, at distributed sites on the lunar surface.	**CN-U-715 L**			
Deploy and operate utilization payload(s), related to in-space weather, at distributed sites on the lunar surface.	**CN-U-706 L**	Improve understanding of space weather phenomena to enable enhanced observation and prediction of the dynamic environment from space to the surface at the Moon and Mars.	**HS-01 LM**	**Heliophysics Science (HS)**
Deploy and operate utilization payload(s) relevant to assessing space weather phenomena, including ability to conduct long looks at the Sun, in a variety of lunar orbits.	**CN-U-707 L**			
Provide capabilities for local data storage and processing to enable Earth-independent space weather forecasting.	**CN-U-708 L**			
Deploy and operate utilization payloads that monitor real-time space weather in deep space.	**CN-U-718 L**			
Visit diverse sites of key scientific interest on the lunar surface, including polar and non-polar destinations to address high priority science goals.	**CN-T-108 L**	Determine the history of the Sun and solar system as recorded in the lunar and Martian regolith.	**HS-02 LM**	
Transfer, return, and curate a small amount (10s of kg) or a large amount (100s of kg) of unconditioned samples and containers from key destinations across the lunar surface and back to Earth, while maintaining scientific integrity of the samples.	**CN-T-302 L**			
Identify, collect, and document deep subsurface samples from key destinations in non-PSRs and other sunlit areas on the lunar surface, while maintaining scientific integrity of the samples.	**CN-U-301 L**			
Identify, collect, and document surface and shallow subsurface samples from key destinations in non-PSRs and other sunlit areas on the lunar surface, while maintaining scientific integrity of the samples.	**CN-U-303 L**			
Transfer, return, and curate a small amount (10s of kg) or a large amount (100s of kg) of unconditioned samples and containers from key destinations across the lunar surface and back to Earth, while maintaining scientific integrity of the samples.	**CN-T-302 L**	Investigate and characterize fundamental plasma processes, including dust-plasma interactions, using the cislunar, near-Mars, and surface environments as laboratories.	**HS-03 LM**	
Identify, collect, and document surface and shallow subsurface samples from key destinations in non-PSRs and other sunlit areas on the lunar surface, while maintaining scientific integrity of the samples.	**CN-U-303 L**			
Deploy and operate utilization payload(s) relevant to assessing space weather phenomena, including ability to conduct long looks at the Sun, in a variety of lunar orbits.	**CN-U-707 L**			

Lunar Goals, Objectives, and Characteristics and Needs				
Characteristics and Needs	**ID**	**Objectives**	**ID**	**Goal**
Deploy and operate utilization payloads, related to fundamental plasma processes, in cislunar space.	**CN-U-709 L**			
Deploy and operate utilization payload(s) related to fundamental plasma processes around globally distributed locations on the lunar surface.	**CN-U-710 L**			
Deploy and operate utilization payload(s), related to the magnetotail and solar wind, in cislunar space, including the ability to conduct long looks at the Sun.	**CN-U-711 L**	Improve understanding of magnetotail and pristine solar wind dynamics in the vicinity of the Moon and around Mars.	**HS-04 LM**	
Deploy and operate utilization payload(s), related to the magnetotail and solar wind, at distributed sites on the lunar surface.	**CN-U-712 L**			
Transition crew from partial gravity environment to micro-gravity environment.	**CN-T-111 L**	Understand the effects of short- and long-duration exposure to the environments of the Moon, Mars, and deep space on biological systems and health, using humans, model organisms, systems of human physiology, and plants.	**HBS-01 LM**	**Human and Biological Science (HBS)**
Transition crew from micro-gravity environment to partial gravity environment, following a duration in space	**CN-T-112 L**			
Transfer, return, and curate a small amount (10s of kg) or a large amount (100s of kg) of unconditioned samples and containers from key destinations across the lunar surface and back to Earth, while maintaining scientific integrity of the samples.	**CN-T-302 L**			
Transfer, return and curate a small amount (10s of kg) or a large amount (100s of kg) of refrigerated sample(s), containers, and freezers from key destinations across the lunar surface to Earth while maintaining scientific integrity of the samples.	**CN-T-303 L**			
Transfer, return and curate a small amount (10s of kg) or a large amount (100s of kg) of frozen sample(s), containers, and freezers from key destinations across the lunar surface to Earth while maintaining scientific integrity of the samples.	**CN-T-304 L**			
Transfer, return and curate a small amount (10s of kg) or a large amount (100s of kg) of unconditioned sample(s) and containers from cislunar assets back to Earth while maintaining scientific integrity of the samples.	**CN-T-307 L**			
Transfer, return and curate a small amount (10s of kg) or a large amount (100s of kg) of refrigerated sample(s) and containers from cislunar assets back to Earth while maintaining scientific integrity of the samples.	**CN-T-308 L**			
Transfer, return and curate a small amount (10s of kg) or a large amount (100s of kg) of frozen sample(s) and containers from cislunar assets back to Earth while maintaining scientific integrity of the samples.	**CN-T-309 L**			
Conduct short-duration (days to weeks) to mid-duration (month+) crew exploration mission(s) on the lunar surface.	**CN-H-101 L**			
Conduct short-duration (days to weeks), mid-duration (month+), and extended-duration (year+) crew exploration mission(s) in cislunar space	**CN-H-102 L**			
Provide intravehicular activity accommodations (e.g., instruments, racks, stowage, power) on the lunar surface during crewed and uncrewed mission phases to enable biological science analysis and human research.	**CN-U-201 L**			
Provide intravehicular activity accommodations (e.g., instruments, racks, stowage, power) in cislunar space to enable biological science analysis and human research.	**CN-U-202 L**			

Lunar Goals, Objectives, and Characteristics and Needs				
Characteristics and Needs	**ID**	**Objectives**	**ID**	**Goal**
Provide intravehicular utilization accommodation and resources during crew transit between Earth and cislunar space to enable biological science analysis and human research.	**CN-U-205 L**			
Deploy and operate external utilization payload(s) addressing biological science analysis and human research around globally distributed locations on the lunar surface for a minimum of mid-duration (month+) missions.	**CN-U-701 L**			
Deploy and operate internal and external utilization payload(s) addressing biological science analysis and human research in cislunar space for mid-duration (month+) to extended-duration (year+) missions.	**CN-U-705 L**			
Transition crew from partial gravity environment to micro-gravity environment.	**CN-T-111 L**	Evaluate and validate progressively Earth-independent crew health & performance systems and operations with mission durations representative of Mars-class missions.	**HBS-02 LM**	
Transition crew from micro-gravity environment to partial gravity environment, following a duration in space	**CN-T-112 L**			
Transfer, return, and curate a small amount (10s of kg) or a large amount (100s of kg) of unconditioned samples and containers from key destinations across the lunar surface and back to Earth, while maintaining scientific integrity of the samples.	**CN-T-302 L**			
Transfer, return and curate a small amount (10s of kg) or a large amount (100s of kg) of refrigerated sample(s), containers, and freezers from key destinations across the lunar surface to Earth while maintaining scientific integrity of the samples.	**CN-T-303 L**			
Transfer, return and curate a small amount (10s of kg) or a large amount (100s of kg) of frozen sample(s), containers, and freezers from key destinations across the lunar surface to Earth while maintaining scientific integrity of the samples.	**CN-T-304 L**			
Transfer, return and curate a small amount (10s of kg) or a large amount (100s of kg) of unconditioned sample(s) and containers from cislunar assets back to Earth while maintaining scientific integrity of the samples.	**CN-T-307 L**			
Transfer, return and curate a small amount (10s of kg) or a large amount (100s of kg) of refrigerated sample(s) and containers from cislunar assets back to Earth while maintaining scientific integrity of the samples.	**CN-T-308 L**			
Transfer, return and curate a small amount (10s of kg) or a large amount (100s of kg) of frozen sample(s) and containers from cislunar assets back to Earth while maintaining scientific integrity of the samples.	**CN-T-309 L**			
Conduct short-duration (days to weeks) to mid-duration (month+) crew exploration mission(s) on the lunar surface.	**CN-H-101 L**			
Conduct short-duration (days to weeks), mid-duration (month+), and extended-duration (year+) crew exploration mission(s) in cislunar space	**CN-H-102 L**			
Provide intravehicular activity accommodations (e.g., instruments, racks, stowage, power) on the lunar surface during crewed and uncrewed mission phases to enable biological science analysis and human research.	**CN-U-201 L**			
Provide intravehicular activity accommodations (e.g., instruments, racks, stowage, power) in cislunar space to enable biological science analysis and human research.	**CN-U-202 L**			
Provide intravehicular utilization accommodation and resources during crew transit between Earth and cislunar space to enable biological science analysis and human research.	**CN-U-205 L**			

Lunar Goals, Objectives, and Characteristics and Needs				
Characteristics and Needs	**ID**	**Objectives**	**ID**	**Goal**
Deploy and operate external utilization payload(s) addressing biological science analysis and human research around globally distributed locations on the lunar surface for a minimum of mid-duration (month+) missions.	**CN-U-701 L**			
Deploy and operate internal and external utilization payload(s) addressing biological science analysis and human research in cislunar space for mid-duration (month+) to extended-duration (year+) missions.	**CN-U-705 L**			
Transition crew from partial gravity environment to micro-gravity environment.	**CN-T-111 L**	Characterize and evaluate how the interaction of exploration systems and the deep space environment affect human health, performance, and space human factors to inform future exploration-class missions.	**HBS-03 LM**	
Transition crew from micro-gravity environment to partial gravity environment, following a duration in space	**CN-T-112 L**	Characterize and evaluate how the interaction of exploration systems and the deep space environment affect human health, performance, and space human factors to inform future exploration-class missions.	**HBS-03 LM**	
Transfer, return, and curate a small amount (10s of kg) or a large amount (100s of kg) of unconditioned samples and containers from key destinations across the lunar surface and back to Earth, while maintaining scientific integrity of the samples.	**CN-T-302 L**	Characterize and evaluate how the interaction of exploration systems and the deep space environment affect human health, performance, and space human factors to inform future exploration-class missions.	**HBS-03 LM**	
Transfer, return and curate a small amount (10s of kg) or a large amount (100s of kg) of refrigerated sample(s), containers, and freezers from key destinations across the lunar surface to Earth while maintaining scientific integrity of the samples.	**CN-T-303 L**	Characterize and evaluate how the interaction of exploration systems and the deep space environment affect human health, performance, and space human factors to inform future exploration-class missions.	**HBS-03 LM**	
Transfer, return and curate a small amount (10s of kg) or a large amount (100s of kg) of frozen sample(s), containers, and freezers from key destinations across the lunar surface to Earth while maintaining scientific integrity of the samples.	**CN-T-304 L**	Characterize and evaluate how the interaction of exploration systems and the deep space environment affect human health, performance, and space human factors to inform future exploration-class missions.	**HBS-03 LM**	
Transfer, return and curate a small amount (10s of kg) or a large amount (100s of kg) of unconditioned sample(s) and containers from cislunar assets back to Earth while maintaining scientific integrity of the samples.	**CN-T-307 L**	Characterize and evaluate how the interaction of exploration systems and the deep space environment affect human health, performance, and space human factors to inform future exploration-class missions.	**HBS-03 LM**	
Transfer, return and curate a small amount (10s of kg) or a large amount (100s of kg) of refrigerated sample(s) and containers from cislunar assets back to Earth while maintaining scientific integrity of the samples.	**CN-T-308 L**	Characterize and evaluate how the interaction of exploration systems and the deep space environment affect human health, performance, and space human factors to inform future exploration-class missions.	**HBS-03 LM**	
Transfer, return and curate a small amount (10s of kg) or a large amount (100s of kg) of frozen sample(s) and containers from cislunar assets back to Earth while maintaining scientific integrity of the samples.	**CN-T-309 L**	Characterize and evaluate how the interaction of exploration systems and the deep space environment affect human health, performance, and space human factors to inform future exploration-class missions.	**HBS-03 LM**	
Conduct short-duration (days to weeks) to mid-duration (month+) crew exploration mission(s) on the lunar surface.	**CN-H-101 L**	Characterize and evaluate how the interaction of exploration systems and the deep space environment affect human health, performance, and space human factors to inform future exploration-class missions.	**HBS-03 LM**	
Conduct short-duration (days to weeks), mid-duration (month+), and extended-duration (year+) crew exploration mission(s) in cislunar space	**CN-H-102 L**	Characterize and evaluate how the interaction of exploration systems and the deep space environment affect human health, performance, and space human factors to inform future exploration-class missions.	**HBS-03 LM**	
Provide intravehicular activity accommodations (e.g., instruments, racks, stowage, power) on the lunar surface during crewed and uncrewed mission phases to enable biological science analysis and human research.	**CN-U-201 L**	Characterize and evaluate how the interaction of exploration systems and the deep space environment affect human health, performance, and space human factors to inform future exploration-class missions.	**HBS-03 LM**	
Provide intravehicular activity accommodations (e.g., instruments, racks, stowage, power) in cislunar space to enable biological science analysis and human research.	**CN-U-202 L**	Characterize and evaluate how the interaction of exploration systems and the deep space environment affect human health, performance, and space human factors to inform future exploration-class missions.	**HBS-03 LM**	
Provide intravehicular utilization accommodation and resources during crew transit between Earth and cislunar space to enable biological science analysis and human research.	**CN-U-205 L**	Characterize and evaluate how the interaction of exploration systems and the deep space environment affect human health, performance, and space human factors to inform future exploration-class missions.	**HBS-03 LM**	
Deploy and operate external utilization payload(s) addressing biological science analysis and human research around globally distributed locations on the lunar surface for a minimum of mid-duration (month+) missions.	**CN-U-701 L**	Characterize and evaluate how the interaction of exploration systems and the deep space environment affect human health, performance, and space human factors to inform future exploration-class missions.	**HBS-03 LM**	

Lunar Goals, Objectives, and Characteristics and Needs				
Characteristics and Needs	**ID**	**Objectives**	**ID**	**Goal**
Deploy and operate internal and external utilization payload(s) addressing biological science analysis and human research in cislunar space for mid-duration (month+) to extended-duration (year+) missions.	**CN-U-705 L**			
Deploy and operate astrophysics and fundamental physics utilization payload(s) on the far side of the lunar surface.	**CN-U-716 L**	Conduct astrophysics and fundamental physics investigations of space and time from the radio quiet environment of the lunar far side.	**PPS-01 L**	**Physics and Physical Science (PPS)**
Transfer, return, and curate a small amount (10s of kg) of unconditioned samples, containers, and freezers from key destinations across the lunar surface back to Earth while maintaining scientific integrity of the samples.	**CN-T-306 L**	Advance understanding of physical systems and fundamental physics by utilizing the unique environments of the Moon, Mars, and deep space.	**PPS-02 LM**	
Transfer, return and curate a small amount (10s of kg) of unconditioned sample(s) and containers from cislunar assets back to Earth while maintaining scientific integrity of the samples.	**CN-T-310 L**			
Provide intravehicular activity accommodations (e.g., instruments, racks, stowage, power) on the lunar surface to enable fundamental physics experiments.	**CN-U-203 L**			
Provide intravehicular activity accommodations (e.g., instruments, racks, stowage, power) in cislunar space to enable fundamental physics experiments.	**CN-U-204 L**			
Provide intravehicular utilization accommodation and resources during crew transit between Earth and cislunar space to enable fundamental physics experiments.	**CN-U-206 L**			
Deploy and operate utilization payload(s), related to the physical systems and fundamental physics, in cislunar space.	**CN-U-703 L**			
Deploy and operate utilization payload(s), related to the physical systems and fundamental physics, at areas of key scientific interest on the lunar surface, including polar and non-polar destinations.	**CN-U-704 L**			
Train astronauts to be field scientists and to perform additional science tasks during crewed missions, through integrated geology, field and EVA ops and classroom training.	**CN-X-202 L**	Provide in-depth, mission-specific science training for astronauts to enable crew to perform high-priority or transformational science on the surface of the Moon, and Mars, and in deep space.	**SE-01 LM**	**Science-Enabling (SE)**
Train Earth-based scientists to support crew activities in real time.	**CN-X-203 L**	Enable Earth-based scientists to remotely support astronaut surface and deep space activities using advanced techniques and tools.	**SE-02 LM**	
Provide scalable communication system(s) to enable high bandwidth, high availability communications between Earth-based personnel, surface crew, and assets on the surface.	**CN-C-101 L**			
Provide scalable communication system(s) to enable high bandwidth, high availability communications between Earth-based personnel, in-space crew, and in-space assets.	**CN-C-102 L**			
Transfer, return, and curate a large amount (100s of kg) of cryogenic samples, containers, and freezers from key destinations across the lunar surface back to Earth while maintaining scientific integrity of the samples.	**CN-T-305 L**	Develop the capability to retrieve core samples of frozen volatiles from permanently shadowed regions on the Moon and volatile-bearing sites on Mars and to deliver them in pristine states to modern curation facilities on Earth.	**SE-03 LM**	
Provide curation or other appropriate facilities on Earth equipped for preserving acquired samples in their pristine state.	**CN-G-201 L**			

Lunar Goals, Objectives, and Characteristics and Needs				
Characteristics and Needs	**ID**	**Objectives**	**ID**	**Goal**
Identify, collect, and document deep-surface samples from key destinations in PSRs on the lunar surface, while maintaining scientific integrity of the samples.	**CN-U-302 L**			
Provide capabilities to visit geographically diverse sites on the lunar surface, including the south polar region, and non-polar destinations.	**CN-T-107 L**	Return representative samples from multiple locations across the surface of the Moon and Mars, with sample mass commensurate with mission-specific science priorities.	**SE-04 LM**	
Visit diverse sites of key scientific interest on the lunar surface, including polar and non-polar destinations to address high priority science goals.	**CN-T-108 L**			
Transfer, return, and curate a small amount (10s of kg) or a large amount (100s of kg) of unconditioned samples and containers from key destinations across the lunar surface and back to Earth, while maintaining scientific integrity of the samples.	**CN-T-302 L**			
Transfer, return and curate a small amount (10s of kg) or a large amount (100s of kg) of frozen sample(s), containers, and freezers from key destinations across the lunar surface to Earth while maintaining scientific integrity of the samples.	**CN-T-304 L**			
Transfer, return, and curate a large amount (100s of kg) of cryogenic samples, containers, and freezers from key destinations across the lunar surface back to Earth while maintaining scientific integrity of the samples.	**CN-T-305 L**			
Provide curation or other appropriate facilities on Earth equipped for preserving acquired samples in their pristine state.	**CN-G-201 L**			
Identify, collect, and document deep-surface samples from key destinations in PSRs on the lunar surface, while maintaining scientific integrity of the samples.	**CN-U-302 L**			
Identify, collect, and document surface and shallow subsurface samples from key destinations in non-PSRs and other sunlit areas on the lunar surface, while maintaining scientific integrity of the samples.	**CN-U-303 L**			
Identify, collect, and document surface and shallow subsurface samples from key destinations in PSRs on the lunar surface, while maintaining scientific integrity of the samples.	**CN-U-304 L**			
Conduct robotic surveys of potential landing sites, including video and in situ measurements.	**CN-A-105 L**	Use robotic techniques to survey sites, conduct in-situ measurements, and identify/stockpile samples in advance of and concurrent with astronaut arrival, to optimize astronaut time on the lunar and Martian surface and maximize science return.	**SE-05 LM**	
Provide appropriate robotic tools to support acquisition of samples, including dust, soil, pebbles, hand-sized rock samples, and drill cores, manufactured in accordance with science requirements to minimize sample contamination.	**CN-A-106 L**			
Deploy and operate utilization payloads, related to fundamental plasma processes, in cislunar space.	**CN-U-709 L**	Enable long-term, planet-wide research by delivering science instruments to multiple science-relevant orbits and surface locations at the Moon and Mars.	**SE-06 LM**	
Deploy and operate utilization payload(s) around globally distributed locations on the lunar surface relevant to addressing associated science objectives.	**CN-U-717 L**			
Coordinate delivery and deployment of utilization payloads in cislunar space and on the lunar surface to address associated science objectives.	**CN-U-801 L**			
Limit contamination of PSRs.	**CN-U-802 L**	Preserve and protect representative features of special interest, including lunar permanently shadowed regions	**SE-07 LM**	

Lunar Goals, Objectives, and Characteristics and Needs				
Characteristics and Needs	**ID**	**Objectives**	**ID**	**Goal**
Preserve radio free environment on the far side of the Moon.	**CN-U-803 L**	and the radio quiet far side as well as Martian recurring slope lineae, to enable future high-priority science investigations.		
Protect sites of historic significance.	**CN-U-804 L**			
Minimize environmental impacts on the lunar surface to preserve scientific integrity for future exploration.	**CN-U-805 L**			
Provide system(s) to monitor cislunar space and lunar surface natural environments, including space weather, meteoroids, cosmic weather, thermal conditions, and plasma environments, and provide early warnings to in-space and surface assets and crew.	**CN-U-102 L**	Characterize and monitor the contemporary environments of the lunar and Martian surfaces and orbits, including investigations of micrometeorite flux, atmospheric weather, space weather, space weathering, and dust, to plan, support, and monitor safety of crewed operations in these locations.	**AS-01 LM**	**Applied Science (AS)**
Deploy and operate external utilization payload(s) addressing biological science analysis and human research around globally distributed locations on the lunar surface for a minimum of mid-duration (month+) missions.	**CN-U-701 L**			
Coordinate delivery and deployment of utilization payloads in cislunar space and on the lunar surface to address associated science objectives.	**CN-U-801 L**	Coordinate on-going and future science measurements from orbital and surface platforms to optimize human-led science campaigns on the Moon and Mars.	**AS-02 LM**	
Visit diverse sites of key scientific interest on the lunar surface, including polar and non-polar destinations to address high priority science goals.	**CN-T-108 L**	Characterize accessible lunar and Martian resources, gather scientific research data, and analyze potential reserves to satisfy science and technology objectives and enable In-Situ Resource Utilization (ISRU) on successive missions.	**AS-03 LM**	
Transfer, return, and curate a small amount (10s of kg) or a large amount (100s of kg) of unconditioned samples and containers from key destinations across the lunar surface and back to Earth, while maintaining scientific integrity of the samples.	**CN-T-302 L**			
Transfer, return and curate a small amount (10s of kg) or a large amount (100s of kg) of frozen sample(s), containers, and freezers from key destinations across the lunar surface to Earth while maintaining scientific integrity of the samples.	**CN-T-304 L**			
Provide mobility capabilities to conduct prospecting traverses with appropriate scientific instrumentation and drill capabilities over sites of interest.	**CN-M-301 L**			
Identify, collect, and document deep subsurface samples from key destinations in non-PSRs and other sunlit areas on the lunar surface, while maintaining scientific integrity of the samples.	**CN-U-301 L**			
Identify, collect, and document deep-surface samples from key destinations in PSRs on the lunar surface, while maintaining scientific integrity of the samples.	**CN-U-302 L**			
Identify, collect, and document surface and shallow subsurface samples from key destinations in non-PSRs and other sunlit areas on the lunar surface, while maintaining scientific integrity of the samples.	**CN-U-303 L**			
Identify, collect, and document surface and shallow subsurface samples from key destinations in PSRs on the lunar surface, while maintaining scientific integrity of the samples.	**CN-U-304 L**			
Deploy and operate exploration asset(s), related to available resources, at distributed and south polar region sites on the lunar surface.	**CN-U-702 L**			

Lunar Goals, Objectives, and Characteristics and Needs				
Characteristics and Needs	**ID**	**Objectives**	**ID**	**Goal**
Demonstrate operation of bioregenerative ECLSS sub-systems in LEO and/or deep space.	**CN-U-601 LM**	Conduct applied scientific investigations essential for the development of bioregenerative-based, ecological life support systems.	**AS-04 LM**	
Demonstrate operation of plant based ECLSS sub-systems in LEO and/or deep space.	**CN-U-602 LM**	Define crop plant species, including methods for their productive growth, capable of providing sustainable and nutritious food sources for lunar, Deep Space transit, and Mars habitation.	**AS-05 LM**	
Deploy and operate utilization payload(s), related to the physical systems and fundamental physics, in cislunar space.	**CN-U-703 L**	Advance understanding of how physical systems and fundamental physical phenomena are affected by partial gravity, microgravity, and general environment of the Moon, Mars, and deep space transit.	**AS-06 LM**	
Deploy and operate utilization payload(s), related to the physical systems and fundamental physics, at areas of key scientific interest on the lunar surface, including polar and non-polar destinations.	**CN-U-704 L**			
Provide scalable power generation, energy storage, and power distribution system(s) on the lunar surface to support large exploration assets.	**CN-P-101 L**	Develop an incremental lunar power generation and distribution system that is evolvable to support continuous robotic/human operation and is capable of scaling to global power utilization and industrial power levels.	**LI-01 L**	**Lunar Infrastructure (LI)**
Provide scalable power generation, energy storage, and power distribution system(s) on the lunar surface to allow power utilization to support assets at multiple distributed locations around exploration sites.	**CN-P-102 L**			
Provide power generation, energy storage, and power distribution system(s) on the lunar surface that are able to supply continuous power availability during crew safety critical mission operation and are able to support contingency operations.	**CN-P-103 L**			
Provide scalable communication system(s) to enable high bandwidth, high availability communications between Earth-based personnel, surface crew, and assets on the surface.	**CN-C-101 L**	Develop a lunar surface, orbital, and Moon-to-Earth communications architecture capable of scaling to support long term science, exploration, and industrial needs.	**LI-02 L**	
Provide scalable communication system(s) to enable high bandwidth, high availability communications between Earth-based personnel, in-space crew, and in-space assets.	**CN-C-102 L**			
Provide scalable communication system(s) to enable high bandwidth, high availability communications between In-space personnel, surface crew, and assets on the surface.	**CN-C-103 L**			
Provide communication capabilities to allow NASA to inspire and inform the general public, students, and teachers by enabling them to interact, learn about, and experience missions in a direct and tangible way.	**CN-C-104 L**			
Provide scalable communication system(s) to enable high bandwidth, high availability communications between different crew and assets on the lunar surface.	**CN-C-105 L**			
Provide scalable navigation, positioning, and timing system(s) to enable high availability navigation and tracking in cislunar space.	**CN-C-201 L**	Develop a lunar position, navigation and timing architecture capable of scaling to support long term science, exploration, and industrial needs.	**LI-03 L**	
Provide scalable navigation, positioning, and timing system(s) to enable high availability navigation and tracking on the lunar surface.	**CN-C-202 L**			
Provide system(s) to enable accurate location identification, tracking, and documentation of collected surface samples.	**CN-C-203 L**			

Lunar Goals, Objectives, and Characteristics and Needs				
Characteristics and Needs	**ID**	**Objectives**	**ID**	**Goal**
Deploy and operate autonomous construction demonstration asset(s) to the lunar surface, including partial-scale demonstrations of regolith manipulation and construction of structures, to demonstrate scalable capabilities and applications.	**CN-I-201 L**	Demonstrate advanced manufacturing and autonomous construction capabilities in support of continuous human lunar presence and a robust lunar economy.	**LI-04 L**	
Deploy and operate advanced manufacturing demonstration asset(s) to the lunar surface, including scaled demonstration of additive/subtractive/joining manufacturing techniques and inspection/certification processes, to demonstrate scalable capabilities and applications to create a wide variety or products with metallic/polymer/composites materials.	**CN-I-202 L**	Demonstrate advanced manufacturing and autonomous construction capabilities in support of continuous human lunar presence and a robust lunar economy.	**LI-04 L**	
Demonstrate the capability for lunar landers to reliably and safely land within a defined radius around an intended location.	**CN-T-401 L**	Demonstrate precision landing capabilities in support of continuous human lunar presence and a robust lunar economy.	**LI-05 L**	
Demonstrate the capability for crew to access surface assets at different potential locations distributed across the lunar globe.	**CN-T-109 L**	Demonstrate local, regional, and global surface transportation and mobility capabilities in support of continuous human lunar presence and a robust lunar economy.	**LI-06 L**	
Demonstrate the capability to allow crew to move locally around landing sites to visit multiple locations of interest.	**CN-M-302 L**	Demonstrate local, regional, and global surface transportation and mobility capabilities in support of continuous human lunar presence and a robust lunar economy.	**LI-06 L**	
Demonstrate the capability to regionally relocate exploration assets.	**CN-M-601 L**	Demonstrate local, regional, and global surface transportation and mobility capabilities in support of continuous human lunar presence and a robust lunar economy.	**LI-06 L**	
Deploy scalable demonstration ISRU exploration asset(s) on the lunar surface.	**CN-I-102 LM**	Demonstrate industrial scale ISRU capabilities in support of continuous human lunar presence and a robust lunar economy.	**LI-07 L**	
Operate demonstration exploration asset(s) on the lunar surface to collect, produce, store, and transfer commodities, including water, oxygen, and/or construction feedstock, for potential use.	**CN-I-103 LM**	Demonstrate industrial scale ISRU capabilities in support of continuous human lunar presence and a robust lunar economy.	**LI-07 L**	
Demonstrate the capability to identify and locate potential site(s) for resource utilization.	**CN-U-101 L**	Demonstrate industrial scale ISRU capabilities in support of continuous human lunar presence and a robust lunar economy.	**LI-07 L**	
Limit contamination of PSRs.	**CN-U-802 L**	Demonstrate industrial scale ISRU capabilities in support of continuous human lunar presence and a robust lunar economy.	**LI-07 L**	
Deploy and operate autonomous demonstration construction exploration asset(s) that are reliant on surface-borne feedstock to demonstrate scalable capabilities and applications, such as additive manufacturing and autonomous construction of structures.	**CN-I-203 L**	Demonstrate technologies supporting cislunar orbital/surface depots, construction and manufacturing maximizing the use of in-situ resources, and support systems needed for continuous human/robotic presence.	**LI-08 L**	
Demonstrate the capability to transfer propellant from one spacecraft to another in space (including interfaces for non-cryogenic propellants, cryogenic propellants, power, data, commands, and buffer gases).	**CN-U-501 L**	Demonstrate technologies supporting cislunar orbital/surface depots, construction and manufacturing maximizing the use of in-situ resources, and support systems needed for continuous human/robotic presence.	**LI-08 L**	
Demonstrate the capability to transfer propellant from one asset to another on the lunar surface (including interfaces for non-cryogenic propellants, cryogenic propellants, power, data, commands, and buffer gases).	**CN-U-502 L**	Demonstrate technologies supporting cislunar orbital/surface depots, construction and manufacturing maximizing the use of in-situ resources, and support systems needed for continuous human/robotic presence.	**LI-08 L**	
Demonstrate the capability to store propellant for extended-durations (year+) in space (including cryogenic propellant, leak management, and mass gauging).	**CN-U-503 L**	Demonstrate technologies supporting cislunar orbital/surface depots, construction and manufacturing maximizing the use of in-situ resources, and support systems needed for continuous human/robotic presence.	**LI-08 L**	
Demonstrate the capability to store propellant for extended-durations (year+) on the lunar surface (including cryogenic propellant, leak management, and mass gauging).	**CN-U-504 L**	Demonstrate technologies supporting cislunar orbital/surface depots, construction and manufacturing maximizing the use of in-situ resources, and support systems needed for continuous human/robotic presence.	**LI-08 L**	

Lunar Goals, Objectives, and Characteristics and Needs				
Characteristics and Needs	**ID**	**Objectives**	**ID**	**Goal**
Demonstrate technologies for support systems needed for continuous human/robotic presence including mobility repair and outfitting facilities, logistics facilities, and recycling plants.	**CN-A-101 LM**	Develop environmental monitoring, situational awareness, and early warning capabilities to support a resilient, continuous human/robotic lunar presence.	**LI-09 L**	
Provide system(s) to monitor cislunar space and lunar surface natural environments, including space weather, meteoroids, cosmic weather, thermal conditions, and plasma environments, and provide early warnings to in-space and surface assets and crew.	**CN-U-102 L**			
Provide system(s) to monitor cislunar space and lunar surface induced environments, including radiation, thermal conditions, dust, high-energy debris, contamination, electrostatics, and acoustics, and provide early warnings to in-space and surface assets and crew.	**CN-U-103 L**			
Implement stable transportation capabilities, which minimize required upgrades over time, to support lunar missions.	**CN-T-101 L**	Develop cislunar systems that crew can routinely operate to and from lunar orbit and the lunar surface for extended durations.	**TH-01 L**	**Transportation and Habitation (TH)**
Implement robust transportation capabilities, where systems can perform a variety of design reference missions, to support lunar missions.	**CN-T-102 L**			
Enable routine access to the lunar surface.	**CN-T-103 L**			
Enable routine access to cislunar space.	**CN-T-104 L**			
Provide capabilities to transport crew from Earth to cislunar space.	**CN-T-105 L**			
Provide capabilities to transport crew between stable lunar orbit, including NRHO, and the lunar surface.	**CN-T-106 L**			
Provide capabilities to enable staging and/or assembly operations of crew and cargo system(s) in cislunar space with accessibility to both Earth and the lunar surface, including the lunar South Polar region.	**CN-T-110 L**			
Provide capabilities to operate crew transportation system(s) in uncrewed mode for mid-durations (month+) to extended-durations (year+) in cislunar space and on the lunar surface.	**CN-T-113 L**			
Provide capabilities to safely return crew and system(s) to Earth from lunar surface and cislunar space.	**CN-T-114 L**			
Enable routine access to the lunar surface.	**CN-T-103 L**	Develop system(s) that can routinely deliver a range of elements to the lunar surface.	**TH-02 L**	
Provide capabilities to deliver system(s) from Earth to the lunar surface.	**CN-T-201 L**			
Provide capabilities to unload cargo from delivery system(s).	**CN-M-401 L**			

Lunar Goals, Objectives, and Characteristics and Needs				
Characteristics and Needs	**ID**	**Objectives**	**ID**	**Goal**
Implement end-of-life strategies for transportation systems to ensure future viable usage of exploration sites on the lunar surface.	**CN-U-808 L**			
Provide capabilities to conduct short-duration (days to weeks) crew exploration mission(s) on the lunar surface.	**CN-H-105 L**	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.	**TH-03 L**	
Provide capabilities to conduct mid-duration (month+) crew exploration mission(s) on the lunar surface.	**CN-H-106 L**			
Provide capabilities to conduct moderate durations (months) to extended-duration (year+) crew exploration mission(s) in cislunar and deep space.	**CN-H-107 L**			
Implement stable habitation capabilities, which minimize required upgrades over time, to support lunar missions.	**CN-H-108 L**			
Implement robust habitation capabilities, where systems can support all design reference missions, to support lunar missions.	**CN-H-109 L**			
Provide capabilities to enable crew transition in/out of habitable space to conduct EVA activities.	**CN-M-102 L**			
Provide capabilities to enable staging and/or assembly operations of crew and cargo system(s) in cislunar space with accessibility to both Earth and the lunar surface, including the lunar South Polar region.	**CN-T-110 L**	Develop in-space and surface habitation system(s) for crew to live in deep space for extended durations, enabling future missions to Mars.	**TH-04 LM**	
Provide capabilities to conduct short-duration (days to weeks) crew exploration mission(s) on the lunar surface.	**CN-H-105 L**			
Provide capabilities to conduct mid-duration (month+) crew exploration mission(s) on the lunar surface.	**CN-H-106 L**			
Provide capabilities to conduct moderate durations (months) to extended-duration (year+) crew exploration mission(s) in cislunar and deep space.	**CN-H-107 L**			
Provide appropriate medical capabilities (including behavioral health) that allow for autonomous crew health decision making and care, and are preparatory of a mission to Mars.	**CN-X-101 LM**	Develop systems that monitor and maintain crew health and performance throughout all mission phases, including during communication delays to Earth, and in an environment that does not allow emergency evacuation or terrestrial medical assistance.	**TH-08 LM**	
Provide countermeasures capabilities that are commensurate in scope with the human system needs for the mission.	**CN-X-102 L**			
Demonstrate crew survival capabilities in cislunar space and on the lunar surface, including safe havens, system supportability, and/or aborts, for nominal and off-nominal scenarios to prepare for future Mars missions.	**CN-X-103 L**			
Provide appropriate environmental monitoring capabilities that enables inflight crew health decision making and mitigation of relevant system/vehicle hazards.	**CN-U-104 L**			
Provide appropriate robotic system(s) that can conduct or assist in tasks that would otherwise be performed by the crew alone on the lunar surface.	**CN-A-102 L**	Develop integrated human and robotic systems with inter-relationships that enable maximum science and	**TH-09 L**	

Lunar Goals, Objectives, and Characteristics and Needs				
Characteristics and Needs	**ID**	**Objectives**	**ID**	**Goal**
Provide appropriate robotic system(s) that can conduct or assist in tasks that would otherwise be performed by the crew alone in cislunar or deep space.	**CN-A-107 L**	exploration during lunar missions.		
Provide capabilities to return cargo from the lunar surface back to cislunar space.	**CN-T-202 L**	Develop systems capable of returning a range of cargo mass from the lunar surface to Earth, including the capabilities necessary to meet scientific and utilization objectives.	**TH-11 L**	
Provide capabilities to return cargo from cislunar space back to Earth-based facilities.	**CN-T-301 L**			
Transfer, return, and curate a small amount (10s of kg) or a large amount (100s of kg) of unconditioned samples and containers from key destinations across the lunar surface and back to Earth, while maintaining scientific integrity of the samples.	**CN-T-302 L**			
Transfer, return and curate a small amount (10s of kg) or a large amount (100s of kg) of refrigerated sample(s), containers, and freezers from key destinations across the lunar surface to Earth while maintaining scientific integrity of the samples.	**CN-T-303 L**			
Transfer, return and curate a small amount (10s of kg) or a large amount (100s of kg) of frozen sample(s), containers, and freezers from key destinations across the lunar surface to Earth while maintaining scientific integrity of the samples.	**CN-T-304 L**			
Transfer, return, and curate a large amount (100s of kg) of cryogenic samples, containers, and freezers from key destinations across the lunar surface back to Earth while maintaining scientific integrity of the samples.	**CN-T-305 L**			
Transition crew from micro-gravity environment to partial gravity environment, following a duration in space	**CN-T-112 L**	Conduct human research and technology demonstrations on the surface of Earth, low-Earth orbit platforms, cislunar platforms, and on the surface of the moon, to evaluate the effects of extended mission durations on the performance of crew and systems, reduce risk, and shorten the timeframe for system testing and readiness prior to the initial human Mars exploration campaign.	**OP-01 L**	**Operations (OP)**
Conduct short-duration (days to weeks) to mid-duration (month+) crew exploration mission(s) on the lunar surface.	**CN-H-101 L**			
Conduct short-duration (days to weeks), mid-duration (month+), and extended-duration (year+) crew exploration mission(s) in cislunar space	**CN-H-102 L**			
Conduct crewed and uncrewed testing of surface habitable system(s).	**CN-H-103 L**			
Conduct crewed and uncrewed testing of in-space habitable system(s).	**CN-H-104 L**			
Operate and gain experience with flight control and mission integration to ensure safety and mission success in nominal and off-nominal conditions.	**CN-T-402 LM**	Optimize operations, training and interaction between the team on Earth, crew members on orbit, and a Martian surface team considering communication delays, autonomy level, and time required for an early return to the Earth.	**OP-02 LM**	
Operate and gain experience with in-situ training and planning capabilities to ensure safety and mission success.	**CN-X-201 LM**			
Operate and gain experience with onboard autonomous system(s) and crew autonomy to train, plan, and execute safe mission(s) with reduced reliance on Earth based systems.	**CN-A-401 LM**			
Operate and gain experience with remote & autonomous system(s) to reduce crew workload.	**CN-A-402 LM**			

Lunar Goals, Objectives, and Characteristics and Needs				
Characteristics and Needs	**ID**	**Objectives**	**ID**	**Goal**
Visit diverse sites of key scientific interest on the lunar surface, including polar and non-polar destinations to address high priority science goals.	**CN-T-108 L**	Characterize accessible resources, gather scientific research data, and analyze potential reserves to satisfy science and technology objectives and enable use of resources on successive missions.	**OP-03 LM**	
Transfer, return, and curate a small amount (10s of kg) or a large amount (100s of kg) of unconditioned samples and containers from key destinations across the lunar surface and back to Earth, while maintaining scientific integrity of the samples.	**CN-T-302 L**			
Transfer, return and curate a small amount (10s of kg) or a large amount (100s of kg) of frozen sample(s), containers, and freezers from key destinations across the lunar surface to Earth while maintaining scientific integrity of the samples.	**CN-T-304 L**			
Demonstrate the capability to identify and locate potential site(s) for resource utilization.	**CN-U-101 L**			
Identify, collect, and document deep subsurface samples from key destinations in non-PSRs and other sunlit areas on the lunar surface, while maintaining scientific integrity of the samples.	**CN-U-301 L**			
Identify, collect, and document deep-surface samples from key destinations in PSRs on the lunar surface, while maintaining scientific integrity of the samples.	**CN-U-302 L**			
Identify, collect, and document surface and shallow subsurface samples from key destinations in non-PSRs and other sunlit areas on the lunar surface, while maintaining scientific integrity of the samples.	**CN-U-303 L**			
Identify, collect, and document surface and shallow subsurface samples from key destinations in PSRs on the lunar surface, while maintaining scientific integrity of the samples.	**CN-U-304 L**			
Deploy and operate exploration asset(s), related to available resources, at distributed and south polar region sites on the lunar surface.	**CN-U-702 L**			
Provide capabilities to integrate networks and mission systems to exchange data between Earth-based systems, in-space exploration assets, and surface exploration assets.	**CN-D-101 L**	Establish command and control processes, common interfaces, and ground systems that will support expanding human missions at the Moon and Mars.	**OP-04 LM**	
Provide capabilities to utilize common data interface(s) for exchanges between Earth-based systems, in-space exploration assets, and surface exploration assets.	**CN-D-102 L**			
Provide capabilities to store and protect data on exploration assets.	**CN-D-103 L**			
Operate and gain experience with capabilities to conduct extravehicular activities utilizing mobility assets and tools.	**CN-M-101 LM**	Operate surface mobility systems, e.g., extra-vehicular activity (EVA) suits, tools and vehicles.	**OP-05 LM**	
Operate and gain experience with capabilities to transport crew and cargo between landing, exploration, and utilization sites at varying distances from assets on the lunar surface.	**CN-M-501 L**			
Transition crew from partial gravity environment to micro-gravity environment.	**CN-T-111 L**	Evaluate, understand, and mitigate the impacts on crew health and performance of a long deep space orbital mission, followed by partial gravity surface operations on the Moon.	**OP-06 L**	
Transition crew from micro-gravity environment to partial gravity environment, following a duration in space	**CN-T-112 L**			

Lunar Goals, Objectives, and Characteristics and Needs				
Characteristics and Needs	**ID**	**Objectives**	**ID**	**Goal**
Conduct short-duration (days to weeks) to mid-duration (month+) crew exploration mission(s) on the lunar surface.	**CN-H-101 L**			
Conduct short-duration (days to weeks), mid-duration (month+), and extended-duration (year+) crew exploration mission(s) in cislunar space	**CN-H-102 L**			
Conduct crewed and uncrewed testing of surface habitable system(s).	**CN-H-103 L**	Validate readiness of systems and operations to support crew health and performance for the initial human Mars exploration campaign.	**OP-07 LM**	
Conduct crewed and uncrewed testing of in-space habitable system(s).	**CN-H-104 L**			
Provide appropriate medical capabilities (including behavioral health) that allow for autonomous crew health decision making and care, and are preparatory of a mission to Mars.	**CN-X-101 LM**			
Provide countermeasures capabilities that are commensurate in scope with the human system needs for the mission.	**CN-X-102 L**			
Demonstrate crew survival capabilities in cislunar space and on the lunar surface, including safe havens, system supportability, and/or aborts, for nominal and off-nominal scenarios to prepare for future Mars missions.	**CN-X-103 L**			
Demonstrate the capabilities to locate, access, and reuse surface assets from previous crewed and uncrewed missions.	**CN-U-105 L**	Demonstrate the capability to find, service, upgrade, or utilize instruments and equipment from robotic landers or previous human missions on the surface of the Moon and Mars.	**OP-08 LM**	
Demonstrate the capabilities to service and/or upgrade assets.	**CN-U-806 L**			
Provide appropriate robotic system(s) that can conduct or assist in tasks that would otherwise be performed by the crew alone on the lunar surface.	**CN-A-102 L**	Demonstrate the capability of integrated robotic systems to support and maximize the useful work performed by crewmembers on the surface, and in orbit.	**OP-09 LM**	
Demonstrate the capabilities to operate appropriate robotic system(s) that can conduct or assist in tasks that would otherwise be performed by the crew alone on the lunar surface.	**CN-A-103 L**			
Demonstrate the capabilities to operate appropriate robotic system(s) that can conduct or assist in tasks that would otherwise be performed by the crew alone in cislunar space.	**CN-A-104 L**			
Minimize crew time required for inspection, commissioning, maintenance, and logistics operations to maximize crew time available for science and exploration activities.	**CN-A-108 L**			
Demonstrate capabilities to allow in-space and surface crew to control and command robotic system(s).	**CN-A-201 L**			
Demonstrate the capability for safe and effective interactions between crew and automated/autonomous system(s).	**CN-A-301 L**			
Demonstrate the capability for safe and effective interactions between crew and automated/autonomous system(s).	**CN-A-301 L**	Demonstrate the capability to operate robotic systems that are used to support crew members on the lunar or Martian surface,	**OP-10 LM**	

Lunar Goals, Objectives, and Characteristics and Needs				
Characteristics and Needs	**ID**	**Objectives**	**ID**	**Goal**
		autonomously or remotely from the Earth or from orbiting platforms.		
Operate demonstration exploration asset(s) on the lunar surface to collect, produce, store, and transfer commodities, including water, oxygen, and/or construction feedstock, for potential use.	**CN-I-103 LM**	Demonstrate the capability to use commodities produced from planetary surface or in-space resources to reduce the mass required to be transported from Earth.	**OP-11 LM**	
Demonstrate the capability to use surface-borne resources for potential construction and/or manufacturing on the lunar surface.	**CN-I-204 L**			
Demonstrate the capabilities to use surface-borne commodities to support exploration assets on the lunar surface.	**CN-I-205 L**			
Demonstrate the capabilities to recovery of excess fluids and gases and separation of products, including propellant residuals, from lunar landers.	**CN-I-101 L**	Establish procedures and systems that will minimize the disturbance to the local environment, maximize the resources available to future explorers, and allow for reuse/recycling of material transported from Earth (and from the lunar surface in the case of Mars) to be used during exploration.	**OP-12 LM**	
Limit contamination of PSRs.	**CN-U-802 L**			
Preserve radio free environment on the far side of the Moon.	**CN-U-803 L**			
Demonstrate the capabilities to recover useful equipment from surface assets, where valuable.	**CN-U-807 L**			

2.6.2 Mars Goals, Objectives, and Characteristics and Needs

Mars Goals, Objectives, and Characteristics and Needs				
Characteristics and Needs	**ID**	**Objectives**	**ID**	**Goal**
Visit diverse sites on the Martian surface to address high priority science and utilization goals.	**CN-T-105 M**	Uncover the record of solar system origin and early history, by determining how and when planetary bodies formed and differentiated, characterizing the impact chronology of the inner solar system as recorded on the Moon and Mars, and characterize how impact rates in the inner solar system have changed over time as recorded on the Moon and Mars.	**LPS-01 LM**	**Lunar/Planetary Science (LPS)**
Transfer, return, and curate a small amount (10s of kg) or a large amount (100s of kg) of unconditioned samples and containers from key destinations across the Martian surface, while maintaining scientific integrity of the samples.	**CN-T-301 M**			
Provide the ability for the Science Team to directly or indirectly communicate in nonrealtime via either written or verbal means with the crew for EVA and IVA activities.	**CN-C-105 M**			
Identify, collect, and document surface and shallow subsurface samples from key destinations on the Martian surface, while maintaining scientific integrity of the samples.	**CN-U-303 M**			
Deploy and operate utilization payload(s), related to understanding impact chronology, at distributed sites on the Martian surface.	**CN-U-712 M**			

Mars Goals, Objectives, and Characteristics and Needs				
Characteristics and Needs	**ID**	**Objectives**	**ID**	**Goal**
Visit diverse sites on the Martian surface to address high priority science and utilization goals.	**CN-T-105 M**	Advance understanding of the geologic processes that affect planetary bodies by determining the interior structures, characterizing the magmatic histories, characterizing ancient, modern, and evolution of atmospheres/exospheres, and investigating how active processes modify the surfaces of the Moon and Mars.	**LPS-02 LM**	
Transfer, return, and curate a small amount (10s of kg) or a large amount (100s of kg) of unconditioned samples and containers from key destinations across the Martian surface, while maintaining scientific integrity of the samples.	**CN-T-301 M**			
Provide the ability for the Science Team to directly or indirectly communicate in nonrealtime via either written or verbal means with the crew for EVA and IVA activities.	**CN-C-105 M**			
Identify, collect, and document surface and shallow subsurface samples from key destinations on the Martian surface, while maintaining scientific integrity of the samples.	**CN-U-303 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.	**CN-U-304 M**			
Conduct borehole measurements at varying depths, including ionizing radiation and heat flow.	**CN-U-305 M**			
Deploy and operate utilization payload(s) and equipment, related to geologic processes, at key destinations across the Martian surface, for mid-durations (month+) to long-durations (year+).	**CN-U-713 M**			
Visit diverse sites on the Martian surface to address high priority science and utilization goals.	**CN-T-105 M**	Reveal inner solar system volatile origin and delivery processes by determining the age, origin, distribution, abundance, composition, transport, and sequestration of lunar and Martian volatiles.	**LPS-03 LM**	
Transfer, return and curate a small amount (10s of kg) or a large amount (100s of kg) of frozen sample(s), containers, and freezers from key destinations across the Martian surface, while maintaining scientific integrity of the samples.	**CN-T-303 M**			
Transfer, return, and curate a large amount (100s of kg) of cryogenic samples, containers, and freezers from key destinations across the Martian surface, while maintaining scientific integrity of the samples.	**CN-T-304 M**			
Provide the ability for the Science Team to directly or indirectly communicate in nonrealtime via either written or verbal means with the crew for EVA and IVA activities.	**CN-C-105 M**			
Identify, collect, and document deep subsurface samples from key destinations on the Martian surface, with the potential to contain volatiles or biologics, while maintaining scientific integrity of the samples.	**CN-U-301 M**			
Identify, collect, and document surface and shallow subsurface samples from key destinations in special regions on the Martian surface, while maintaining scientific integrity of the samples.	**CN-U-302 M**			
Identify, collect, and document surface and shallow subsurface samples from key destinations on the Martian surface, while maintaining scientific integrity of the samples.	**CN-U-303 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.	**CN-U-304 M**			

Mars Goals, Objectives, and Characteristics and Needs				
Characteristics and Needs	**ID**	**Objectives**	**ID**	**Goal**
Conduct borehole measurements at varying depths, including ionizing radiation and heat flow.	**CN-U-305 M**			
Deploy and operate utilization payload(s) and equipment, related to Solar System volatiles, at key destinations across the Martian surface.	**CN-U-714 M**			
Minimize environmental impacts on the Martian surface to preserve scientific integrity for future exploration.	**CN-U-805 M**			
Monitor the pre-, during-, and post-mission presence of Earth life at various distances from the landing site to help determine the degree of terrestrial contamination caused by a human mission and the contamination lifetime on the surface.	**CN-U-808 M**			
Visit diverse sites on the Martian surface to address high priority science and utilization goals.	**CN-T-105 M**	Advance understanding of the origin of life in the solar system by identifying where and when potentially habitable environments exist(ed), what processes led to their formation, how planetary environments and habitable conditions have co-evolved over time, and whether there is evidence of past or present life in the solar system beyond Earth.	**LPS-04 M**	
Transfer, return, and curate a large amount (100s of kg) of cryogenic samples, containers, and freezers from key destinations across the Martian surface, while maintaining scientific integrity of the samples.	**CN-T-304 M**			
Provide the ability for the Science Team to directly or indirectly communicate in nonrealtime via either written or verbal means with the crew for EVA and IVA activities.	**CN-C-105 M**			
Identify, collect, and document deep subsurface samples from key destinations on the Martian surface, with the potential to contain volatiles or biologics, while maintaining scientific integrity of the samples.	**CN-U-301 M**			
Identify, collect, and document surface and shallow subsurface samples from key destinations in special regions on the Martian surface, while maintaining scientific integrity of the samples.	**CN-U-302 M**			
Identify, collect, and document surface and shallow subsurface samples from key destinations on the Martian surface, while maintaining scientific integrity of the samples.	**CN-U-303 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.	**CN-U-304 M**			
Conduct borehole measurements at varying depths, including ionizing radiation and heat flow.	**CN-U-305 M**			
Minimize environmental impacts on the Martian surface to preserve scientific integrity for future exploration.	**CN-U-805 M**			
Monitor the pre-, during-, and post-mission presence of Earth life at various distances from the landing site to help determine the degree of terrestrial contamination caused by a human mission and the contamination lifetime on the surface.	**CN-U-808 M**			
Deploy and operate utilization payload(s) in deep space, during Mars transit, and in Martian orbit relevant to addressing the associated science objectives.	**CN-U-701 M**	Improve understanding of space weather phenomena to enable enhanced observation and prediction of the dynamic	**HS-01 LM**	**Heliophysics Science**

Mars Goals, Objectives, and Characteristics and Needs				
Characteristics and Needs	**ID**	**Objectives**	**ID**	**Goal**
Deploy and operate utilization payload(s), related to in-space weather, at distributed sites on the Martian surface.	**CN-U-708 M**	environment from space to the surface at the Moon and Mars.		
Provide capabilities for local data storage and processing to enable Earth-independent space weather forecasting.	**CN-U-709 M**			
Visit diverse sites on the Martian surface to address high priority science and utilization goals.	**CN-T-105 M**	Determine the history of the Sun and solar system as recorded in the lunar and Martian regolith.	**HS-02 LM**	
Transfer, return, and curate a small amount (10s of kg) or a large amount (100s of kg) of unconditioned samples and containers from key destinations across the Martian surface, while maintaining scientific integrity of the samples.	**CN-T-301 M**			
Identify, collect, and document deep subsurface samples from key destinations on the Martian surface, with the potential to contain volatiles or biologics, while maintaining scientific integrity of the samples.	**CN-U-301 M**			
Identify, collect, and document surface and shallow subsurface samples from key destinations on the Martian surface, while maintaining scientific integrity of the samples.	**CN-U-303 M**			
Transfer, return, and curate a small amount (10s of kg) or a large amount (100s of kg) of unconditioned samples and containers from key destinations across the Martian surface, while maintaining scientific integrity of the samples.	**CN-T-301 M**	Investigate and characterize fundamental plasma processes, including dust-plasma interactions, using the cislunar, near-Mars, and surface environments as laboratories.	**HS-03 LM**	
Identify, collect, and document surface and shallow subsurface samples from key destinations on the Martian surface, while maintaining scientific integrity of the samples.	**CN-U-303 M**			
Deploy and operate utilization payloads and equipment, related to fundamental plasma processes, at designated locations on the Martian surface.	**CN-U-710 M**			
Deploy and operate science package(s), related to the magnetotail and solar wind, in Martian obit.	**CN-U-711 M**	Improve understanding of magnetotail and pristine solar wind dynamics in the vicinity of the Moon and around Mars.	**HS-04 LM**	
Transition crew from micro-gravity environment to partial gravity environment, following various durations in space.	**CN-T-108 M**	Understand the effects of short- and long-duration exposure to the environments of the Moon, Mars, and deep space on biological systems and health, using humans, model organisms, systems of human physiology, and plants.	**HBS-01 LM**	**Human and Biological Science (HBS)**
Transition crew from partial gravity environment to micro-gravity environment.	**CN-T-109 M**			
Transition biological experiments from micro-gravity environment to partial gravity environment, following various durations in space.	**CN-T-110 M**			
Transition biological experiments from partial gravity environment to micro-gravity environment.	**CN-T-111 M**			
Transfer, return, and curate a small amount (10s of kg) or a large amount (100s of kg) of unconditioned samples and containers from key destinations across the Martian surface, while maintaining scientific integrity of the samples.	**CN-T-301 M**			
Transfer, return and curate a small amount (10s of kg) or a large amount (100s of kg) of refrigerated sample(s), containers, and freezers from key destinations across the Martian surface, while maintaining scientific integrity of the samples.	**CN-T-302 M**			

Mars Goals, Objectives, and Characteristics and Needs				
Characteristics and Needs	**ID**	**Objectives**	**ID**	**Goal**
Transfer, return and curate a small amount (10s of kg) or a large amount (100s of kg) of frozen sample(s), containers, and freezers from key destinations across the Martian surface, while maintaining scientific integrity of the samples.	**CN-T-303 M**			
Transfer, return and curate a small amount (10s of kg) or a large amount (100s of kg) of unconditioned sample(s) and containers from deep space and Mars vicinity assets back to Earth while maintaining scientific integrity of the samples.	**CN-T-306 M**			
Transfer, return and curate a small amount (10s of kg) or a large amount (100s of kg) of refrigerated sample(s) and containers from deep space and Mars vicinity assets back to Earth while maintaining scientific integrity of the samples.	**CN-T-307 M**			
Transfer, return and curate a small amount (10s of kg) or a large amount (100s of kg) of frozen sample(s) and containers from deep space and Mars vicinity assets back to Earth while maintaining scientific integrity of the samples.	**CN-T-308 M**			
Conduct short-duration (days to weeks) crew exploration mission(s) on the Martian surface.	**CN-H-102 M**			
Provide in-space system(s) to monitor deep space, Martian orbit, and Martian surface natural environments, including incoming and albedo radiation.	**CN-U-103 M**			
Provide surface system(s) to monitor deep space, Martian orbit, and Martian surface natural environments, including incoming and albedo radiation.	**CN-U-104 M**			
Provide intravehicular activity facilities (e.g., instruments, racks, stowage, power) on the Martian surface and/or in Martian orbit to enable biological science analysis and human research.	**CN-U-201 M**			
Provide intravehicular activity accommodations (e.g., instruments, racks, stowage, power) during transits in deep space and/or Mars vicinity to enable biological science analysis and human research.	**CN-U-204 M**			
Deploy and operate internal and external utilization payload(s) and equipment addressing biological science analysis and human research at key destinations across the Martian surface for a minimum of mid-durations (month+) missions.	**CN-U-703 M**			
Deploy and operate internal and external utilization payload(s) and equipment in deep space, during Mars transit, and in Mars vicinity relevant to addressing biological science analysis and human research objectives for a minimum of mid-duration (month+) missions.	**CN-U-707 M**			
Transition crew from micro-gravity environment to partial gravity environment, following various durations in space.	**CN-T-108 M**	Evaluate and validate progressively Earth-independent crew health & performance systems and operations with mission durations representative of Mars-class missions.	**HBS-02 LM**	
Transition crew from partial gravity environment to micro-gravity environment.	**CN-T-109 M**			
Transfer, return, and curate a small amount (10s of kg) or a large amount (100s of kg) of unconditioned samples and containers from key destinations across the Martian surface, while maintaining scientific integrity of the samples.	**CN-T-301 M**			
Transfer, return and curate a small amount (10s of kg) or a large amount (100s of kg) of refrigerated sample(s), containers, and freezers from key destinations across the Martian surface, while maintaining scientific integrity of the samples.	**CN-T-302 M**			

Mars Goals, Objectives, and Characteristics and Needs				
Characteristics and Needs	**ID**	**Objectives**	**ID**	**Goal**
Transfer, return and curate a small amount (10s of kg) or a large amount (100s of kg) of frozen sample(s), containers, and freezers from key destinations across the Martian surface, while maintaining scientific integrity of the samples.	**CN-T-303 M**			
Transfer, return and curate a small amount (10s of kg) or a large amount (100s of kg) of unconditioned sample(s) and containers from deep space and Mars vicinity assets back to Earth while maintaining scientific integrity of the samples.	**CN-T-306 M**			
Transfer, return and curate a small amount (10s of kg) or a large amount (100s of kg) of refrigerated sample(s) and containers from deep space and Mars vicinity assets back to Earth while maintaining scientific integrity of the samples.	**CN-T-307 M**			
Transfer, return and curate a small amount (10s of kg) or a large amount (100s of kg) of frozen sample(s) and containers from deep space and Mars vicinity assets back to Earth while maintaining scientific integrity of the samples.	**CN-T-308 M**			
Conduct short-duration (days to weeks) crew exploration mission(s) on the Martian surface.	**CN-H-102 M**			
Provide intravehicular activity facilities (e.g., instruments, racks, stowage, power) on the Martian surface and/or in Martian orbit to enable biological science analysis and human research.	**CN-U-201 M**			
Provide intravehicular activity accommodations (e.g., instruments, racks, stowage, power) during transits in deep space and/or Mars vicinity to enable biological science analysis and human research.	**CN-U-204 M**			
Deploy and operate internal and external utilization payload(s) and equipment addressing biological science analysis and human research at key destinations across the Martian surface for a minimum of mid-durations (month+) missions.	**CN-U-703 M**			
Deploy and operate internal and external utilization payload(s) and equipment in deep space, during Mars transit, and in Mars vicinity relevant to addressing biological science analysis and human research objectives for a minimum of mid-duration (month+) missions.	**CN-U-707 M**			
Transition crew from micro-gravity environment to partial gravity environment, following various durations in space.	**CN-T-108 M**	Characterize and evaluate how the interaction of exploration systems and the deep space environment affect human health, performance, and space human factors to inform future exploration-class missions.	**HBS-03 LM**	
Transition crew from partial gravity environment to micro-gravity environment.	**CN-T-109 M**			
Transition biological experiments from micro-gravity environment to partial gravity environment, following various durations in space.	**CN-T-110 M**			
Transition biological experiments from partial gravity environment to micro-gravity environment.	**CN-T-111 M**			
Transfer, return, and curate a small amount (10s of kg) or a large amount (100s of kg) of unconditioned samples and containers from key destinations across the Martian surface, while maintaining scientific integrity of the samples.	**CN-T-301 M**			
Transfer, return and curate a small amount (10s of kg) or a large amount (100s of kg) of refrigerated sample(s), containers, and freezers from key destinations across the Martian surface, while maintaining scientific integrity of the samples.	**CN-T-302 M**			

Mars Goals, Objectives, and Characteristics and Needs				
Characteristics and Needs	**ID**	**Objectives**	**ID**	**Goal**
Transfer, return and curate a small amount (10s of kg) or a large amount (100s of kg) of frozen sample(s), containers, and freezers from key destinations across the Martian surface, while maintaining scientific integrity of the samples.	**CN-T-303 M**			
Transfer, return and curate a small amount (10s of kg) or a large amount (100s of kg) of unconditioned sample(s) and containers from deep space and Mars vicinity assets back to Earth while maintaining scientific integrity of the samples.	**CN-T-306 M**			
Transfer, return and curate a small amount (10s of kg) or a large amount (100s of kg) of refrigerated sample(s) and containers from deep space and Mars vicinity assets back to Earth while maintaining scientific integrity of the samples.	**CN-T-307 M**			
Transfer, return and curate a small amount (10s of kg) or a large amount (100s of kg) of frozen sample(s) and containers from deep space and Mars vicinity assets back to Earth while maintaining scientific integrity of the samples.	**CN-T-308 M**			
Conduct short-duration (days to weeks) crew exploration mission(s) on the Martian surface.	**CN-H-102 M**			
Provide intravehicular activity facilities (e.g., instruments, racks, stowage, power) on the Martian surface and/or in Martian orbit to enable biological science analysis and human research.	**CN-U-201 M**			
Provide intravehicular activity accommodations (e.g., instruments, racks, stowage, power) during transits in deep space and/or Mars vicinity to enable biological science analysis and human research.	**CN-U-204 M**			
Deploy and operate internal and external utilization payload(s) and equipment addressing biological science analysis and human research at key destinations across the Martian surface for a minimum of mid-durations (month+) missions.	**CN-U-703 M**			
Deploy and operate internal and external utilization payload(s) and equipment in deep space, during Mars transit, and in Mars vicinity relevant to addressing biological science analysis and human research objectives for a minimum of mid-duration (month+) missions.	**CN-U-707 M**			
Transfer, return, and curate a small amount (10s of kg) of unconditioned samples, containers, and freezers from key destinations across the Martian surface, while maintaining scientific integrity of the samples.	**CN-T-305 M**	Advance understanding of physical systems and fundamental physics by utilizing the unique environments of the Moon, Mars, and deep space.	**PPS-02 LM**	**Physics and Physical Science (PPS)**
Transfer, return and curate a small amount (10s of kg) of unconditioned sample(s) and containers from deep space and Mars vicinity assets back to Earth while maintaining scientific integrity of the samples.	**CN-T-309 M**			
Provide intravehicular activity accommodations (e.g., instruments, racks, stowage, power) in deep space and Mars vicinity to enable fundamental physics experiments.	**CN-U-202 M**			
Provide intravehicular activity accommodations (e.g., instruments, racks, stowage, power) on the Martian surface to enable fundamental physics experiments.	**CN-U-203 M**			
Deploy and operate utilization payload(s) and equipment, related to the physical systems and fundamental physics, in deep space and in Mars vicinity.	**CN-U-705 M**			
Deploy and operate utilization payload(s) and equipment, related to the physical systems and fundamental physics, at areas of key scientific interest on the Martian surface.	**CN-U-706 M**			

Mars Goals, Objectives, and Characteristics and Needs				
Characteristics and Needs	**ID**	**Objectives**	**ID**	**Goal**
Train astronauts to be field scientists and to perform additional science tasks during crewed missions, through integrated geology, field and EVA ops and classroom training.	**CN-X-202 M**	Provide in-depth, mission-specific science training for astronauts to enable crew to perform high-priority or transformational science on the surface of the Moon, and Mars, and in deep space.	**SE-01 LM**	**Science-Enabling (SE)**
Train Earth-based scientists to support crew activities asynchronously.	**CN-X-203 M**	Enable Earth-based scientists to remotely support astronaut surface and deep space activities using advanced techniques and tools.	**SE-02 LM**	
Transfer, return, and curate a large amount (100s of kg) of cryogenic samples, containers, and freezers from key destinations across the Martian surface, while maintaining scientific integrity of the samples.	**CN-T-304 M**	Develop the capability to retrieve core samples of frozen volatiles from permanently shadowed regions on the Moon and volatile-bearing sites on Mars and to deliver them in pristine states to modern curation facilities on Earth.	**SE-03 LM**	
Provide curation or other appropriate facilities on Earth equipped for preserving acquired samples in their pristine state.	**CN-G-201 M**			
Identify, collect, and document deep subsurface samples from key destinations on the Martian surface, with the potential to contain volatiles or biologics, while maintaining scientific integrity of the samples.	**CN-U-301 M**			
Provide capabilities to visit one or more sites with access to multiple regions of interest on the Martian surface that can address high-priority science goals.	**CN-T-104 M**	Return representative samples from multiple locations across the surface of the Moon and Mars, with sample mass commensurate with mission-specific science priorities.	**SE-04 LM**	
Transfer, return, and curate a small amount (10s of kg) or a large amount (100s of kg) of unconditioned samples and containers from key destinations across the Martian surface, while maintaining scientific integrity of the samples.	**CN-T-301 M**			
Transfer, return and curate a small amount (10s of kg) or a large amount (100s of kg) of frozen sample(s), containers, and freezers from key destinations across the Martian surface, while maintaining scientific integrity of the samples.	**CN-T-303 M**			
Provide curation or other appropriate facilities on Earth equipped for preserving acquired samples in their pristine state.	**CN-G-201 M**			
Identify, collect, and document deep subsurface samples from key destinations on the Martian surface, with the potential to contain volatiles or biologics, while maintaining scientific integrity of the samples.	**CN-U-301 M**			
Identify, collect, and document surface and shallow subsurface samples from key destinations in special regions on the Martian surface, while maintaining scientific integrity of the samples.	**CN-U-302 M**			
Identify, collect, and document surface and shallow subsurface samples from key destinations on the Martian surface, while maintaining scientific integrity of the samples.	**CN-U-303 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.	**CN-U-304 M**			
Provide capabilities to deploy assets in advance of crew arrival to minimize crew setup time for operation.	**CN-T-204 M**	Use robotic techniques to survey sites, conduct in-situ measurements, and identify/stockpile samples in advance of and concurrent with astronaut arrival, to optimize astronaut time on the lunar and Martian surface and maximize science return.	**SE-05 LM**	
Conduct robotic surveys of potential landing sites, including video and in-situ measurements.	**CN-A-105 M**			

Mars Goals, Objectives, and Characteristics and Needs				
Characteristics and Needs	**ID**	**Objectives**	**ID**	**Goal**
Provide appropriate robotic tools support acquisition of samples, including dust, soil, sand, hand-sized rock samples, and drill cores, manufactured in accordance with science requirements to minimize sample contamination.	**CN-A-106 M**			
Deploy and operate utilization payload(s) in deep space, during Mars transit, and in Martian orbit relevant to addressing the associated science objectives.	**CN-U-701 M**	Enable long-term, planet-wide research by delivering science instruments to multiple science-relevant orbits and surface locations at the Moon and Mars.	**SE-06 LM**	
Deploy and operate utilization payload(s) and equipment on the Martian surface at locations relevant to addressing associated science objectives.	**CN-U-702 M**			
Coordinate delivery and deployment of utilization payloads in Martian orbit and on the Martian surface to address associated science objectives.	**CN-U-801 M**			
Abide by planetary protection protocols, policies, and guidelines.	**CN-U-802 M**	Preserve and protect representative features of special interest, including lunar permanently shadowed regions and the radio quiet far side as well as Martian recurring slope lineae, to enable future high-priority science investigations.	**SE-07 LM**	
Monitor the pre-, during-, and post-mission presence of Earth life around representative features of special interest to help determine the degree of terrestrial contamination caused by a human mission and the contamination lifetime on the surface.	**CN-U-803 M**			
Protect sites of historic significance.	**CN-U-804 M**			
Minimize environmental impacts on the Martian surface to preserve scientific integrity for future exploration.	**CN-U-805 M**			
Provide system(s) to monitor deep space, Martian orbit, and Martian surface natural environments, including space weather, meteoroids, cosmic weather, thermal conditions, and plasma environments, and provide Earth-independent early warnings to in-space and surface assets and crew.	**CN-U-102 M**	Characterize and monitor the contemporary environments of the lunar and Martian surfaces and orbits, including investigations of micrometeorite flux, atmospheric weather, space weather, space weathering, and dust, to plan, support, and monitor safety of crewed operations in these locations.	**AS-01 LM**	**Applied Science (AS)**
Provide capabilities to enable strategic pointing, e.g., Sun-facing, for external utilization payloads on orbital and transit platforms.	**CN-U-205 M**			
Deploy and operate utilization payload(s) and equipment on the Martian surface at locations relevant to addressing associated science objectives.	**CN-U-702 M**			
Coordinate delivery and deployment of utilization payloads in Martian orbit and on the Martian surface to address associated science objectives.	**CN-U-801 M**	Coordinate on-going and future science measurements from orbital and surface platforms to optimize human-led science campaigns on the Moon and Mars.	**AS-02 LM**	
Visit diverse sites on the Martian surface to address high priority science and utilization goals.	**CN-T-105 M**	Characterize accessible lunar and Martian resources, gather scientific research data, and analyze potential reserves to satisfy science and technology objectives and enable In-Situ Resource Utilization (ISRU) on successive missions.	**AS-03 LM**	
Transfer, return, and curate a small amount (10s of kg) or a large amount (100s of kg) of unconditioned samples and containers from key destinations across the Martian surface, while maintaining scientific integrity of the samples.	**CN-T-301 M**			
Transfer, return and curate a small amount (10s of kg) or a large amount (100s of kg) of frozen sample(s), containers, and freezers from key destinations across the Martian surface, while maintaining scientific integrity of the samples.	**CN-T-303 M**			

Mars Goals, Objectives, and Characteristics and Needs				
Characteristics and Needs	**ID**	**Objectives**	**ID**	**Goal**
Provide mobility capabilities to conduct prospecting traverses with appropriate scientific instrumentation and drill capabilities over sites of interest.	**CN-M-301 M**			
Identify, collect, and document deep subsurface samples from key destinations on the Martian surface, with the potential to contain volatiles or biologics, while maintaining scientific integrity of the samples.	**CN-U-301 M**			
Identify, collect, and document surface and shallow subsurface samples from key destinations in special regions on the Martian surface, while maintaining scientific integrity of the samples.	**CN-U-302 M**			
Identify, collect, and document surface and shallow subsurface samples from key destinations on the Martian surface, while maintaining scientific integrity of the samples.	**CN-U-303 M**			
Deploy and operate exploration asset(s), related to available resources, at key destinations across the Martian surface.	**CN-U-704 M**			
Demonstrate operation of bioregenerative ECLSS sub-systems in LEO and/or deep space.	**CN-U-601 M**	Conduct applied scientific investigations essential for the development of bioregenerative-based, ecological life support systems.	**AS-04 LM**	
Demonstrate operation of plant based ECLSS sub-systems in LEO and/or deep space.	**CN-U-602 M**	Define crop plant species, including methods for their productive growth, capable of providing sustainable and nutritious food sources for lunar, Deep Space transit, and Mars habitation.	**AS-05 LM**	
Deploy and operate utilization payload(s) and equipment, related to the physical systems and fundamental physics, in deep space and in Mars vicinity.	**CN-U-705 M**	Advance understanding of how physical systems and fundamental physical phenomena are affected by partial gravity, microgravity, and general environment of the Moon, Mars, and deep space transit.	**AS-06 LM**	
Deploy and operate utilization payload(s) and equipment, related to the physical systems and fundamental physics, at areas of key scientific interest on the Martian surface.	**CN-U-706 M**			
Provide power generation, energy storage, and power distribution system(s) on the Martian surface to support large exploration assets.	**CN-P-101 M**	Develop Mars surface power sufficient for an initial human Mars exploration campaign.	**MI-01 M**	**Mars Infrastructure (MI)**
Provide power generation, energy storage, and power distribution system(s) on the Martian surface to allow power utilization to support assets at multiple distributed locations around exploration sites.	**CN-P-102 M**			
Provide power generation, energy storage, and power distribution system(s) on the Martian surface that are able to supply continuous power availability during crew safety critical mission operations and are able to support contingency operations.	**CN-P-103 M**			
Provide communication system(s) to enable high-bandwidth, high-availability communications between Earth-based personnel, surface crew, and assets on the surface.	**CN-C-101 M**	Develop Mars surface, orbital, and Mars-to-Earth communications to support an initial human Mars exploration campaign.	**MI-02 M**	
Provide communication system(s) to enable high-bandwidth, high-availability communications between Earth-based personnel, in-space crew, and in-space assets.	**CN-C-102 M**			
Provide communication system(s) to enable high-bandwidth, high-availability communications between in-space crew, surface crew, and assets on the surface.	**CN-C-103 M**			

Mars Goals, Objectives, and Characteristics and Needs				
Characteristics and Needs	**ID**	**Objectives**	**ID**	**Goal**
Provide communication capabilities to allow NASA to inspire and inform the general public, students, and teachers by enabling them to interact, learn about, and experience missions in a direct and tangible way.	**CN-C-104 M**			
Demonstrate the capability for Mars landers to safely land within a defined radius around an intended location.	**CN-T-401 M**	Develop Mars position, navigation and timing capabilities to support an initial human Mars exploration campaign.	**MI-03 M**	
Provide navigation, positioning, and timing system(s) to enable high-availability navigation and tracking in deep space and in Mars vicinity.	**CN-C-201 M**			
Provide navigation, positioning, and timing system(s) to enable high-availability navigation and tracking on the Martian surface.	**CN-C-202 M**			
Provide system(s) to enable accurate location identification, tracking, and documentation of collected surface samples.	**CN-C-203 M**			
Deploy scalable ISRU demonstration exploration asset(s) on the Martian surface.	**CN-I-102 M**	Demonstrate Mars ISRU capabilities to support an initial human Mars exploration campaign.	**MI-04 M**	
Operate demonstration exploration asset(s) on the Martian surface to collect, produce, store, and transfer commodities, including water, oxygen and/or fuel, for potential use.	**CN-I-103 M**			
Demonstrate the capability to identify and locate potential site(s) for resource utilization.	**CN-U-101 M**			
Provide capabilities to enable staging and/or assembly operations of crew and cargo system(s) in Earth vicinity with accessibility to Earth and to support departure for Mars missions.	**CN-T-106 M**	Develop in-space and surface habitation system(s) for crew to live in deep space for extended durations, enabling future missions to Mars.	**TH-04 LM**	**Transportation and Habitation (TH)**
Provide capabilities to conduct mid-duration (month+) crew exploration mission(s) on the Martian surface.	**CN-H-101 M**			
Provide capabilities that allow crew to live in deep space for Mars-duration mission(s).	**CN-H-103 M**			
Implement robust transportation capabilities, where systems can support all design reference missions, to support Mars missions.	**CN-T-101 M**	Develop transportation systems that crew can routinely operate between the Earth-Moon vicinity and Mars vicinity, including the Martian surface.	**TH-05 M**	
Provide capabilities to transport crew and system(s) between Earth, Earth vicinity, and Mars vicinity.	**CN-T-102 M**			
Provide capabilities to transport crew between Mars vicinity and the Martian surface.	**CN-T-103 M**			
Provide capabilities to enable staging and/or assembly operations of crew and cargo system(s) in space to enable access to deep space and Mars.	**CN-T-107 M**			
Provide capabilities to operate system(s) in uncrewed mode for mid-duration (month+) to extended-duration (year+) in Earth vicinity, Mars vicinity, and/or Martian surface.	**CN-T-112 M**			

Mars Goals, Objectives, and Characteristics and Needs				
Characteristics and Needs	**ID**	**Objectives**	**ID**	**Goal**
Provide capabilities to safely return crew and system(s) to Earth from Mars.	**CN-T-113 M**			
Implement robust transportation capabilities, where systems can support all design reference missions, to support Mars missions.	**CN-T-101 M**	Develop transportation systems that can deliver a range of elements to the Martian surface.	**TH-06 M**	
Provide capabilities to deliver system(s) from Earth and Earth vicinity to Mars vicinity and Mars surface.	**CN-T-201 M**			
Provide capabilities to unload cargo from delivery system(s).	**CN-M-401 M**			
Implement end-of-life strategies for transportation systems to ensure future viable usage of exploration sites on the Martian surface.	**CN-U-807 M**			
Provide capabilities to conduct mid-duration (month+) crew exploration mission(s) on the Martian surface.	**CN-H-101 M**	Develop systems for crew to explore, operate, and live on the Martian surface to address key questions with respect to science and resources.	**TH-07 M**	
Provide capabilities to enable crew transition in/out of habitable space to conduct EVA activities.	**CN-M-102 M**			
Provide appropriate medical capabilities (including behavioral health) that allow for autonomous crew health decision making and care, and are preparatory of a mission to Mars.	**CN-X-101 M**	Develop systems that monitor and maintain crew health and performance throughout all mission phases, including during communication delays to Earth, and in an environment that does not allow emergency evacuation or terrestrial medical assistance.	**TH-08 LM**	
Provide crew health and performance capabilities in deep space and Mars vicinity, including demonstration of remote and autonomous health care and advanced diagnostics.	**CN-X-102 M**			
Provide crew health and performance capabilities on the Martian surface, including demonstration of remote and autonomous health care and advanced diagnostics.	**CN-X-103 M**			
Provide countermeasures capabilities that are commensurate in scope with the human system needs for the mission.	**CN-X-104 M**			
Provide crew survival capabilities in deep space, Mars vicinity, and on the Martian surface, including safe havens, system supportability, and/or aborts, for nominal and off-nominal scenarios.	**CN-X-105 M**			
Provide appropriate environmental monitoring capabilities that enables inflight crew health decision making and mitigation of relevant system/vehicle hazards.	**CN-U-105 M**			
Provide appropriate robotic system(s) that can conduct or assist in tasks that would otherwise be performed by the crew alone in Mars vicinity or deep space.	**CN-A-101 M**	Develop integrated human and robotic systems with inter-relationships that enable maximum science and exploration during Martian missions.	**TH-10 M**	
Provide appropriate robotic system(s) that can conduct or assist in tasks that would otherwise be performed by the crew alone on the Martian surface.	**CN-A-102 M**			
Provide capabilities to return cargo from Earth vicinity back to Earth-based facilities.	**CN-T-202 M**	Develop systems capable of returning a range of cargo mass from the Martian surface to Earth, including the capabilities	**TH-12 M**	

Mars Goals, Objectives, and Characteristics and Needs				
Characteristics and Needs	**ID**	**Objectives**	**ID**	**Goal**
Provide capabilities to return cargo from the Martian surface back to Earth vicinity.	**CN-T-203 M**	necessary to meet scientific and utilization objectives.		
Transfer, return, and curate a small amount (10s of kg) or a large amount (100s of kg) of unconditioned samples and containers from key destinations across the Martian surface, while maintaining scientific integrity of the samples.	**CN-T-301 M**			
Transfer, return and curate a small amount (10s of kg) or a large amount (100s of kg) of refrigerated sample(s), containers, and freezers from key destinations across the Martian surface, while maintaining scientific integrity of the samples.	**CN-T-302 M**			
Transfer, return and curate a small amount (10s of kg) or a large amount (100s of kg) of frozen sample(s), containers, and freezers from key destinations across the Martian surface, while maintaining scientific integrity of the samples.	**CN-T-303 M**			
Transfer, return, and curate a large amount (100s of kg) of cryogenic samples, containers, and freezers from key destinations across the Martian surface, while maintaining scientific integrity of the samples.	**CN-T-304 M**			
Operate and gain experience with flight control and mission integration to ensure safety and mission success in nominal and off-nominal conditions.	**CN-T-402 M**	Optimize operations, training and interaction between the team on Earth, crew members on orbit, and a Martian surface team considering communication delays, autonomy level, and time required for an early return to the Earth.	**OP-02 LM**	**Operations (OP)**
Operate and gain experience with in-situ training and planning capabilities to ensure safety and mission success.	**CN-X-201 M**			
Operate and gain experience with onboard autonomous system(s) and crew autonomy to train, plan, and execute safe mission(s) with reduced reliance on Earth based systems.	**CN-A-401 M**			
Operate and gain experience with remote & autonomous system(s) to reduce crew workload.	**CN-A-402 M**			
Visit diverse sites on the Martian surface to address high priority science and utilization goals.	**CN-T-105 M**	Characterize accessible resources, gather scientific research data, and analyze potential reserves to satisfy science and technology objectives and enable use of resources on successive missions.	**OP-03 LM**	
Transfer, return, and curate a small amount (10s of kg) or a large amount (100s of kg) of unconditioned samples and containers from key destinations across the Martian surface, while maintaining scientific integrity of the samples.	**CN-T-301 M**			
Transfer, return and curate a small amount (10s of kg) or a large amount (100s of kg) of frozen sample(s), containers, and freezers from key destinations across the Martian surface, while maintaining scientific integrity of the samples.	**CN-T-303 M**			
Demonstrate the capability to identify and locate potential site(s) for resource utilization.	**CN-U-101 M**			
Identify, collect, and document deep subsurface samples from key destinations on the Martian surface, with the potential to contain volatiles or biologics, while maintaining scientific integrity of the samples.	**CN-U-301 M**			
Identify, collect, and document surface and shallow subsurface samples from key destinations in special regions on the Martian surface, while maintaining scientific integrity of the samples.	**CN-U-302 M**			
Identify, collect, and document surface and shallow subsurface samples from key destinations on the Martian surface, while maintaining scientific integrity of the samples.	**CN-U-303 M**			

Mars Goals, Objectives, and Characteristics and Needs				
Characteristics and Needs	**ID**	**Objectives**	**ID**	**Goal**
Deploy and operate exploration asset(s), related to available resources, at key destinations across the Martian surface.	**CN-U-704 M**			
Provide capabilities to integrate networks and mission systems to exchange data between Earth-based systems, in-space exploration assets, and surface exploration assets.	**CN-D-101 M**	Establish command and control processes, common interfaces, and ground systems that will support expanding human missions at the Moon and Mars.	**OP-04 LM**	
Provide capabilities to utilize common data interface(s) for exchanges between Earth-based systems, in-space exploration assets, and surface exploration assets.	**CN-D-102 M**	Establish command and control processes, common interfaces, and ground systems that will support expanding human missions at the Moon and Mars.	**OP-04 LM**	
Provide capabilities to store and protect data on exploration assets.	**CN-D-103 M**	Establish command and control processes, common interfaces, and ground systems that will support expanding human missions at the Moon and Mars.	**OP-04 LM**	
Operate and gain experience with capabilities to conduct extravehicular activities utilizing mobility assets and tools.	**CN-M-101 M**	Operate surface mobility systems, e.g., extra-vehicular activity (EVA) suits, tools and vehicles.	**OP-05 LM**	
Operate and gain experience with capabilities to transport crew and cargo between landing, exploration, and utilization sites at varying distances from assets on the Martian surface.	**CN-M-501 M**	Operate surface mobility systems, e.g., extra-vehicular activity (EVA) suits, tools and vehicles.	**OP-05 LM**	
Provide appropriate medical capabilities (including behavioral health) that allow for autonomous crew health decision making and care, and are preparatory of a mission to Mars.	**CN-X-101 M**	Validate readiness of systems and operations to support crew health and performance for the initial human Mars exploration campaign.	**OP-07 LM**	
Provide crew health and performance capabilities in deep space and Mars vicinity, including demonstration of remote and autonomous health care and advanced diagnostics.	**CN-X-102 M**	Validate readiness of systems and operations to support crew health and performance for the initial human Mars exploration campaign.	**OP-07 LM**	
Provide crew health and performance capabilities on the Martian surface, including demonstration of remote and autonomous health care and advanced diagnostics.	**CN-X-103 M**	Validate readiness of systems and operations to support crew health and performance for the initial human Mars exploration campaign.	**OP-07 LM**	
Provide countermeasures capabilities that are commensurate in scope with the human system needs for the mission.	**CN-X-104 M**	Validate readiness of systems and operations to support crew health and performance for the initial human Mars exploration campaign.	**OP-07 LM**	
Provide crew survival capabilities in deep space, Mars vicinity, and on the Martian surface, including safe havens, system supportability, and/or aborts, for nominal and off-nominal scenarios.	**CN-X-105 M**	Validate readiness of systems and operations to support crew health and performance for the initial human Mars exploration campaign.	**OP-07 LM**	
Demonstrate the capabilities to locate, access, and reuse surface assets from previous crewed and uncrewed missions.	**CN-U-106 M**	Demonstrate the capability to find, service, upgrade, or utilize instruments and equipment from robotic landers or previous human missions on the surface of the Moon and Mars.	**OP-08 LM**	
Demonstrate the capabilities to service and/or upgrade assets.	**CN-U-806 M**	Demonstrate the capability to find, service, upgrade, or utilize instruments and equipment from robotic landers or previous human missions on the surface of the Moon and Mars.	**OP-08 LM**	
Demonstrate the capabilities to operate appropriate robotic system(s) that can conduct or assist in tasks that would otherwise be performed by the crew alone on the Martian surface.	**CN-A-103 M**	Demonstrate the capability of integrated robotic systems to support and maximize the useful work performed by crewmembers on the surface, and in orbit.	**OP-09 LM**	
Demonstrate the capabilities to operate appropriate robotic system(s) that can conduct or assist in tasks that would otherwise be performed by the crew alone in deep space and/or Mars vicinity.	**CN-A-104 M**	Demonstrate the capability of integrated robotic systems to support and maximize the useful work performed by crewmembers on the surface, and in orbit.	**OP-09 LM**	
Demonstrate capabilities to allow in-space and surface crew to control and command robotic system(s).	**CN-A-201 M**	Demonstrate the capability of integrated robotic systems to support and maximize the useful work performed by crewmembers on the surface, and in orbit.	**OP-09 LM**	

Mars Goals, Objectives, and Characteristics and Needs				
Characteristics and Needs	**ID**	**Objectives**	**ID**	**Goal**
Demonstrate the capability for safe and effective interactions between crew and automated/autonomous system(s).	**CN-A-301 M**			
Demonstrate autonomous and remote operations of robotic surface systems from external systems, including Earth, orbital, and/or other surface locations.	**CN-A-202 M**	Demonstrate the capability to operate robotic systems that are used to support crew members on the lunar or Martian surface, autonomously or remotely from the Earth or from orbiting platforms.	**OP-10 LM**	
Demonstrate autonomous and remote operations of in-space robotic systems from external systems, including Earth, orbital, and/or other surface locations.	**CN-A-203 M**			
Demonstrate the capability for safe and effective interactions between crew and automated/autonomous system(s).	**CN-A-301 M**			
Operate demonstration exploration asset(s) on the Martian surface to collect, produce, store, and transfer commodities, including water, oxygen and/or fuel, for potential use.	**CN-I-103 M**	Demonstrate the capability to use commodities produced from planetary surface or in-space resources to reduce the mass required to be transported from Earth.	**OP-11 LM**	
Demonstrate the capability to use surface-borne resources for potential construction and/or manufacturing on the Martian surface.	**CN-I-104 M**			
Demonstrate the capabilities to recover excess fluids and gases, including propellant residuals, from Mars landers and separation of products.	**CN-I-101 M**	Establish procedures and systems that will minimize the disturbance to the local environment, maximize the resources available to future explorers, and allow for reuse/recycling of material transported from Earth (and from the lunar surface in the case of Mars) to be used during exploration.	**OP-12 LM**	
Abide by planetary protection protocols, policies, and guidelines.	**CN-U-802 M**			

3.0 MOON TO MARS ARCHITECTURE

The architecture methodology process described in Section 1.3 has yielded a structured approach to objective decomposition and applicability to system definition to establish the architecture.

Return — The architecture starts with the development and demonstration of the systems that transport crew and exploration capabilities to target destinations. The successful Artemis I mission was the first step in this progressive expansion of the capability envelope over a series of missions where a minimum crew of four can support missions in deep space and on the lunar surface, and eventually future destinations.

Explore — Using an evolutionary approach, the architecture enables high-priority science, technology demonstrations, systems validation, and operations for crew to live and work on a non-terrestrial planetary surface, with a safe return to Earth at the completion of the mission(s). Key characteristics include operating and designing the lunar systems with Mars risk reduction in mind, from a systems, operations, and human perspective. The architecture accommodates this approach in the context of available capabilities and differences in the lunar and Mars environments. Initially, this is done at the element level, then through combined operations that eventually culminate in several precursor missions in the lunar vicinity, where the crew experiences long durations in the deep space environment coupled with rapid acclimation to partial gravity excursions using Mars-like systems and operations. The Mars-forward exploration systems also have the goal of maximizing crew efficiency for utilization, which will be tested by a continuum of excursions to a diverse set of sites driven by science needs. The balance between diverse site access and long-duration infrastructure objectives will inform the allocation of functions across systems.

Sustain — The Foundational Exploration capabilities serve as a basis to increase global access, industrial-scale ISRU, and crew durations beyond NASA's initial needs. Although evolution of the Lunar architecture along the lines of these greater capabilities would seem to occur later in the architecture, the implications of the potential future lunar states are initiated at the very beginning of the architecture with the early reconnaissance missions, where factors like access to and purity of volatiles in several regions may dictate the role and level of ISRU.

The Lunar architecture is developing, deploying, and operating systems for lunar vicinity exploration; performing science at diverse locations and returning lunar samples; preparing for further exploration with Mars-capable systems, operations, and precursor missions; and establishing a permanent lunar presence that could one day support a lunar economy. The Mars architecture can follow the same basic approach as the Moon to achieve a human presence, explore, and then sustain development.

The architecture has been structured to reflect the incremental buildup of capabilities and objective satisfaction. These campaign segments have been crafted along the return, explore, and sustain approach to further delineate the continuum of evolving capability and objective satisfaction. They are described in Table 3-1 below. Although the segments appear sequential in the table, they are not exclusively serialized, as the segments build upon each other and focus on how systems will work together to achieve objective satisfaction.

Table 3-1. Moon to Mars Campaign Segments

	Human Lunar Return	Initial capabilities, systems, and operations necessary to re-establish human presence and initial utilization (science, etc.) on and around the Moon.
	Foundational Exploration	Expansion of lunar capabilities, systems, and operations supporting complex orbital and surface missions to conduct utilization (science, etc.) and Mars forward precursor missions.
	Sustained Lunar Evolution	Enabling 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.
	Humans to Mars	Initial capabilities, systems, and operations necessary to establish human presence and initial utilization (science, etc.) on Mars and continued exploration.
	Future Segments	Additional segment(s) will be added to enable continued exploration for the Moon, Mars, or beyond as objectives are accomplished and/or added to in the future.

The initial segment is **Human Lunar Return**. This segment includes the initial capabilities, systems, and operations necessary to re-establish human presence and initial utilization (science, etc.) on and around the Moon. This segment's primary focus is establishing the missions and supporting infrastructure to perform sortie crewed missions to the Moon. The systems and support span Earth, cislunar orbiting platforms, and the foothold capabilities on the lunar surface. The initial support of utilization focuses on the human-conducted science, sample collection, human research, and initial capabilities, among others, for the first time outside LEO in over 50 years.

The **Foundational Exploration** segment includes lunar excursions to diverse sites of interest with increasingly complex missions, enabling science and other utilization exploration. This segment also contributes to evaluating the systems, operations, human adaptation, or technologies required for Mars. These missions will enable increasingly extended time in deep 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. Prior to the crewed Mars mission, these precursor missions would be performed in time to inform element design, testing, and operation. Foundational Exploration also starts the development of a sustainable human presence with the deployment of demonstrations and capabilities that will enable long-term infrastructure and sustained surface operations in the third segment.

The third segment, **Sustained Lunar Evolution**, is the broad and undefined end state that builds on the foundation of the first two 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.

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

As objectives are accomplished or added in the future, additional segments will be defined to enable continued exploration. These segments will be captured to reflect agency objectives and continue the expansion of human/robotic exploration of the solar system. These efforts will enable NASA led efforts to go, explore, and sustain for continued discovery on the Moon, Mars, and beyond.

3.1 HUMAN LUNAR RETURN SEGMENT

The Human Lunar Return (HLR) segment of the exploration campaign includes the inaugural Artemis missions to enable returning humans to the Moon and demonstrate both crewed and uncrewed lunar systems, including the support to initial utilization (science, etc.) capabilities. This segment will be used to demonstrate initial systems to validate system performance and to establish a core capability for follow-on campaign segments. It captures the missions that test NASA's deep space crew and cargo transportation system(s), deploy the initial cislunar capabilities to support lunar missions, deploy and establish lunar orbital communication relays, and bring two crew members to the lunar surface and return them safely to Earth. Additionally, a variety of other efforts are working to support data-gathering and risk-reduction activities to help inform future decisions. These currently include, but are not limited to, the Cislunar Autonomous Positioning System Technology Operations and Navigation Experiment (CAPSTONE), Commercial Lunar Payload Services (CLPS) provider landers, and the Volatiles Investigating Polar Exploration Rover (VIPER).

3.1.1 Summary of Objectives

The objectives that drive the HLR segment include achieving science, inspiration, and national posture goals around and on the surface of the Moon. Initial missions will be used to deliver science value through operations in cislunar space and on the lunar surface, along with the return of samples to Earth. Key science objectives addressable during HLR include 1) exploring the lunar South Pole region to understand chronology, composition, and structure of this region (e.g., LPS-1 and LPS-2); 2) understanding volatile composition and the environment of shallow permanently shadowed regions (PSRs) near the lunar South Pole (e.g., LPS-3); 3) assessing the history of the Sun as preserved in lunar regolith (e.g., HS-2); 4) characterizing space weather dynamics to enable future forecasting capabilities (e.g., HS-1); and 5) characterizing plant, model organism/systems, and human physiological responses in partial-gravity environments (e.g., HBS-1). These HLR science priorities were identified by the Science Mission Directorate (SMD).

To achieve these key science, inspiration, and national posture goals, the HLR segment is focused on demonstrating initial capabilities, systems, and operations necessary to re-establish human presence around and on the Moon. This segment began successfully with the Artemis I mission to systematically and progressively test areas such as crewed transportation to cislunar space (TH-1, TH-2), supporting ground infrastructure (OP-4), and deep space communications and tracking systems (OP-2). The next steps are crewed transportation to and from cislunar space, initial Gateway deployment (OP-6), rendezvous and docking, uncrewed Human Landing System demonstration, initial human landing (TH-2), and initial surface EVA capability, and uncrewed payload delivery. It encompasses the return of humans to the Moon for approximately six-day surface missions and establishes the foundational capabilities that will enable future campaign segments.

The objectives linked to the HLR segment will be a subset of the total, and even of those linked, some will be only partially satisfied; however, the segment serves as the starting point to define and validate capabilities and functions in later segments that will be driven by the objectives. The complete set of objectives can be found in Appendix A.

3.1.2 Use Cases and Functions

The objectives and mapping to the use cases and functions (shown in Appendix A) are used to drive the elements for this segment. Because many HLR elements are operational or in design/development stages, these elements form the basis of satisfying the functional needs. The mappings help identify functional gaps that must be addressed in the follow-on segments. Section 3.1.5 shows the mapping of the use cases and functions to the elements. Many of the use cases and functions will require additional elements or new functional capabilities that go beyond what is being assigned to the HLR elements described below. Key gaps between planned HLR capabilities and Moon to Mars Objectives needs are noted later in this document and will continue to be expanded through the ACR process. Note that not all use cases (UC-#) and functions (FN-#) are sequential in this segment mapping. The numbering represents use cases and functions that have been identified through the overall objective decompositions process, but not all are applicable to the HLR segment.

The mapped elements in HLR segment and their corresponding descriptions are in the respective sub-sections of Section 3.1.3. 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.

3.1.3 Reference Missions and Concepts of Operations

As described in the objective decomposition methodology, use cases may be grouped into reference missions to provide examples of how several use cases may be accomplished with a particular concept of operations. Appendix A.3 shows the full set of lunar use cases, so only a representative subset is discussed below in two reference missions. While there is a certain temporal aspect to these reference missions, as the architecture capabilities are grown and enhanced, each individual reference mission simply represents an example of how architecture capabilities can be used; these are not planned missions to be flown.

3.1.3.1 Crewed Initial Lunar Surface Reference Mission

As the first crewed mission returning to the lunar surface, this reference mission 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 includes use cases such as crew operations on the lunar surface, frequent crew EVAs on the surface, and crew-conducted utilization activities (including science, crew health and performance, and other operations) on the surface and in space.

3.1.3.2 Crewed Gateway and Lunar Surface Reference Mission

Building up from the initial return mission to the lunar surface, more capabilities in cislunar space address additional use cases, particularly for lunar orbital operations. As a habitable outpost located in NRHO, Gateway enables additional use cases in HLR beyond those in the initial crewed mission to the lunar surface. In particular, Gateway allows for crew to conduct utilization activities in cislunar space; allows for ground personnel and science teams to directly engage with astronauts on the surface and in lunar orbit, augmenting the crew's effectiveness at conducting science activities; enables crew and/or robotic emplacement and set-up of science instrumentation in lunar orbit with long-term remote operation; and includes autonomous/semi-autonomous mission operations in cislunar space.

3.1.4 Sub-Architectures and Element Descriptions

Elements represent capabilities that are available in the HLR campaign segment that meet the designated agency objectives and derived functions needed to support those objectives. The elements are described in the sub-architectures they support; they are not in chronological order.

3.1.4.1 Communication and Positioning, Navigation, and Timing Systems

During the HLR, C&PNT services will be provided through a combination of assets on Earth, in lunar orbit, and on the lunar surface. NASA will lead a distributed team of government, commercial, and international partners to implement this approach. Cooperation among multiple service providers and users across government, industry, and international partners requires coordination and planning through established and new interface and operations standards. This will enable a long-term, scalable, and interoperable architecture that provides communication and position, navigation, and timing services as needed across all the assets.

This infrastructure, which will provide both communication and PNT functionality to users in cislunar space and on the lunar surface, is called "LunaNet." LunaNet[5] is an internationally coordinated framework for lunar interoperability, envisioned as a set of cooperating networks providing C&PNT and other services for users on and around the Moon. The LunaNet concept is based on a structure of mutually agreed-upon standards, protocols, and interface requirements that enable interoperability, known as the LunaNet Interoperability Specification (LNIS). The International Communication Systems Interoperability Standard[6] was developed to enable collaborative operations for the user community. Reference systems and time are fundamental to safety of navigation, precision science, and interoperability at the Moon. Lunar reference systems and time standards must be defined, agreed to, and implemented while lunar C&PNT infrastructure is in the early stages of development. As at Earth, standards are agreed to internationally, but often implemented by individual nations, so close coordination is essential. US policy on these topics is in development[7] and international coordination is already underway[8].

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[5] LunaNet Interoperabilty Specification," National Aeronautics and Space Administration, Washington, DC, 2022. https://www.nasa.gov/wp-content/uploads/2023/09/lunanet-interoperability-specification-v5-draft.pdf?emrc=6f4483 and https://www.nasa.gov/wp-content/uploads/2023/09/lsis-afs-v1-draft-.pdf?emrc=33f92a

[6] International Deep Space Interoperability Standard. www.internationaldeepspacestandards.com

[7] Policy on Celestial Time Standardization in Support of the National Cislunar Science and Technology (S&T) Strategy," Office of Science and Technology Policy, Washington, DC, 4 April 2024, https://www.whitehouse.gov/wp-content/uploads/2024/04/Celestial-Time-Standardization-Policy.pdf

[8] Resolutions to be Voted on at the Upcoming XXXII General Assembly," International Astronautical Union, accessed 6 August 2024, https://iau.org/news/announcements/detail/ann24013/

Direct-to-Earth (DTE, also known as Direct-with-Earth (DWE)) service needs will be met through a combination of an upgraded Deep Space Network (DSN); NASA's Near Space Network (NSN), including Lunar Exploration Ground System (LEGS) and other assets; the European Space Agency's European Space Tracking (Estrack) network; and other international and commercial ground assets. Together, these will provide near-continuous coverage of the near side of the Moon and NRHO. Orbiting assets such as Gateway, the Lunar Communications Relay and Navigation System (LCRNS), and partner assets will provide service to users without line-of-sight to Earth and reduce the required size, weight, and power for a user's communications and PNT systems while accounting for real-time and store-and-forward data needs and real-time position, velocity, and time knowledge to provide robust services under challenging conditions systems. The LCRNS will initially, in this segment, cover a service volume from -80° S to the South Pole of the Moon and up to 125 km altitude. C&PNT services will be supported by one S-band bidirectional link and one simultaneous Ka-band return link, as well as broadcast service through an Augmented Forward Signal (AFS). In the later part of the HLR segment, LCRNS service will expand the service volume to 75° S and up to 200 km and include two to bidirectional simultaneous S-band and Ka-band links and multiple AFS links. Surface-to-surface communications may initially rely on legacy systems such as ultra-high frequency (UHF) and WiFi but will seek to leverage terrestrial standards such as 3GPP/5G within this segment of the architecture to increase mobility, positioning, and capacity. NASA's PNT architecture is comprised of both the infrastructure described above for radionavigation sources and user capabilities. Infrastructure also includes critical reference system components and a time standard upon which C&PNT rely. User-side capabilities include the onboard systems that collect, process, and filter the data required to successfully navigate. These could include cameras and optical sensors, light detection and ranging (lidar) payloads, solar compasses, and inertial measurement units to determine specific force, angular rate, and orientation. The growth of C&PNT services throughout the HLR segment, through technology demonstrations and initial operational support, will enable the near-term exploration objectives of the HLR segment while providing a robust foundation upon which a scalable infrastructure can grow to support the needs of a sustained lunar presence, including precursor missions that will inform and validate a Mars architecture.

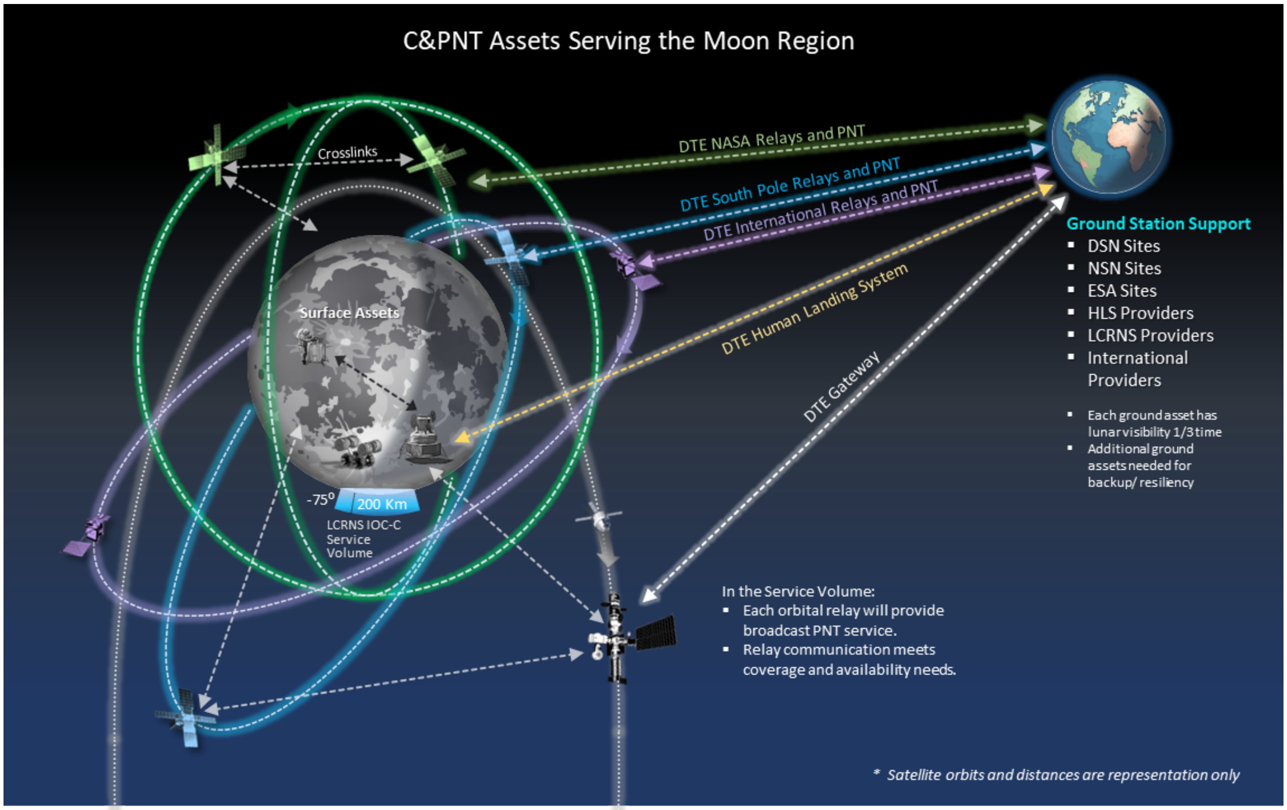


Figure 3-1. LunaNet C&PNT Sub-architecture for HLR

The functions the lunar relay, LCRNS, fulfills in the HLR campaign segment are shown in Table 3-2.

The functions the DSN and NSN fulfill in the HLR campaign segment are shown in Table 3-3.

3.1.4.2 Habitation Systems

3.1.4.2.1 Gateway[9] Crew-Capable Configuration Overview

The Gateway architecture is composed of several modules incrementally launched and assembled in NRHO around the Moon in a system that provides for continuous architectural evolution. Individual Gateway modules are launched either as co-manifested payloads (CPL) on the Space Launch System (SLS) along with the Orion crew vehicle or on commercial launch vehicles. The modules combined in the Gateway architecture represent a meaningful series of demonstration steps in the direction of enabling the more extensive exploration effort in the future.

The HLR campaign segment comprises the Gateway Crew-Capable Configuration: Power and Propulsion Element (PPE), Habitation and Logistics Outpost (HALO), International Habitation Module (I-Hab), and Gateway Logistics Element. For this segment, Gateway capability represents a minimum functional core to support the initial human landing missions to the lunar surface. The I-Hab is being provided by the European Space Agency (ESA), with contributions from the Japan Aerospace Exploration Agency (JAXA). These modules provide pressurized volume for the crew to move between the docked vehicles, space for crew habitation activities (food and water consumption, sleep, hygiene), and internal and external utilization capabilities. They also provide initial life support services and docking ports for additional modules and visiting vehicles. The

[9] For more information, please visit: www.nasa.gov/gateway

PPE is a commercially based spacecraft that 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, translation maneuvers and orbital maintenance are primarily performed using a solar electric propulsion (SEP) system. The PPE has power storage and the systems necessary to convert and distribute power to the rest of Gateway. It provides internal avionics systems and is one part of an integrated command and control architecture for Gateway.

Figure 3-2. Gateway Crew-Capable Configuration

The integrated PPE/HALO configuration also provides communication via PPE and the ESA HALO Lunar Communications Systems (HLCS) for space-to-Earth and space element–to–space element; with visiting vehicles during rendezvous, proximity operations, and docking/undocking; and between lunar surface systems and Earth. NASA utilizes deep space logistics (see Section 3.1.4.6) to deliver cargo and other supplies to Gateway, including critical spares and outfitting for HALO and I-Hab, cargo stowage, and trash disposal. Gateway will launch with an initial suite of internal and external science utilization payloads, provided by NASA, ESA, and JAXA, that will operate and collect data in transit and in NRHO during crewed and uncrewed operations. External payload sites and future robotic attach points will be provided by the Canadian Space Agency (CSA) on PPE, HALO, and I-Hab. The Gateway Crew-Capable Configuration is shown in Figure 3-2. Expansion of Gateway is planned to include additional capabilities and systems as part of the Foundational Exploration segment.

The functions Gateway Crew-Capable Configuration fulfills in the HLR campaign segment are shown in Table 3-4.

3.1.4.3 Human Systems

The humans who embark on the exploration missions are the most critical component of the campaign to get humans to the Moon, to Mars, and beyond. Proper vehicle and mission design for the crew encompasses a complex and extensive list of human system integration and crew health and performance needs that must be considered. If inadequately addressed, these can translate into negative crew health and performance outcomes both during and after the mission. The HLR campaign is the first step in deep space exploration and presents a human systems challenge that is different from Apollo and the International Space Station. These challenges and experiences will build with each successive mission across the campaign segments. Figure 3-3 shows a crewmember working in a pressurized volume in space.

Figure 3-3. Crewmember Working in Space

To emphasize the unique capability and impact to exploration of the crew, they are represented in the Moon to Mars Architecture as both a sub-architecture and an element. As such, crew are required to achieve several of the functions and use cases driven by the Moon to Mars Objectives. Humans are a unique exploration resource, capable of flexibility and adaptation, real-time analysis and independent decision making, and fine motor-skill operations. Humans also have unique sensory and perceptive capabilities that are often difficult to reproduce in hardware. As such, humans are irreplaceable in their ability to perform highly varied and complex tasks in space and on planetary bodies. There will be unanticipated non-conformances that humans are best qualified to detect and resolve. And working toward increasing Earth-independent operations, the humans onboard will be the most adaptive, inductive problem-solving systems available to address emergent, unforeseen time-critical vehicle/habitat issues. Vehicle systems must be designed to enable crew to execute these operations with reduced ground support.

Complex and highly varied tasks will be necessary to accomplish mission objectives such as surface infrastructure installation, geological site analysis and sample collection, planetary science payload deployment, and in-space biological experiments. Without human presence, each of these goals would require highly specialized robotic systems and remote human input. Human assets also present the opportunity to study and assess human-rated systems, human operations, human factors, and other aspects of human research in an environment similar to future Artemis or Mars missions. These studies will provide critical data related to performance, efficiency, and safety, which will inform future technology development, operational planning, and risk assessment for Artemis and Mars missions. Ultimately, humans are critical as operators, subjects, and inspirational figures throughout the Artemis missions and are intrinsic to the Moon to Mars and agency strategic goals of furthering human presence on the Moon and beyond.

3.1.4.4 Infrastructure Support

3.1.4.4.1 Exploration Ground Systems[10] Overview

Figure 3-4. Exploration Ground Systems

The Exploration Ground Systems (EGS) Program was established to develop and operate systems and facilities necessary to process, launch, and recover vehicles. EGS provides the ground infrastructure for launch and landing in support of processing and launch of the SLS and Orion. EGS also provides recovery capabilities for the Orion spacecraft. EGS utilizes the Vehicle Assembly Building (VAB) for integration and testing and vertical stacking on the Mobile Launcher (ML). The ML with the fully stacked SLS and Orion secured is moved to Launch Pad 39B by the crawler-transporter. Vehicle testing, vehicle final propellant servicing, launch countdown, and launch take place at Launch Pad 39B. Additional capabilities, such as the Mobile Launcher 2 (ML2) will be included in the infrastructure of EGS to support the SLS Block 1B missions. The VAB is shown in Figure 3-4.

The functions EGS fulfills in the HLR campaign segment are shown in Table 3-5.

3.1.4.5 In-Situ Resource Utilization Systems

3.1.4.5.1 ISRU Demonstrations

Permanently shadowed region classification and environmental characterization are aided by current orbital missions, such as the Lunar Reconnaissance Orbiter, and planned near-term

[10] For more information, please visit: www.nasa.gov/exploration/systems/ground/index.html

technology demonstrations. The Polar Resources Ice Mining Experiment-1 (PRIME-1) is an example of a planned near-term demonstration to assist in understanding lunar resources, which will help to fulfil the function “Collect water/ice from the polar region of the lunar surface”.

Scheduled to launch on a CLPS mission, PRIME-1 will be the first in-situ resource utilization demonstration on the lunar surface. For the first time, NASA will robotically sample and analyze sub-surface material for ice below the surface. PRIME-1 includes two components, both of which will be mounted to a commercial lunar lander. The Regolith and Ice Drill for Exploring New Terrain (TRIDENT) will drill up to one meter deep, extracting lunar regolith, or soil, up to the surface. The instrument can drill in multiple segments, pausing and retracting to deposit cuttings on the surface after each depth increment. Mass Spectrometer observing lunar operations (MSolo), a modified-for-spaceflight, commercial-off-the-shelf mass spectrometer, will evaluate the drill cuttings from multiple depths for water and other chemical compounds. The data from PRIME-1 will help us understand in-situ resources on the Moon, including resource location mapping, and demonstrate the performance and operation of these important instruments before use in the subsequent VIPER mission.

The VIPER mission will explore the relatively nearby but more extreme environment of the lunar South Pole region around Nobile crater in search of ice and other potential resources. VIPER will characterize the distribution and physical state of lunar polar water and volatiles and minerals outside, near, and inside small PSRs. VIPER will help evaluate the resource potential for ISRU at the lunar polar regions and help determine how to harvest the Moon's resources for future human space exploration. VIPER has three instruments and a 3.28-foot (1-meter) drill to detect and analyze various lunar soil environments at a range of depths and temperatures. VIPER’s instruments will also make important science measurements. Determining the distribution, physical state and composition of these ice deposits will aid in understanding the sources of the lunar polar water, giving insight into distribution and origin of water and other volatiles across the solar system.

To advance the technologies and operations associated with extracting and processing lunar resources into usable products as well as demonstrating other lunar infrastructure–related capabilities for sustained lunar presence, NASA, in partnership with industry, is planning one or more demonstrations. The purpose of these demonstrations is to evaluate the performance of critical technologies and capabilities with actual lunar regolith and under lunar environmental conditions, instead of simulants and terrestrial environmental simulation facilities, to reduce the risk associated with incorporating them into subsequent lunar systems and missions. Following subscale demonstration missions, NASA, in partnership with industry, is planning to demonstrate the end-to-end system and operations associated with resource extraction to product generation and storage to reduce the risk of missions relying on ISRU products for mission success. Referred to as the ISRU Pilot Plant, this demonstration will be performed for a duration and at a scale that will significantly reduce the risks associated with deployment and the commercial life of a full-scale system and demonstrate the quality of the product produced. Several pilot plant concepts are under consideration, including liquefaction and storage of oxygen extracted from regolith, oxygen and hydrogen liquefaction and storage from water extracted from within a permanently shadowed region, and metal and silicon extraction from regolith to produce solar cells and wires for future in-situ production of solar arrays and electrical power transmission cables.

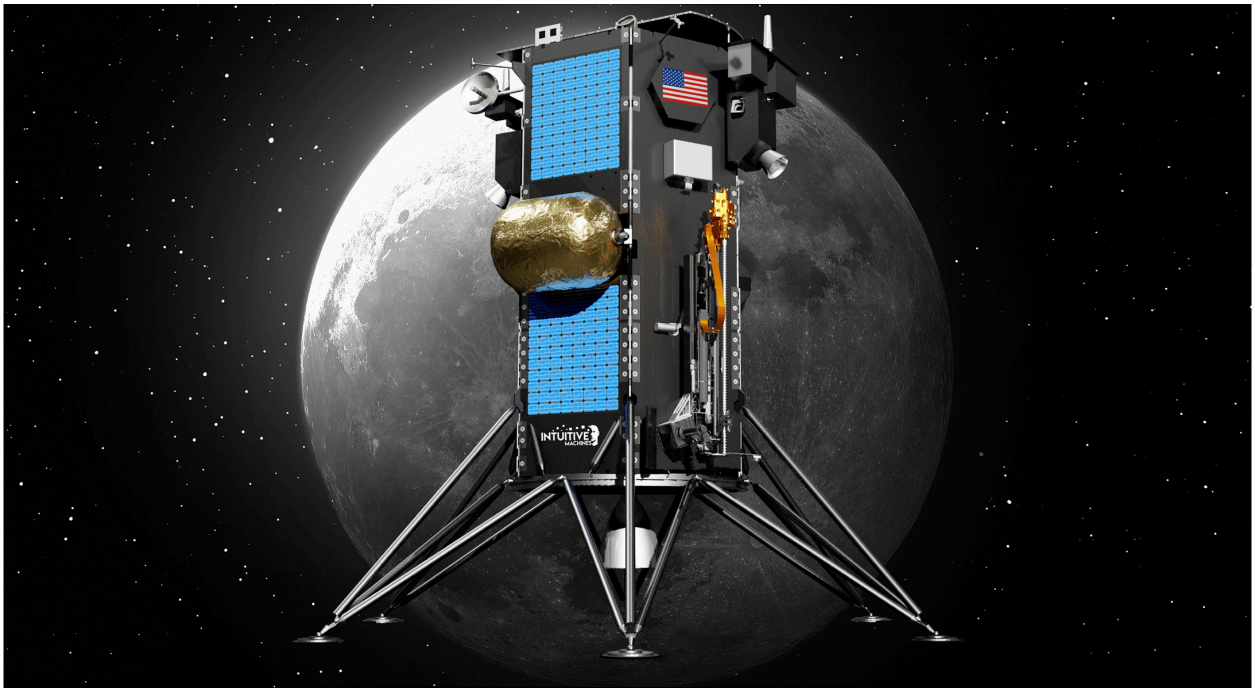


Figure 3-5. PRIME-1 Payload on CLPS Lander

3.1.4.6 Logistics Systems

3.1.4.6.1 Gateway Logistics Element

Exploration activities will need logistics deliveries to satisfy objectives. Logistics items represent all equipment and supplies that are needed to support mission activities that are not installed as part of the vehicle. Logistics typically includes consumables (e.g., food, water, oxygen), maintenance items (planned replacement items), spares (for unexpected/unplanned failures), utilization (e.g., science and technology demonstrations), and outfitting (additional systems/sub-systems for the elements), as well as the associated packaging. Logistics deliveries of critical pressurized and unpressurized cargo and payloads will be needed to support activities with and without crew. In the HLR segment of the exploration campaign, the Gateway Logistics Element (GLE) will provide logistics delivery to cislunar space.

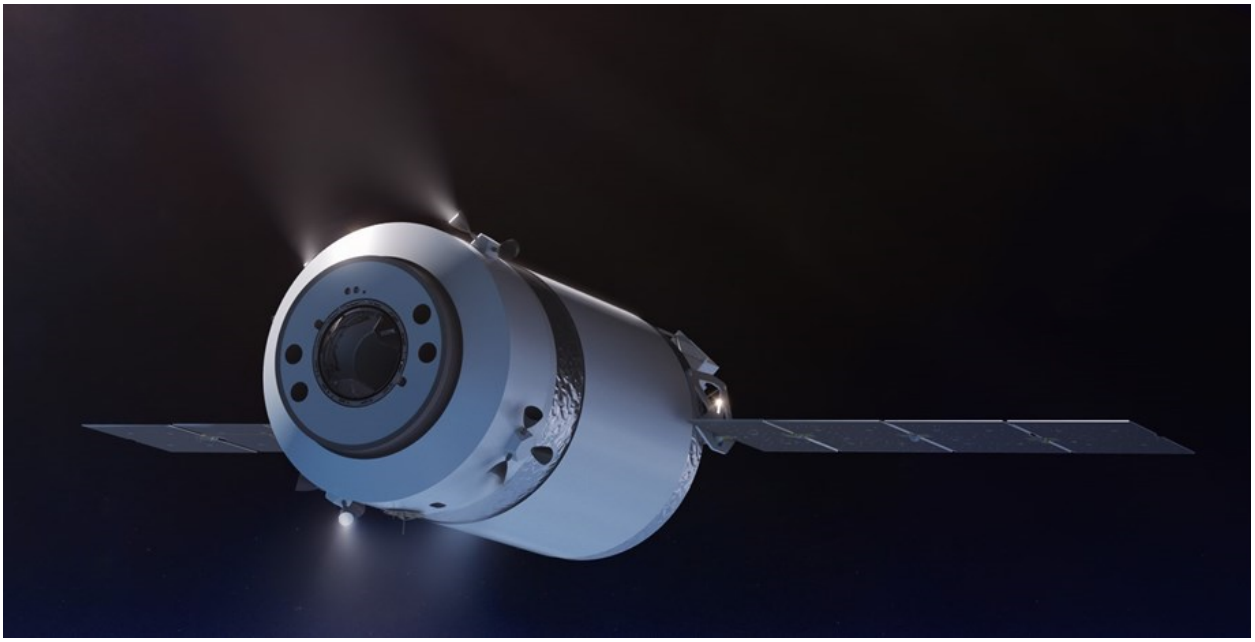


Figure 3-6. Gateway Logistics Element (Image credit: SpaceX)

During HLR, GLE will be used for transporting cargo, payloads, equipment, and consumables to enable exploration of the Moon and Mars. Logistics flights are necessary to supply Gateway with critical cargo deliveries and maximize the length of crew stays on Gateway. The Gateway Logistics Services contract and technical capability are extensible to deliver unique payload configurations and supply cargo deliveries to other destinations. Additional capabilities may be added in future segments. At least one logistics services delivery is anticipated for each Artemis mission to Gateway of 30 days. Dragon XL is shown in Figure 3-6 as one of the providers of Gateway logistics.

The functions the GLE fulfills in the HLR campaign segment are shown in Table 3-6.

3.1.4.7 Mobility Systems

3.1.4.7.1 Exploration Extravehicular Activity System Overview

Figure 3-7. Exploration Extravehicular Activity System

The Exploration Extravehicular Activity (xEVA) System allows crew members to perform extravehicular exploration, research, construction, servicing, repair operations, and utilization and science on the lunar surface. EVA traverse and tasks may be augmented by robotics and rovers. The xEVA System includes the EVA suit, EVA tools, and vehicle interface equipment. Through Exploration Extravehicular Activity Services, Axiom Space has been selected to build the next generation of spacesuit and spacewalk systems.

The functions the xEVA fulfills in the HLR campaign segment are shown in Table 3-7.

3.1.4.8 Transportation Systems

3.1.4.8.1 Space Launch System (SLS)[11] Overview

Figure 3-8. Space Launch System

The SLS is a super-heavy-lift launch vehicle that provides the foundation for human exploration beyond Earth orbit (BEO). With its unprecedented power and capabilities, SLS is the only launch vehicle that can send Orion, astronauts, and payloads directly to the Moon on a single launch. The SLS is designed to be evolvable, which makes it possible to conduct more types of missions, including human missions to Mars; assembly of large structures; and robotic, scientific, and exploration missions to destinations such as the Moon, Mars, Saturn, and Jupiter. Humans will be transported safely, and different payloads will be delivered efficiently and effectively, to enable a variety of complex missions in cislunar and deep space. The first SLS crew transportation system, called Block 1, uses an Interim Cryogenic Propulsion Stage (ICPS) to send the Orion spacecraft on towards the Moon. Block 1 was used for Artemis I and is planned for use for Artemis II and III. The Block 1B variant will use an Exploration Upper Stage (EUS) to enable more ambitious missions, such as carrying the Orion crew vehicle along with large cargo (co-manifested payload) in a single launch. SLS also enables free-flyer science payloads in cislunar space and beyond as secondary payloads. Although Block 1 and Block 1B Crew are the only two variants in HLR, Block 1B Cargo and Block 2 Crew and Cargo variants are key capabilities for future campaign segments. Figure 3-8 exhibits the SLS in the Block 1 configuration for Artemis I.

The functions the SLS fulfills in the HLR campaign segment are shown in Table 3-8.

[11] For more information, please visit: www.nasa.gov/exploration/systems/sls/index.html

3.1.4.8.2 Orion[12] Overview

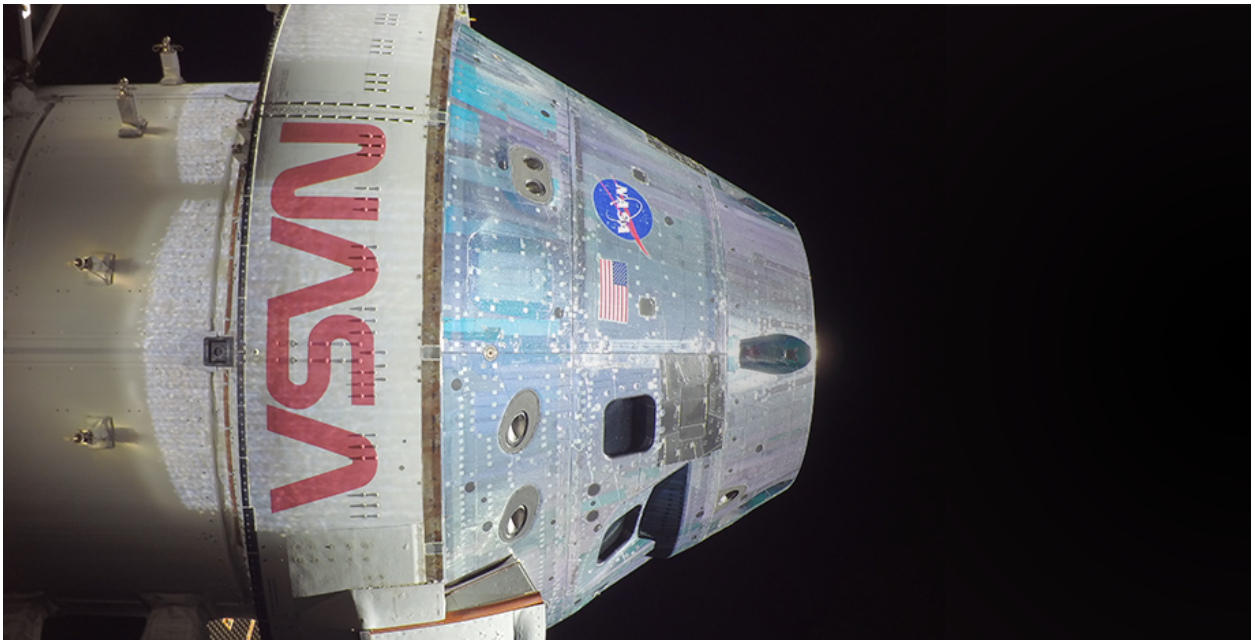


Figure 3-9. Orion Spacecraft

The Orion spacecraft, NASA's next-generation spacecraft to take astronauts on a journey of exploration to the Moon and on to Mars, is shown in Figure 3-9. 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 SLS. The Orion spacecraft includes the Crew Module (CM), Service Module (SM), and Launch Abort System (LAS). The CM is capable of transporting four crew members beyond the Moon, providing a safe habitat from launch through landing and recovery. The SM, made up of the NASA-provided Crew Module Adapter (CMA) and the ESA-provided European Service Module (ESM), provides support to the crew module from launch through separation prior to entry. The SM 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 SM also provides water and air to support the crew. The LAS, positioned on a tower atop the CM, can activate within milliseconds to propel the vehicle to safety and position the CM for a safe landing.

The functions the Orion spacecraft fulfills in the HLR campaign segment are shown in Table 3-9.

[12] For more information, please visit: www.nasa.gov/exploration/systems/orion/index.html

3.1.4.8.3 Human Landing System—Initial and Integrated Lander Configurations Overview

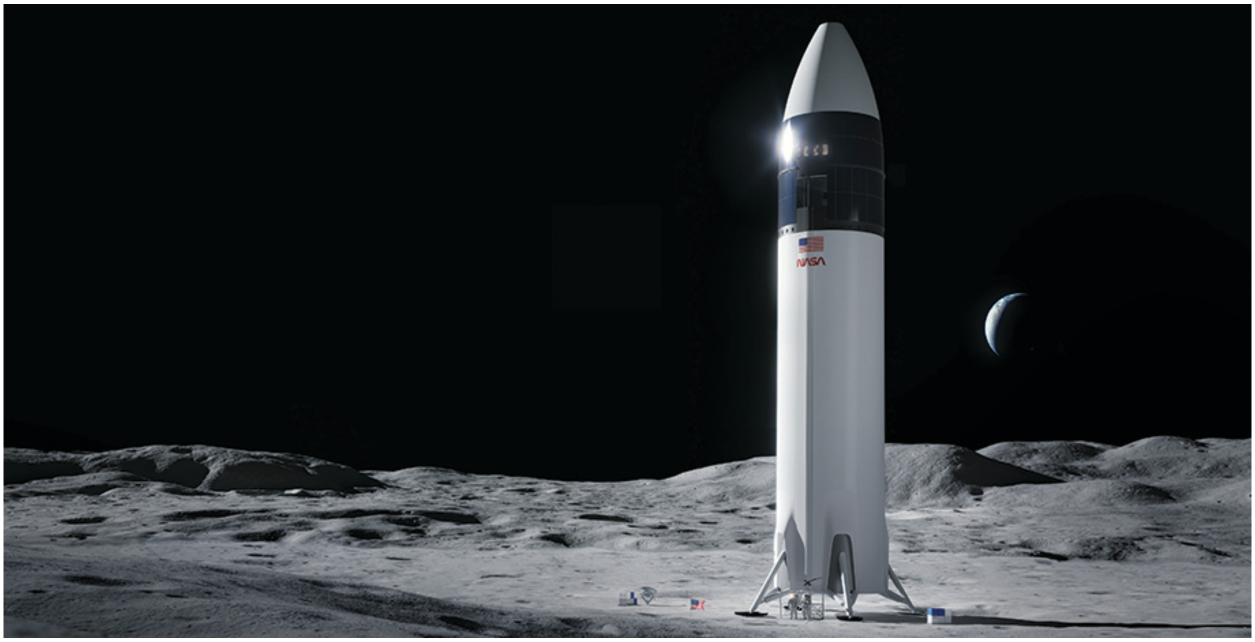


Figure 3-10. Human Landing System—Initial and One of the Integrated Lander Configurations as Awarded (Image credit: SpaceX)

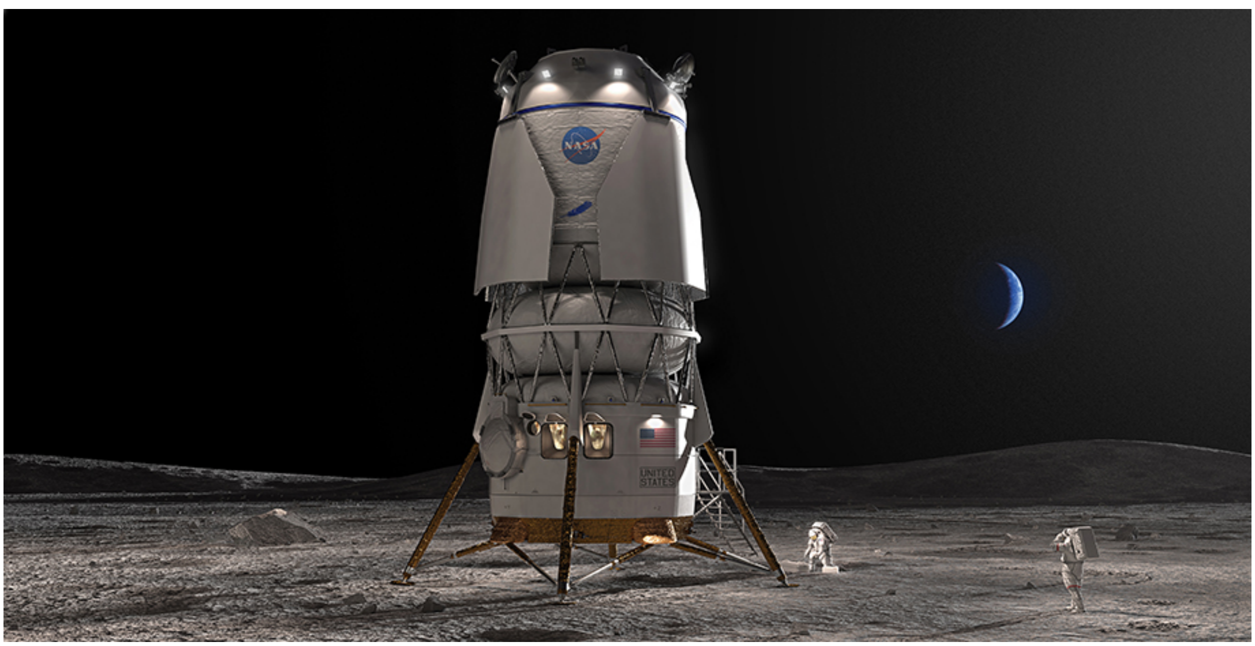


Figure 3-11. Human Landing System—One of the Integrated Lander Configurations as Awarded (Image credit: Blue Origin)

The Human Landing System (HLS) will transport crew members, support payloads, cargo, and logistics between a crew staging vehicle (either Orion or Gateway) orbiting the Moon in NRHO and the lunar surface. On the lunar surface, HLS provides the habitable volume, consumables, and design features, enabling crew surface stay and execution of lunar surface EVAs, along with utilization accommodations inside the cabin as well as external attached payloads. The specific HLS architecture is subject to commercial provider design implementation approach.

The initial HLS configuration supports a crew of two and will operate between Orion in NRHO and a landing site in the vicinity of the lunar South Pole. Additionally, in this configuration, HLS will deliver the cargo and support logistics to NRHO from Earth prior to the start of the crewed phase of the mission. The initial human landing mission will be a demonstration of this initial HLS configuration and of the minimum basic technologies and innovation required to safely transport crew and utilization cargo to and from the lunar surface.

The HLS integrated lander will build on the initial configuration's base capabilities to enable the full range of crewed lunar mission objectives, including accommodating additional internal and external payloads. More ambitious missions will also be pursued as lunar surface exploration evolves toward the Foundational Exploration segment. Missions with the HLS integrated lander will require HLS to support landing a crew of up to four, leveraging additional habitable surface assets to support the larger crew for the duration of the lunar stay. These missions may include the capability to land and operate at non-polar landing sites or for extended durations at the lunar South Pole. This HLS configuration has increased performance capabilities, allowing for enhanced up and down mass and increased darkness survivability. These missions will also seek sustainable HLS designs that may include reusable elements or interactions with other systems in the lunar vicinity. All missions with the HLS integrated lander will begin and end at Gateway—enabling extended missions on the lunar surface, as Orion will be able to remain in lunar orbit longer docked with Gateway. The initial HLS and HLS integrated lander configurations are shown in Figure 3-10 and Figure 3-11.

The functions the HLS fulfills in the HLR campaign segment are shown in Table 3-10.

3.1.4.8.4 Cargo Landers—Commercial Lunar Payload Services (CLPS)[13] Provider Landers

Lunar surface exploration will require the delivery of assets, equipment, and supplies to the lunar surface. While some supplies and equipment may be delivered with crew on HLS, cargo landers provide additional flexibility and capability for robust exploration. In the HLR segment of the exploration campaign, additional cargo delivery can be provided through NASA's CLPS Provider Landers.

NASA's CLPS initiative allows rapid acquisition of lunar delivery services from American companies for payloads that advance capabilities for science, technology, exploration, or commercial development of the Moon. Investigations and demonstrations launched on commercial Moon flights will help the agency study Earth's nearest neighbor under the Artemis approach. Companies are encouraged to fly commercial and other partner payloads in addition to the NASA payloads. NASA has awarded 11 task orders to 6 different CLPS lander providers for delivery of more than 40 payloads to the lunar surface during the HLR exploration segment. Additional task orders will be awarded as mission and payload definition continues. Current CLPS Provider Landers deliveries are sending science and technology payloads. SMD plans to continue annual calls for new payload suites through the Payload and Research Investigations from the Surface of the Moon (PRISM) solicitation. PRISM will enable high-priority science and will be complemented by other NASA-sponsored payloads.

The functions CLPS Provider Landers fulfill in the HLR campaign segment are shown in Table 3-11.

[13] For more information, please visit: www.nasa.gov/clps

3.1.4.9 Utilization Systems

3.1.4.9.1 Utilization Payloads and Equipment

The transportation, delivery, deployment, and operation of utilization payloads and equipment to cislunar space and the lunar surface, as well as the return to Earth of samples and other cargo, is a key service provided by the Moon to Mars Architecture and a critical enabler of every NASA utilization objective. Utilization payloads and equipment are broadly characterized here to encompass any item transported and supported by the Moon to Mars Architecture that is primarily in support of and attributed to utilization objectives, as distinct from other components in the baseline platform of services provided by the architecture. Utilization payload is defined to include science/research payloads, technology demonstrations, etc. Utilization equipment includes other internal and external hardware tools, supplies, etc. Examples of utilization systems include:

Utilization Payloads

- Secondary SLS payloads, including CubeSats
- Externally mounted scientific sensors on Gateway, HLS, logistics modules, and other surface elements
- Science experiments and technology demonstrators deployed to the lunar surface by the crew or by robotic landers
- Internally operated experiments in every crew volume, including Orion, Gateway, and HLS
- Portable devices used to make scientific observations of the lunar surface, including cameras and other instruments
- Scientific samples and data related to planetary science, human research, space biology, physics, and physical science

Utilization Equipment

- Tools and containers used to collect geological samples from the lunar surface, as well as samples collected from other science experiments and human research activities
- The HLR segment will include a freezer that will be capable of conditioning geology, human research, space biology, and other samples at near -85°C

Note that some payloads and equipment, including some multi-purpose cameras and medical equipment, are dual use, supporting both utilization and operations, and may be considered a part of the utilization systems sub-architecture or a part of other sub-architectures, depending on the context.

The functions Equipment fulfills in the HLR campaign segment are shown in Table 3-12. Mappings to science/research payloads and technology demonstrations are removed for this revision and are forward work.

3.1.5 Exploration Asset Mapping

The following tables map assets to the functions they fulfill. Functions mapped to exploration assets do not indicate that an asset fully satisfies the use case or blueprint objective, or that completion is achieved. While some of the functions are grouped into performance classes, for most of the functions, there is no intent to indicate how well the asset accomplishes the function and supports the use case. Rather, in those cases, it represents the asset contributes to the architecture by providing the associated function. Unmapped functions are indicators of where there are gaps in the current architecture and where future efforts can be focused. Note: mapping to science/research payloads and technology demonstrations are removed for this revision and are forward work.

Table 3-2. Functions Fulfilled by LCRNS During the HLR Segment

Functions Fulfilled by LCRNS During the HLR Segment			
		ID	Functions
EM-006-HLR	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

Table 3-3. Functions Fulfilled by NSN/DSN During the HLR Segment

Functions Fulfilled by NSN/DSN During the HLR Segment			
		ID	Functions
EM-010-HLR	NSN/DSN	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

Functions Fulfilled by NSN/DSN During the HLR Segment			
		ID	**Functions**
		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 of asset(s) from Earth in cislunar space during uncrewed periods

Table 3-4. Functions Fulfilled by Gateway During the HLR Segment

Functions Fulfilled by Gateway During the HLR Segment			
		ID	**Functions**
EM-004-HLR	**Gateway**	**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-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

Functions Fulfilled by Gateway During the HLR Segment			
		ID	Functions
		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-D-202 L	Process data locally in cislunar space
		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

Table 3-5. Functions Fulfilled by Exploration Ground Systems During the HLR Segment

Functions Fulfilled by Exploration Ground Systems During the HLR Segment			
		ID	Functions
EM-002-HLR	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)

Functions Fulfilled by Exploration Ground Systems During the HLR Segment			
		ID	**Functions**
		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

Table 3-6. Functions Fulfilled by Gateway Logistics Element During the HLR Segment

Functions Fulfilled by Gateway Logistics Element During the HLR Segment			
		ID	**Functions**
EM-009-HLR	**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

Table 3-7. Functions Fulfilled by xEVA System During the HLR Segment

Functions Fulfilled by xEVA System During the HLR Segment			
		ID	**Functions**
EM-007-HLR	**xEVA System**	**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 sub-surface samples, maintaining scientific integrity of the samples, from non-PSRs and sunlit regions on the lunar surface

Table 3-8. Functions Fulfilled by SLS During the HLR Segment

Functions Fulfilled by SLS During the HLR Segment			
		ID	**Functions**
EM-001-HLR	**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)

Table 3-9. Functions Fulfilled by Orion During the HLR Segment

Functions Fulfilled by Orion During the HLR Segment			
		ID	**Functions**
EM-003-HLR	**Orion**	**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-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

Table 3-10. Functions Fulfilled by HLS During the HLR Segment

Functions Fulfilled by HLS During the HLR Segment			
		ID	**Functions**
EM-005-HLR	**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-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

Functions Fulfilled by HLS During the HLR Segment			
		ID	Functions
		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-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-414 L	Provide resources to condition refrigerated sample containers on the lunar surface

Table 3-11. Functions Fulfilled by CLPS Provider Landers During the HLR Segment

Functions Fulfilled by CLPS Provider Landers During the HLR Segment			
		ID	Functions
EM-008-HLR	**CLPS Provider Landers**	**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

Functions Fulfilled by CLPS Provider Landers During the HLR Segment			
		ID	**Functions**
		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-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

Table 3-12. Functions Fulfilled by Equipment During the HLR Segment

Functions Fulfilled by Equipment During the HLR Segment			
		ID	**Functions**
EM-018-HLR	**Equipment**	**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

3.1.6 Unallocated Functions

Use case and functional decomposition focused on near-term achievability of the lunar objectives has been completed. Once the Mars objectives decomposition is complete, there may be additional lunar use cases and functions to be included in the HLR segment.

The current list of functions that are unallocated for HLR are listed below. Note, mapping to science/research payloads and technology demonstrations is forward work.

Table 3-13. Unallocated Functions for the HLR Segment

Unallocated Functions for the HLR Segment			
		ID	**Functions**
EM-012-HLR	Unallocated	**FN-T-103 L**	Transport crew from cislunar space to distributed sites outside of the south pole region on the lunar surface
		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-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-206 L	Transport large exploration 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-212 L	Transport a large amount of cargo (100s of kg) from cislunar space to Earth
		FN-T-215 L	Transport cargo from Earth to assets in deep 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

Unallocated Functions for the HLR Segment			
		ID	Functions
		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-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 moderate duration (month+) use
		FN-H-104 L	Enable a pressurized, habitable environment in cislunar space for moderate (month+) durations
		FN-H-105 L	Enable a pressurized, habitable environment in cislunar space for extended (year+) duration
		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-X-103 L	Provide crew countermeasure system(s) to support the crew for moderate durations (month+) on the lunar surface
		FN-X-104 L	Provide crew countermeasure system(s) to support the crew for moderate (month+) to long (year+) durations 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	Mating between pressurized assets on the lunar surface
		FN-L-201 L	Transfer pressurized cargo into habitable assets on the lunar surface

Unallocated Functions for the HLR Segment			
		ID	**Functions**
		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
		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-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 long durations (months to years+)
		FN-M-103 L	Enable crew surface extravehicular activities at the lunar far side region
		FN-M-104 L	Enable crew extravehicular activity in cislunar space

Unallocated Functions for the HLR Segment			
		ID	Functions
		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-403 L	Unload large exploration 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-M-509 L	Reposition a large amount of frozen samples and containers (100s of kg) on the lunar surface

Unallocated Functions for the HLR Segment			
		ID	**Functions**
		FN-M-510 L	Reposition a large amount of cryogenic samples and containers (100s of kg) on the lunar surface
		FN-M-601 L	Relocation of exploration assets at lunar surface polar locations
		FN-M-602 L	Relocation of 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-103 L	Provide communications and data exchange between assets on the lunar surface
		FN-C-107 L	Provide high bandwidth, high availability communications and data exchange between assets 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-205 L	Provide a coordinated lunar time scale
		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-201 L	Process data locally on the lunar surface
		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

Unallocated Functions for the HLR Segment			
		ID	**Functions**
		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-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-403 L	Transition assets between crewed and uncrewed mode on the lunar surface
		FN-I-101 L	Collect water/ice from the polar 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

Unallocated Functions for the HLR Segment			
		ID	Functions
		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 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-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-U-203 L	Provide extravehicular utilization accommodation, interfaces, and resources, operable during crewed and uncrewed increments, on the lunar surface

Unallocated Functions for the HLR Segment			
		ID	Functions
		FN-U-204 L	Provide intravehicular activity facilities, utilization accommodation, and resources, operable during crewed and uncrewed increments, on the lunar surface
		FN-U-301 L	Provide capability to recover and package sub-surface 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 sub-surface samples, maintaining scientific integrity of the samples, from PSRs on the lunar surface
		FN-U-304 L	Provide capability to recover and package surface and/or shallow sub-surface samples, maintaining scientific integrity of the samples, from PSRs on the lunar surface
		FN-U-305 L	Provide capability to recover and package deep sub-surface 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 sub-surface 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-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-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-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

Unallocated Functions for the HLR Segment			
		ID	**Functions**
		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

3.1.7 Open Questions, Ongoing Assessments, and Future Work

Open questions, ongoing assessments, and future work for HLR segment include:

- What options are available to increase down-mass to the lunar surface to support utilization?
- What options are available to enable late access to utilization payloads, including late delivery of actively growing biological specimens, prior to launch?
- What opportunities are available to transport powered cargo to deep space?
- To what extent can current systems be used to support non-polar sorties in the HLR segment?
- What elements need to enable in-situ training of crew in cislunar space?
- What options are available to enable utilization operations at the maximum allowable crew EVA walking distance?
- What options are available to provide power to deployed utilization payloads, during the HLR segment, enabling payloads to survive extended lunar nights on the lunar surface?
- Are any additional functions and use cases needed to address public affairs and outreach?

3.2 Foundational Exploration Segment

The Foundational Exploration (FE) segment builds on the initial capabilities of Human Lunar Return (HLR) and prepares for future segments through the lunar expansion of operations, capabilities, and systems supporting complex orbital and surface missions to conduct utilization and Mars-forward precursor missions. With the continued use of the elements in HLR and the deployment of new capabilities, surface missions will feature increased duration, 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, will serve as Mars mission analogs, validating both the systems and the exploration concepts of operations for future Mars mission profiles. FE will have to initiate activities and capabilities that will be influenced by the future needs in the Sustained Lunar Evolution (SLE) and Humans to Mars segments. Such activities include reconnaissance, Mars risk reduction, and initial infrastructure supporting the long-term SLE evolution.

3.2.1 Use Cases and Functions

As seen in the HLR segment, by starting with the agency objectives and their associated characteristics and needs, particular use cases and functions may be defined. As the FE segment continues to be matured, so will the functional breakdown from the objectives. The complete set of objectives can be found in Appendix A.

As a representative example, objective 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) drives several characteristics and needs. These include demonstration of capabilities to allow crew to live and work inside habitable spaces and to exit them to conduct EVA activities in both cislunar space and on the lunar surface. Sample use cases that contribute to fulfilling those characteristics and needs include crew operations, habitation, EVA, collection of samples, and crew emplacement and set-up of science and utilization packages. Some of the functions that map to these use cases include transportation, crew health and human performance, habitation, and integrated human-robotic operations.

For FE, several elements are in design/development stages; these elements form the basis of satisfying some of the functional needs. Element mappings for elements that have passed NASA's Mission Concept Review[14] are provided in Section 3.2.5. As additional elements are added to the architecture for FE, updates to the element mapping will be provided. Many of the use cases and functions will require additional elements or new functional capabilities that go beyond what is being assigned to the current FE elements described below. Key gaps between planned FE capabilities and Moon to Mars Objectives needs are noted later in this document and will continue to be expanded through the ACR process. Note that not all use cases (UC-#) and functions (FN-#) are sequential in this segment mapping. The numbering represents use cases and functions that have been identified through the overall objective decompositions process but not all are applicable to the FE segment.

3.2.2 Summary of Objectives

Increased mission durations, expanded capabilities, and the ability to access various regions of the lunar surface enable a growth in utilization during both crewed and uncrewed mission phases. A variety of science objectives may be addressed during the FE segment, ranging from lunar and planetary science to human and biological science and science-enabling and applied science goals. During the FE campaign segment, enhanced architecture capabilities would further enhance the ability to address and achieve science objectives, including 1) expanding accessible regions of exploration from the South Pole region to key locations across the Moon to further advance understanding of the chronology, composition, and internal structure of the Moon (LPS-1 and LPS-2), 2) characterizing the distribution, source, and composition of volatile-bearing materials across the lunar south polar region, including within larger PSRs (LPS-3) and determine their viability for ISRU, 3) generating forecasting capabilities for space weather monitoring off the Earth-Sun line (HS-1), 4) characterizing plant, model organisms/systems, and human physiological responses to long-term exposure to extreme environments with microgravity or partial gravity (HBS-1, HBS-3), 5) characterizing physical systems in partial-gravity environments and associated models (HBS-2), and 6) conducting relativity and quantum physics experiments in the lunar environment (PPS-1, PPS2). These FE science priorities were identified by NASA's SMD, Human Research Program (HRP), Space Technology Mission Directorate (STMD), and other stakeholders in FE execution.

All of the lunar infrastructure (LI) objectives help define FE. Expansion of the power (LI-1), communications/position/navigation/timing (LI-2, LI-3), transportation (LI-5, LI-6), mobility (LI-6), ISRU (LI-7), infrastructure (LI-4, LI-8), and utilization (LI-9) sub-architectures builds toward the LI 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."

The transportation and habitation (TH) objectives drive the additional capabilities in mobility, habitation, and transportation systems during FE. For example, TH-1, TH-2, and TH-11 all 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 (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

[14] Mission Concept Review as defined in NASA Procedural Requirement 7120.5F, https://nodis3.gsfc.nasa.gov/displayDir.cfm?t=NPR&c=7120&s=5F

industrial utilization as well as Mars analog activities) and TH-4 (develop in-space and surface habitation system(s) for crew to live in deep space for extended durations, enabling future missions to Mars) define FE as a campaign segment.

A number of operations (OP) objectives drive the capabilities needed for FE. 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, the need to develop methods to work with robotic systems (OP-9, OP-10) and characterize in-situ resources (OP-3) defines other aspects of FE.

3.2.3 Reference Missions and Concepts of Operations

As described in the Objective Decomposition section, use cases may be grouped into reference missions to show examples of how several use cases may be accomplished with a particular concept of operations. Expanding on the types of mission phases expected in HLR, several notional reference mission phases are presented below, showing progress toward the FE objectives. Reference missions represent how architecture capabilities can be used; these are not planned missions to be flown.

3.2.3.1 Sortie Reference Mission with Unpressurized Mobility

The FE segment will build on the types of lunar surface exploration conducted in the HLR segment, which includes crew habitation in an EVA-capable crew lander. Additional FE use cases may be implemented with the addition of an unpressurized mobility platform to extend EVA range and scientific exploration. This enables the use case for crew excursions to locations distributed around the landing site and has the potential to enable others, such as robotic assistance of crew exploration, the locating of samples and resources, and retrieval of samples; crewed/robotic collection of samples from PSRs; and deployment of power generation, storage, and distribution systems at multiple locations around the lunar South Pole, among others.

3.2.3.2 Reference Mission with Pressurized Mobility

Working toward the objectives to expand exploration for longer durations while conducting scientific and industrial utilization, developing surface habitation systems, and performing Mars risk reduction activities prompt the inclusion of additional functional capabilities. With initial surface crew sizes, one method to accomplish these objectives is by adding functionality for pressurized mobility systems. This function may enable use cases such as crew intra-vehicular activity (IVA) research, expanded durations for crew operations on the lunar surface (including 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.

With the addition of pressurized habitation and mobility, as well as potentially increased number of crew, mission durations, and sites, other needs will arise, such as logistics transport and stowage, trash disposal, maintenance, and other infrastructure services and support. Challenges with the lunar environment, such as dust, plasma interactions, radiation, etc., will become increasingly complex and will need to be mitigated.

3.2.3.3 Robotic Uncrewed Operations

Even with the opportunity to extend surface mission durations from those in HLR, assets on the surface of the Moon are currently planned to be uncrewed for the majority of each year in the FE segment. Functions regarding autonomous, local tele-operations, or Earth-based remote operations enabled by the C&PNT sub-architecture provide additional exploration and utilization opportunities during the uncrewed portions of the year. Assuming a main function of autonomous and/or tele-operations, 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 PSRs), uncrewed relocation of mobility elements to landing sites around the lunar South Pole, and autonomous deployment of science and utilization packages.

3.2.3.4 Extended Cislunar Operations at Gateway

A key aspect of FE is preparing for crewed exploration of Mars through lunar precursor missions. In addition to an extension in duration for surface mission segments from HLR, other main characteristics are to provide numerous long-duration crew increments in cislunar space to compliment crewed surface mission segments and to support crew transitions from microgravity to partial gravity. Extended mission segments in cislunar space at Gateway and accompanying visiting vehicles also allow for increased time for IVA science and utilization. A main use case to accomplish these characteristics and needs is to utilize precursor Mars mission profiles with extended durations in NRHO, followed by lunar surface missions. Although these missions are not identical, they allow for long-term physiological, psychological, team performance, and operational assessments of crew and systems as a precursor to Mars missions.

Other use cases applicable to Gateway reference missions 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 setup 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.

3.2.3.5 Extended Surface Habitation Operations

The addition of dedicated surface habitation enables longer-duration missions, increased crew size, and enhanced surface utilization and exploration to help meet objectives that lead to continuous presence. With dedicated habitation capability, additional use cases to support science and utilization are achievable, enhancing crew EVA exploration, sample collection, and emplacement of science and/or utilization packages. Performing in-situ science through allocated workspaces and demonstrating progressively regenerative and self-sustaining ECLS systems are example use cases that might be addressed with additional surface habitation capability. Increased functional capabilities that support longer-duration deep space and partial-gravity crew habitation include robust crew medical systems and health kits; space-based manufacturing techniques allowing repairs and replacement; enhancing surface EVAs; and providing interfaces for logistics transfers (e.g., solid and fluid consumables, maintenance, utilization, and waste) all further contribute towards fulfilling Moon to Mars Objectives focused on building a sustained lunar presence. Systems that were originally sized to maintain elements during extended uncrewed periods and early FE missions will need augmentation to permit increased objective satisfaction and longer-duration human presence.

3.2.3.6 Non-Polar Lunar Sortie Reference Mission

Although the focus for lunar surface exploration is the South Pole, several objectives, particularly those related to science and utilization, motivate looking at landing sites beyond the South Pole. The use case of transportation of crew to non-polar landing sites would allow for exploration of alternative locations with enabling functions like crew descent, landing, and ascent at non-polar sites. Each area presents its own challenges and points of interests. This allows for sample collection and/or return from various locations of interest across the lunar surface via EVA without surface mobility.

3.2.3.7 Cislunar Orbit Only

During the FE segment, there may be periods where strategic objectives or mission implementation necessitate crew missions to orbit only without a subsequent landing on the lunar surface. This exploration strategy would require capabilities to not only perform crew missions in cislunar orbit (i.e., NRHO), but also the ability to control lunar surface assets from Earth and lunar orbit. This would allow faster control response by the crew (near–real time), which could include cargo unloading, logistics transfer, surface and/or sub-surface sample collection, and infrastructure development (e.g., landing site scouting or preparation).

3.2.4 Sub-Architectures and Element and Functional Descriptions

Elements introduced in HLR will continue to be utilized, as additional capabilities will become available, flowing from the agency objectives. As element concepts mature, they have been added to the FE segment. Other concepts can be grouped into general functional categories and/or associated sub-architectures. As the architecture matures and the Artemis campaign advances, new elements will be conceptualized to meet these needs. Other important aspects to consider include interoperability between elements, the associated functions necessary to achieve interoperability, and the impacts of functional groupings on the overall architecture.

Forward work remains to further define the sub-architectures and their expansion for FE. In addition to integrating with particular elements, the sub-architectures bridge elements and operations, necessitating high levels of long-term planning and coordination across the overall exploration architecture. For other sub-architectures, notional, non-comprehensive functions are included here. Images shown are examples of concepts that may meet (or partially meet) the capabilities in these functional descriptions; they should not be taken as recommendations for design solutions or treated as the only concept(s) under consideration.

3.2.4.1 Communication and Position, Timing, and Navigation Systems

Building upon the HLR segment, the C&PNT capabilities expand in the FE segment to include greater coverage, availability, and more capable system capacity. Greater C&PNT coverage and availability involves expanding the orbital relay service to increase coverage and availability over the South Pole and other lunar regions of interest. A surface wireless networking infrastructure enables direct surface/local communication and aggregates data for backhaul transmission to Earth and offers supplemental local PNT. An increasingly capable orbital relay network will provide additional communication and PNT services to the expected increase in number of surface users/assets and support increased data volume and growth, while improving accurate and timely PNT services over the global lunar surface volume. As more elements are deployed to the surface, many will be telerobotically controlled or operate autonomously under remote supervision, including the commanding of rovers and control and monitoring of science payloads. Each of these elements and users will have a variety of communication and PNT needs to accurately land, move, localize, time-stamp, and navigate about the surface; travel to and record locations of interest and samples; communicate and exchange data with other elements on the surface, with Gateway, and with operations on Earth; and collect and return telemetry, video, and other science data. As the number of simultaneous users increases, the PNT architecture for global coverage would not require a parallel increase in orbital nodes. NASA's current spectrum plans and coordination for LunaNet incorporate the Interagency Operations Advisory Group (IOAG) Architecture, the International Communication System Interoperability Standards (ICSIS), the International Telecommunications Union (ITU), and the Space Frequency Coordination Group (SFCG). As future elements are defined, example functions (from the current function list in Appendix A) that are new or significantly enhanced in the FE segment for this sub-architecture include:

- Provide high bandwidth, high availability communications and data exchange between assets on the lunar surface
- Provide high bandwidth, high availability communications and data exchange between cislunar space and the lunar surface

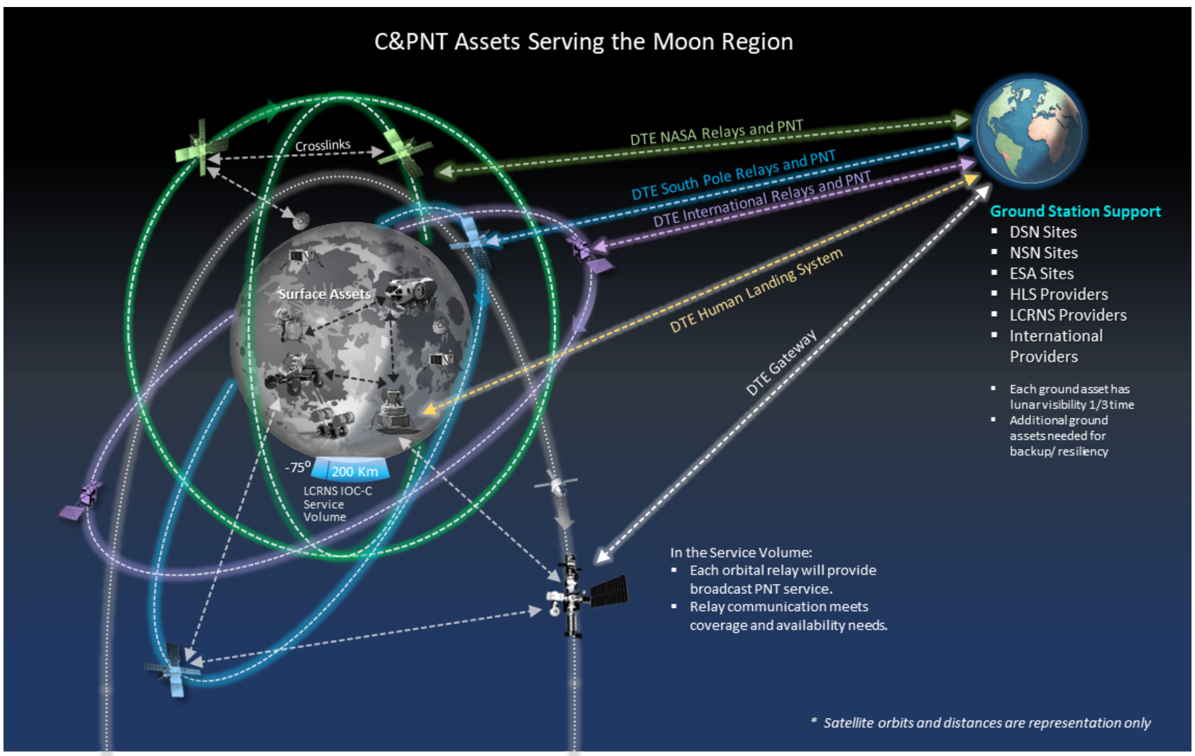


Figure 3-12. LunaNet C&PNT Sub-Architecture for FE

The functions the lunar relay, LCRNS, fulfills in the FE campaign segment are shown in Table 3-14.

The functions the DSN and NSN fulfill in the FE campaign segment are shown in Table 3-15.

3.2.4.2 Data Systems and Management Sub-Architecture

The data systems and management sub-architecture will leverage initial capabilities put in place in HLR for managing and moving data across the architecture; it is highly dependent on the C&PNT, and Human Systems sub-architectures. Capabilities to be added in FE focus on a more robust data management strategy that considers data quality, interoperability, security, privacy, latency, and compliance to ensure that the full potential of the expansive amount of lunar data can be harnessed. This sub-architecture, like many others, spans not only the lunar surface and cislunar space, but also includes the data obtained, needed, stored, or shared on Earth. With elements yet to be defined, example functions (from the current function list in Appendix A) that are new or significantly enhanced in the FE segment for this sub-architecture include:

- Collect, store, and locally distribute data on the lunar surface
- Collect, store, and locally distribute data between assets in cislunar space
- Process data locally on the lunar surface

3.2.4.3 Habitation Systems

Building upon the initial Gateway capability described in HLR, both cislunar and surface habitation are expanded during FE. Concepts for such expanded functionality are under assessment and may support Mars analogs in the lunar vicinity. For such analogs, long-duration habitation system operations in a relevant environment will support risk reduction and crew preparation for Mars transit. For the lunar surface, extending durations and crew size beyond HLR durations of more than seven days on the surface with two crew will afford opportunities to achieve several Moon to Mars Objectives. Examples of expanded functional capabilities in the FE segment (from the current function list in Appendix A) for this sub-architecture include:

- Enable a pressurized, habitable environment in cislunar space for moderate (months+) durations
- Enable a pressurized, habitable environment on the lunar surface for short durations (days to weeks)
- Enable a pressurized, habitable environment on the lunar surface for moderate duration (month+) use
- Operate habitation system(s) in uncrewed mode between crewed missions on the lunar surface

3.2.4.3.1 Gateway Expanded Capability Configuration

The FE segment includes planned upgrades from the Gateway Crew-Capable configuration, described in HLR, to the Gateway Expanded Capability configuration. These upgrades include the previously described Gateway External Robotic System (GERS) to be provided by CSA, the European System Providing Refueling Infrastructure and Telecommunications (ESPRIT) Refueling Module (ERM) to be provided by ESA, logistics resupply to be provided by JAXA, and the Gateway airlock provided by the Mohammed Bin Rashid Space Center (MBRSC). The Gateway airlock is a multipurpose element that provides the capability for EVAs while supporting scientific research and day-to-day Gateway operations with a specialized science airlock. By leveraging the capabilities provided by GERS/Canadarm3, the science airlock will allow scientific experiments and Gateway hardware to move between the pressurized cabin and unpressurized destinations outside of Gateway. The Gateway airlock is also planned to provide an additional docking port for visiting vehicles, supplementary storage, and the capability for unattended robotic maintenance of Gateway. NASA expands on the flexible deep space logistics capabilities (see Section 3.1.4.3) to deliver elements (i.e., GERS), payloads, cargo, experiments, and other supplies to Gateway, to extend the duration of crewed missions. The ERM enables the Gateway PPE's refueling and provides the capability for external viewing of the Moon and cislunar space.

The ERM will include a docking port for the logistics module and supports expanded cargo stowage for Gateway. The Gateway Expanded Capability Configuration is shown in Figure 3-13.

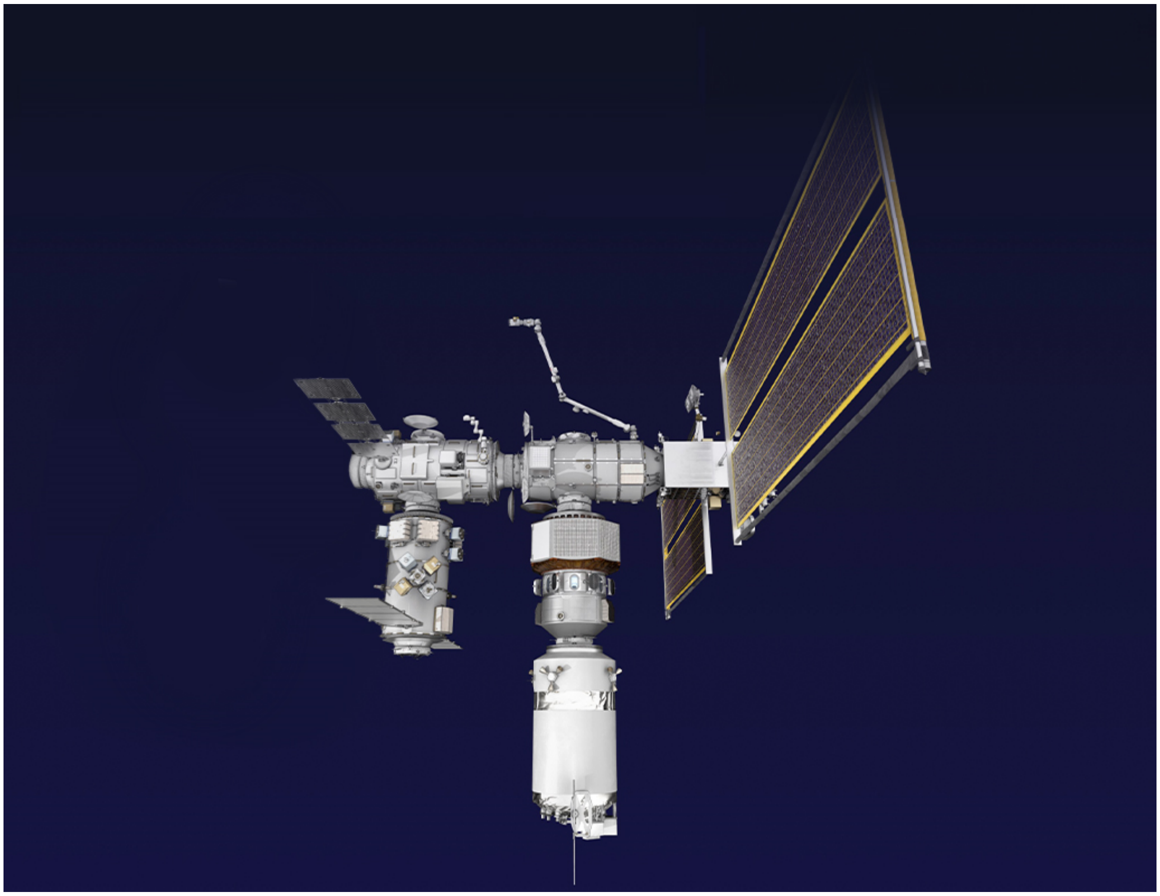


Figure 3-13. Gateway Extended Capability Configuration

The functions Gateway Expanded Capability Configuration fulfills in the FE campaign segment are shown in Table 3-16.

3.2.4.3.2 Initial Surface Habitat

The FE segment also includes the initial surface habitat. The initial surface habitat builds upon HLR to conduct expanded exploration capabilities, establish opportunities for Mars-forward precursor missions, and increase the crew size, range, and enhanced utilization achieved during exploration missions. The habitat can house two crew members as they live and work on the lunar surface for a minimum of 7 to 33 days with logistics resupply. The habitat enables EVAs and science and technology utilization during crewed and uncrewed periods. It will also support general habitation functions, such as provision of medical systems and utilization hardware accommodation, supplying ECLS capabilities, and supporting logistics transfer. As stated in NASA's 2024 "Lunar Mobility Drivers and Needs" white paper, several factors may drive NASA to select habitation points that are separated from landing sites. This means the architecture will need to provide capabilities for elements, including the initial surface habitat, to move away from landers once on the surface, either using independent or integrated mobility systems. A representative initial surface habitat is shown in Figure 3-14.

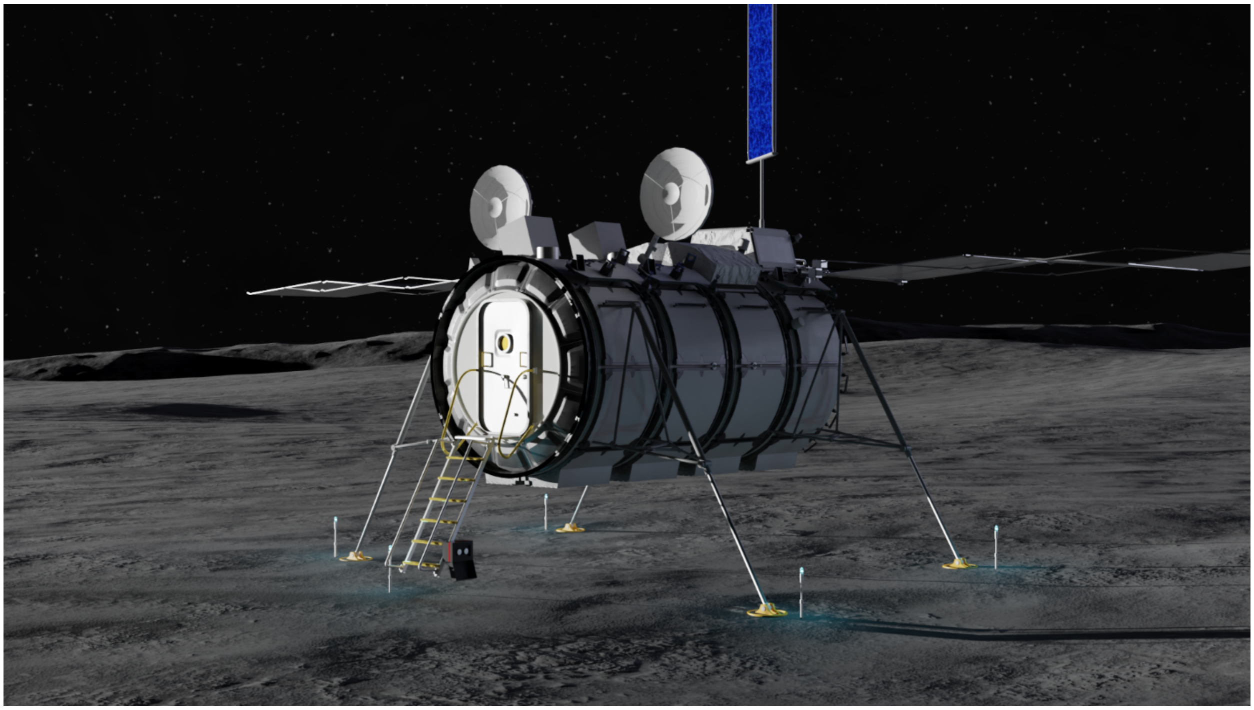


Figure 3-14. Representative Initial Surface Habitat

The functions the initial surface habitat fulfills in the FE campaign segment are shown in Table 3-17.

3.2.4.3.3 Habitation Concepts

FE emphasizes extended duration and preparing for crewed Mars mission profiles through analog missions in lunar vicinity. An important aspect is long-duration mission segments in the deep space microgravity environment, which mimics the transit phases between Earth and Mars. To that end, a growth in cislunar orbital operations will occur as Gateway's capabilities expand (as shown in Figure 3-15) and visiting vehicles, such as a Mars transit habitat, can be deployed. This expansion will support extended mission durations in preparation for Mars missions (e.g., objectives TH-3, TH-4, TH-8, HBS-1, HBS-2, HBS-3, OP-1, OP-4).

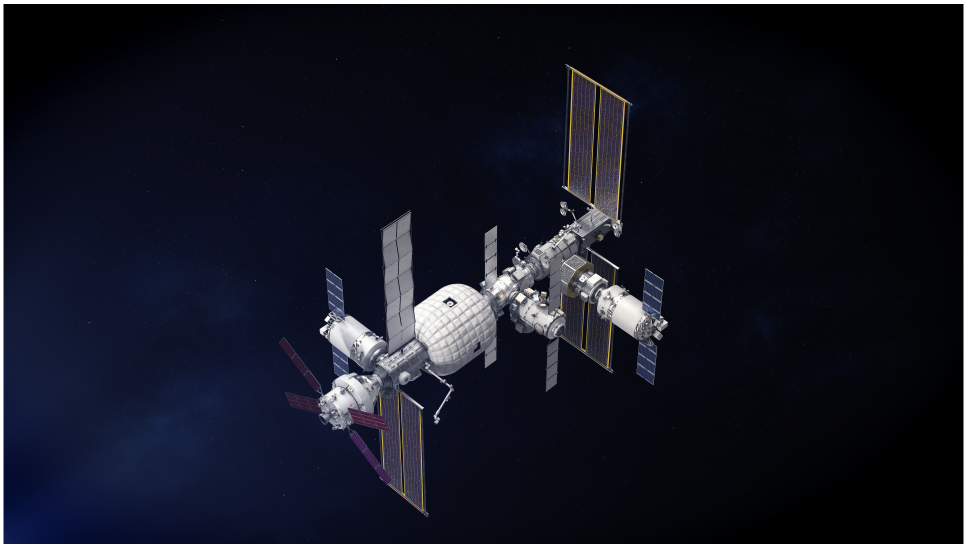


Figure 3-15. Gateway Expanded Capability Configuration with Visiting Expanded Habitation Example Concept

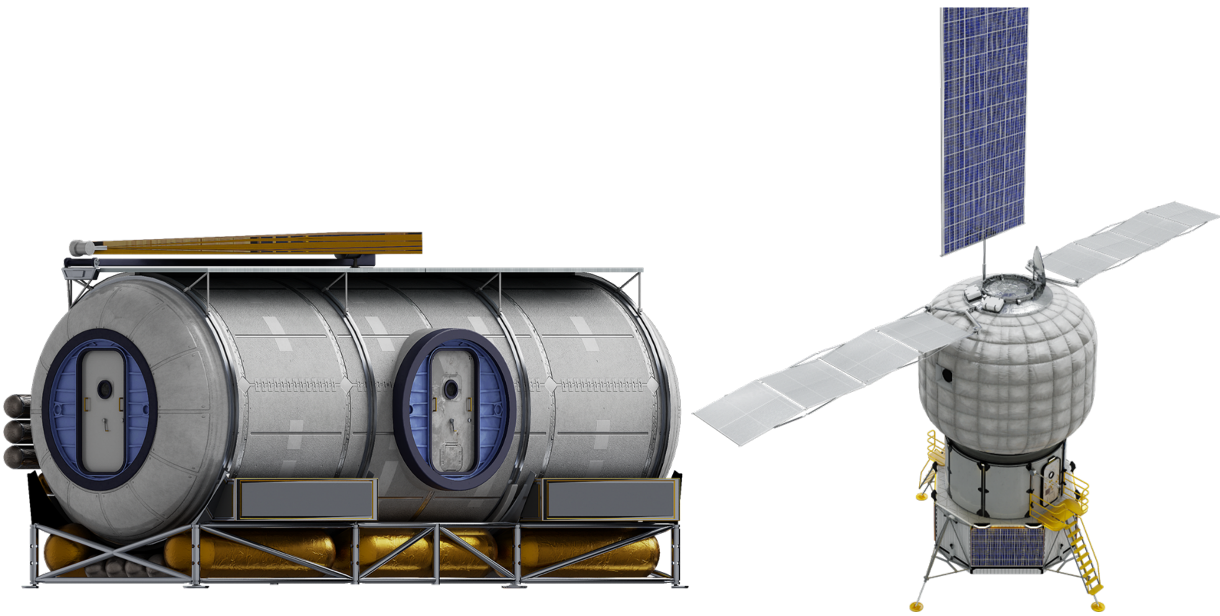


Figure 3-16. Example Concepts for Surface Habitation

With objectives aiming for long-term surface exploration, additional capabilities for surface habitation beyond the initial surface habitat allow progressive advancement toward sustained human lunar operations. General habitation functions may be common across surface habitation elements and can include providing IVA workspaces, supporting internal and external utilization, supplying ECLS capabilities, enabling EVAs, and supporting logistics transfer. Such functions may be shared between several elements of varying designs and levels of capability. Other unique functions that may be implemented include support and storage of ISRU-produced materials and/or consumables, demonstration of bioregenerative ECLS systems, and demonstration of plant growth sub-systems. Some notional surface habitation concepts are shown in Figure 3-16.

3.2.4.4 Human Systems

In HLR, FE, and other campaign segments, vehicles, systems, training, and operations all must be designed for the "human system" — the crew, the crew support systems, and supporting mission systems and ground teams. Knowledge and lessons learned from missions accomplished in HLR will be incorporated and advanced to support longer-duration missions in space and on the lunar surface. Activities in FE will be more complex, will involve crew moving between more elements when compared to HLR, and will incrementally utilize increasing Earth-independent operations. Therefore, additional capabilities will be necessary. Example functions (from the current function list in Appendix A) that are new or significantly enhanced in the FE segment for this sub-architecture include:

- Provide in-mission crew training on the lunar surface
- Provide hardware for crew medical care on the lunar surface
- Provide crew countermeasure system(s) to support the crew for moderate (month+) to long (year+) durations in cislunar space

3.2.4.5 Infrastructure Support

EGS is a key pillar of the infrastructure sub-architecture in HLR and throughout the follow-on campaign segments, established to develop and operate systems and facilities necessary to process, launch, and recover vehicles. As human exploration expands into cislunar space, the Moon, Mars, and beyond, capabilities and lessons learned from Earth infrastructure will be applied to the exploration destinations and expanded capabilities on Earth. The infrastructure sub-architecture supports the other sub-architectures in terms of facilities, systems, equipment, and services on the ground (Earth), in space, and while on the surface. The infrastructure sub-architecture will expand to support other sub-architectures as they mature.

The functions EGS fulfills in the FE campaign segment are shown in Table 3-18.

3.2.4.6 In-Situ Resource Utilization Systems

Knowledge and lessons learned from the demonstration activities in HLR will be applied to the next steps in the ISRU sub-architecture for FE. The shift from reconnaissance, initial resource assessment, and sampling to resource reserve estimation, acquisition, and processing occurs in this segment. Because of the significant differences in resource understanding and characteristics, terrain, environments, extraction, and processing technologies, and ISRU products, a dual path that includes both water mining in PSRs and oxygen and/or metal extraction from regolith is being pursued. Demonstrations to prove out technologies to enable both pathways are envisioned. Both pathways support surface construction activities that occur in this segment. In addition, the ISRU sub-architecture is directly tied to the power sub-architecture given the significant power demands of supporting large-scale ISRU; to the C&PNT sub-architecture for command, control, and monitoring for ISRU operations and navigating about the lunar surface to locations of interest; and to the mobility and logistics sub-architectures to move and/or transfer commodities between exploration assets on the lunar surface. Example functions (from the current function list in Appendix A) that are new or significantly enhanced in the FE segment for this sub-architecture include:

- Produce scalable quantities of water from in-situ materials on the lunar surface
- Process and refine scalable quantities of in-situ feedstock resources on the lunar surface

- Conduct additive/subtractive manufacturing utilization payload and/or equipment operations on the lunar surface

3.2.4.7 Logistics Systems

For the HLR segment, logistics deliveries include logistics modules to Gateway and what can be transported with the crew to the lunar surface in the HLS. Additionally, during HLR, any trash or waste generated that remains on the lunar surface will be positioned so as not to impact operations. As capabilities expand for the FE segment, dedicated lunar surface delivery platforms are needed to support more crew and longer durations on the lunar surface. To align with the recurring tenet of maximizing crew time for exploration, NASA needs a strategy that minimizes crew-time needed for logistics operations while also maximizing delivery efficiency. The first step is to understand the amount and types of logistics items needed, which, along with the interfaces of the planned surface elements, drive the type and quantity of the logistics carriers needed. Carrier types would include those suitable for EVA transfer and sized to be carriable through a hatch or an airlock while accommodating various logistics items including dry goods and water. Other carrier types, such as tanks, would be used to transport gases, unless there is an umbilical transfer capability. Additionally, pressurized carriers that use a berthing/docking-type interface will be used, when possible, to replace or house the smaller, carriable carriers to allow for shirt-sleeve transfer of the logistics items. Finally, certain unpressurized items (e.g., oversized items or those for external utilization) may require specialized carriers that account for operational considerations. Once these carriers have been used for logistics delivery, they will be used for long-term storage of trash and waste. As capabilities to recover or process trash and waste become available, they may be incorporated into the sub-architecture. Example functions (from the current function list in Appendix A) that are new or significantly enhanced in the FE segment this sub-architecture include:

- Manage waste from habitable asset(s) on the lunar surface
- Transfer gases to habitable assets on the lunar surface
- Transfer water to habitable assets on the lunar surface

The functions the GLE fulfills in the FE campaign segment are shown in Table 3-19.

3.2.4.8 Mobility Systems

Mobility capabilities are necessary to enable exploration in the FE segment beyond the EVA walking range of the crew described in the HLR segment. The lunar terrain vehicle (LTV) and the pressurized rover (PR) are elements in development to meet several of the mobility-related Moon to Mars Objectives. Functions that typically fall into this category include providing local unpressurized and pressurized crew and uncrewed surface mobility, as well as autonomous and/or tele-operations and enabling additional science and utilization. Additional capabilities beyond the LTV and PR are currently under assessment. Example functions (from the current function list in Appendix A) that are new or significantly enhanced in the FE segment of this sub-architecture include:

- Reposition a moderate amount of cargo (1000s of kg) at the south pole region on the lunar surface
- Enable crew surface extravehicular activities at the lunar far side region
- Enable pressurized surface mobility in sunlit areas and non-PSRs

3.2.4.8.1 Exploration Extravehicular Activity System Overview

With the addition of the airlock at Gateway, the xEVA System allows crew members to perform extravehicular exploration, research, construction, servicing, repair operations, and utilization and science in cislunar orbit in addition to on the lunar surface. EVA traverse and tasks may be augmented by robotics and rovers. The xEVA System includes the EVA suit, EVA tools, and vehicle interface equipment. Gateway EVAs and lunar surface EVAs will utilize xEVA suits, which could be from different vendors or include upgrades (utilizing the common vehicle interfaces).

The functions the xEVA fulfills in the FE campaign segment are shown in Table 3-20.

3.2.4.8.2 Lunar Terrain Vehicle

The LTV is an unpressurized rover with the primary role of transporting two suited crewmembers and secondary role of supporting science, exploration, and operations objectives. The LTV provides reliable and safe transportation between waypoints for two suited crew members and cargo. The LTV can carry cargo, including various payloads, work packages, logistics supplies, science tools, samples, and associated stowage containers, etc., across the lunar surface. The LTV can act as a communications relay in the surface architecture and can provide PNT to support crewed and uncrewed traverses, as well as uncrewed science payload operations, enhancing coverage and range for exploration. It can also be used for landing site reconnaissance and payload utilization. It can be operated manually by a single suited crew member, remotely by teleoperators, or via some autonomous operations. Another of its primary functions will be to provide the crew a companion platform in the event of another mobile asset’s failure to return to the habitation asset. Two mobility platforms operating together allows for farther crewed traverses than would be possible utilizing a single mobility platform.

Figure 3-17. Lunar Terrain Vehicle (Artist Rendition)

The functions the LTV fulfills in the FE campaign segment are shown in Table 3-21.

3.2.4.8.3 Japanese Pressurized Rover

The Japan-provided PR is a mobile habitable vehicle whose primary purpose is to support crew, utilization, operations, and Mars analog objectives. The PR 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 PR can be operated manually by a single IVA crew member from the cabin, remotely by tele-operators on Earth, or via some autonomous operations. The PR will travel distances compatible with exploration traverses, as well as uncrewed traverses. The PR can perform extended exploration missions lasting up to 28 days with logistics resupply necessary for missions longer than 14 days. When operated in conjunction with the LTV, the traverse distance could be increased over the limitations of the PR alone, since the LTV can be used as a backup mobility asset in the event of a failure.

Figure 3-18. Pressurized Rover (Artist Rendition)

The functions the PR fulfills in the FE campaign segment are shown in Table 3-22.

3.2.4.8.4 Mobility Concepts

The current defined mobility elements, LTV and PR, are primarily for crew transportation, with limited cargo mobility functions. Other planned near-term robotic missions, such as those being delivered through the CLPS program, provide only small-scale mobility. Cargo offloading and handling will need to be conducted before the crew arrives at each landing location (point of origin) and then again at local lunar exploration and habitation sites (point of use). These exploration and habitation sites will likely be located away from each landing location, requiring mobility and handling capabilities to transport cargo of varying size and mass for full utilization within the architecture. Additional mobility and handling concepts are under study to support manipulation and movement of cargo between and at points of use. As discussed in NASA's 2024 "Lunar

Mobility Drivers and Needs" white paper, these additional capabilities may include the ability to aggregate infrastructure, driven by larger elements such as habitation systems.

3.2.4.9 Power Systems

The baseline power strategy for HLR is element self-sufficiency, which presumes that every element can provide its own power and energy storage needed to perform the intended mission for a given time span. The HLR approach is to locate elements at lunar South Pole sites with favorable solar illumination and short eclipse periods. Lunar missions beyond a few specific South Pole locations will require power production through the approximately 360-hour lunar night, which significantly impacts power system mass and volume. As the lunar surface architecture expands and likely becomes more integrated, the power sub-architecture will likely expand to include internal augmentation (e.g., power added after delivery of an asset to the surface), external augmentation (e.g., a surface asset can connect to a single independent power element to charge/recharge) and/or a power grid (e.g., multiple independent power elements that form a power network for elements and other surface assets to utilize). These capabilities will be further refined through future assessments. In addition, transitioning samples and other utilization packages from the lunar surface, through cislunar space, and back to Earth will require interoperability and resources (e.g., power). A key objective is to develop an incremental lunar power generation and distribution system that is evolvable to support continuous robotic/human operation and is capable of scaling to global power utilization and industrial power levels. Example functions (from the current function list in Appendix A) that are new or significantly enhanced in the FE segment this sub-architecture include:

- Generate power in the south pole region on the lunar surface
- Store energy in the south pole region on the lunar surface
- Provide power for deployed surface utilization payload(s) and/or equipment
- Distribute power in the south pole region on the lunar surface

3.2.4.10 Autonomous Systems & Robotics Systems

As the number of astronauts and the availability of the surface crew to perform tasks could be limited, a balance of crewed and uncrewed operations will maximize crew exploration time. Robots are well suited to performing tasks that are tedious, highly repetitive, or dangerous. In addition, uncrewed operations can continue throughout the year while crew are not present on the surface or in space. Robots may be operated autonomously with or without human supervision, remotely by nearby crew, or by mission controllers on Earth, with progressive reductions in situational awareness and response time. Although the Autonomous Systems and Robotics (AS&R) sub-architecture is apparent during HLR with the use of rovers, such as PRIME-1 and VIPER, to perform various objectives, the human-robotic partnership is embraced starting in the FE segment. Robotic and autonomous systems are being used as precursor explorers preceding crewed missions to inform scientific investigations, mission planning, identification and availability of usable resources, and ISRU technologies. Robots can serve as crew assistants in space and on the lunar surface and as caretakers for conducting utilization and science activities. Robotic reconnaissance (e.g., scouting, surveying, mapping, collecting samples), site preparation ahead of human exploration missions, and robotic and autonomous systems capable of offloading, handling, staging, and prepositioning cargo and logistics supplies can save valuable crew time. The first of many capabilities is GERS. GERS provides the capability to deploy and retrieve external utilization payloads; inspect the Gateway system; capture, berth, and relocate robotic spacecraft or modules; support contingency maintenance; support self-maintenance of robotic components; and support crew EVAs. As there are comparable needs for robotic manipulation on the lunar surface (among other robotic use cases), synergistic opportunities will continue to be assessed to identify additional capabilities and elements needed to achieve Moon to Mars Objectives. Example functions (from the current function list in Appendix A) that are new or significantly enhanced in the FE segment of this sub-architecture include:

- Control robotic system(s) in cislunar space by in-situ crew
- Control robotic system(s) in PSRs on the lunar surface from Earth and/or cislunar space
- Interface robotic system(s) with logistics carriers on the lunar surface
- Perform robotic manipulation of payloads, logistics, and/or equipment on the lunar surface

3.2.4.11 Transportation Systems

The Transportation Systems sub-architecture builds upon the SLS, Orion, HLS, and CLPS Provider Landers accomplishments planned during HLR and continues to emphasize these elements in the FE segment. As the Moon to Mars Objectives point to expansion of crew size and longer durations on the surface, cargo landers and return vehicles become a necessity. The Human-class Delivery Lander (HDL) and small-to-medium class payload landers are needed to deliver cargo to the lunar surface, ranging from utilization payloads and logistics to additional surface elements like the PR and surface habitation. An increase in capabilities for the HLS Integrated Lander is also planned to accommodate four crew and longer durations on the lunar surface. Additional capabilities that may be grouped into this sub-architecture include spacecraft aggregation in cislunar space, cargo delivery (e.g., science, utilization, technology, crew logistics) from Earth and unloading on the lunar surface, logistics transfer (e.g., fluids and gasses), cargo return (e.g., increased cargo return mass and size) from the lunar surface to Earth, and in-space and/or surface cryogenic storage of propellant. Additional example functions (from the current function list in Appendix A) that that are new or significantly enhanced in the FE segment for this sub-architecture include:

- Transport a large amount of cargo (100s of kg) from lunar surface to Earth
- Provide precision landing for cargo transport to the lunar surface
- Transport crew from cislunar space to distributed sites outside of the south pole on the lunar surface
- Transport a limited amount of cargo (100s of kg) from Earth to the far side of the lunar surface

The functions the SLS fulfills in the FE campaign segment are shown in Table 3-23.

The functions the Orion spacecraft fulfills in the FE campaign segment are shown in Table 3-24.

3.2.4.11.1 Human Landing System Integrated Lander

Additional capabilities planned for the HLS Integrated Lander will be exercised in the FE segment. Missions with the HLS Integrated Lander will use the HLS land a crew of up to four and will leverage additional habitable surface assets to support the larger crew for the duration of the lunar stay. These missions may include the capability to land and operate at non-polar landing sites or to operate for extended durations at the lunar South Pole. This HLS configuration has increased performance capabilities, allowing for enhanced up and down mass to and from the lunar surface and increased darkness survivability. These missions will also seek sustainable HLS designs that may include reusable elements or interactions with other systems in the lunar vicinity.

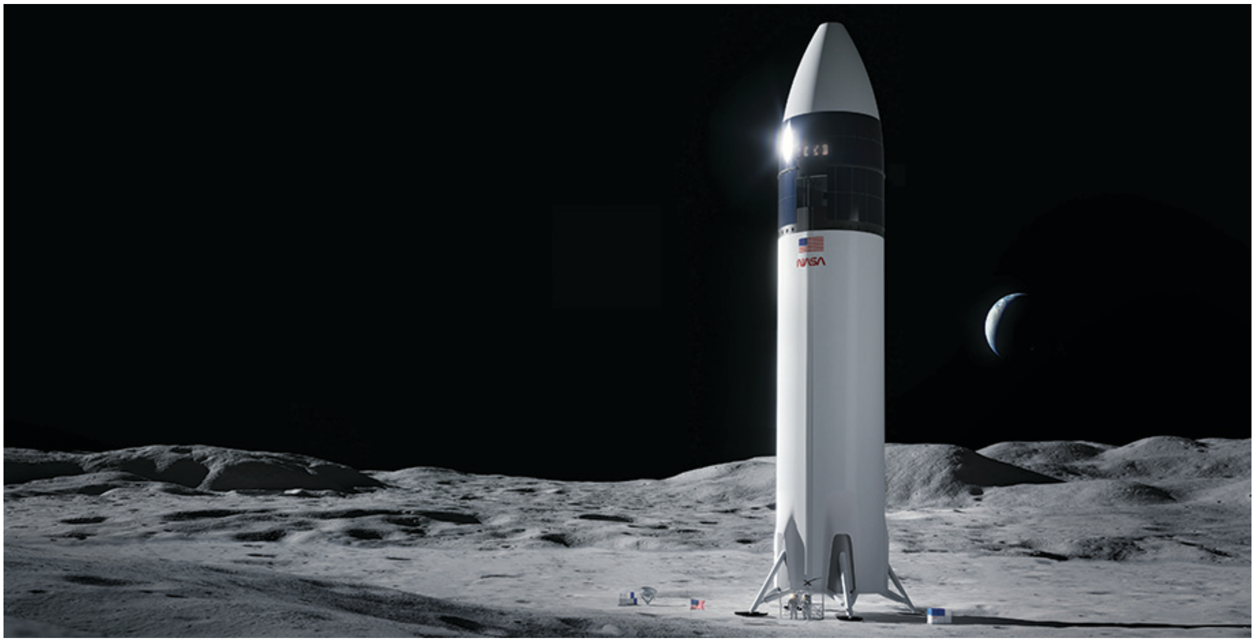


Figure 3-19. Human Landing System—One of the Integrated Lander Configurations as Awarded (Image credit: SpaceX)

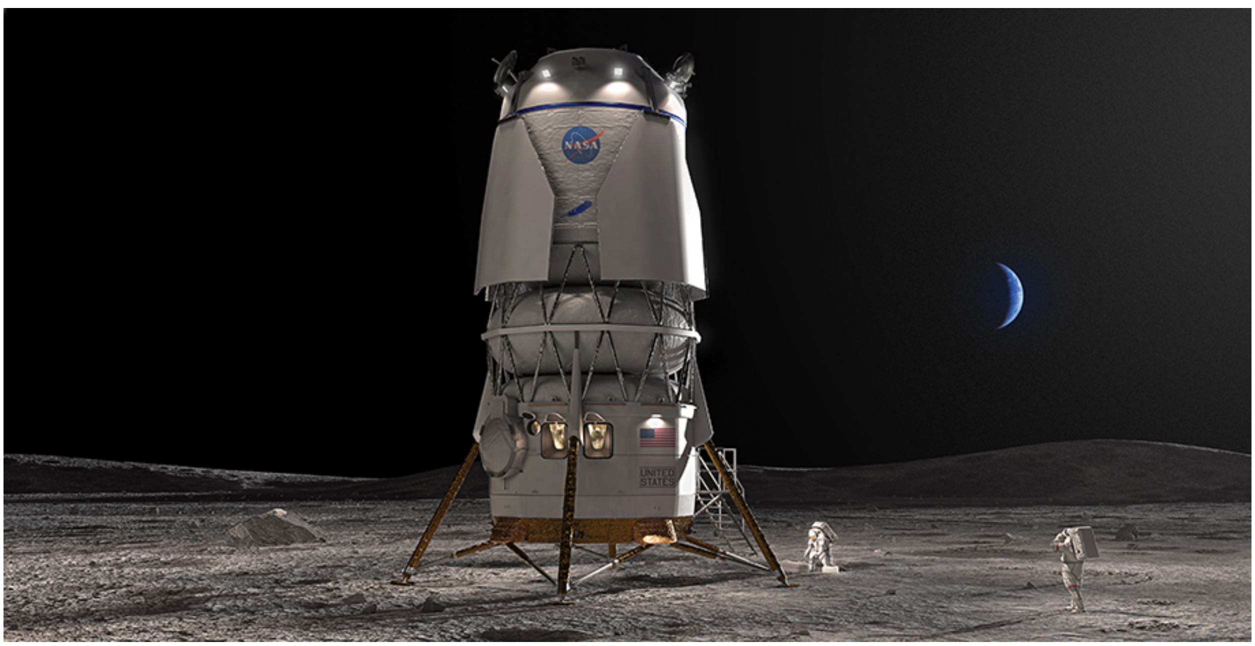


Figure 3-20. Human Landing System—One of the Integrated Lander Configurations as Awarded (Image credit: Blue Origin)

The functions the HLS fulfills in the FE campaign segment are shown in Table 3-25.

3.2.4.11.2 Human-class Delivery Lander

A large cargo lander will support delivery missions to the lunar South Pole region and will be capable of delivering a wide range of small to large lunar surface assets as cargo. The large cargo lander can support cargo that remains integrated with the lander on the lunar surface and can provide offloading capability to deliver cargo such as a rover directly to the lunar surface. Examples of large cargo that may be delivered are the PR, surface habitation elements, and surface power elements. Smaller cargo items can also be delivered co-manifested with the larger items or as several small items that are grouped together or individually. The large cargo lander 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 the Earth and while on the lunar surface, the large cargo lander will support the cargo with services until the cargo is ready to operate independently. Once the large cargo lander completes its operations and enables the cargo to operate independently, it will transition to a safe condition/state.

The functions the Human-class Delivery Lander fulfills in the FE campaign segment are shown in Table 3-26.

3.2.4.11.3 Lunar Surface Cargo Lander

The lunar surface cargo lander will deliver cargo to the lunar surface, similar to HDL and CLPS. The payload capability is anticipated to be much smaller than that of HDL, with the lunar surface cargo lander targeted to support delivery of logistics, utilization payloads, power systems, communications systems, and other potential payloads. The lunar surface cargo lander will provide all services necessary to maintain cargo from launch vehicle integration through landing on the lunar surface until the cargo is either offloaded from the lander or in an operational state. Figure 3-21 shows a representative concept of a lunar surface cargo lander.

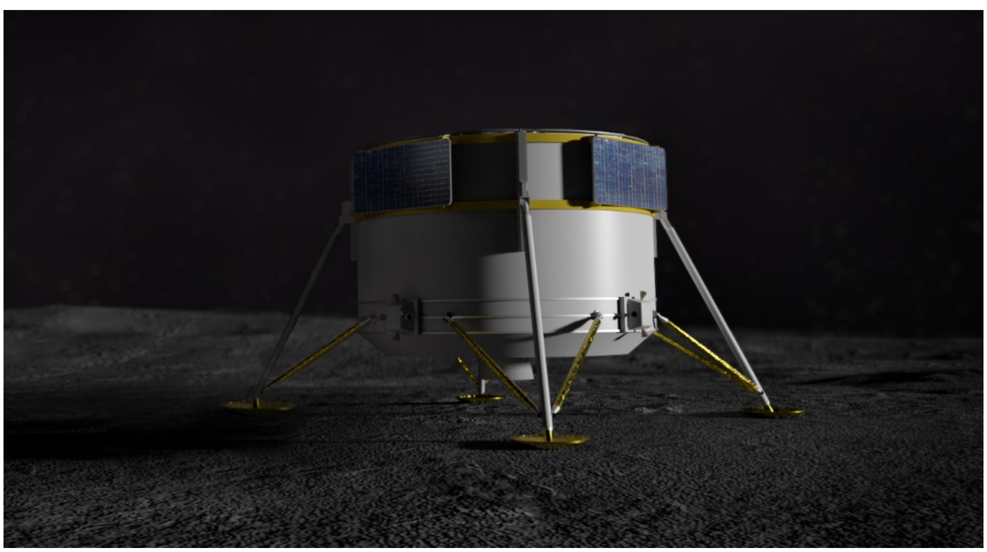


Figure 3-21. Lunar Surface Cargo Lander Representative Concept

The functions the lunar surface cargo lander fulfills in the FE campaign segment are shown in Table 3-27.

3.2.4.11.4 Cargo Lander Concepts

In addition to the large surface elements delivered by the HDL landers and lunar surface cargo lander, the longer duration, larger crew sizes, and more extensive lunar surface operations possible in the FE segment will require the routine delivery of equipment and supplies to the lunar surface. The FE segment will also require continued delivery of utilization payloads for reconnaissance and scientific observations across many potential exploration regions. Additionally, there is the need for delivery of technology demonstration payloads, mobility systems, and logistics to support longer-duration surface missions and resupply of a variety of surface assets. While some of these items may be delivered with crew on HLS or co-manifested with larger elements on HDL, additional cargo landers will provide flexibility and capability for robust exploration. Options for cargo landers to deliver these assets include those under NASA's CLPS program described in previous sections and other cargo landers still in formulation.

The functions CLPS Provider Landers fulfill in the FE campaign segment are shown in Table 3-28.

3.2.4.12 Utilization Systems

The utilization sub-architecture will continue to expand on the accomplishments of HLR to take advantage of new architecture capabilities, including extended traverse capability with mobility platforms; enhancement of the end-to-end sampling capability, including returning of conditioned samples from PSRs; extended-duration mission capability on the lunar surface and in cislunar orbit; and increased facilities for IVA and EVA research. A common enabler of utilization accomplishments is the capability to deliver to and return from the lunar surface larger quantities of cargo. Each of these aspects is currently being assessed to drive conceptual elements that can aid in achieving the capabilities needed to accomplish NASA's utilization objectives. Example functions (from the current function list in Appendix A) that are new or significantly enhanced in the FE segment for this sub-architecture include:

- Provide intravehicular activity facilities utilization accommodation, and resources, operable during crewed and uncrewed increments, on the lunar surface
- Provide capability to recover and package surface and/or shallow sub-surface samples, maintaining scientific integrity of the samples, from PSRs on the lunar surface
- Provide capability to recover and package sub-surface samples from non-PSRs and sunlit regions on the lunar surface
- Provide capability to recover and package sub-surface samples maintaining scientific integrity of the samples, from PSRs on the lunar surface
- Stow collected samples on exploration assets while on the lunar surface, while maintaining scientific integrity of the samples

The functions Equipment fulfills in the FE campaign segment are shown in Table 3-29. Mappings to science/research payloads and technology demonstrations are removed for this revision and are forward work.

3.2.5 Exploration Asset Mapping

The following tables map assets to the functions they fulfill. Functions mapped to exploration assets do not indicate that an asset fully satisfies the use case or blueprint objective, or that completion is achieved. While some of the functions are grouped into performance classes, for most of the functions, there is no intent to indicate how well the asset accomplishes the function and supports the use case. Rather, in those cases, it represents the asset contributes to the architecture by providing the associated function. Unmapped functions are indicators of where there are gaps in the current architecture and where future efforts can be focused. Note: mapping to science/research payloads and technology demonstrations are removed for this revision and is forward work.

Table 3-14. Functions Fulfilled by LCRNS During the FE Segment

Functions Fulfilled by LCRNS During the FE Segment			
		ID	**Functions**
EM-006-FE	**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

Table 3-15. Functions Fulfilled by NSN/DSN During the FE Segment

Functions Fulfilled by NSN/DSN During the FE Segment			
		ID	**Functions**
EM-010-FE	**NSN/DSN**	**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

Functions Fulfilled by NSN/DSN During the FE Segment			
		ID	Functions
		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 of asset(s) from Earth in cislunar space during uncrewed periods

Table 3-16. Functions Fulfilled by Gateway Expanded Capability During the FE Segment

Functions Fulfilled by Gateway Expanded Capability During the FE Segment			
		ID	Functions
EM-004-FE	Gateway Expanded Capability	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

Functions Fulfilled by Gateway Expanded Capability During the FE Segment			
		ID	**Functions**
		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-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

Table 3-17. Functions Fulfilled by Initial Surface Habitation During the FE Segment

Functions Fulfilled by Initial Surface Habitation During the FE Segment			
		ID	Functions
EM-016-FE	Initial Surface Habitation	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	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 long durations (months to years+)
		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-103 L	Provide communications and data exchange between assets on the lunar surface
		FN-C-107 L	Provide high bandwidth, high availability communications and data exchange between assets 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-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

Functions Fulfilled by Initial Surface Habitation During the FE Segment			
		ID	**Functions**
		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

Table 3-18. Functions Fulfilled by Exploration Ground Systems During the FE Segment

Functions Fulfilled by Exploration Ground Systems During the FE Segment			
		ID	**Functions**
EM-002-FE	**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

Table 3-19. Functions Fulfilled by Gateway Logistics Element During the FE Segment

Functions Fulfilled by Gateway Logistics Element During the FE Segment			
		ID	**Functions**
EM-009-FE	**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

Table 3-20. Functions Fulfilled by xEVA System During the FE Segment

Functions Fulfilled by xEVA System During the FE Segment			
		ID	**Functions**
EM-007-FE	**xEVA System**	**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

Functions Fulfilled by xEVA System During the FE Segment			
		ID	Functions
		FN-U-301 L	Provide capability to recover and package sub-surface 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 sub-surface 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 sub-surface 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 sub-surface samples, maintaining scientific integrity of the samples, from PSRs on the lunar surface

Table 3-21. Functions Fulfilled by Lunar Terrain Vehicle During the FE Segment

Functions Fulfilled by Lunar Terrain Vehicle During the FE Segment			
		ID	Functions
EM-014-FE	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	Relocation of exploration assets at lunar surface polar locations

Functions Fulfilled by Lunar Terrain Vehicle During the FE Segment			
		ID	**Functions**
		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-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

Table 3-22. Functions Fulfilled by Pressurized Rover During the FE Segment

Functions Fulfilled by Pressurized Rover During the FE Segment			
		ID	**Functions**
EM-015-FE	**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

Functions Fulfilled by Pressurized Rover During the FE Segment			
		ID	**Functions**
		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	Relocation of exploration assets at lunar surface polar locations
		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-403 L	Transition assets between crewed and uncrewed mode on the lunar surface

Functions Fulfilled by Pressurized Rover During the FE Segment			
		ID	Functions
		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-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

Table 3-23. Functions Fulfilled by SLS During the FE Segment

Functions Fulfilled by SLS During the FE Segment			
		ID	Functions
EM-001-FE	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)

Table 3-24. Functions Fulfilled by Orion During the FE Segment

Functions Fulfilled by Orion During the FE Segment			
		ID	Functions
EM-003-FE	Orion	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

Table 3-25. Functions Fulfilled by HLS During the FE Segment

Functions Fulfilled by HLS During the FE Segment			
		ID	**Functions**
EM-005-FE	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

Functions Fulfilled by HLS During the FE Segment			
		ID	**Functions**
		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-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

Table 3-26. Functions Fulfilled by Human-Class Delivery System During the FE Segment

Functions Fulfilled by Human-Class Delivery System During the FE Segment			
		ID	Functions
EM-013-FE	Human-Class Delivered System	FN-T-206 L	Transport large exploration 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 exploration assets on the lunar surface

Table 3-27. Functions Fulfilled by Lunar Surface Cargo Lander During the FE Segment

Functions Fulfilled by Lunar Surface Cargo Lander During the FE Segment			
		ID	Functions
EM-017-FE	Lunar Surface Cargo 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

Table 3-28. Functions Fulfilled by CLPS Provider Landers During the FE Segment

Functions Fulfilled by CLPS Provider Landers During the FE Segment			
		ID	Functions
EM-008-FE	CLPS Provider	FN-T-201 L	Transport a limited amount of cargo (100s of kg) from Earth to south pole region sites on the lunar surface

Functions Fulfilled by CLPS Provider Landers During the FE Segment			
		ID	Functions
		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-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-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

Table 3-29. Functions Fulfilled by Equipment During the FE Segment

Functions Fulfilled by Equipment During the FE Segment			
		ID	Functions
EM-018-FE	Equipment	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

3.2.6 Unallocated Use Cases and Functions

As the architecture matures and the FE segment is refined, use cases and functions will be mapped to FE elements, with a partial mapping already completed. The complete list of unallocated functions appears below. Note, mapping to science/research payloads and technology demonstrations is forward work. The following is an abbreviated list of topics areas for those functions:

- Habitation for moderate (month+) to extended (year+) durations
- Repositioning moderate and large cargo
- Dedicated power generation and distribution
- Crew far side activities
- Most ISRU functions
- Crew working with autonomous systems
- Transfer of water and gases between assets

Table 3-30. Unallocated Functions for the FE Segment

Unallocated Functions for the FE Segment			
		ID	**Functions**
EM-012-HLR	**Unallocated**	**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-212 L	Transport a large amount of cargo (100s of kg) from cislunar space to Earth
		FN-T-215 L	Transport cargo from Earth to assets in deep 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-306 L	Provide resources to condition cryogenic sample containers during transit from the lunar surface to cislunar space

Unallocated Functions for the FE Segment			
		ID	**Functions**
		FN-T-309 L	Provide resources to condition cryogenic sample containers during transit from cislunar space to Earth
		FN-H-102 L	Enable a pressurized, habitable environment on the lunar surface for moderate duration (month+) use
		FN-H-104 L	Enable a pressurized, habitable environment in cislunar space for moderate (month+) durations
		FN-H-105 L	Enable a pressurized, habitable environment in cislunar space for extended (year+) duration
		FN-X-103 L	Provide crew countermeasure system(s) to support the crew for moderate durations (month+) on the lunar surface
		FN-X-104 L	Provide crew countermeasure system(s) to support the crew for moderate (month+) to long (year+) durations 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-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
		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

Unallocated Functions for the FE Segment			
		ID	**Functions**
		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-304 L	Distribute power to utilization payloads and/or equipment in deep space
		FN-M-103 L	Enable crew surface extravehicular activities at the lunar far side region
		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-M-503 L	Reposition a moderate amount of cargo (1000s of kg) at the south pole region on the lunar surface
		FN-M-602 L	Relocation of exploration assets 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-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-205 L	Provide a coordinated lunar time scale
		FN-D-201 L	Process data locally on the lunar surface
		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-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

Unallocated Functions for the FE Segment			
		ID	**Functions**
		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-105 L	Interface robotic system(s) with logistics carriers on the lunar surface
		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-I-101 L	Collect water/ice from the polar 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

Unallocated Functions for the FE Segment			
		ID	Functions
		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 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-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-U-305 L	Provide capability to recover and package deep sub-surface 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 sub-surface samples, including drill cores, maintaining scientific integrity of the samples, from PSRs on the lunar surface
		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

Unallocated Functions for the FE Segment			
		ID	**Functions**
		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
		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-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

3.2.7 Open Questions, Ongoing Assessments, and Future Work

With forward work remaining to define the FE segment, there are open questions on the segment, from the architectural approach(es) to accomplish the objectives to specific element and sub-architecture planning and design. The open questions here are non-comprehensive examples of the types of areas that will be addressed in future work; they are only notionally binned for FE. This section will be updated in future revisions of the ADD.

- What is an attainable balance in mission types and locations to address infrastructure buildup objectives and scientific exploration of diverse sites objectives?
- How can Gateway and future cislunar assets along with lunar surface assets be utilized to prepare for crewed Mars exploration?
- With the expansion of mission types and durations, what are the options for logistics resupply, both for delivery to cislunar space and the lunar surface and for transfer to the necessary location(s)?
- What waste management and element repurposing, recycling, or disposal approaches should be utilized for sustainable exploration?
- What assets should be available to support non-polar sorties?
- What benefits do various levels of ISRU provide for the lunar surface activities?
- How can the architecture expansion in FE, such as deep drilling and expanded access to regions of interest beyond the South Pole region, enable key science and technology needs (e.g., polar volatiles, ISRU, biological, planetary protection, environments)?
- What options are available to increase sample return and conditioned cargo from the lunar surface to Earth?
- What options are available to significantly enhance cargo return from the lunar surface?
- What assets should be available to support sustained scientific activity in the South Pole region (e.g., external power augmentation)? How should the assets be distributed, and what are the supporting infrastructure dependencies?
- What strategies should be considered for maintaining asset health through uncrewed periods?
- When should ISRU strategies be applied to the architecture?
- What assets should be available to support surveillance and reconnaissance of the lunar surface from lunar orbit?

Even as FE expands on what was accomplished in HLR, the FE missions set the stage for Sustained Lunar Evolution and make progress toward Humans to Mars.

3.3 SUSTAINED LUNAR EVOLUTION SEGMENT

3.3.1 Summary of Objectives

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

This segment is an “open canvas,” embracing new ideas, systems, and partners to grow to a true sustained lunar presence. The steps for obtaining use cases for the SLE segment will involve broad coordination. Given the maturity of this segment, there is insufficient depth to allocate functions at this time beyond the high-level capabilities associated with the objectives. However, for context, notional examples of the future use case and the sub-architecture dependencies over time are discussed as a placeholder for the initial work that needs to be completed.

Sustained lunar presence represents responsible long-term exploration of the surface and the establishment of a robust lunar economy. This segment is driven by RT-9 (Commerce and Space Development: foster the expansion of the economic sphere beyond 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 infrastructure objectives with the overarching goal of: “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 achievement of key science objectives in lunar/planetary science, heliophysics, human and biological science, and physics and physical science and facilitate addressing new science objectives identified as a result of discoveries made during the previous campaign segments.

3.3.2 Use Cases and Functions

Architecting from the right requires the development of use cases that are coordinated with NASA’s partners and based in economic plausibility to derive the functional needs. Table 3-31 is an example set of interconnected notional paths worked in parallel to incrementally achieve sustained states of increased duration and population, increased economic opportunity, and increased science capability as guided by the objectives and recurring tenets. Future work will involve developing uses cases in coordination with NASA’s partners.

Table 3-31. Example Sub-Architectures and Use Case Evolution for SLE Segment

Foundational Exploration Segment	Sub-Architecture and Use Case Evolution			Notional SLE Use Cases
Foundational Capabilities for: • **Lunar Surface Access** • **Mobility** • **Habitation** • **Logistics** • **Power** • **Manufacturing** • **Construction** • **In-Situ Resource Utilization & Production**	Expanded Power for Expanded Missions *More mission opportunities further from the South Pole for longer durations*	Increased Crew Size & Duration *Replicated surface habitats, laboratories and increased logistics*	Permanent Lunar Outpost *Crew/cargo access to and from the lunar surface enabled by ISRU, scores of crew*	Increased Duration & Population
	Minimal ISRU & Regolith Utilization *100s of kg of water/propellant produced*	ISRU Derived Propellants *1,000s of kg of water/propellant produced, minor civil engineering*	*Industrial-Scale ISRU & Mining* *10,000s of kg of ISRU propellant with regolith used for raw materials, 3D printing, propellant manufacturing, and mining*	Increased Economic Opportunity
	Expanded Mobility & Range *10s of km to 100s of km range from South Pole*	Increased Sample Return *100s of kg from non-polar regions cached and returned to Earth in addition to FE capabilities, cryogenic samples returned to Earth*	Lunar Global Access (Crew & Cargo) *1,000s of kg from global locations returned to central location, then returned to Earth*	Increased Science Capability

3.3.2.1 Increased Science Capability

The science objectives are supported by the ability to deliver science instruments to various locations in cislunar space and the lunar surface and return the acquired data or samples to Earth. In addition, providing real-time human interaction where science activities are being performed increases the ability to rapidly react to discoveries and to determine optimal areas and samples to explore. When coupled with the ability to update, replace, and repair the systems for performing science, human presence is extremely beneficial. Prior to this segment, science capability is governed by the initial orbital platforms, landers, and regional exploration infrastructure, coupled with the HLS's ability to support global lunar sorties, including to the lunar far side. Although the FE segment will include the function to return the required science samples gathered during a 30-day–class mission, approaches to increase the science capability as mission duration and available power grow beyond the previous segment's limits will have to be addressed. A notional path working across the sub-architectures to increase science abilities beyond the previous segment is discussed next, in the context of the objectives and key characteristics.

Increasing science capability is enabled by enhancing multiple sub-architectures, with trades within those architectures to understand the best approach. If global concurrent lunar science activities represent the desired end state, then the lunar communications and navigation sub-architecture will need to evolve via interoperability, scalability, and reconfigurability to allow concurrent science missions distributed across the lunar globe to send back data via high-speed links. This would represent a continued evolution beyond the initial communications/navigation infrastructure that features direct-to-Earth for the lunar near side, relay service for the South Pole region and limited relay services for non–South Pole regions. 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.

Working backwards from and forward to the notional use cases across the segments informs key sub-architecture questions like what access and purity for viable ISRU are needed; what power interface and standards can enable a power grid that evolves to industrial scale; and what communications, navigation, and positioning architecture features will be required to scale to an evolved lunar future.

3.3.2.2 Increased Economic Opportunity

Economic opportunity on and around the Moon in the context of this discussion means that governments are no longer the sole source of support for the funding of the lunar activities and that non-governmental entities would like to 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 to provide capabilities others can leverage. Artemis is making the foundational investments for access to the Moon from a transportation, exploration, and science perspective. Building upon investments initiated in HLR and FE, the opportunity for industry at this point is to leverage those investments to enable regular and likely reusable lunar access (both robotic and human) to additional governmental entities, scientific institutions, international entities, and industry partners. Additional investments in communications, navigation, ISRU, power, and transportation sub-architectures will be needed to enhance access and return, facilitating the beginning of new supporting service economic opportunities in those areas.

Economic opportunity/profitability could progress along the lines of 1) information transfer, 2) delivering goods, 3) providing services at the Moon to enable others, and 4) bringing resources from the Moon to other destinations. Larger-scale economic opportunity begins to emerge when lunar reach and access are expanded, 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 become more economical than importing everything from Earth. Once ISRU production is of sufficient scale, exporting propellant and material beyond the lunar surface manifests as an economic opportunity.

3.3.2.3 Increased Duration and Population

Increased science capability influences economic opportunity, which overlaps both with the need to increase the population of humans at the lunar South Pole region and the need for them 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, local resources will eventually be required to provide water, support food growth, and build out infrastructure, with commercial or internationally provided crew transportation systems infused to increase mission frequency and crew population. As an interim step, small modular systems could be supplied by multiple partners to act as a bridge between the initial FE capabilities and the full-up ISRU systems to provide additional habitation and logistics. Fission power augmentation will also be required to achieve a year-round population at the lunar South Pole region, as available sunlight oscillates by month and season. At some point in this evolution, the possibility of lunar tourism appears, possibly at first with Earth-provided modular systems at a higher cost, then later at a larger, more affordable scale once lunar resources can be fully leveraged.

3.3.3 Reference Missions and Concepts of Operations

Given the maturity of this segment, future work will include defining reference missions and detailed concepts of operations as the architecture matures.

3.3.4 Elements and Sub-Architectures

Although the notional use cases discuss the implications of sub-architecture evolution across those use cases and time, actual element functional allocation and sub-architecture evolution will require the development of the use cases by the appropriate stakeholders before further decomposition can be performed.

3.3.5 Open Questions, Ongoing Assessments, and Future Work

Increased science capability, economic opportunity, and duration/population at the lunar South Pole region have the potential to evolve and merge in the future to form the first sustained human civilization beyond Earth. The capabilities put in place during the initial Artemis segments feed forward and enable the future enhancements, and the partnerships forged grow to incorporate a broader community. As Artemis solidifies its implementation of the previous segments, planning for the SLE segment needs to begin in earnest, as the ideation of both the future lunar state and the path(s) for getting there will impact what comes before it. Given the objective decomposition process as described in Section 1.3.1, the notional use cases and functions described in this section need to be replaced with ones developed by the segment stakeholders in future revisions of the ADD.

Input from across Moon to Mars workshops, DARPA's LunA-10 study, the Lunar Surface Innovation Consortium, (LSIC) and the Consortium for Space Mobility and In-space servicing, assembly, and manufacturing (ISAM) Capabilities (COSMIC) have indicated the need to identify "demand signals" for services that would begin in FE segment and grow in the SLE segment. These services include logistics, mobility, robotic servicing, ISRU propellant, power/energy, crew habitation, assembly and construction, exploration/science systems, and communications/data/navigation systems. Work has begun to take these inputs and derive an initial vision of what SLE could be after the FE segment is complete. New reference missions for the SLE segment are in the process of being identified and should help drive mapping of use cases for the SLE segment.

3.4 Humans to Mars Segment

3.4.1 Summary of Objectives

NASA's Moon to Mars Strategy laid out specific tenets and goals to guide the development of an integrated Moon to Mars Architecture. In addition to the cross-cutting science and operations goals, Mars-specific goals both in infrastructure and in transportation and habitation provide further architecture implementation guidance.

3.4.2 Use Cases and Functions

The decomposition of objectives into characteristics and needs, use cases, and functions is provided in Appendix A for the Humans to Mars (H2M) segment. The decomposition follows a similar philosophy to the HLR, FE, and SLE segments, whereby beginning with agency objectives for the Mars segment, the use cases and functions necessary to accomplish the objectives are identified. As the H2M segment continues to be matured, so will the functional breakdown from the objectives. As the use cases and functions for this segment are still in flux and elements have not been defined, mapping to elements has not begun yet and remains as forward work.

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, to manage crew health and performance, and to conduct missions on the Martian surface. Sample use cases that contribute to fulfilling those characteristics and needs include, but are not limited to:

- UC-H-102-M, Habitation for extended duration (year+) crew mission(s) in deep space and/or Mars vicinity
- UC-H-103-M, Habitation for crew mission(s) on the Martian surface
- UC-H-104-M, Crew living for extended duration (year+) crew mission(s) in deep space and/or Mars vicinity
- UC-H-105-M, Crew living for mid-duration (month+) crew mission(s) on the Martian surface

Some of the functions that map to these use cases include:

- FN-X-101-M, Manage crew health and performance (medical, physiological, psychological, environmental, task support, etc.) for extended duration (year+) in deep space and/or Mars vicinity
- FN-X-103-M, Enable crew exercise in deep space and/or Mars vicinity
- 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-H-105-M, Manage a pressurized habitable environment for crew for extended duration (year+) in deep space and/or Mars vicinity

Note that the numbering applied to Mars use cases and functions does *not* follow sequentially from the lunar functions; all numbers in each category (e.g., Transportation, Habitation, Infrastructure Support, etc.) start over from 001 and are mapped only to the H2M segment.

Additionally, the decomposition considered the existence of certain "support functions" that are inherent to almost all spaceflight elements and therefore need not be explicitly mapped within every single objective. These support functions are documented, but they are mapped to other objectives that more specifically address the functional area. For example, MI-01-M, "Develop Mars surface power sufficient for an initial human Mars exploration campaign" is the objective that was decomposed to a variety of Mars surface power functions; however, these surface power functions are "support" and therefore not mapped to every single objective whose decomposed use cases would feasibly need power. Instead, it is understood that support functions such as those under MI-01-M are needed to enable other use cases. Support functions generally cover power, communications, command and data handling, positioning, navigation, and timing. Support functions are applicable to use cases performed in any location — including Earth vicinity, deep space, Mars vicinity, or the Martian surface.

Finally, the term "deep space and/or Mars vicinity" has been used intentionally in the objective decomposition. Per the glossary, "deep space" is the vast region of space that extends to interplanetary space, to Mars and beyond. The term "Mars vicinity" here refers to the region of space around the Mars system, including Mars orbit. As the Mars architecture continues to be defined over time, there will be more information about where and how certain use cases and functions are performed, such as on what trajectory or in what orbit, so the only appropriate level of specificity at this time is "Mars vicinity."

3.4.3 Mars Trade Space, Reference Missions, and Concepts of Operations

For the purpose of initial analysis, a technically feasible early practical Mars mission was used. For example, a Mars surface mission would be too challenging for a solo explorer, so two crew to the surface is the current practical minimum working assumption. However, the trade space remains wide open. Definition of the full trade space, along with updated reference missions and concepts of operations, are being developed in the context of the Moon to Mars Objectives and will aid in developing the Mars architecture decision roadmap.

3.4.3.1 "How" to Get to Mars and Back?

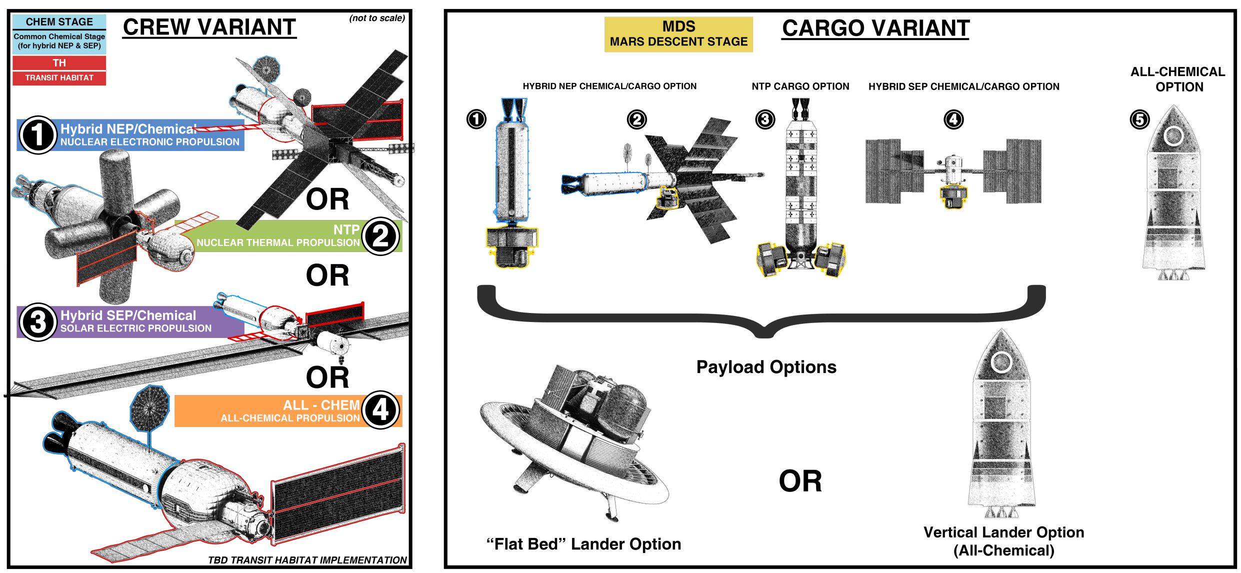


Figure 3-22. Major Mars Architecture Transportation Options Trade Space

Because the first challenge of any Mars mission is simply to get to Mars safely and return to Earth, the Earth-Mars transportation system elicits a substantial amount of discussion relative to the "How?" trade space. To that end, recent analysis was designed to explore the pros and cons of different transportation system options across a wider range of mission profiles than previously considered. The initial metric of interest for recent assessments was total roundtrip mission duration, due to the significant duration-related flow-down impacts to crew health and performance, technology investment, development timelines, and cost. Historically, Mars mission duration has been treated as a binary choice: either an approximately two-year opposition-class mission characterized by at least one high-energy transit leg and a very short Mars stay (measured in days), or a three-or-more-year conjunction-class mission characterized by low-energy transits with at least a year-long loiter period at Mars. In truth, mission duration can be thought of as a continuum: the architecture can be optimized for any given duration for a particular opportunity year or a range of durations over different opportunities.

To inform the total mission duration decision, which in turn will inform a host of other decisions (including transportation propulsion technology investments), stakeholders will need several pieces of information: an understanding of system-by-system performance sensitivity over the entire duration trade space and an integrated campaign and risk assessment for the various possible implementations, including integrated risks to the human system. To that end, the Mars architecture concepts presented here are intended to populate a broad swath of the "How" trade space, allowing decision-makers to see how different implementations of four different transportation systems fare in the context of different reference missions (the "Why," "What," and "Where").

As shown in Figure 3-22, transportation system concepts currently under evaluation include hybrid nuclear electric propulsion/chemical (NEP/Chem), nuclear thermal propulsion (NTP), hybrid solar electric propulsion/chemical (SEP/Chem), and all-chemical (All-Chem). Additional transportation system concepts, such as hybrid nuclear thermal/electric propulsion, have been added to the trade space and will be evaluated in the future. For comparison purposes, a common transit habitat (TH) is assumed for all crew transportation systems in the crewed variant; cargo variants of each concept are also available. Two different Mars Descent System (MDS) concepts have also been developed: a relatively small 25 metric ton (t) payload capacity "flat-bed" lander and a larger vertical lander capable of landing the minimum total surface payload cumulative mass of 75 t. For comparison purposes, a common set of surface systems is assumed for all architectures, as is a common Mars Ascent Vehicle (MAV) concept. To bound the trade space, recent analysis has focused on a minimal two-crew MAV concept that relies on Earth-delivered ascent propellant, but more complex options capable of ferrying larger crew complements using ISRU propellants have been studied and will be revisited for later sustained exploration missions as the Mars architecture evolves. Details of these concepts are provided in subsequent sections of this document.

3.4.3.2 Mars Initial Analysis Assumptions

Human Mars mission requirements will be developed under an eventual human Mars exploration program. In lieu of requirements, guidance provided by NASA leadership heavily influenced the architecture concepts used for human Mars mission architecture development.

Recent analysis assumptions used to assess impacts for the Mars exploration campaign's architecture development include the following:

- A light initial exploration footprint: as few as two or as many as six crew members to Mars orbit, and a minimum of two crew members descending and living on the surface for a minimum 30-sol surface stay
- Multiple Mars landers, with the first lander(s) pre-deploying cargo to prepare for a later crew landing
- Modest initial surface infrastructure: a 10 kWe minimum FSP system and communications infrastructure, but no surface habitat, and no return-mission-critical ISRU propellant production
- "All-up mission" approach: crew depart Earth with all the transit propellant they need for the round-trip journey, a consequence if there is no ISRU for early missions

Note that these assumptions are considered for a basis of comparison only. More complex mission scenarios will be addressed in subsequent analysis cycles, but the initial step is to define a practical architecture for the first human Mars mission campaign, from which subsequent missions can expand. It is important to note that none of these assumptions are fixed; they provide a framework for direct architecture comparisons, and all decisions will be made with architecture evolution in mind.

3.4.3.3 Reference Missions for Assessments

To provide stakeholders with a sense for how the Mars architecture changes as just a single constraint is varied, three reference missions of different total durations — but all with the same surface and transit operational constraints, such as environmental exposure, communication delays, and blackout periods — are defined to enable assessment of the architecture to inform the eventual decision roadmap (Figure 3-23): Reference Mission 0, with an Earth-Mars-Earth transit duration not to exceed 760 days; Reference Mission 1, with a moderate transit duration of 850 days; and Reference Mission 2, with a more relaxed transit duration of up to 1,100 days.

Reference Mission 0 is an opposition-class mission where at least one leg of the transit requires substantial energy to close the distance gap between Earth and Mars rather than loitering in Mars orbit to take advantage of planetary motion, as in Reference Mission 2. Reference Mission 0 reflects the desire to shorten the roundtrip mission duration in an attempt to reduce long-duration spaceflight risk to the crew.

Reference Mission 2 represents the traditional conjunction-class corner of the trade space, taking advantage of minimum-energy trajectories by loitering in Mars' vicinity for up to a year, which in turn reduces overall propellant mass and launch costs. This reference mission represents the desire to minimize the total mass of the transportation system by minimizing the energy required for the roundtrip journey.

Mission Duration Knob	WHO We Send	WHAT We Do	WHERE We Go	WHEN We Go	WHY We Go	HOW We Get There & Back
Fast Roundtrip High Energy **Reference Mission 0**	**Analysis Assumption: Number of Crew Range of 2 – 6**	**Analysis Assumption: 75t Total Landed Payload** Light footprint: Minimal surface infrastructure, crew live in rover, 10 kWe Fission Surface Power (no return propellant ISRU)	**Analysis Assumption: Single Mars Surface Site +35° N Latitude**	**Analysis Assumption: 2039 crew departure to meet "by 2040" boots on Mars**	**Science Inspiration National Posture**	**Mission Time:** **760d or less** in Deep Space, **fixed 50 sols** in Mars Orbit, <u>w/30 sols on Mars Surface</u> (**870-900 days total** crew time off Earth)
Moderate Duration Moderate Energy **Reference Mission 1**						**Mission Time:** **850d** in Deep Space, **fixed 50 sols** in Mars Orbit, <u>w/30 sols on Mars Surface</u> (**960-1020 days total** crew time off Earth)
Long Duration Minimum Energy **Reference Mission 2**		**>75t Total Landed Payload** Light Footprint: Plus leverage additional capacity if available				**Mission Time:** **950-1100d** in Deep Space, **no less than 50 sols** in Mars Orbit, <u>w/30 sols on Mars Surface</u> (**1090-1250 days total** crew time off Earth)

Figure 3-23. SAC22 Humans to Mars Reference Missions for Transportation System Assessments

Reference Mission 1, though accelerated, is not strictly an opposition-class mission; rather, it is on the continuum between traditional opposition-class and conjunction-class missions. This reference mission represents a compromise between Reference Mission 0 and Reference Mission 2 in an attempt to understand the middle ground of this particular trade space.

The rationale for multiple reference missions is twofold: first, to assess candidate transportation propulsion system performance across the continuum from opposition-class to conjunction-class missions, and second, to answer the question, "Is nuclear propulsion needed to enable crewed Mars missions?" A given propulsion concept may perform well for one mission class type but not others; by considering different mission class types, decision-makers can better compare these architectures and understand how constraints such as total mission duration influence performance.

3.4.3.4 Mars Architecture Element Categories

To aid in assessing extensibility of Mars elements to other destinations or programs and vice versa, the Mars architecture elements can be bucketed into four major categories: 1) Mars surface systems that enable crew to live and work on the planetary surface; 2) entry, descent, landing, and ascent (EDLA) systems that are able to move crew and surface systems from Mars orbit to the Mars surface and return crew and cargo back to Mars orbit; 3) transportation systems that are able to move crew and cargo from Earth to Mars orbit and back again; and 4) crew support systems that cross multiple missions, phases, and destinations, such as EVA spacesuits, distributed communications networks, or crew healthcare systems. These categories, and the key architecture considerations associated with each category, are outlined in Figure 3-24.

Figure 3-24. Major Mars Architecture Categories and Sample of Related Architecture Key Decisions

As noted above, major decisions (the "Why" or "When," for example) will heavily influence subsequent decisions within each architecture category. Because decisions in one architecture category will ripple across the other categories as mass, cost, or complexity, NASA will study the effects of options across the end-to-end architecture under various decision structures. This process will enable NASA to develop a roadmap of key architecture decisions. It is important to note that Figure 3-24 and the description provided in this document are not intended to provide an exhaustive list of decisions and categories, but rather to begin development of the integrated Mars architecture decision roadmap for eventual implementation. Key decisions that will affect all four Mars architecture system categories (i.e., Surface, EDLA, Transportation, and Crew Support) are the Mars architecture Loss-of-Crew Risk Posture and Loss-of-Mission Risk Posture decisions. The loss-of-crew Safety Reporting Thresholds (SRTs) and loss-of-mission requirements specify the minimum tolerable/allowable levels of crew safety (maximum tolerable level of risk) and mission loss, respectively, for the design in the context of the proposed design reference mission(s). These are key early steps in the human-rating certification process that will aid in allocating reliability requirements and identifying safety/risk technological areas that require further development, prioritization, and/or demonstration.

3.4.4 Mars Surface Systems

The initial focus for Mars exploration is the development of a modest first exploration mission, framed as a first step to a sustained human exploration campaign. For the sake of comparison, initial analysis assumes the same surface system elements, regardless of how those systems are transported or deployed to the Martian surface. Long-duration crew stays at Mars will be assessed as future work related to sustained human exploration analysis.

3.4.4.1 Functions

The primary function of human Mars surface systems is to protect crew and utilization payloads from the Mars environment for the duration of the Mars surface mission. Mars surface systems will also be critical to enabling science investigations before the crew arrives, while they are on the surface, and after they depart. For utilization payloads, this includes the pre-deployed cargo phase prior to crew arrival and an extended robotic operations phase following crew departure. Capabilities required to perform this function include utilities such as power and communications, surface mobility assets, and habitable volumes.

3.4.4.2 Key Drivers

Virtually every other surface system decision will hinge on the desired number of crew members on the surface ("Who?") and their purpose ("Why?"). Other decisions could be made first, but these two decisions may be considered anchoring decisions for a logical flow of subsequent surface architecture decisions. Understanding the relationships between these decisions is vital to developing an integrated surface architecture.

3.4.4.2.1 Surface Mission Purpose

The Mars surface systems architecture will vary significantly depending on whether the surface mission purpose is confined to a narrow set of specific human-assisted science objectives, a set of tasks intended to lay the groundwork for sustained human presence, or some combination of the two. Key decisions related to mission purpose will include Science Objectives Priorities, Target State, and High Priority Technology Demonstration Objectives.

Note that decisions involving the surface mission purpose will have impacts beyond the surface systems architecture. For example, Science Objective Priorities and Target State will inform landing site selection, which will drive the EDLA and transportation architectures. These decisions also potentially influence the payload capacity and/or number of landers required.

3.4.4.2.2 Number of Crew Members to the Surface

The minimum practical number of crew members to be sent to the surface is assumed to be two, given NASA's long-standing "buddy rule" for critical spaceflight operations. Initial crew complements as high as six have been analyzed, but ultimately the number of crew members required will be tied to the surface mission purpose, with more crew members needed for more elaborate mission plans and managing critical operations in an environment where communication delay precludes Earth-based ground support. Technology autonomy may support reducing the number of crew; however, architecture design supportive of effective human system integration will be a necessity, especially if the number of crew is minimized. Whether to split crew (with some remaining in orbit while others descend to the surface) will depend on orbital and surface tasks, technology autonomy, and risk to crew and mission during critical operations. Iterative analyses may be required to assess different architectures and concepts of operations.

Designs for systems such ECLSS (and associated maintenance and spares logistics) are driven by the number of crew, as are logistics consumables such as oxygen, food, water, medicine, clothing, and hygiene supplies. The number and type of science objectives that can be addressed is also contingent on the number of crew available to perform utilization tasks.

3.4.4.2.3 Surface Stay Duration

Minimum surface stay duration will be a function of the surface mission purpose and how many crew are available to accomplish the mission. Depending on the architecture, there may be logical stay duration break points, beyond which additional elements may be required to complete the mission.

3.4.4.2.4 Habitation Options

The multiple habitation options are largely based on architecture decisions about crew size, surface mobility strategy, EDLA and transportation capability, utilization needs, and the location of initial and subsequent crewed Mars missions. Numerous studies have analyzed the necessary habitable volumes for a surface crew for various mission scenarios, as well as the EDLA and transportation architectures that must deliver these elements. Habitat reuse or repurpose from previous missions must also be considered as part of the surface habitation strategy.

3.4.4.2.5 Crew and Logistics Ingress/Egress

Habitation decisions will, in turn, inform crew ingress/egress options, with key considerations being dust mitigation, planetary protection, logistics management, contingency access, system maintenance needs, and operational efficiency. Crew and logistics ingress/egress strategy is expected to be substantially informed by Artemis experience on and around the Moon, along with mission-specific constraints such as schedule, mass, and cost. Options include ingress/egress via airlocks, hatches directly into the habitable volume, and/or use of a (suit) port that allows crew to directly don a spacesuit via a detachable hatch mounted directly to the exterior of the habitable volume.

3.4.4.2.6 Surface Mobility Options

Surface mobility options will be derived from decisions related to mission purpose (e.g., where do we need to go to meet the objectives and what do we need to do there?), stay duration (e.g., how long do we have to get there and back to the MAV?), cargo movement (e.g., what payload elements need to be moved from one location [e.g., the lander deck] to other locations?), and habitation (e.g., are the habitable volumes moveable? what are the traverse distances to/from habitat, landing site, and ascent stage?). Each of these individual considerations will influence the overall exploration radius. Because mobility includes EVA systems, crew ingress/egress must also be considered, as it will influence EVA suit design and operation. Mobility systems may also be required to support autonomous or remotely commanded operations before the crew arrives or after they depart, which may influence the communications architecture. Vehicle mobility systems, such as a pressurized rover, tend to be large, so mobility decisions will impact the EDLA and transportation architectures that must deliver these elements. The functions of the Mars surface mobility systems will need to be supported by PNT systems. Definition of the PNT architecture will be informed by the lunar experience, although the lunar PNT architecture will be intermeshed with Earth-based and Earth-vicinity resources. The Mars PNT architecture will be shaped as the Mars mission(s) is (are) defined.

3.4.4.2.7 Surface Communication Options

Surface communications decisions will ultimately depend on how many surface assets are deployed; their relative proximity to each other and whether there are potential line-of-sight obstructions between them; the mobilization plan as assets move around the surface; which assets need to communicate with each other, with orbiting assets, and/or with Earth; data rates required between various assets; and power available to each asset. Surface communications decisions are expected to be substantially informed by Artemis experience on and around the Moon, and there is likely to be iteration across the elements as mass, power, complexity, or other constraints are balanced.

3.4.4.2.8 Surface Power Options

Fission surface power (FSP) is the leading candidate for primary Mars surface power because of the prevalence of dust storms that have proven difficult for solar-powered Mars surface systems. Although solar-powered short-duration surface missions might have acceptable risk, longer-stay missions or missions pre-deploying powered cargo will likely require surface power technologies, such as FSP, that are resistant to environmental disruption. Initial analysis has identified a minimum power level needed to achieve a 30-sol, light-footprint exploration mission, but assessing and integrating power needs for science and technology demonstration remains as forward work. Therefore, the power level, number of units, and operations plan (e.g., leave surface power system on the lander it arrives on or deploy elsewhere) also remain as forward work.

3.4.4.2.9 Surface Architecture Life and Reuse

Operating life limits, including reuse for subsequent missions, will depend on total surface mission duration (including the pre-deployed cargo and post-crew departure robotic science mission phases) and whether subsequent human missions will return to the first mission landing site.

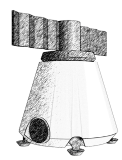
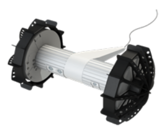
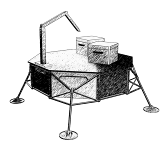
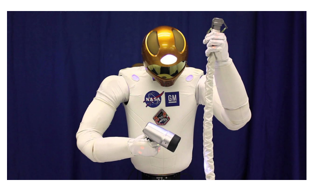
3.4.4.2.10 Return Propellant Strategy

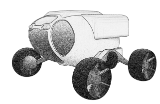
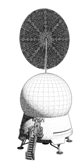
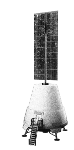
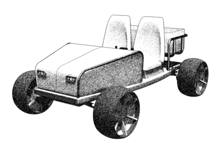
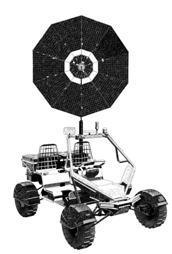
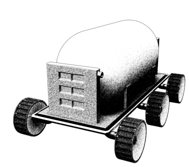
Return propellant strategy — whether manufacturing propellant in-situ on Mars, using Martian-derived resources or Earth-delivered resources — drives surface system mass, power, operational timelines, and potentially landing site selection. The Martian atmosphere is a readily accessible feedstock anywhere on the planet from which oxygen, carbon, and other commodities can be acquired. Water, from which hydrogen and oxygen can be derived, is known to exist in various forms and in discrete locations on the surface or in the near sub-surface across the planet. Acquiring these feedstocks and the choice of propellants to manufacture drive surface system mass, power, operational timelines, and potentially landing site selection.

3.4.4.3 System Concepts

Table 3-32 summarizes the minimum set of surface concepts based on functional needs currently being evaluated in the Mars surface architecture. Note that these are in the conceptual design phase; subsequent publications will contain additional surface concept reference detail as they mature, and more concepts may be added as additional functions are defined.

Table 3-32. Mars Surface System Functions and Example Concepts

Functions	Example Concept(s)		Heritage and Status
Provide power for all surface elements	Surface Power		FSP derivative of the Kilopower concept is in formulation for a lunar demonstration mission. Other options have been evaluated but may not meet constraints.
Provide power storage and distribution from the source to surface end-users or distribution points		 	Derivative of cables used in Earth applications (e.g., solar farms, offshore wind farms, undersea cabling). Various deployment concepts are being evaluated.
Enable automated cargo handling	Robotics		Robotic cargo handler: simple design and components. Should be scalable to multiple cargo types or sizes. Various concepts have been studied; lunar analogs may offer new insights.
Enable autonomous or remoted-controlled fine motor-control manipulation of mechanisms and other components, such as cables, hoses, etc.			Robotic manipulator heritage from ISS robotics, Robonaut, etc.
Provide aerial exploration and contingency support			Advanced generation of Ingenuity, a robotic helicopter landed with Perseverance and currently in use on Mars
Provide ability for crew EVA	Refer to Mars Crew Support Architecture, Section 3.4.7		

Functions	Example Concept(s)		Heritage and Status
Provide habitable volume for shirt-sleeve crew for surface activities	Habitation	  	Lunar habitation and mobility derivative concept
Provide ability to transport crew utilization payloads, and other cargo across the Mars surface (Note: Utilization payloads can include science equipment)	Surface Mobility	 	Mars terrain vehicle Derivatives of lunar mobility concepts
Provide ability to store, condition, and transfer ascent propellant through Earth launch, transit, and Mars landing, as well as the Mars surface environment	Propellant Storage and Transfer		Same design and fluid-compatibility as conceptual ascent vehicle propellant tanks
Provide means to transfer propellant to the ascent vehicle	Propellant Delivery		Potential concept leverages technology developed in support of the satellite servicing mission previously called Restore-L (now OSAM-1) and its predecessor Restore-G

Functions	Example Concept(s)		Heritage and Status
Science: Provide equipment needed to meet Mars transit and surface-based science objectives			To be coordinated with the Science Mission Directorate, the Space Operations Mission Directorate, and possibly the Science and Technology Mission Directorate, or other research stakeholders if new technologies are required
Technology Demonstration: Provide assets needed to meet Mars surface infrastructure technology demonstration objectives			To be coordinated with the Space Technology Mission Directorate
Return Cargo: Provide containment and environmental control for Mars-origin or Mars-contaminated materials			To be determined based on mission objectives and planetary protection constraints
Communication between crew, surface assets, orbital assets, and Earth	Refer to Mars Crew Support Architecture, Section 3.4.7		
Provide logistics	Refer to Mars Crew Support Architecture, Section 3.4.7		

3.4.4.4 Concept of Operations

The Mars surface concept of operations will be a function of the key architecture decisions and considerations, such as science objective priorities, crew complement to the surface, surface infrastructure availability, orbital assets, and other factors. Many examples of surface concepts have been published in the past, on varying points the complexity spectrum. Specific concepts of operations are utilized to help evaluate the trade space and understand the implications of different decisions.

3.4.5 Mars Entry, Descent, Landing, and Ascent Systems

All surface system assets, plus the crew's ascent system, must descend and land on Mars. The landed mass required for a human mission exceeds the practical limits of heritage robotic mission EDL systems such as parachutes, airbags, or sky cranes. Two different types of landing systems are currently being assessed: a "flat bed" lander where the payload is mounted on a cargo deck relatively close to the surface and a "vertical lander" that could accommodate higher-mass payloads. The number of landers needed for a particular mission will depend on the lander's payload capacity (both mass and volume) and any pre-deployment timing constraints. For the sake of comparison, it is assumed that both types of landers could deliver the same surface cargo, including the same surface and ascent system with Earth-origin propellants. There are alternative ascent system schemes employing in-situ propellant manufacturing, but because these options stray from the first mission's "light exploration footprint" assumption, those options are deferred to subsequent analysis cycles.

3.4.5.1 Functions

Regardless of design, all Mars EDLA systems must provide a minimum set of functional capabilities to support the integrated Mars architecture.

3.4.5.1.1 Protect Crew and Cargo During Mars Entry, Descent, and Landing

The Mars EDL system must accommodate rapid changes in temperature, pressure, and gravity while decelerating from orbital velocities without transmitting damaging loads to crew or cargo. Because of a combination of potential crew deconditioning, lengthy communications delays with Earth, and the rapid pace of dynamic events during EDL, Mars EDL systems must be designed for autonomous operation with limited real-time crew input.

3.4.5.1.2 Protect Crew and Cargo During Mars Ascent

The Mars ascent system must accommodate rapid changes in temperature, pressure, and gravity without transmitting damaging loads to crew or cargo. The ascent vehicle will also be responsible for providing a habitable environment to support the crew during ascent from the Martian surface.

3.4.5.1.3 Protect Against Cross-Contamination of Martian and Earth Environments

Descent systems will need to minimize the transfer of uncontained Earth material to prevent forward contaminating the Martian environment to maintain pristine scientific samples to the maximum extent possible. Similarly, ascent systems will need to minimize the transfer of uncontained Martian material to prevent backward contaminating Earth return vehicles.

3.4.5.1.4 Provide Integration Interfaces to Mars Transportation and Surface Systems

Mars EDLA elements must receive services (such as power, data, or thermal control) from the Mars transportation system during transit and must provide similar services to the cargo payloads they carry during transit, entry, descent, landing, and surface operations prior to accessing power from surface infrastructure (i.e., from the FSP).

3.4.5.1.5 Provide Precision Landing Capability to Enable Multi-Lander Surface Operations

Lunar landing systems will be insufficient to meet precision landing requirements on Mars. Technologies developed for the Moon may be applicable but insufficient because of differences in EDL on Mars, primarily because of the presence of the Martian atmosphere. Architectural decisions, such as Mars parking orbit, can also impact the required precision landing technology development because of differences in flight path angles and relative velocities during key phases of EDL. Additionally, there may be constraints on landing precision technology imposed by the need to land multiple landers in close proximity for operational purposes while simultaneously maintaining safe distances from previously landed assets to mitigate the potential damage caused by ejecta lofted by terminal descent rocket engines.

3.4.5.2 Key Drivers

EDLA design will be heavily influenced by two human Mars mission requirements and two constraints. Total required payload mass to the surface and return to Mars orbit is informed by “Why” we are going to Mars and “What” we will do there, which in turn drives the number of crew members we need to land on the surface and return to orbit, the equipment we need to land, and the number of crew members and cargo we need to return to orbit. Whether these systems need to be extensible to larger future payloads may also influence EDLA design. EDLA design will also be constrained by the largest indivisible payload item (mass and volume) and whether the EDLA system is required to support all crew to surface and back to orbit together, and split crew operations, in which some crew members land while others remain in orbit. EDLA design may also be constrained by potential human system risks associated with physical deconditioning from the lack of gravity during the transit phase. This deconditioning can also impact crew readiness timelines for Mars surface EVA. EDLA design may also be influenced by requirements on payload protection from entry environments and orbital debris.

3.4.5.2.1 Payload Mass Landed on the Mars Surface

The largest payload landed to date on Mars is about 1 t, but even the most modest human Mars mission is estimated to require at least 75 t of total landed payload for even a short-duration surface stay. Longer, more ambitious missions will require more landed mass. Total landed payload mass, in combination with EDL technology availability, will determine how many landers are needed to complete the mission, which in turn will inform lander production, launch, and delivery cadence, with flow-down impacts to the Earth-Mars transportation architecture. The number of landers will also inform surface system concepts of operations, depending on how far apart landers are deployed, which payloads need to move between landers, and the power and communications strategy between them.

3.4.5.2.2 Payload Mass Ascended to Mars Orbit

Ascent from the Mars surface has never been attempted. The Mars Sample Return Program's Mars Ascent Vehicle is the first planned ascent from another planet. Mars atmosphere and gravity make this 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 t of propellant to a 5-sol Earth transportation vehicle parking orbit. Each additional kilogram of cargo mass further increases ascent propellant mass; either this mass must be added to the landed payload allocation noted above or propellant production mass and additional power must be added to the landed payload mass, with flow-down impacts to the surface operations timeline.

3.4.5.2.3 Largest Indivisible Payload

Total landed payload mass can be distributed across smaller landers, which could minimize the EDL technology development burden, but the limiting factor will be the largest indivisible payload. For modest missions, this is likely to be the MAV. Propellant can be off-loaded onto other landers or manufactured on the surface to reduce landed mass. MAV hardware (e.g., tanks, engines) assembly is possible, but extremely risky, especially for initial missions. For more ambitious, longer-duration missions, a large surface habitat might be the pacing payload mass item, depending on how much/how fast outfitting could be installed after landing. Note that payload volume will be constrained by the payload shroud of Earth launch systems, potentially requiring additional Earth launches or Mars landers for large items that can be modularized, or larger launch and lander vehicles for those items that cannot be segmented and exceed current payload shroud size.

3.4.5.2.4 Orbital Crew Operations

If all crew members are to land on the surface, then direct entry options are possible, but if the architecture is required to support "split crew" operations (where some crew members remain in Mars orbit), then both the transportation and EDL systems may need to support orbital operations. The parking orbit has a significant impact on vehicle design, orbital operations, and timelines. Landing and ascent durations and time required to accommodate multiple launch/landing opportunities are highly dependent on the parking orbit. Additionally, mass of the MAV, which is already identified as a "high gear ratio" element impacting the design of several other architecture elements, is highly sensitive to parking orbit altitude. In general, EDLA systems favor lower parking orbits. However, in-space transportation systems tend to favor high parking orbits.

Therefore, the optimal parking orbit is an integrated problem between EDLA systems, in-space transportation systems, and crew operations.

3.4.5.2.5 Landing Site Selection

The terrain of a selected Mars landing site location will obviously influence EDLA design, with landing site latitude and elevation affecting both ascent and descent propellant mass, creating flow-down impacts to landed payload mass and surface operations related to MAV fueling strategy. Terrain and whether subsequent missions will return to a given landing site can also influence landing precision requirements. Key reconnaissance parameters (e.g., high-resolution imaging or surface properties assessments) may be needed to inform EDLA design. In addition, the landing site's lighting constraints during the descent phase of the mission could have integrated impacts to the in-space transportation system.

3.4.5.2.6 Ascent Propellant Acquisition Strategy

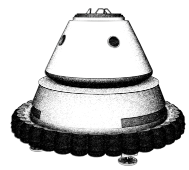
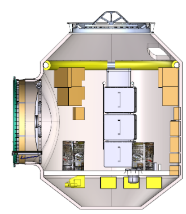
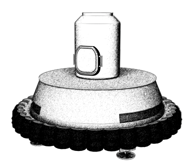
Options include landing a fully fueled MAV on Mars or landing an empty or partially fueled MAV on Mars and either transferring propellant from another lander or manufacturing propellant from in-situ resources. All of these options result in flow-down impacts to other systems: a fully fueled MAV drives MDS payload capacity and Earth launch capacity; a partially fueled MAV drives surface propellant transfer mass and complexity; and in-situ propellant manufacturing drives surface system mass, power, and operational timelines. Constraints such as Earth launch fairing diameter and Mars parking orbit can also have significant constraints on ascent vehicle design choices and propellant acquisition strategy. For example, cryogenic propellant-based MAV to a five-sol orbit challenges the geometry of an 8.4 m diameter Earth launch system fairing due to low density propellants combined with increased propellant loads for higher parking orbits. Workarounds to the Earth launch shroud constraint in turn impact the transportation system by potentially driving it to a lower Mars orbit (at a higher propellant penalty) or require the addition of a "taxi" element to bridge the gap between how low the transportation system can dip into the Mars gravity well and how high the MAV can ascend on a lighter propellant load.

3.4.5.2.7 Element Reuse

Reuse cannot be an afterthought for EDLA systems. It must be integral to the design. Feasibility of reusing EDLA systems is tightly coupled between system design and concept of operation. Initial reference designs are not practical for reuse, but changes to design and operation can enable reuse. Certain designs may be more "evolvable" for reusability than others. Operating life limits, including reuse for subsequent missions, will depend on total surface mission duration (including the pre-deployed cargo and post-crew departure robotic science mission phases), and whether subsequent human missions will return to the first mission landing site.

3.4.5.3 System Concepts

Table 3-33. Mars Entry, Descent, Landing, and Ascent Functions and Example Concepts

Function	Example Concept(s)		Heritage and Status
Delivers crew and surface cargo from Mars orbit to Mars surface Serves as a launch pad for Mars ascent operations	Mars Descent System		MDS conceptual design available for "flat bed" type lander. Hypersonic Inflatable Aerodynamic Decelerator (HIAD) based on Low Earth Orbit Flight Test of an Inflatable Decelerator. Forward work to complete reference design of vertical lander.
Shirt-sleeve environment for transfer of crew and equipment between the deep space transport, habitation element, and MDS crew cabin (which may be a surface cargo element)	Pressurized Mating Adapter		Very high-level reference conceptual design available
Delivers crew and returns crew and cargo to Mars orbit	Mars Ascent Vehicle		Reference conceptual designs available
Shirt-sleeve environment transfer of crew and equipment between a pressurized surface asset and the MAV cabin	Surface Pressurized Tunnel		Very high-level reference conceptual design available

3.4.5.4 Concepts of Operations

Refer to HEOMD-415[15] for the initial surface concepts of operations for various mission and architecture implementations, including MAV fueling strategies; that document will be updated as the architecture evolves.

3.4.6 Earth-Mars Transportation Systems

Earth-Mars transportation systems serve to transport the crew, surface systems, and EDLA systems to Mars and return crew to Earth. All Earth-Mars transportation architectures will consist of a propulsion and power backbone paired with one or more payload elements. For the purpose of this document, this integrated transportation system stack is referred to as the "deep space transport" (DST). A single DST design could be used for both crew and cargo deliveries, but to

[15] *Reference Surface Activities for Crewed Mars Mission Systems and Utilization,* National Aeronautics and Space Administration (2022). HEOMD-415.

optimize for cost, development schedule, or other metrics of interest, variants may be mixed within a single campaign: for example, a slower, less-expensive, non-nuclear transport for pre-deployed cargo with a faster, higher-powered nuclear system for crew transport. In the crew-variant DST, the payload is a crew habitation system and all the utilization payloads, logistics, supplies, and spares for the in-space portion of the mission, including contingency operations. For the purpose of current analyses, a common habitation system is assumed for all transportation architectures. In the cargo-variant DST, payloads include surface systems, surface utilization payloads, EDLA elements, or other support system payloads.

Selection of a human Mars transportation system will be a complex decision shaped by numerous factors, such as mission objectives (the “Why?” question), exploration partner contributions and commitments, programmatic factors, schedules, and integrated risk assessments. The four transportation propulsion systems presented here represent the range of options currently being analyzed.

Specific implementation of the different transportation systems will depend on the reference mission of interest and a balance between the optimization of the system and the robustness to other mission parameters. For each reference mission, transportation systems can be optimized, from both a configuration perspective and a performance perspective, for the specific requirements of that reference mission. But an optimized transportation implementation might come at the cost of compromising the extensibility and flexibility to other mission design parameters that may be of interest.

3.4.6.1 Functions

Regardless of propulsion type, all Earth-Mars transportation systems must provide a minimum set of functional capabilities.

3.4.6.1.1 Provide Sufficient Energy to Transport Crew and Cargo from Earth Vicinity to Mars Vicinity and Back Again

The planetary alignment between Earth and Mars constantly changes over a roughly 15- to 20-year synodic cycle, so the amount of energy needed to make the transit will vary depending on the mission opportunity. If the transport is designed for only the “easiest” opportunity, Mars missions may be possible only once per synodic cycle; if designed for the “hardest” opportunity, the transportation system will be robust for all mission opportunities, but will be over-powered for most opportunities and will likely require more upfront technology investment. If the transport carries all required propulsive energy from Earth, its design must ensure that energy remains available throughout a long round-trip mission duration; if it plans to acquire return energy at Mars or an interim destination, the transport design must accommodate refueling or resupply operations with additional systems. To bound energy requirements, current analyses assume all propellant required for the round trip is launched from Earth and carried roundtrip, without the need to resupply. For the purpose of sizing the transportation concepts, a complement of four Mars crew is currently under evaluation. This is likely a minimum practical limit for the purposes of addressing risk and redundancy; however, larger crew complements would require larger habitats and more consumables, which in turn will increase transportation energy requirements.

3.4.6.1.2 Protect Crew and Cargo from the Deep Space Environment for Transit Duration

In addition to the temperature extremes and near-vacuum pressure common in LEO, Mars transit will have additional complications of increased radiation exposure and prolonged microgravity risks. To protect crew and cargo during the long transit duration, the transport and integrated habitation systems must be sized and configured to mitigate these risks. Leveraging the extensive complement of logistics and consumables (needed due to limited resupply options to address routine and contingency operations) and habitation system arrangement may mitigate long-term radiation exposure while crew exercise and countermeasure systems will address long-term crew health impacts from microgravity. Note that as more mass is added to protect crew and cargo, more energy will be required to transport crew and cargo to Mars and back.

3.4.6.2 Key Drivers

3.4.6.2.1 Total Mission Duration

The in-space transportation architecture is dictated by the celestial mechanics of Earth, Mars, and the Sun. The total roundtrip mission duration for a Mars mission is the primary driver for any in-space transportation decisions. Longer mission durations (approximately three years) typically require lower energy, as they can rely on the more favorable alignments between Earth and Mars to perform two optimal transfers between the planets. Shorter missions would require more energy to complete, as the in-space transportation system will need to complete the roundtrip mission while fighting against the natural orbital energy of the two planets. The energy required, and therefore the propulsion technology and total propellant mass, scales exponentially with mission duration, so the shorter missions are exponentially harder than the longer missions. The total mission duration decision also cannot be made solely on the basis of the in-space transportation system; factors such as crew health and performance as a function of total mission duration must also be considered. This decision has broad implications for crew systems, crew health, Mars orbit time, and Mars surface time, which in turn will influence the scope of utilization activities.

3.4.6.2.2 Mars Vicinity Stay Time

The decision on Mars vicinity stay time is driven by three factors: the Mars surface mission duration, the Mars orbital operation requirements, and the total roundtrip mission duration. The minimum surface stay duration will be the minimum duration that the in-space transportation system needs to remain in Mars orbit. However, additional time is required to prepare and transfer crew to the MDS prior to the surface mission, as well as time for the MAV to rendezvous, dock, and transfer crew and cargo back to the transport after ascent from the surface. The current assumption for these activities is 10 Martian sols prior to descent and 10 sols following ascent, totaling 20 sols, but assessment of operational needs and constraints is required to guide the final Mars orbit stay time decision. Finally, the total roundtrip mission duration will also have significant impact on the orbit stay time. The shorter mission durations will have a lower bound for the orbit stay time, as the interplanetary trajectory is more energy efficient, with more total duration in deep space, rather than in Mars orbit. For longer-duration missions, the need to await optimal planetary alignment for the return journey will likely mean there will be a significant Mars orbit stay time available.

3.4.6.2.3 Mission Operation Mode

Mission operation mode refers to how the end-to-end mission is conducted and has significant implications to all other Mars decisions. The current assumption for the mission mode is an “all-up” mode, where the crew transportation stack departs Earth with all the propellant and logistics required to support the roundtrip mission. This is assumed for crew risk mitigation considerations, as the crew does not need to rendezvous with any propellant or logistics assets after Earth departure to return safely, potentially descoping the surface mission in the event of an anomaly. Shorter duration missions with higher energy may necessitate the pre-deployment of propellant at Mars to reduce the overall size of the transportation system.

To support the surface missions, the current assumption is that the surface assets are pre-deployed to the surface to wait for the crew. Potential options exist to integrate the surface elements with the crew stack so that no rendezvous is required in Mars orbit to support surface missions.

3.4.6.2.4 Mars Parking Orbit

The selection of the parking orbit at Mars for staging and aggregation of the mission will depend on the architecture and mission mode decisions and surface abort timing constraints. The current assumption for Mars parking orbit is a five-sol orbit, with the perigee of the parking orbit directly above the landing site to support a direct landing. This high-altitude parking orbit is beneficial to the transportation system because it does not require the whole transportation stack to insert deep into Mars' gravity well, but it puts an additional burden on the MAV, as the energy and time required to reach five-sol orbit are higher than for a lower parking orbit.

3.4.6.2.5 Mars Landing Site

Related to the selection of the parking orbit, the final selection of the landing site will have significant impact on the transportation system. This decision will be interlinked with the Mars EDLA system. Assuming the EDL system does not have its own cross-range capability, the transportation system needs to deliver the EDL system to the appropriate parking orbit for descent to the surface. This could mean the transportation system needs to perform additional orbital maneuvers to change the orbital parameter of the parking orbit to align for the descent and potentially ascent portions of the mission. This impact is particularly profound for the crew transportation system, as the integrated end-to-end trajectory needs to both bridge between the Mars arrival and departure interplanetary directions and satisfy the potential parking orbit constraint due to the landing site selection.

3.4.6.2.6 Number of Crew Members

The total number of crew members required will have a significant impact on the design of the transit habitation systems. Systems such as ECLSS (and associated maintenance and spares logistics) need to be scaled up as the number of crew increases, as do habitable volume and logistics consumables such as oxygen, food, water, medicine, clothing, and hygiene supplies, which has flow-down effects on the transportation systems. Conversely, selection and design of the propulsion system will also impact the decision about the number of crew members because of maintenance, repair, operational variations, and launch vehicle limitations between the different transportation system options.

3.4.6.2.7 Transit Habitation System

The primary decision about the transit habitation system concerns the integration between the habitat and the in-space transportation system. The habitation system can be integrated as part of the in-space transportation system or can be designed as an independent system. The current assumption for the transit habitation system is an independent system that will first facilitate early long-duration Mars precursor missions and Artemis activity in conjunction with Gateway before serving as the habitation system for the Mars missions. Another aspect to be decided is whether the habitat should be a monolithic unit or modular in nature.

3.4.6.2.8 Propulsion Technology

There are multiple options for the transportation propulsion system. The decision will be informed by a plethora of other decisions, including total mission duration, transit habitation strategy, mission mode operation, and others. Nuclear versus non-nuclear propulsion systems and high-thrust ballistic systems versus low-thrust systems versus hybrid high-/low-thrust systems are just a few of the propulsion technology decisions that must be made. However, propulsion system performance alone may not be a sufficient discriminator. The target date for a first human Mars mission will establish the propulsion system delivery date, which in turn will constrain technology development timelines — and may eliminate technologies that cannot be developed within the timeframe or dictate a phased strategy wherein early missions rely on available propulsion technologies and more advanced technologies are phased in during later missions. These key decisions will also be informed by non-technical considerations, such as the broader strategy question of long-term exploration objectives or technology development partnering arrangements with other agencies, industry partners, or international partners.

3.4.6.2.9 Aggregation Location & Strategy

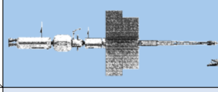
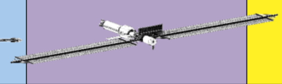
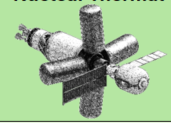
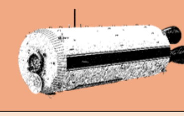
The Artemis campaign's Gateway Program lends itself to aggregation of transportation systems in cislunar space, such as NRHO; however, alternate orbits from LEO, medium Earth orbit, and high Earth orbit could also be considered, which may increase the Earth ascent vehicle options. The decision about where to aggregate the in-space transportation system and the strategy associated with it will depend heavily on several factors, such as the selection and design of the propulsion system, the availability of different launch vehicles and their associated launch mass, volume and crew complement capability, the launch cadence of the aggregation campaign, and the parking orbit distance from the Mars surface. Each transportation system option has optimal aggregation locations and strategies based on launch vehicle cadence and capability; however, the integrated nature of the aggregation strategy means that other variables complicate the decision about aggregation location.

3.4.6.2.10 Element Reuse Strategy

The reusability of any of the transportation elements is a key driver in the design of the system. If additional follow-on missions to Mars are desired to establish routine access to Mars' surface, then the ability to reuse elements will be a key decision in enabling these missions. If reusability drives in-space transportation system mass, impacts may flow down to the Earth launch campaign. Reuse strategy will include deciding whether to optimize the transportation system for all mission opportunities (enabling missions about every 2 years) or to optimize for other constraints (potentially limiting mission availability). Note that a 15-year service life is currently assumed for the transit habitat, enabling it to support dual roles as a Mars crew transport and for analog and lunar support missions.

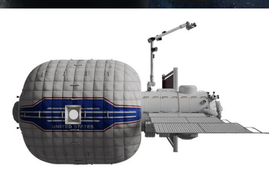
3.4.6.3 System Concepts

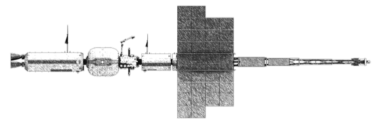
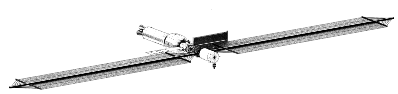
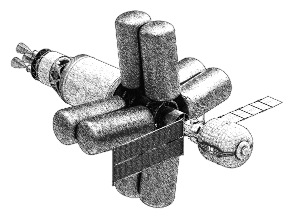
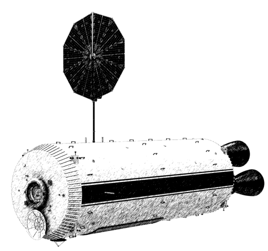
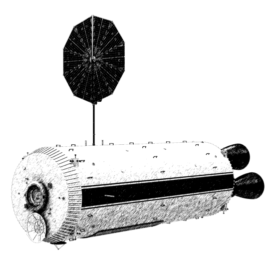
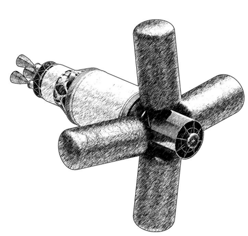
Table 3-34. SAC22 In-Space Transportation Analysis Trade Space

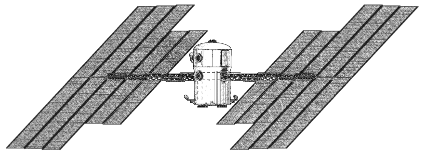
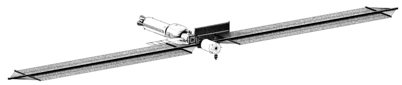
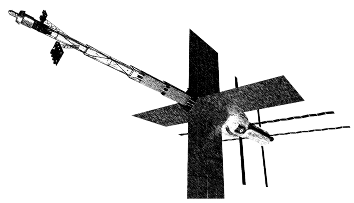
	Hybrid Nuclear Electric / Chemical 	Hybrid Solar Electric / Chemical 	Hybrid Nuclear Thermal / Electric Propulsion	Nuclear Thermal 	All Chemical 
Reference Mission **0** Short Duration Light Footprint Short Surface Stay	**M0-NEP** 1.8 - 3.6 MW NEP 3x 25k lb_f LCH4/LO2 NRHO Assembly NRHO Refueling **SAC21**	M0-SEP TBD ConOps TBD Assembly TBD Refueling	M0-NTEP TBD ConOps TBD Assembly TBD Refueling	**M0-NTP** 4x 25k lb_f NTP 12x 7m⌀ Drop Tanks MEO Assembly No Refueling **FY20 Analysis**	M0-CP TBD ConOps TBD Assembly TBD Refueling
Reference Mission **1** Moderate Duration Light Footprint Short Surface Stay	**M1-NEP** 0.7 - 1.8 MW NEP 3x 25k lb_f LCH4/LO2 NRHO Assembly NRHO Refueling **SAC22/SAC24**	**M1-SEP** 1MW Array/400kW SEP 3x 25k lb_f LCH4/LO2 NRHO Assembly NRHO Refueling **SAC23/SAC24**	M1-NTEP TBD ConOps TBD Assembly TBD Refueling	**M1-NTP** 2x 12.5k lb_f NTP 5x 6m⌀ Drop Tanks MEO Assembly No Refueling **SAC22/SAC24**	**M1-CP** Depot + Tanker Integrated Surface Payload LEO Assembly LEO Refueling **SAC22/SAC24**
Reference Mission **2** Longer Duration Minimum Energy Light Footprint Short Surface Stay	M2-NEP TBD ConOps TBD Assembly TBD Refueling	**M2-SEP** 700kW Array/400kW SEP 6x 1k lb_f LCH4/LO2 NRHO Assembly NRHO Refueling **SAC22/SAC24**	M2-NTEP TBD ConOps TBD Assembly TBD Refueling	**M2-NTP** 2x 12.5k lb_f NTP 5x 6m⌀ Drop Tanks MEO Assembly No Refueling **SAC23**	**M2-CP** Depot + Tanker Integrated Surface Payload LEO Assembly LEO Refueling **SAC22**

To better understand the performance of various propulsion system designs in the context of the analysis reference missions, concepts for four different propulsion and power options have been under evaluation: a hybrid nuclear electric propulsion (NEP)/chemical propulsion system, nuclear thermal propulsion (NTP) system, hybrid solar electric propulsion (SEP)/chemical propulsion system, and all-chemical propulsion systems. Hybrid nuclear thermal/electric propulsion concepts have yet to be evaluated. The NEP/chem hybrid and NTP systems are nuclear options, and the SEP/chem and all-chem systems are non-nuclear. Table 3-34 summarizes the various potential implementations of each system being analyzed, with respect to each of the three reference missions. Campaign manifest designations represent implementations with enough conceptual design fidelity for preliminary campaign assessments; implementations without such designations remain forward work.

Table 3-35. Mars Transportation System Functions and Example Concepts

Functions	Example Concept(s)		Heritage and Status
Transport crew from Earth vicinity to Mars vicinity and return	Transit Habitat	 	Reference conceptual design of an independent transit habitat informed by previous Next Space Technologies for Exploration Partnerships (NextSTEP) Appendix A activities

Functions	Example Concept(s)		Heritage and Status
Transport crew system from Earth vicinity to Mars vicinity and return	Piloted Crewed Hybrid NEP/Chem Propulsion System		Power generation linked to terrestrial power systems; EP system potentially extensible from Gateway PPE
	Piloted Crewed Hybrid SEP/Chem Propulsion System		Reference concepts derived from Gateway PPE, with extensibility to Mars NEP/chem hybrid
	Piloted Crewed Nuclear Thermal/Electric Propulsion System		Future Work
	Piloted Crewed Nuclear Thermal Propulsion System		Heritage to NERVA Program
	Piloted Crewed Chemical Propulsion System		Concepts development ongoing, technology is relatively mature, but challenges remain
Transport cargo from Earth vicinity to Mars vicinity	Cargo Chemical Propulsion System		Potential utilization of chemical stage of the hybrid NEP/chem or SEP/chem system
	Cargo Nuclear Thermal Propulsion System		Similar to piloted variant, but potentially with fewer elements and/or lower thrust needs

Functions	Example Concept(s)		Heritage and Status
	Cargo SEP/Chem Propulsion System		Similar to piloted variant, but potentially lower power needs
	Cargo SEP Propulsion System		SEP Module from SEP-Chem concepts can be used to deliver cargo, potentially lower power required depending on cargo mass
	Cargo NEP Propulsion System		NEP Module from NEP-Chem concepts can be used to deliver cargo, potentially lower power required depending on cargo mass
Crew Earth launch; reposition to DST; and Earth entry, descent, landing	Orion Spacecraft		Flight design Orion available for all mission opportunities for use with all transportation architecture variants
Earth launch for cargo (> 5 m diameter; > 15,000 kg mass to translunar injection condition)	Commercial Heavy Lift Systems		Commercial heavy-lift conceptual designs available

Functions	Example Concept(s)		Heritage and Status
Earth launch for cargo >7 m diameter TBD kg mass to various aggregation orbits	Super Heavy Lift Systems		Space Launch System flight design available; commercial super heavy lift conceptual designs in development
Aggregation and storage of propellant in space	Propellant Tanker Systems		Propellant tanker systems may not be needed for all architecture implementations; concepts development is ongoing
Provide systems and facilities to process, launch, and recover launch vehicles	Ground Systems		Government and commercial infrastructure available

As shown in Figure 3-25, Figure 3-26, Figure 3-27, and Figure 3-28, several conceptual designs of each transportation architecture are being developed to allow stakeholders to better assess performance across the range of mission duration options. These figures demonstrate how vehicle size and complexity vary as just one parameter, total mission duration, is varied.

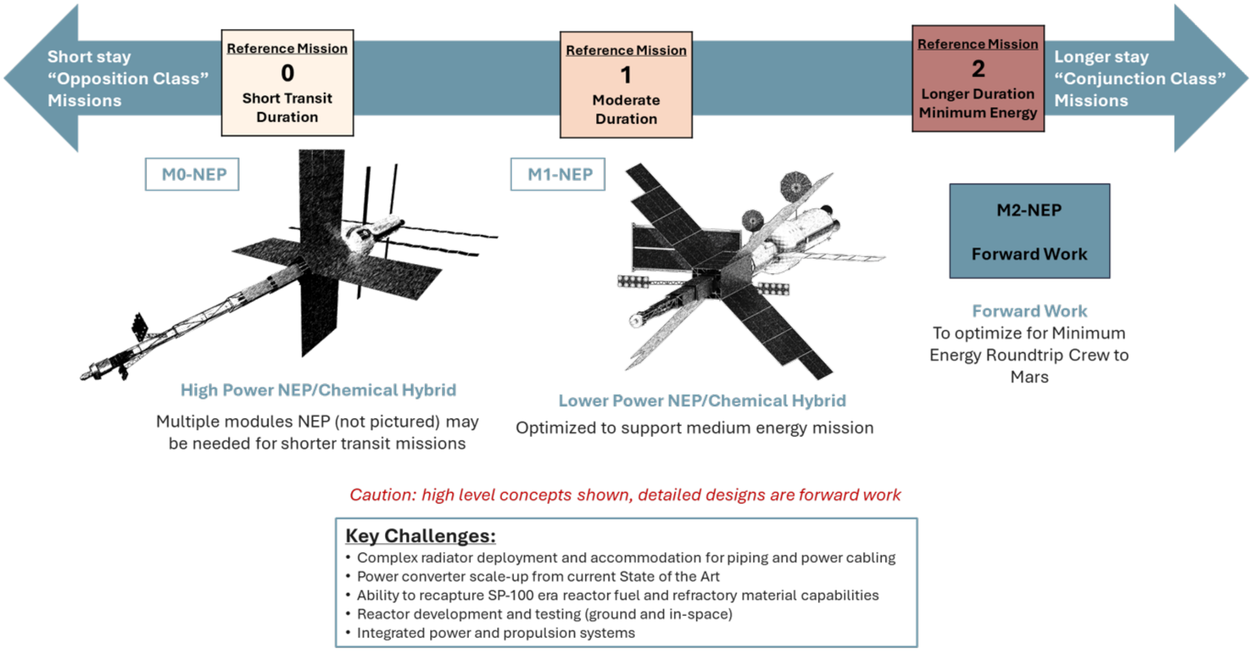


Figure 3-25. Hybrid NEP/Chem Concepts Across a Range of Total Mission Durations

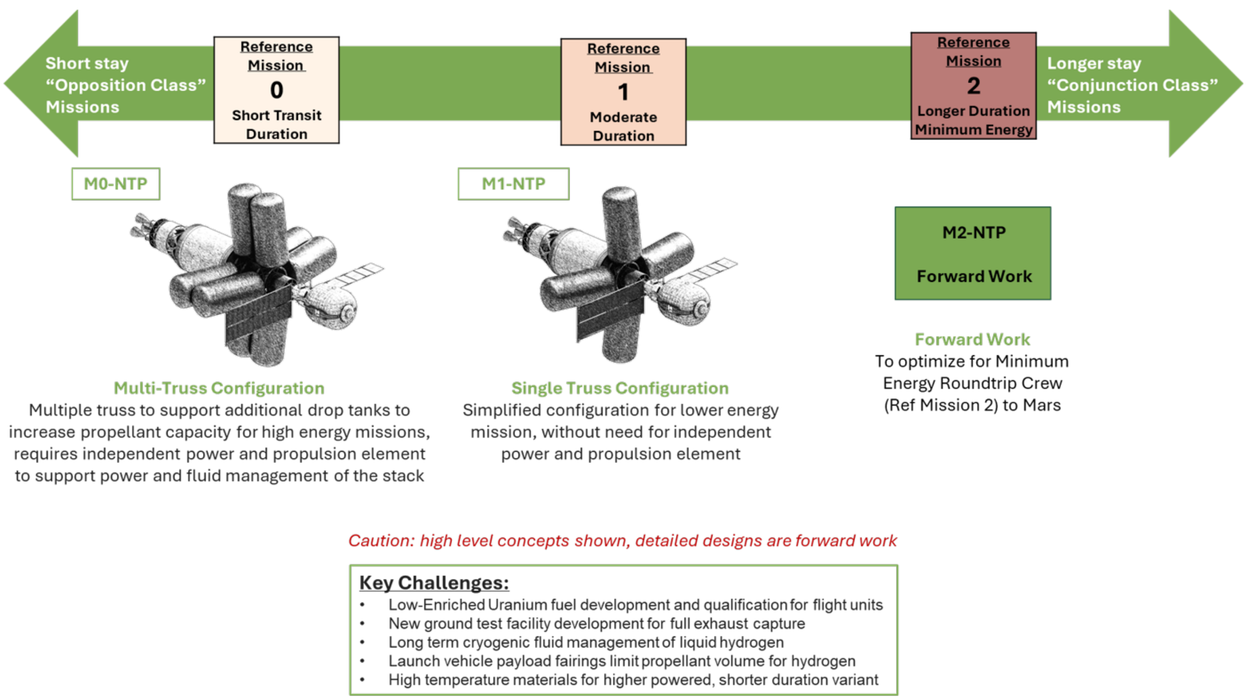


Figure 3-26. NTP Concepts Across a Range of Total Mission Durations

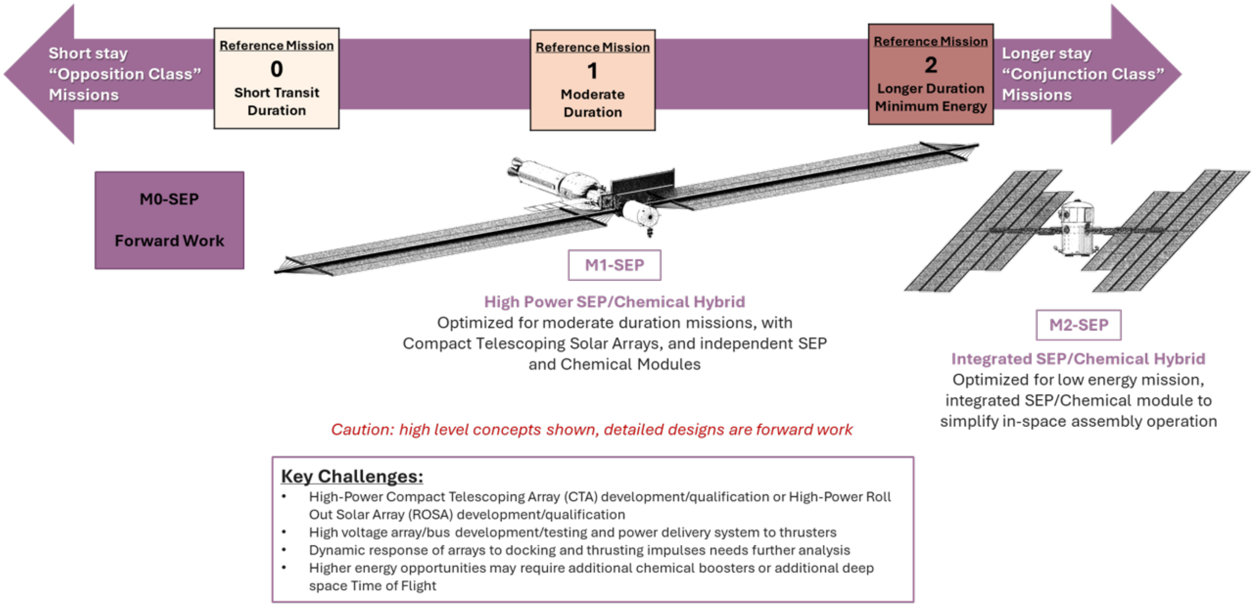


Figure 3-27. Hybrid SEP/Chem Concepts Across a Range of Total Mission Durations

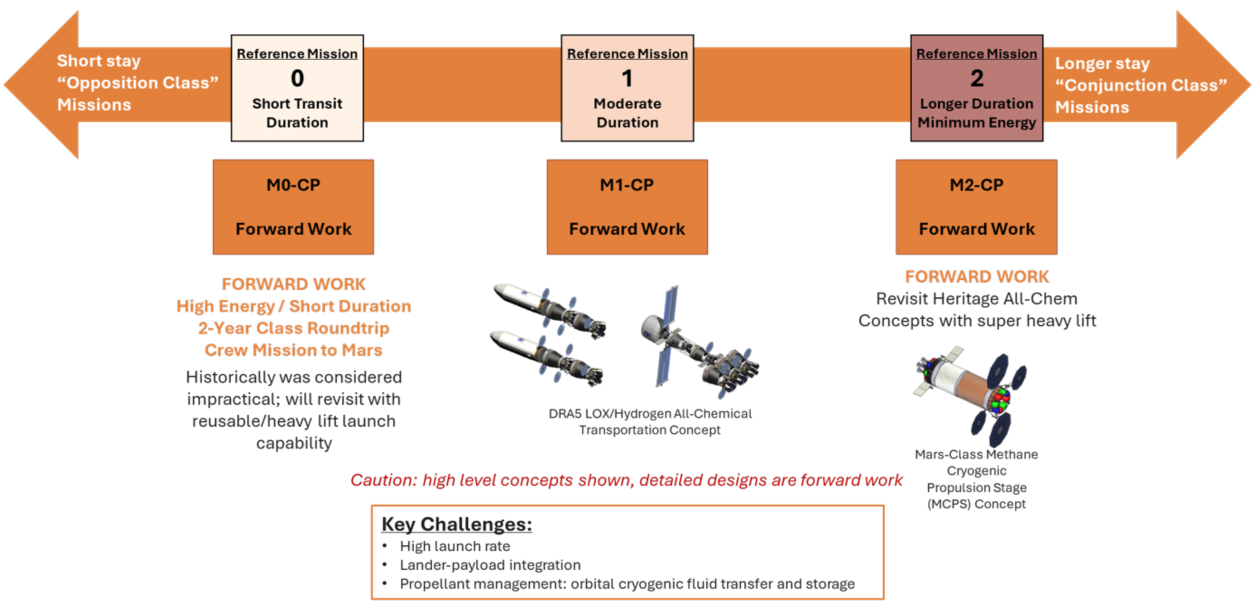


Figure 3-28. All-Chem Concepts Across a Range of Total Mission Durations

3.4.6.4 Concepts of Operations

All four major transportation propulsion system architectures will require multiple Earth launches to an aggregation point, as well as in-space assembly, outfitting, and fueling of the deep space transportation system prior to crew boarding. However, the details of where, how, and when these steps occur vary by architecture, optimization choices made, and potential policy direction.

3.4.7 Mars Crew Support Systems

The Mars crew support architecture category covers elements needed to ensure that crew can perform across multiple mission phases. For the purpose of this document, it is assumed that these systems are common across all transportation architectures and surface concepts.

3.4.7.1 Communications

The Mars surface and close vicinity communications architecture is assumed to closely mirror the Lunar Architecture until further study is completed. A unique challenge for a Mars mission will be addressing the approximately two-week period during which the Sun interrupts the line-of-sight path between the crew and Earth, making direct communication impossible. An uninterruptable relay could mitigate this blackout period, though it should be noted that this potentially increases the communications lag time, since the relay must be placed far enough from Mars to maintain line of sight to Earth when the Sun is between Earth and Mars. In addition to this disruption, the relatively long and variable time delay for communications poses a challenge. Both the disruption and delay will drive a need for more advanced Earth-independent operations.

3.4.7.1.1 Functions

The Mars communications system must transmit voice and data between Earth and the various Mars architecture vehicles (crew and cargo DST, MDS, MAV, and Orion), between Mars architecture vehicles, between Mars surface to Mars orbit, and between surface assets.

3.4.7.1.2 System Concepts

The Mars communications system elements will include communication components for EVA suits, mobility platforms, landers, transit vehicles, and uninterrupted Earth relay. Additional relay assets, if required, will be defined in future studies.

3.4.7.1.3 Concept of Operations

The Mars communications system concept of operations will be substantially different from lunar operations because of the delay caused by the increased distance from Earth-based ground support, up to 22 minutes each way, and the annual communications blackout of up to two weeks. The current architecture concepts posit the Mars transit vehicle acting as the primary relay between the surface systems network to Earth-based networks during the crewed surface phase of the mission. Another concept under consideration is having the surface crew rely on the orbital crew (that remain aboard the Mars transportation system) to provide low-latency verbal guidance and expertise to augment the longer latency-Earth support. It remains forward work to fully develop the Mars communications concept of operations that supports both near- and far-range operations with varying magnitudes of latency.

3.4.7.2 IVA and EVA Suits

3.4.7.2.1 Functions

The primary functions of the Mars IVA suit system are to provide life support and mobility to protect crew from the various environments encountered during Earth or Mars launch and landing. This includes potential contingencies such as cabin depressurization, fire, or toxic atmospheres. In addition, the IVA suit system must provide sufficient safety, mobility, communications, and comfort for crew to perform their duties inside a vehicle.

The primary function of the Mars EVA suit system is to protect crew from the various environments encountered during a Mars mission, independent of a pressurized cabin. This includes potential cabin depressurization or external vehicle contingency excursion events in the deep space transit environment, as well as nominal EVA operations on the Mars surface environment. In addition, the EVA suit system must provide sufficient safety, mobility, communications, and comfort for crew to perform their duties inside or outside a vehicle for time periods of up to a full workday. Functionality and design features of the suit must also support vehicle and element assembly, system check-out, maintenance and repair operations, and mission utilization objectives. The Mars EVA suit must also integrate with Mars surface systems to enable safe, rapid crew ingress/egress to and from Mars surface system habitable volumes.

3.4.7.2.2 System Concepts

Figure 3-26 summarizes the major IVA and EVA suit system concepts and status. The current Mars architecture assumes that IVA and EVA suit system elements used during Earth and Mars launch/entry and microgravity phases will be substantially like those used for similar operations at the Moon. However, the Mars surface suit, intended for Martian surface operations, will have some important differences from its lunar counterpart. The higher Martian gravity may make mass reduction a priority, and the thin Martian atmosphere will require changes in life support system operation. However, increasing mass can also improve joint design for mobility and suit ingress, so mass increases should not be discounted without accounting for the necessary operational, ergonomic, and injury prevention tradeoffs. As noted above, habitable volumes available to at least the first Mars crew are likely to be different than those available to Artemis lunar crews, so ingress/egress strategy for the Mars crew cabins will influence Mars EVA suit design. Finally, planetary protection requirements for Mars are expected to be more stringent than on the Moon, which may influence permissible leakage rates or venting operations, as well as dust control techniques.

Table 3-36. Mars IVA/EVA System Functions and Example Concepts

Functions	Example Concept(s)		Heritage & Status
Crew life support and protection from the environment primarily intended for use inside a decompressed vehicle cabin	Launch and Landing IVA Suit		Orion Crew Survival System planned for use by Artemis
Crew life support and protection from the environment for use inside a decompressed cabin, or for short excursions outside a vehicle in microgravity (not intended for planetary EVA)	Emergency EVA Suit		Reference concept available. May not be required if microgravity EVA suit and Mars surface suit can provide all necessary functionality.

Functions	Example Concept(s)		Heritage & Status
Crew life support and protection from the environment for longer excursions outside a vehicle during Earth-Mars transit	Microgravity EVA Suit		Reference conceptual design available. This concept may be substantially similar to EVA suits used on Gateway. May not be required if no nominal microgravity EVA is planned (default to emergency EVA suit in that case).
Crew life support and protection from the environment for excursions outside a vehicle on the Mars surface	Mars EVA Surface Suit		Reference conceptual design available. Can leverage Artemis lunar suit lessons learned, but the Mars suit will be unique due to gravity, environmental differences, and planetary protection strategies.
Primarily safety equipment, such as tethers	Crew-worn EVA Accessories		Forward work

3.4.7.2.3 Concept of Operation

The Mars IVA suit system concept of operation is expected to be substantially similar to crew Earth launch/landing, lunar transit, and Gateway operations. Mars descent and ascent operations are expected to be similar enough to crew Earth launch/landing that a common IVA suit can be used for both. The Mars EVA suit system will be designed to allow crew members to perform autonomous and robotically assisted EVA exploration, research, construction, servicing, and repair operations in environments that exceed human capability. Current concepts assume the suit can egress and ingress habitable vehicles and provide life support, thermal control, protection from the environment, waste management, hydration and in-suit nutrition, communications, and mobility/dexterity features designed to interact with spacecraft interfaces and supporting tools and equipment, enabling exploration, science, construction, and vehicle maintenance tasks. Advanced concepts may also include designs that support rapid crew ingress/egress (to improve physical health outcomes associated with reduced pressure in suits and to reduce the risks of decompression sickness in crew) and enhance planetary protection protocols for the Mars environment or habitable vehicle and beyond (forward and backward contamination).

Current concepts assume that the pressure garment provides for resizing and modular component interchanges to enable proper fit across a wide range of anthropometries (1st–99th percentile). Interfaces in the Mars portable life support system and pressure garment enable incremental upgrades to new technologies as the mission and destination evolve. Contamination from Mars dust constitutes a challenge to the design of mobility joints and the like, along with solutions to the introduction of surface contamination to crew habitat. The EVA crew will utilize advanced informatics designed into the suit system. These informatics will grant the EVA crew more autonomy with both tasks and suit monitoring due to the signal latency between Mars and Earth. Developing concepts and operations to address compatibility with the chemically reactive soil, as well as forward (planetary protection) and backward (crew health) contamination during crew ingress/egress operations, remains as forward work. As one important link in breaking the chain of backward planetary protection, current operational concepts assume the Mars EVA surface suits are left behind on Mars and crew members return to Mars orbit in their IVA suits.

3.4.7.3 Logistics Management

Requirements for Mars exploration missions often overlap with those driving the Lunar architecture. Where possible, Mars logistics management requirements should be met by leveraging these architectural similarities. In cases where options are also applicable to either the Moon or Mars, Moon to Mars considerations should drive the selection of a concept that can satisfy both. However, some requirements will be specific to Mars and require a different approach.

3.4.7.3.1 Functions

The primary purpose of Mars logistics management is to provide for the transportation, storage, tracking, and disposal of logistics, including crew consumables (e.g., food, clothing), life support system commodities (e.g., breathing air, water), utilization, maintenance and spares, and other supplies and materials needed to implement crewed Mars missions. The logistics functions include coordination with in-space and surface transportation assets for performing support functions (either manually or with robotic assistants) needed to ensure that logistics arrive at the point of use as efficiently as possible. Functional capabilities assumed are detailed in the sections below.

3.4.7.3.2 Mars Transit Logistics Concepts of Operations

Logistics for the in-space phase of the crewed mission are delivered and aggregated within the transportation and habitation system prior to Earth departure. Because of the amount of logistics required for the crewed Mars mission, the majority of the required logistics are delivered to the transportation and habitation system prior to the actual Mars crew departure. Logistics modules (standalone flights, SLS co-manifested, or commercial co-manifested as needed) are used to both supply logistics for crew Gateway/transportation and habitation system operations in those years and to pre-emplace logistics for the crewed Mars mission.

A final logistics module is delivered to the transportation and habitation system in Earth orbit with the Mars crew immediately prior to the Mars mission. This final logistics module is used to deliver the logistics items that are most critical from a lifetime perspective, such as food, medicines, and crew-specific items. The logistics module is detached and disposed of, along with any trash, prior to trans-Mars injection. Lower–time priority items are delivered to the transportation and habitation system earlier.

The logistics stored on the transportation and habitation system prior to Earth departure include all of the logistics necessary to complete the mission. No pre-emplaced logistics are utilized to complete the in-space segment of the Mars mission. The total logistics include the logistics that are required for the crewed in-space duration of the mission, including time in Mars orbit, for the entire crew. While some or all of the crew will nominally spend a portion of that time on the surface, transportation and habitation logistics are still manifested for that period in case the crew are unable to complete the surface mission and must stay aboard the transportation and habitation system. Additional logistics are also manifested to cover the potential maximum crewed pre-departure duration. This period covers the potential Orion launch period, as well as an additional time to allow for logistics transfer and final mission preparations. This will allow Orion enough opportunities to get the crew to the spacecraft in the event of unexpected launch pad delays. Similarly, logistics are manifested to cover the end-of-mission Earth orbital duration, allowing for rendezvous and docking with Orion, as well as any time required for final transfers. If the entire

Orion launch duration is not needed in the transportation and habitation systems, any remaining consumables for that period are disposed of in the logistic module prior to trans-Mars injection.

In addition to the nominal durations listed above, additional logistics are also manifested to cover contingency situations. Contingency gas and water are manifested to cover periods where regenerative ECLSS may be unavailable during repair activities. It is assumed that waste products are stored during this period and then processed after the repair is completed to build the contingency store back up. Additional contingency logistics may be manifested in the safe haven to cover periods where the crew may be forced to shelter there.

Disposal of trash is a key issue for the in-space portion of the Mars mission. Because of the propulsive requirements, it is undesirable to accumulate trash in the transportation and habitation system. Methods to dispose of trash during the transits to and from Mars will be considered to reduce the total transportation and habitation system mass.

3.4.7.3.3 Mars Surface Logistics Concept of Operations

For surface operations, the logistics are pre-positioned in Mars orbit and then delivered to the Martian surface with the crew. Logistics delivery for surface operations is designed to reduce the burden on the crew and to preserve crew time for utilization activities. While logistics may be delivered either internally to the habitable surface elements or in external carriers, it is desirable to deliver the maximum possible amount of logistics in elements directly accessible to the crew, reducing the need to transfer logistics from carriers.

Surface logistics are provided to support the entire surface missions. These include all required consumables and utilization, as well as any maintenance items that are required to provide high availability for surface systems. Logistics are also provided to cover various surface contingency scenarios. This could include consumables to provide protection against system failures, spares for systems, and additional consumables to cover extend duration, if necessary.

Disposal of trash is also a key issue for surface operations. Planetary protection constraints should be considered when disposing of trash on the Martian surface to mitigate forward contamination.

3.4.7.4 Crew Systems

Crew systems for habitability include direct crew care systems, such as food and nutrition consumables and preparation equipment; personal hygiene systems, including body waste management, clothing, housekeeping equipment and consumables; physiological countermeasure systems (such as aerobic and resistance exercise equipment); crew privacy systems; and sleeping accommodations.

Crew systems for in-flight medical operations include medical diagnostic and treatment equipment and consumables typically found in medical kits, plus the appropriate volume and restraints to support and safely restrain an injured or incapacitated crew member. Vehicle systems also need to support accessing and updating crew medical health records, accommodating private medical conferences, and sharing medical data with ground-based flight surgeons. Each program typically includes a more detailed crew health concept of operations document.

Within the architecture, design for crew shall accommodate the physical characteristics, capabilities, and limitations of crew to ensure health, safety, and performance, as well as continued hardware and system functionality. Physical characteristics may include anthropometry as well as range of motion, strength, and visual and hearing acuity. Behavioral capabilities include cognition and perception. Limitations for continued health may include radiation, acceleration and dynamic loads, acoustics, and vibrations, as well as environmental hazards (e.g., thermal, atmospheric, water). Accommodations may drive design for size of physical volumes, configuration of systems within, placement of restraints and mobility aids, accessibility of translation paths through spaces and hatches, and lighting to support tasks, as well as emergencies and circadian alignment for sleep. For usability, durability, and maintenance and training minimization, systems design shall consider how and how often humans perform system tasking, typically planned for via early human system integration and demonstrated by task analysis and human-in-the-loop testing. Systems shall avoid injury to crew through design, such as smoothing of sharp edges, elimination of pinch points, and prevention of unexpected energy release, electrical hazards, or chemical release, etc. Finally, systems shall be designed to account for crew survival during various defined contingency scenarios.

As much as possible, these systems will be derived from Artemis and International Space Station systems, though the longer Mars mission duration, combined with limited resupply options, minimal spare parts, shelf-life limitations, and longer communications lag times will necessarily require modifications, particularly to medical capabilities and food systems. These systems also need to integrate Earth-independent operations strategies to support associated maintenance, repair, state monitoring and diagnostics, etc., during continuous long-duration operation with reduced/delayed ground support capability.

3.4.8 Open Questions, Ongoing Assessments, and Future Work

As noted, objective decomposition and use case and function definitions for the Mars segment have not been fully completed, and much of the trade space, particularly for sustained human presence, is still being assessed. Ongoing studies are evaluating return propellant strategies, surface infrastructure needs, and EDLA options to build integrated end-to-end campaign models, which in turn will support trade studies between the four candidate transportation technologies. Additional analysis remains to evaluate infrastructure and science objective implementation options, assess end-to-end architecture impacts, and develop integrated concepts of operation. Continuing human health and performance research is being assessed in the context of Mars mission durations and operational challenges, and risk mitigation options are being identified and evaluated. These examples are not intended to be a comprehensive list of open work; this document will be updated as additional analysis and research are identified and completed. NASA also commissioned the National Academies of Science, Engineering, and Medicine to perform a study titled "A Science Strategy for the Human Exploration of Mars," which will inform future surface science objectives.

4.0 ASSESSMENT TO THE RECURRING TENETS

Within the Moon to Mars Strategy and Objectives Document, NASA established a high-level set of recurring tenets (RTs) 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. Using these objectives as a guide, the Moon to Mars Architecture and the elements will be managed and coordinated through a framework of sub-architectures and campaign segments to organize the decomposition. The essential nature of this framework is to ensure the progression of development toward greater objective satisfaction through campaign segments to return and sustain human presence in deep space. This constant traceability and iteration through the architecture process between the current state of execution and future goals and desired outcome will ensure infusion of technology, innovation, and emerging partners.

To ensure this progression and iteration of approach, assessments of progress and adherence to the RTs is incorporated as an ongoing process. The Moon to Mars Architecture will be assessed against each tenet, evaluating how these guiding principles are reflected in the current architecture. In addition, potential gaps in the current Moon to Mars Architecture will also be identified to help guide future iteration and refinement of the architecture. These assessments will be coordinated with the stakeholders of each tenet. The assessments are not exhaustive and future revisions of this document will continue to update, evaluate, and assess the progress of the architecture in adhering to the tenets.

4.1 RT-1 INTERNATIONAL COLLABORATION

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

Architecture Assessments:

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

The Moon to Mars Architecture outlines opportunities for international partners to propose cooperation that addresses architecture gaps. To identify mutually beneficial cooperation, 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 formalize the cooperation in an international agreement. At this point, the project formally enters the Moon to Mars Architecture and becomes a part of the next ADD.

NASA has already established significant international cooperative activities in support of Artemis and is actively pursuing discussions with prospective partners about other potential cooperation. The following represent cooperative activities that have been formalized:

- **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:** In 2024, NASA and Japan's Ministry of Education, Culture, Sports, Science and Technology (MEXT) signed an implementing agreement for Japan to provide a pressurized crew rover for the lunar surface. The pressurized rover will provide advanced astronaut mobility and science opportunities for Artemis crewed missions to the lunar surface.
- **Additional capabilities:** NASA is conducting technical studies and discussions with partners such as ESA, JAXA, CSA, MBRSC, the Italian Space Agency (ASI), The French Centre National D'Études Spatiales (CNES), the Australian Space Agency (ASA), the Korean AeroSpace Agency (KASA), and the Luxembourg Space Agency to develop concepts in multiple areas in support of the Moon to Mars architecture, including 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. These partners included ESA, the German Aerospace Center (DLR), the Israel Space Agency (ISA), which provided radiation experiments, and JAXA and ASI, which provided CubeSats. Similar international collaboration is planned for the Artemis II mission.
- **Lunar science:** NASA's Science Mission Directorate (SMD) is leading the CLPS initiative, to deliver payloads to cislunar orbit and the lunar surface. NASA has sponsored CLPS deliveries for payloads from ESA, CSA, 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 will select scientific payloads to be deployed on the lunar surface by the crew. In the recent Artemis III Deployed Instruments call, a dielectric analyzer from the University of Tokyo and JAXA was selected.
- **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:** SMD 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, a radiation experiment on ISA's Beresheet-2 mission, and a neutron spectrometer on JAXA and ISRO's Lunar Polar Exploration (LuPEX) mission. In addition, NASA contributed the ShadowCam, a camera that scans shadowed areas for ice deposits and landing zones, for the Korea Pathfinder Lunar Orbiter (KPLO), which was launched in 2022.
- **Space life sciences and human research**: NASA's Biological and Physical Sciences Division investigate the properties of physical systems, including their functions and behavior, in the Moon's radiation environment and partial gravity. The Human Research Program (HRP) focuses on developing methods to protect the health and performance of humans in space. In addition to the objectives in the Artemis III Science Definition Team Report, research priorities will be based on the 2023 life and physical sciences decadal

survey. Space and life sciences cooperative activities are discussed with international partners in the International Space Life Sciences Working Group (ISLSWG). Human health and biological sciences utilization on Gateway is also coordinated in working groups established through the Gateway Program.

- **Mars science**: 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 the first leg of the joint NASA-ESA Mars Sample Return campaign, which includes several international participants. International partners have contributed in various ways to the NASA-led Mars orbiters, landers, and rovers in the past decades. The International Mars Exploration Working Group (IMWEG) and the Mars Exploration Program Analysis Group (MEPAG) facilitate international dialogue on Mars science.
- **Space communications and PNT**: 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. These international partners include ESA, ASI, JAXA, KASA, ASA, as well as the United Kingdom Space Agency (UKSA), the South African National Space Agency (SANSA), and the New Zealand Space Agency (NZSA), among others. In addition, NASA is coordinating its commercial lunar relay procurement in parallel with a similar ESA commercially supported activity called Moonlight. NASA is also leading an effort to develop and build a ground station network of Lunar Exploration Ground Sites (LEGS), including NASA-owned assets, commercial service–provided assets, and international partner contributions; South Africa and Australia are expected to each host one of these NASA-owned ground stations. NASA is collaborating with other U.S. government departments and agencies to collectively define foundational reference systems and time standards through international standards bodies. The International Committee on GNSS's (ICG) newly formed Lunar PNT Working Group provides a forum for discussing, assessing, and recommending guidance for compatibility, interoperability, and availability among lunar PNT systems.
- **Technology:** International space technology partnerships generally focus on low technology readiness levels and fundamental research, the results of which are then shared publicly. An example of this type of cooperation involves dissimilar but redundant capabilities to augment common technology development objectives, such as NASA's ongoing collaboration with the ASA regarding an alternative lunar surface regolith acquisition capability that will collect and deliver lunar regolith samples to an analysis instrument in support of scientific and ISRU demonstration objectives.
- **Public diplomacy/education:** NASA conducted public diplomacy and educational outreach events before and after the successful Artemis I mission to raise awareness and excitement about the Artemis Program. These efforts included translating the children's book *You Are Going* into languages such as French, German, Italian, and Spanish. Prior to the launch of Artemis I, NASA and the Department of State organized a meeting with all the Artemis Accords signatories to brief them on the mission and NASA's public engagement plans. NASA will continue to consolidate and share Artemis-related educational materials with a global audience.

RT Considerations:

A wide range of international partnerships will support and be enabled by the Moon to Mars Architecture. Cooperation will occur across the full spectrum of opportunities from major elements to utilization. As potential gaps are identified, new opportunities for cooperation will emerge. The architecture will evolve each year as NASA and its prospective international partners discuss collaboration opportunities. International cooperation will advance broad infrastructure, science, exploration, and space technology goals and objectives, as well as education, inspiration, and public engagement.

In addition to bilateral engagements with international partners, NASA will continue to use multilateral forums to articulate its exploration and science objectives, with an eye toward identifying additional areas of potential cooperation:

- NASA hosts annual architecture workshops to provide international partners with updates to the latest ADD and gather stakeholder feedback on how partnerships can help NASA achieve its Moon to Mars Objectives.
- The International Space Exploration Coordination Group (ISECG) is a coordination forum for interested space agencies to share their objectives and plans for exploration.
- The Lunar Surface Innovation Consortium (LSIC) was established by NASA 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.
- The Lunar Exploration Analysis Group (LEAG) was established to support NASA in providing analysis of scientific, technical, commercial, and operational issues in support of lunar exploration objectives and their implications for lunar architecture planning and activity prioritization.
- The Mars Exploration Program Analysis Group (MEPAG) serves as a community-based, interdisciplinary forum for inquiry and analysis to support NASA's Mars exploration objectives. MEPAG is responsible for providing the science input needed to plan and prioritize Mars exploration activities.
- The Solar System Exploration Research Virtual Institute (SSERVI) was formed 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. SSERVI funds investigators from a broad range of domestic institutions and brings them together with international partners to enable new scientific efforts.
- The International Mars Exploration Working Group (IMEWG) 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 (ISLSWG) 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 (IOAG) provides a forum for identifying common needs and opportunities for interoperability in mission operations, space communications, and navigation interoperability.
- NASA and the Department of State engage with the community of Artemis Accords signatories to discuss the implementation of the principles of the Accords to ensure safe and sustainable space exploration.

4.2 RT-2 INDUSTRY COLLABORATION

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

Architecture Assessments:

NASA has long called upon the U.S. industrial base to provide the development and production of key exploration assets and provide foundational research to advance and enhance exploration capabilities. U.S. industry partners have contributed to the success of the Artemis I flight, which includes major hardware deliveries for three programs: EGS, Orion, and SLS. U.S. industry contributions will be critical throughout the Moon to Mars campaign segments. 2The elements included in the Human Lunar Return segment are already leveraging 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 III through V. Additionally, the Moon to Mars Program 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 is aligned with mission priorities and schedules.

Historically, NASA has partnered with industry to develop capabilities and technology that are needed for exploration, science, and technological development. STMD is collaborating with industry on technology developments in major areas including, enabling safe landing on the lunar surface, enabling or increasing the ability to live in the lunar environment, and increasing our capability to explore the lunar surface. NASA expects to develop or increase capabilities that lower crew risk and increase crew survivability in harsh environments, provide evolvable communication and power systems, and develop in-situ manufacturing methods. The successful deployment of these capabilities will further enable the development of habitable structures and critical improvements in infrastructure, which will likely increase mission effectiveness, mission durations, and overall safety. To expand our ability to explore during later Artemis missions, NASA is focusing on technologies to increase the ability to map and locate lunar features, navigate in complex terrain, and travel between lunar surface assets.

Through the CLPS Program, NASA has engaged U.S. industry in a new way, introducing members of academia that wish to perform standalone cislunar science missions and corporations that desire to test hardware in the lunar environment to suppliers of multiple launch vehicles and lunar landers. This 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 this partnership. NASA will continue collaboration with industry to develop technologies that continue to enable exploration, science and technology maturation, or demonstrations in preparation for Mars. The Moon to Mars Architecture will depend on partnership with U.S. industry to provide exploration services and critical technologies in a sustainable and affordable manner.

RT Considerations:

U.S. industry contribution in future segments to enable exploration activities has not been fully captured or leveraged. With significant commercial interest in developing LEO destinations in the near future, NASA needs to investigate opportunities to leverage and potentially supplement those investments to advance the state of knowledge of human spaceflight in support of the Moon to Mars Architecture. NASA will leverage U.S. industry plans for cislunar and lunar commercialization and look for key opportunities for partnering in support of long-term exploration of the lunar surface and Mars in a sustainable way. NASA will team with industry to develop and mature systems that will contribute to future Artemis missions and are beneficial to the commercial partner. Some potential areas for collaboration of U.S. industry and the Moon to Mars Program are:

- Team with industry to develop, verify, and sufficiently validate new technology that future missions will need.
- Partner with industry to mature current technologies with risk and cost-cutting potential.
- Understand industry goals and 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, which could include robotic interfaces; software information and management systems; rover systems; in-space servicing, assembly, and manufacturing (ISAM); power systems; and habitation systems.
- Collaborate with industry through appropriate mechanisms to address and resolve technical issues related to space exploration.
- Request industry develop concepts for the end-to-end management of pressurized logistics, beginning with loading on Earth and ending with the disposal or reuse of containers.
- Request industry develop concepts for the provision of uncrewed transportation capability for lunar surface assets.
- Encourage industry collaboration in specific areas (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 the use of technology demonstration and the communication of long-term strategic goals.

4.3 RT-3 Crew Return

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

Architecture Assessments:

In recognition of the inherent risks associated with human spaceflight, NASA considers the wellbeing and safe return of crews to be of paramount importance. Considerations for safe crew return start well before the mission and are included in the system design, test and verification, and end-to-end mission testing and training using high-fidelity hardware, software, and mission support personnel. The following top-level standards to ensure safe crew return are assessed and appropriately applied across the architecture:

- 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)

These requirements are tailored and applicable to every crewed vehicle across all campaign segments, including the integrated architecture or system of systems. For each crew mission, the integrated system capabilities will be assessed and certified as acceptably safe to carry NASA or NASA-sponsored crewmembers by meeting the 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. While hazard controls (and required control redundancy) prevent hazardous events from occurring, crew survival methods are an independent layer of protection in the event those controls fail and enable the crew to survive the immediate hazard, reach a safe state, and ultimately return to Earth. The Moon to Mars Program will derive contingency and abort use cases and functions by applying the Human Rating Standard. The results can be broadly categorized as architecture capabilities/system and integrated mission operations, which include strategies, constraints, and vehicle uses to manage crew risk.

Architecture capabilities/system provide:

- Appropriate failure tolerance to catastrophic hazards, which can include 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; the strategy may include pre-cursor uncrewed demonstrations and an incremental approach to build up capability (e.g., two crew for HLR; increasing to four crew for FE)
- Clear mission authority, roles, and responsibilities across the entire Artemis team
- 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)
- 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:

- Uncrewed initial lunar mission demonstrated the crewed launch and reentry systems prior to crewed flight.
- Crewed initial lunar mission will demonstrate life support and habitability in the lunar vicinity while minimizing return risk via a free-return trajectory.
- Crewed initial lunar surface mission will demonstrate complex operations with 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 sustainable crewed and uncrewed mission capabilities in lunar orbit and on the lunar surface.
- As new assets are added in the Artemis campaign program, to extend human exploration further across the lunar surface, ensuring safe crew return will become increasingly complex and crew return will rely on EVA suits, rovers, surface habitats, landers, Gateway, and Orion, plus any supporting architecture, like communication and power systems. Furthermore, NASA's experience is to maintain a crew presence with the crew return vehicle; however, Artemis will demonstrate the concept of landing all crew on the lunar surface while Gateway/Orion is unoccupied.

RT Considerations:

The Moon to Mars Architecture treats the safety of the crew as an utmost concern. However, significant knowledge gaps exist relative to the adverse effects of long-term exposure to the deep space environment. The architecture will be developed to account for known health and medical concerns and for contingency scenarios involving failures in mission elements and systems. Significant knowledge has been gained from ongoing human health research aboard the International Space Station and will continue with lunar orbital and surface missions. Long-duration Mars precursor missions conducted in cislunar space and on the lunar surface will address some knowledge gaps and build operational experience. Likewise, knowledge of the reliability gaps with mission hardware, software, and operations will be tested and refined based on knowledge of 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 the Mars exploration crew, regardless of the architecture, and that lack remains a significant challenge to crew safety.

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 and may not significantly shorten the return. Extending the capabilities outlined above will require a combination of system reliability, system redundancy, vehicle/crew autonomy, critical sparing, abort and crew survival options, crew health/performance/psychological support, and general robustness at a level higher than previous missions. The fault tolerance approach, covered in the previous section, is applicable for Artemis lunar missions but may need to be reassessed for Mars missions.

The following set of challenges are included in the "architecture gap" section for context. Some of these gaps may not be solved by the architecture alone; they are gaps in the knowledge, experience, and technology required to advance, test, and implement more complex lunar and Mars missions.

- Onboard autonomy capabilities for a Mars crew and their vehicle to account for time latency to Earth and time-to-effect events. Essentially, the crew will not have the real-time response capability of the mission control center (MCC).
- In the event of an unrecoverable loss of communication with Earth during lunar and Mars missions, onboard autonomy should provide a safe crew return, which includes 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.
- Capabilities for a Mars crew to monitor, command, and control any uncrewed vehicle from other vehicles in the Mars vicinity to ensure their safe return. NASA's historical experience is to maintain a crew presence with the crew return vehicle. Artemis will demonstrate the capability to send the entire crew to the lunar surface with MCC oversight of nominal and off-nominal events aboard the uncrewed vehicles.
- Availability of robust crew survival methods, which may include safe havens, additional resources, rescue systems/vehicles, and more.
- Advanced health and performance monitoring and response, both onboard and on the ground.
- High-bandwidth telecom capabilities to upload video learning or instructional materials to guide medical procedures or critical equipment repairs that will be needed during multi-year crewed missions to Mars.

4.4 RT-4 Crew Time

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

Architecture Assessments:

One of the three pillars of the exploration strategy that guides the Moon to Mars Architecture is the pursuit of scientific knowledge. Maximizing crew time is a critical driver for the exploration architecture across all segments of the campaign. Specifically, this refers to crew time made available for utilization activities, separate from other crew time allocations, such as maintenance time. During the lunar campaign segments, the architecture and reference missions emphasize crew exploration on the lunar surface. This is enabled by allocating functions to the elements in this phase to minimize maintenance and construction overhead activities. Concurrently, utilization activities at Gateway are conducted in cislunar space to complement the surface exploration activities. The experiences gained in the exploration activities with the optimization of surface exploration missions on the Moon will guide the planning for the initial Mars surface mission to maximize the efficiency of crew time available for science and engineering activities.

Similar to RT-3, the approach is a combination of architecture/system capabilities and integrated mission operations to optimize crew time allocated towards exploration and utilization.

Architecture/System capabilities:

- Lunar campaign elements have allocated limited time for system maintenance on Gateway, HLS, EVA suits, and rover(s). This may be designed and implemented via system reliability, sparing strategy, crew accessibility, ease of use, operational use, and other methods.
- Engineering, operations, and crew evaluations of vehicle mockups and simulations influence capabilities in early design and development to enable reliable and efficient operations.
- Campaign elements incorporate automation/autonomy for routine housekeeping and system management to offload crew.

Integrated mission operations:

- Artemis crew training and integrated Artemis mission simulations (with full team) commence approximately two years and one year before the crew launch, respectively. These milestones drive the vehicle and personnel readiness to allow sufficient time to train critical skills and tasking across all Artemis vehicles and utilization tasks.
- Artemis training philosophy exercises the crew and ground teams in mission planning, decision making, and execution of critical and complex tasks. In addition to the skills, a time multiplier is applied in ground training for every hour of critical/complex mission execution to ensure efficient use of crew time.
- Distribution of system (monitor/control) functions from crew to the MCC to will enable more crew time for exploration and mission objectives.
- Use of tele-robotics, robotic assistance, and autonomous systems to increase crew time and effectiveness for science and utilization. For example, uncrewed operations like pre-positioning an asset can reduce the crew task burden before they arrive.
- Development of contingency plans and capabilities, including backup crew, to allow the mission to continue for non-critical events.
- Availability of task lists or alternate plans to efficiently pivot from the nominal plan and optimize the mission results. For example, if a lower-priority EVA or surface utilization task becomes time consuming, the crew may pursue other achievable tasks on the fly to optimize utilization. This may also include get-ahead tasks to support a downstream activity or a future Artemis mission.

RT Considerations:

There are knowledge gaps associated with the increasing exploration infrastructure and capabilities needed for the Foundational Exploration, Sustained Lunar Evolution, and Humans to Mars segments. Although these increases are intended to result in a net benefit to available crew time, there is some uncertainty associated with the operational complexity, maintenance, and refurbishment demands they bring. Additional assessment is needed to bridge the knowledge gap and inform system design and operational planning.

4.5 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.

Architecture Assessments:

To enable a safe, effective, and affordable architecture that achieves NASA's long-term exploration goals, the Moon to Mars Architecture must be assessed to understand the implication of system maintainability, reuse, and/or recycling in support of long-term operation and increase Earth independence. Almost every element in the architecture is being designed to take advantage of some level of reuse, but understanding of risks associated with maintainability and reuse and their impact on safety, science, and long-term sustainability goals will be vital as the architecture is refined and matured. Beyond the sustainability of elements with maintenance, there is also the opportunity to further enhance crew safety, with proper planning, by enabling the repair of systems that would otherwise put the crew in a survival situation or lead to a catastrophic hazard.

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 of time 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 principal areas drive maintainability and reuse within the Moon to Mars Architecture: mass delivery and available crew time. The delivery of mass to lunar orbit, the lunar surface, or Mars has 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 is currently an architecture gap that needs additional development of concepts, potential operations, and understanding of potential tasks that can leverage the use of robotics and/or automation.

The Moon to Mars Architecture will promote the use of common orbital replaceable units (ORUs) when a common component can be incorporated into designs and must be periodically replaced (e.g., air filters). This philosophy will allow a set of ORUs to be shared across multiple elements within the architecture, thus reducing the amount of logistics and increasing contingency options. In addition, an EVA compatibility standard has been developed to ensure ORUs and worksites are compatible with the spacesuit interaction, range of motion, and do not present hazards to the crewmember.

Because many of the major systems in the Moon to Mars Architecture are designed to be in either lunar orbit or on the lunar surface for multiple years and missions, extended gaps between missions drive systems to react, 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 will increase crew time for science and exploration.

As a preventative measure, it is important that designers consider reliability early in the design process to reduce future maintenance needs of a system and target a practical mean time to repair. Designing systems with human factors in mind to achieve easy accessibility, standardized replacement methods, and limited specialized tool requirements and considering the training required to perform maintenance operations should be key parts of the up-front design process. The combination of the complex lunar environment, with its changes in lighting conditions and terrain variation; the variety of systems being developed; and the need for crew time to perform science, exploration, and technology demonstrations point to a stronger need to reduce mean time to repair.

Moon to Mars architects and designers must also consider uses for decommissioned hardware. Can batteries or other consumables be recycled or reused? Could targeted system components be repurposed or reused beyond their original functions for another vehicle or element? Initially, the reuse of components or system may not be possible, but as we learn more about the lunar environment and ORU designs evolve, a good steward strategy will be developed.

RT Considerations:

The maintainability of the exploration assets remains a major concern especially with the desire to maximize crew time for science and engineering activities. Traditionally, a certain level of crew time was dedicated to the maintenance of systems to extend the lifetime of any asset. However, the advancement of robotics and autonomous systems provides a range of options for the maintenance of systems. Trades must be performed to determine which systems and maintenance tasks should be automated and which should be manually performed. Other areas of maintainability that should be studied include:

- Incorporation of robotic systems to perform maintenance on one or more lunar surface systems.
- An integrated system to track maintenance items/ORUs location and availability across the Moon to Mars Architecture.
- A process to dispose of or reuse systems or selected system components upon completion of their primary mission.
- Should a modular open systems approach be applied, and at what level, to enable a long-term autonomous repair capability supporting the Sustained Lunar Evolution segment?
- Evaluation of in-flight maintenance strategies 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 Artemis campaign, could enhance maintainability and reuse of systems. Each of these design features has an associated cost that must be considered along with the potential benefits. The Moon to Mars Architecture should consider incorporating such design features, including:

- Maintenance items/ORUs designed to provide notification of a degraded capability or failure to the broader system, allowing timely corrective actions to be taken.
- Maintenance items/ORUs designed to be easily exchanged, both manually and by robotic means.
- Design systems/components to be robotically manipulated so that tasks can be performed without crew present.
- Design major systems to be maintained using robotic capabilities — either automated or remotely operated under a variety of environmental conditions.

- Reduce the logistics train as much as possible by using common limited-life items (e.g., filters, lights).
- Standardize or require a set of common battery sizes, including enclosures and contact points.

Additional assessment is needed to bridge the knowledge gap and inform system designs and operational planning. The reuse of elements will also likely require the refurbishment of elements and these activities are not well defined within the current architecture. Finally, system lifetime limitations from both reuse and maintenance perspectives must be evaluated.

4.6 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.

Architecture Assessments:

Responsible use of space follows guidelines and principles of responsible behavior that are set forth in international agreements, international and national policies, and law. Given the uncertainties about how humanity will explore the broader solar system, questions about the nature of responsible activity will surely arise. The likelihood of creating a future where humanity collectively benefits from Moon to Mars activities will be increased by considering the responsible use of space from several legal, policy, ethical, and societal perspectives. The following context explores relevant history for how to consider the responsible use of space.

The legislation that founded NASA declared 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."[16] The U.S. also ratified the Outer Space Treaty of 1967, which identifies principles of behavior that represent the belief that the exploration and use of outer space should be for peaceful purposes, for the benefit of all peoples, and contribute to broad international cooperation in scientific and legal aspects of exploration. Article VI is of specific interest, as it expands the obligation of nations to ensure responsible behavior, even when activities are carried out by "non-governmental entities," like commercial companies. This extends to private-sector operations not conducted on behalf of a nation. In addition, Article IX addresses the avoidance of harmful (forward) contamination, and of adverse consequences to the terrestrial biosphere from introduction of extra-terrestrial material (backward contamination), typically managed under planetary protection.

The Artemis Accords reinforce and implement key obligations in the 1967 Outer Space Treaty. They also reinforce the commitment by the U.S. and signatory nations to the Registration Convention, the Rescue and Return Agreement, and best practices and guidelines for responsible behavior that NASA and its partners have supported, including the public release of scientific data. The Artemis Accords establish a practical set of principles to guide space exploration cooperation among nations, including those participating in NASA's Artemis Program. Key tenets of the Artemis Accords include:

- Calls for partner nations to utilize open international standards, develop new standards when necessary, and strive to support interoperability to the greatest extent practical.
- Calls to provide public information regarding the general nature of operations, which will inform the sale and scope of safety zones to deconflict activities.

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

- 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.

The tenet of "responsible use of space" became enshrined in the 2010 National Space Policy, which sought to encourage responsible use of space and the long-term sustainability of the space environment, with a focus on the minimization of debris. The 2020 U.S. National Space Policy provides additional clarity on the definition of responsible norms of behavior. It defines and advocates for development and promotion of responsible behaviors, including "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 adds additional considerations about the responsible use in space. It leads with the concept that activities in space benefit the American people and that the U.S. should "lead the international community in preserving the benefits of space for future generations." The section on maintaining a robust and responsible U.S. space enterprise notes that "such efforts will be informed by economic data and research to better understand the space economy and will reflect the importance of the responsible and sustainable use of space." The section on preserving space for current and future generations acknowledges that as space activities evolve, norms, rules, and principles also must evolve. It goes on to clarify that "the United States will bolster space situational awareness sharing and space traffic coordination." It also identifies responsible behaviors; of interest here are "minimize the impact of space activities on the outer space environment" and "protect the Earth's biosphere by avoiding biological contamination by spacecraft returning to Earth."

In April 2024, NASA defined space sustainability in its release of its Space Sustainability Strategy, Volume 1: Earth Orbit 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 would be forthcoming.

NASA has provided domestic guidance on the preservation of lunar heritage sites, and the preservation of ongoing science at those sites, in its 2011 report NASA's Recommendations to Space-Faring Entities: How to Protect and Preserve the Historic and Scientific Value of U.S. Government Lunar Artifacts. The report's recommendations were enshrined into law in 2020 under the One Small Step To Protect Human Heritage Space Act (P.L. 116-275), which required that NASA add these recommendations into its contracts, grants, agreements, or other arrangements. The Lunar Exploration Analysis Group, an interdisciplinary group created to "support NASA in providing analysis of scientific, technical, commercial, and operational issues in support of lunar exploration objectives and of their implications for lunar architecture planning and activity prioritization," created a 2016 Lunar Exploration Roadmap that provided goals, objectives, and investigations for lunar science, and detailed preservation priorities to enable future lunar science. However, there is no overarching U.S. guidance on the safe, peaceful, and responsible use of space to ensure the preservation of Moon to Mars sites to meet long-term heritage, technical, scientific, or other conservation objectives.

In establishing the Artemis Accords, NASA is signaling intent for responsible behavior around Moon to Mars efforts and has identified a need for practices, rules, and standards in a number of areas that will be addressed by signatories moving forward. Development of technical and policy guidance on the responsible use of space and sustainable operations in Moon to Mars efforts should seek to build upon existing domestic and international practices. NASA is working to identify gaps in best practices for safe, peaceful, and responsible space operations for Moon to

Mars and intends to engage and work with Artemis Accords signatories and international technical and standards bodies on the issue.

From a technical perspective, payloads manifested on CLPS flights to the Moon are collecting data needed to enable future responsible behavior. For example, the Stereo Cameras for Lunar Plume-Surface Studies (SCALPSS) is an experiment to determine 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. Ongoing work in multilateral coordination groups such as the International Space Exploration Coordination Group (ISECG), Inter-Agency Space Debris Coordination Committee (IADC), Interagency Operations Advisory Group (IOAG), International Astronomical Union (IAU), International Committee on GNSS (ICG), and the International Telecommunications Union (ITU) may provide venues to develop further approaches to the sustainable use of space to meet Moon to Mars Objectives.

Recent calls from the 2022 planetary science and astrobiology decadal survey and the National Science and Technology Council's cislunar strategy 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 cultural and societal implications of future human exploration.

RT Considerations:

While NASA and its partners have made the commitment to pursue peaceful exploration and responsible use of space, significant policy questions and framework gaps exist with regard to the protection of future scientific and exploration needs. While there are treaties, law, policy, and guidelines on responsible use, the implementation is still in development. The Artemis Accords signatories are working on some of those issues now. Future success or failure will be driven by processes that embed responsible use in the exploration architecture as it is developed and implemented through programs, projects, procurements, and operations.

Given the global impact and influence of space exploration on the human condition, NASA must think about responsible use broadly, including the impact of Artemis on society. For conversations and considerations of this nature to be effective, NASA must avoid making premature judgements about behaviors or outcomes. There must be discussion of costs in addition to benefits, with a goal of maximizing benefit to society, while minimizing potential harms. Reflection and discussion can be facilitated by deliberate analytical conversations as part of the architecture and systems engineering process. NASA has a mandate to explore and has now published objectives that outline what needs to be done to enable exploration of the inner solar system. Decisions about how those objectives are accomplished must also consider their meaning and impact.

For future ACRs, NASA will continue to reflect on how to best pursue responsible use of space.

4.7 RT-7 Interoperability

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

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. Artemis programs have applied existing interoperability standards in many areas of system design, including avionics, communication, PNT, docking, power rendezvous, 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 addition to the interoperability areas mentioned above, NASA is implementing interoperability standards in the areas: ECLSS, robotics, thermal control, logistics, and utilization. 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 to assign responsibility for ensuring needed standards are developed and applied.

The International Deep Space Interoperability Standards[17] serve as the starting point for future interoperability assessments. Currently, nine International Deep Space Interoperability Standards exist and continue to be refined as needed. Two additional standards have identified forward work to be addressed. To the greatest extent possible, interfaces are being developed to enable application of the same or very similar interface to be used during the Humans to Mars segment. Other actions taken to improve interoperability within the Moon to Mars Architecture include the following:

- Since 2020, The Moon to Mars Program has begun releasing interoperability standards as Moon to Mars Program documents to facilitate their application in NASA's cislunar and lunar surface activities.
- ACR process will endorse new and revised interoperability standards to ensure broad awareness and acceptance.
- Architectural studies have mapped functional interoperability between systems assumed to be deployed for a given mission. These assessments have been and are being updated to reflect changes in the mission assumptions. The related results have already driven changes to the communication systems, identified potential gaps, and initiated specific tasks focused on closing assumptions and requirements.
- NASA developed a document that defines physical, data, power, and other interfaces for utilization across the Moon to Mars Architecture. The interfaces are consistent with existing Gateway requirements, the International Space Power System Interoperability Standards (ISPSIS), the International External Robotic Interface Interoperability Standards (IERIIS), and other applicable standards and supports the movement of payloads between systems.
- A standard for the development of graphical user interfaces across Artemis has been developed and approved. This standard helps establish a usable design framework, with consistency for critical components 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.
- The Icon and Symbol Library drives commonality in the use of icons and symbols across Artemis flight and lunar surface systems. The document includes icons and symbols approved for Orion consistently used by Gateway and HLS systems. As new symbols and icons are developed for new functions, the document will be updated and shared throughout NASA and with partners in international space agencies, industry, and academia. This should further promote consistency across multiple lunar and Mars systems while also increasing the overall ease of use.

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

- Evolving lunar power concepts and emerging issues have impacted program/project analysis cycles that are driving trade studies and other specific analysis. One of the results of these discussions is the assignment of a task to determine which systems should be able to share power, and what power quality should be shared for each defined mission.
- A related item is the need for a standardized power connector for use on the lunar surface. Discussions have focused on dust tolerance, what voltages needs to be transmitted, the need to be "bi-directional," and other requirements to allow functionality with and without suited crews.
- The Moon to Mars Program maintains an interoperability working group and has participated in several forums addressing interoperability, including the Lunar Surface Innovation Consortium (LSIC), Lunar Exploration Analysis Group (LEAG), and the Mars Exploration Program Analysis Group (MEPAG). Interoperability is also one of the Artemis Accords principles. These forums enable sharing of concepts, hearing international partner, commercial, and academic perspectives, and facilitate community consensus.
- NASA has developed and traced RPODU requirements to the system-to-system level to ensure that all requirements for planned and contingency docking operations for Artemis III and IV are addressed and have appropriate verification planning. This activity highlighted a gap in testing and verification activities supporting contingency docking.
- The LunaNet Interoperability Specification for lunar communication and PNT standards have been developed by a team from NASA, ESA, and JAXA, with input from the Interagency Operations Advisory Group (IOAG) and other government and commercial entities. The specification has been applied as a requirement in the NASA and ESA service procurements and is gaining widespread acceptance.
- Another aspect of interoperability is the mission operations and crew interactions across all the Artemis elements. To address this, the Artemis Flight Operations Standards were baselined and contain details of NASA expectations for operational products, processes, and facilities. NASA-operated vehicles (e.g., Orion, Gateway) use this consistent approach and NASA coordinates these standards and integrates mission operations with all providers across the Artemis campaign.

RT Considerations:

The RTs guide interface standardization for all elements, but specific designs and requirements for interoperability are still being studied and refined. In many cases, these studies focus on a subset of relevant elements and may fall short of enterprise-wide coordination. Three examples of lunar surface gaps related to the Moon to Mars Architecture are:

- 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 IERIIS currently only addresses robotic attachments in a microgravity environment. It needs additional work to define requirements for operation on the lunar and Martian surfaces.
- Creating an interoperable network that enables data connectivity, command, and control among a distributed set of local and remote users is an area of open work.

Efforts have been initiated to address the identification, development, approval, and levying of interoperability standards in the Moon to Mars Architecture. These efforts are being developed to govern cross-program and cross-partner element application. Architectural needs will guide the development of interoperability artifacts which, when communicated through NASA to international and commercial partners for feedback, will drive system configuration functions and requirements.

4.8 RT-8 Leverage Low Earth Orbit

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

Architecture Assessments:

The Moon to Mars Architecture builds upon and leverages 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 hosted a continuous human presence in LEO for more than two decades. During this time, over 3,700 scientific experiments have been conducted and more than 270 astronauts from 21 countries have lived and worked there. The space station has facilitated the development of mature technological and operational concepts that will be leveraged as we embark upon more complex missions much further from home.

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 (CLDs) become available, NASA intends to implement an 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 towards 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 may include 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, and others.

RT Considerations:

Potential opportunities to leverage LEO infrastructure have not been fully explored, and additional studies and refinement are needed to evaluate all available options. LEO will be leveraged to the extent practical to inform human system risks for Mars, despite inherent limitations in the fidelity of certain spaceflight hazards. NASA will continue planning to ensure we take full advantage of the International Space Station before its planned decommission after 2030, and to ensure we 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.

4.9 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.

Architecture Assessments:

NASA and its partners have a clear intent to stimulate the expansion of the economic sphere. The industrial base has always been an enabler of space exploration activities. Historically its role has included development of technologies and systems for use in NASA missions. Over the last few decades, this role has evolved to even greater public-private partnerships, and even primarily commercial-driven endeavors in space. Using the foundation of policy, the Moon to Mars Architecture further fosters commercial industry and economic opportunities beyond Earth orbit. Indeed, the architecture seeks the expansion of the economic sphere in all architecture segments, explicitly aiming to build a future of economic opportunity, expanded utilization (including science), and greater participation on and around the Moon and in the rest of the solar system.

Existing policy and legislation provide the basis for measuring progress toward RT-9. Such 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 and 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 will help provide the means by which economic activity beyond agency could take root. Examples of such areas in near- and farther-term areas include 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 systems 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, invested in multiple performers with the goal of generating commercial suppliers. These commercial elements 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 the reasons for and a culture of exploration that excite governments, companies, and private citizens to venture away from Earth. It seeks to establish the science discoveries and capabilities that will bring continued expeditions to answer key questions about the Moon and the universe. It 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 to 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.

RT Considerations:

While the current architecture makes progress towards this tenet, the undefined Sustained Lunar Evolution segment specifically has areas that point 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, 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 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 as it expands architecture and systems beyond the Moon.

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. This includes 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. This includes 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:

- 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. Resource exploration 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 around the world for lunar capabilities given the likely limited non-NASA sources of recurring revenue for lunar activities in the near to mid term.

APPENDIX A: DECOMPOSITION OF OBJECTIVES

This appendix shows the decomposition for the lunar and Mars objectives into characteristic and needs, use cases, and functions.

A.1 FULL LUNAR OBJECTIVE DECOMPOSITION

Functions		Use Cases		Characteristics/Needs		Objectives	
Transport crew from cislunar space to lunar surface sites in the south pole region	**FN-T-102 L**	Transportation of crew between cislunar space and lunar south pole region landing sites	**UC-T-105 L**	Visit diverse sites of key scientific interest on the lunar surface, including polar and non-polar destinations to address high priority science goals.	**CN-T-108 L**	Uncover the record of solar system origin and early history, by determining how and when planetary bodies formed and differentiated, characterizing the impact chronology of the inner solar system as recorded on the Moon and Mars, and characterize how impact rates in the inner solar system have changed over time as recorded on the Moon and Mars.	**LPS-01 LM**
Transport crew from the lunar surface to cislunar space	**FN-T-104 L**						
Enable crew habitation during transit from cislunar space to lunar surface sites in the south pole region	**FN-T-108 L**						
Enable crew habitation during transit from the lunar surface to cislunar space	**FN-T-110 L**						
Transport crew from cislunar space to distributed sites outside of the south pole region on the lunar surface	**FN-T-103 L**	Transportation of crew from cislunar space to distributed landing sites outside of the south pole region on the lunar surface	**UC-T-106 L**				
Enable crew habitation during transit from cislunar space to distributed sites outside of the south pole region on the lunar surface	**FN-T-109 L**						
Transport a small amount of cargo (10s of kg) from the lunar surface to Earth	**FN-T-207 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-301 L**	Transfer, return, and curate a small amount (10s of kg) or a large amount (100s of kg) of unconditioned samples and containers from key destinations across the lunar surface and back to Earth, while maintaining scientific integrity of the samples.	**CN-T-302 L**		
Transport a small amount of cargo (10s of kg) from the lunar surface to cislunar space	**FN-T-209 L**						
Transport a small amount of cargo (10s of kg) from cislunar space to Earth	**FN-T-211 L**						
Reposition a small amount of unconditioned samples and containers (10s of kg) on the lunar surface	**FN-M-504 L**						
Stow collected unconditioned samples on exploration assets while on the lunar surface, while maintaining scientific integrity of the samples	**FN-U-401 L**						
Transport a large amount of cargo (100s of kg) from the lunar surface to Earth	**FN-T-208 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-302 L**				
Transport a large amount of cargo (100s of kg) from the lunar surface to cislunar space	**FN-T-210 L**						
Transport a large amount of cargo (100s of kg) from cislunar space to Earth	**FN-T-212 L**						
Reposition a large amount of unconditioned samples and containers (100s of kg) on the lunar surface	**FN-M-505 L**						
Stow collected unconditioned samples on exploration assets while on the lunar surface, while maintaining scientific integrity of the samples	**FN-U-401 L**						
BLANK	**BLANK**	Delivery of collected samples to curation facilities or other appropriate facilities on Earth, while maintaining scientific integrity of the samples	**UC-G-202 L**				

Functions		Use Cases		Characteristics/Needs		Objectives	
Provide high bandwidth, high availability communications and data exchange between the lunar surface and Earth	**FN-C-105 L**	Communications and data exchange with high bandwidth and high availability between assets on the lunar surface and the Earth	**UC-C-101 L**	Provide the ability for the Science Team to directly or indirectly communicate in real-time via either written or verbal means with the crew for EVA and IVA activities.	**CN-C-106 L**		
Enable crew lunar surface extravehicular activity in sunlit areas and non-PSRs	**FN-M-101 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-301 L**	Identify, collect, and document surface and shallow subsurface samples from key destinations in non-PSRs and other sunlit areas on the lunar surface, while maintaining scientific integrity of the samples.	**CN-U-303 L**		
Enable local unpressurized surface mobility in sunlit areas and non-PSRs at distributed sites on the lunar surface	**FN-M-303 L**						
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 L**						
Provide communications and data exchange between assets on the lunar surface	**FN-C-103 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-202 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 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-U-102 L**				
Provide position, navigation, and timing services at the south pole region on the lunar surface	**FN-C-201 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						
Provide a robotic system capable of conducting reconnaissance	**FN-A-103 L**						
Control robotic system(s) in sunlit areas and non-PSRs on the lunar surface from Earth and/or cislunar space	**FN-A-201 L**						
Enable crew lunar surface extravehicular activity in sunlit areas and non-PSRs	**FN-M-101 L**	Crew identification of surface samples in sunlit areas and non-PSRs in the south pole region on the lunar surface	**UC-U-103 L**				
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 L**						
Provide position, navigation, and timing services at the south pole region on the lunar surface	**FN-C-201 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						
Capture imagery on the lunar surface	**FN-U-102 L**						
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 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-105 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-202 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						
Provide a robotic system capable of conducting reconnaissance	**FN-A-103 L**						
Control robotic system(s) in sunlit areas and non-PSRs on the lunar surface from Earth and/or cislunar space	**FN-A-201 L**						

Functions		Use Cases		Characteristics/Needs		Objectives	
Provide communications and data exchange between the lunar surface and Earth	FN-C-101 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-106 L				
Provide position, navigation, and timing services at the far side and outside the south pole region on the lunar surface	FN-C-203 L						
Provide a coordinated lunar time scale	FN-C-205 L						
Provide a robotic system capable of conducting reconnaissance	FN-A-103 L						
Control robotic system(s) in sunlit areas and non-PSRs on the lunar surface from Earth and/or cislunar space	FN-A-201 L						
Enable crew lunar surface extravehicular activity in sunlit areas and non-PSRs	FN-M-101 L	Crew identification of surface samples in sunlit areas and non-PSRs in distributed sites on the lunar surface	UC-U-107 L				
Provide communications and data exchange between the lunar surface and Earth	FN-C-101 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-202 L						
Provide a coordinated lunar time scale	FN-C-205 L						
Capture imagery on the lunar surface	FN-U-102 L						
Enable crew lunar surface extravehicular activity in sunlit areas and non-PSRs	FN-M-101 L	Crew identification of surface samples in sunlit areas and non-PSRs in the far side on the lunar surface	UC-U-108 L				
Provide communications and data exchange between the lunar surface and Earth	FN-C-101 L						
Provide position, navigation, and timing services at the far side and outside the south pole region on the lunar surface	FN-C-203 L						
Provide a coordinated lunar time scale	FN-C-205 L						
Capture imagery on the lunar surface	FN-U-102 L						
Enable crew lunar surface extravehicular activity in sunlit areas and non-PSRs	FN-M-101 L	Collection, documentation, and packaging of surface and/or shallow sub-surface samples, maintaining scientific integrity of the samples, from non-PSRs and sunlit areas in the south pole region on the lunar surface	UC-U-301 L				
Provide position, navigation, and timing services at the south pole region on the lunar surface	FN-C-201 L						
Provide a coordinated lunar time scale	FN-C-205 L						
Capture imagery on the lunar surface	FN-U-102 L						
Provide capability to recover and package surface and/or shallow sub-surface samples, maintaining scientific integrity of the samples, from non-PSRs and sunlit regions on the lunar surface	FN-U-303 L						
Enable crew lunar surface extravehicular activity in sunlit areas and non-PSRs	FN-M-101 L	Collection, documentation, and packaging of surface and/or shallow sub-surface samples, maintaining scientific integrity of the samples, from non-PSRs and sunlit areas in	UC-U-305 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-202 L						
Provide a coordinated lunar time scale	FN-C-205 L						

Functions		Use Cases		Characteristics/Needs		Objectives	
Capture imagery on the lunar surface	FN-U-102 L	distributed locations on the lunar surface					
Provide capability to recover and package surface and/or shallow sub-surface samples, maintaining scientific integrity of the samples, from non-PSRs and sunlit regions on the lunar surface	FN-U-303 L						
Enable crew lunar surface extravehicular activity in sunlit areas and non-PSRs	FN-M-101 L	Collection, documentation, and packaging of surface and/or shallow sub-surface samples, maintaining scientific integrity of the samples, from non-PSRs and sunlit areas in the far side on the lunar surface	UC-U-306 L				
Provide position, navigation, and timing services at the far side and outside the south pole region on the lunar surface	FN-C-203 L						
Provide a coordinated lunar time scale	FN-C-205 L						
Capture imagery on the lunar surface	FN-U-102 L						
Provide capability to recover and package surface and/or shallow sub-surface samples, maintaining scientific integrity of the samples, from non-PSRs and sunlit regions on the lunar surface	FN-U-303 L						
Transport a limited amount of cargo (100s of kg) from Earth to south pole region sites on the lunar surface	FN-T-201 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-701 L	Deploy and operate utilization payload(s) and equipment, related to understanding impact chronology, at distributed sites on the lunar surface for a minimum of a short-duration (days to weeks).	CN-U-713 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-204 L						
Provide power for deployed external surface utilization payloads(s) and/or equipment for long durations (months to years+)	FN-P-402 L						
Enable crew lunar surface extravehicular activity in sunlit areas and non-PSRs	FN-M-101 L						
Enable local unpressurized surface mobility in sunlit areas and non-PSRs in the south pole region on the lunar surface	FN-M-302 L						
Enable local unpressurized surface mobility in sunlit areas and non-PSRs at distributed sites on the lunar surface	FN-M-303 L						
Unload a limited amount of cargo (100s of kg) on the lunar surface	FN-M-401 L						
Unload a moderate amount of cargo (1000s of kg) on the lunar surface	FN-M-402 L						
Reposition a limited amount of cargo (100s of kg) in the south pole region on the lunar surface	FN-M-501 L						
Reposition a limited amount of cargo (100s of kg) at distributed sites on the lunar surface	FN-M-502 L						
Provide communications and data exchange between the lunar surface and Earth	FN-C-101 L						
Perform robotic manipulation of payloads, logistics, and/or equipment on the lunar surface	FN-A-104 L						
Transport crew from cislunar space to lunar surface sites in the south pole region	FN-T-102 L	Transportation of crew between cislunar space and lunar south pole region landing sites	UC-T-105 L	Visit diverse sites of key scientific interest on the lunar surface, including polar and non-polar destinations to address high priority science goals.	CN-T-108 L	Advance understanding of the geologic processes that affect planetary bodies by determining the interior structures, characterizing the magmatic histories, characterizing ancient, modern, and evolution of atmospheres/exospheres,	LPS-02 LM
Transport crew from the lunar surface to cislunar space	FN-T-104 L						
Enable crew habitation during transit from cislunar space to lunar surface sites in the south pole region	FN-T-108 L						
Enable crew habitation during transit from the lunar surface to cislunar space	FN-T-110 L						

Functions		Use Cases		Characteristics/Needs		Objectives	
Transport crew from cislunar space to distributed sites outside of the south pole region on the lunar surface	FN-T-103 L	Transportation of crew from cislunar space to distributed landing sites outside of the south pole region on the lunar surface	UC-T-106 L			and investigating how active processes modify the surfaces of the Moon and Mars.	
Enable crew habitation during transit from cislunar space to distributed sites outside of the south pole region on the lunar surface	FN-T-109 L						
Transport a small amount of cargo (10s of kg) from the lunar surface to Earth	FN-T-207 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-301 L	Transfer, return, and curate a small amount (10s of kg) or a large amount (100s of kg) of unconditioned samples and containers from key destinations across the lunar surface and back to Earth, while maintaining scientific integrity of the samples.	CN-T-302 L		
Transport a small amount of cargo (10s of kg) from the lunar surface to cislunar space	FN-T-209 L						
Transport a small amount of cargo (10s of kg) from cislunar space to Earth	FN-T-211 L						
Reposition a small amount of unconditioned samples and containers (10s of kg) on the lunar surface	FN-M-504 L						
Stow collected unconditioned samples on exploration assets while on the lunar surface, while maintaining scientific integrity of the samples	FN-U-401 L						
Transport a large amount of cargo (100s of kg) from the lunar surface to Earth	FN-T-208 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-302 L				
Transport a large amount of cargo (100s of kg) from the lunar surface to cislunar space	FN-T-210 L						
Transport a large amount of cargo (100s of kg) from cislunar space to Earth	FN-T-212 L						
Reposition a large amount of unconditioned samples and containers (100s of kg) on the lunar surface	FN-M-505 L						
Stow collected unconditioned samples on exploration assets while on the lunar surface, while maintaining scientific integrity of the samples	FN-U-401 L						
BLANK	BLANK	Delivery of collected samples to curation facilities or other appropriate facilities on Earth, while maintaining scientific integrity of the samples	UC-G-202 L				
Provide high bandwidth, high availability communications and data exchange between the lunar surface and Earth	FN-C-105 L	Communications and data exchange with high bandwidth and high availability between assets on the lunar surface and the Earth	UC-C-101 L	Provide the ability for the Science Team to directly or indirectly communicate in real-time via either written or verbal means with the crew for EVA and IVA activities.	CN-C-106 L		
Enable crew lunar surface extravehicular activity in sunlit areas and non-PSRs	FN-M-101 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-301 L	Identify, collect, and document surface and shallow subsurface samples from key destinations in non-PSRs and other sunlit areas on the lunar surface, while maintaining scientific integrity of the samples.	CN-U-303 L		
Enable local unpressurized surface mobility in sunlit areas and non-PSRs at distributed sites on the lunar surface	FN-M-303 L						
Provide communications and data exchange between the lunar surface and Earth	FN-C-101 L						
Provide communications and data exchange between assets on the lunar surface	FN-C-103 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-202 L						
Provide a coordinated lunar time scale	FN-C-205 L						
Provide communications and data exchange between the lunar surface and Earth	FN-C-101 L	Robotic surveillance of potential crewed landing and exploration sites	UC-U-102 L				

Functions		Use Cases		Characteristics/Needs		Objectives	
Provide position, navigation, and timing services at the south pole region on the lunar surface	**FN-C-201 L**	in sunlit areas and non-PSRs in the south pole region on the lunar surface to identify locations of interest					
Provide a coordinated lunar time scale	**FN-C-205 L**						
Provide a robotic system capable of conducting reconnaissance	**FN-A-103 L**						
Control robotic system(s) in sunlit areas and non-PSRs on the lunar surface from Earth and/or cislunar space	**FN-A-201 L**						
Enable crew lunar surface extravehicular activity in sunlit areas and non-PSRs	**FN-M-101 L**	Crew identification of surface samples in sunlit areas and non-PSRs in the south pole region on the lunar surface	**UC-U-103 L**				
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 L**						
Provide position, navigation, and timing services at the south pole region on the lunar surface	**FN-C-201 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						
Capture imagery on the lunar surface	**FN-U-102 L**						
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 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-105 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-202 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						
Provide a robotic system capable of conducting reconnaissance	**FN-A-103 L**						
Control robotic system(s) in sunlit areas and non-PSRs on the lunar surface from Earth and/or cislunar space	**FN-A-201 L**						
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 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-106 L**				
Provide position, navigation, and timing services at the far side and outside the south pole region on the lunar surface	**FN-C-203 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						
Provide a robotic system capable of conducting reconnaissance	**FN-A-103 L**						
Control robotic system(s) in sunlit areas and non-PSRs on the lunar surface from Earth and/or cislunar space	**FN-A-201 L**						
Enable crew lunar surface extravehicular activity in sunlit areas and non-PSRs	**FN-M-101 L**	Crew identification of surface samples in sunlit areas and non-PSRs in distributed sites on the lunar surface	**UC-U-107 L**				
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 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-202 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						
Capture imagery on the lunar surface	**FN-U-102 L**						

Functions		Use Cases		Characteristics/Needs		Objectives	
Enable crew lunar surface extravehicular activity in sunlit areas and non-PSRs	**FN-M-101 L**	Crew identification of surface samples in sunlit areas and non-PSRs in the far side on the lunar surface	**UC-U-108 L**				
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 L**						
Provide position, navigation, and timing services at the far side and outside the south pole region on the lunar surface	**FN-C-203 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						
Capture imagery on the lunar surface	**FN-U-102 L**						
Enable crew lunar surface extravehicular activity in sunlit areas and non-PSRs	**FN-M-101 L**	Collection, documentation, and packaging of surface and/or shallow sub-surface samples, maintaining scientific integrity of the samples, from non-PSRs and sunlit areas in the south pole region on the lunar surface	**UC-U-301 L**				
Provide position, navigation, and timing services at the south pole region on the lunar surface	**FN-C-201 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						
Capture imagery on the lunar surface	**FN-U-102 L**						
Provide capability to recover and package surface and/or shallow sub-surface samples, maintaining scientific integrity of the samples, from non-PSRs and sunlit regions on the lunar surface	**FN-U-303 L**						
Enable crew lunar surface extravehicular activity in sunlit areas and non-PSRs	**FN-M-101 L**	Collection, documentation, and packaging of surface and/or shallow sub-surface samples, maintaining scientific integrity of the samples, from non-PSRs and sunlit areas in distributed locations on the lunar surface	**UC-U-305 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-202 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						
Capture imagery on the lunar surface	**FN-U-102 L**						
Provide capability to recover and package surface and/or shallow sub-surface samples, maintaining scientific integrity of the samples, from non-PSRs and sunlit regions on the lunar surface	**FN-U-303 L**						
Enable crew lunar surface extravehicular activity in sunlit areas and non-PSRs	**FN-M-101 L**	Collection, documentation, and packaging of surface and/or shallow sub-surface samples, maintaining scientific integrity of the samples, from non-PSRs and sunlit areas in the far side on the lunar surface	**UC-U-306 L**				
Provide position, navigation, and timing services at the far side and outside the south pole region on the lunar surface	**FN-C-203 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						
Capture imagery on the lunar surface	**FN-U-102 L**						
Provide capability to recover and package surface and/or shallow sub-surface samples, maintaining scientific integrity of the samples, from non-PSRs and sunlit regions on the lunar surface	**FN-U-303 L**						
Transport a limited amount of cargo (100s of kg) from Earth to south pole region sites on the lunar surface	**FN-T-201 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-702 L**	Deploy and operate utilization payload(s) and equipment, related to geologic processes, at distributed sites on the lunar surface, for mid-durations	**CN-U-714 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-204 L**						
Provide power for deployed external surface utilization payloads(s) and/or equipment for long durations (months to years+)	**FN-P-402 L**						

Functions		Use Cases		Characteristics/Needs		Objectives	
Enable crew lunar surface extravehicular activity in sunlit areas and non-PSRs	**FN-M-101 L**			(month+) to long-durations (year+).			
Enable local unpressurized surface mobility in sunlit areas and non-PSRs in the south pole region on the lunar surface	**FN-M-302 L**						
Enable local unpressurized surface mobility in sunlit areas and non-PSRs at distributed sites on the lunar surface	**FN-M-303 L**						
Unload a limited amount of cargo (100s of kg) on the lunar surface	**FN-M-401 L**						
Unload a moderate amount of cargo (1000s of kg) on the lunar surface	**FN-M-402 L**						
Reposition a limited amount of cargo (100s of kg) in the south pole region on the lunar surface	**FN-M-501 L**						
Reposition a limited amount of cargo (100s of kg) at distributed sites on the lunar surface	**FN-M-502 L**						
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 L**						
Perform robotic manipulation of payloads, logistics, and/or equipment on the lunar surface	**FN-A-104 L**						
Transport crew from cislunar space to lunar surface sites in the south pole region	**FN-T-102 L**	Transportation of crew between cislunar space and lunar south pole region landing sites	**UC-T-105 L**	Visit diverse sites of key scientific interest on the lunar surface, including polar and non-polar destinations to address high priority science goals.	**CN-T-108 L**	Reveal inner solar system volatile origin and delivery processes by determining the age, origin, distribution, abundance, composition, transport, and sequestration of lunar and Martian volatiles.	**LPS-03 LM**
Transport crew from the lunar surface to cislunar space	**FN-T-104 L**						
Enable crew habitation during transit from cislunar space to lunar surface sites in the south pole region	**FN-T-108 L**						
Enable crew habitation during transit from the lunar surface to cislunar space	**FN-T-110 L**						
Transport crew from cislunar space to distributed sites outside of the south pole region on the lunar surface	**FN-T-103 L**	Transportation of crew from cislunar space to distributed landing sites outside of the south pole region on the lunar surface	**UC-T-106 L**				
Enable crew habitation during transit from cislunar space to distributed sites outside of the south pole region on the lunar surface	**FN-T-109 L**						
Transport a small amount of cargo (10s of kg) from the lunar surface to Earth	**FN-T-207 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-305 L**	Transfer, return and curate a small amount (10s of kg) or a large amount (100s of kg) of frozen sample(s), containers, and freezers from key destinations across the lunar surface to Earth while maintaining scientific integrity of the samples.	**CN-T-304 L**		
Transport a small amount of cargo (10s of kg) from the lunar surface to cislunar space	**FN-T-209 L**						
Transport a small amount of cargo (10s of kg) from cislunar space to Earth	**FN-T-211 L**						
Provide resources to condition frozen 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 cislunar space	**FN-T-305 L**						
Provide resources to condition frozen sample containers during transit from cislunar space to Earth	**FN-T-308 L**						
Reposition a small amount of frozen samples and containers (10s of kg) on the lunar surface	**FN-M-508 L**						
Stow frozen 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 cislunar space, while maintaining scientific integrity of samples	**FN-U-406 L**						

Functions		Use Cases		Characteristics/Needs		Objectives	
Stow frozen samples during transport from cislunar space to Earth, while maintaining scientific integrity of samples	**FN-U-409 L**						
Stow collected frozen samples on exploration assets while on the lunar surface, while maintaining scientific integrity of the samples	**FN-U-412 L**						
Provide resources to condition frozen sample containers on the lunar surface	**FN-U-415 L**						
Transport a large amount of cargo (100s of kg) from the lunar surface to Earth	**FN-T-208 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-306 L**				
Transport a large amount of cargo (100s of kg) from the lunar surface to cislunar space	**FN-T-210 L**						
Transport a large amount of cargo (100s of kg) from cislunar space to Earth	**FN-T-212 L**						
Provide resources to condition frozen 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 cislunar space	**FN-T-305 L**						
Provide resources to condition frozen sample containers during transit from cislunar space to Earth	**FN-T-308 L**						
Reposition a large amount of frozen samples and containers (100s of kg) on the lunar surface	**FN-M-509 L**						
Stow frozen 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 cislunar space, while maintaining scientific integrity of samples	**FN-U-406 L**						
Stow frozen samples during transport from cislunar space to Earth, while maintaining scientific integrity of samples	**FN-U-409 L**						
Stow collected frozen samples on exploration assets while on the lunar surface, while maintaining scientific integrity of the samples	**FN-U-412 L**						
Provide resources to condition frozen sample containers on the lunar surface	**FN-U-415 L**						
BLANK	**BLANK**	Delivery of conditioned cargo to curation facilities or other appropriate facilities on Earth after landing, while maintaining scientific integrity of the samples	**UC-G-201 L**				
Transport a large amount of cargo (100s of kg) from the lunar surface to Earth	**FN-T-208 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-T-307 L**	Transfer, return, and curate a large amount (100s of kg) of cryogenic samples, containers, and freezers from key destinations across the lunar surface back to Earth while maintaining scientific integrity of the samples.	**CN-T-305 L**		
Transport a large amount of cargo (100s of kg) from the lunar surface to cislunar space	**FN-T-210 L**						
Transport a large amount of cargo (100s of kg) from cislunar space to Earth	**FN-T-212 L**						
Provide resources to condition cryogenic 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 cislunar space	**FN-T-306 L**						
Provide resources to condition cryogenic sample containers during transit from cislunar space to Earth	**FN-T-309 L**						
Reposition a large amount of cryogenic samples and containers (100s of kg) on the lunar surface	**FN-M-510 L**						

Functions		Use Cases		Characteristics/Needs		Objectives	
Stow cryogenic 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 cislunar space, while maintaining scientific integrity of samples	FN-U-407 L						
Stow cryogenic samples during transport from cislunar space to Earth, while maintaining scientific integrity of samples	FN-U-410 L						
Stow collected cryogenic samples on exploration assets while on the lunar surface, while maintaining scientific integrity of the samples	FN-U-413 L						
Provide resources to condition cryogenic sample containers on the lunar surface	FN-U-416 L						
BLANK	BLANK	Delivery of conditioned cargo to curation facilities or other appropriate facilities on Earth after landing, while maintaining scientific integrity of the samples	UC-G-201 L				
Provide high bandwidth, high availability communications and data exchange between the lunar surface and Earth	FN-C-105 L	Communications and data exchange with high bandwidth and high availability between assets on the lunar surface and the Earth	UC-C-101 L	Provide the ability for the Science Team to directly or indirectly communicate in real-time via either written or verbal means with the crew for EVA and IVA activities.	CN-C-106 L		
Enable crew lunar surface extravehicular activity in sunlit areas and non-PSRs	FN-M-101 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-301 L	Identify, collect, and document deep subsurface samples from key destinations in non-PSRs and other sunlit areas on the lunar surface, while maintaining scientific integrity of the samples.	CN-U-301 L		
Enable local unpressurized surface mobility in sunlit areas and non-PSRs at distributed sites on the lunar surface	FN-M-303 L						
Provide communications and data exchange between the lunar surface and Earth	FN-C-101 L						
Provide communications and data exchange between assets on the lunar surface	FN-C-103 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-202 L						
Provide a coordinated lunar time scale	FN-C-205 L						
Provide communications and data exchange between the lunar surface and Earth	FN-C-101 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-U-102 L				
Provide position, navigation, and timing services at the south pole region on the lunar surface	FN-C-201 L						
Provide a coordinated lunar time scale	FN-C-205 L						
Provide a robotic system capable of conducting reconnaissance	FN-A-103 L						
Control robotic system(s) in sunlit areas and non-PSRs on the lunar surface from Earth and/or cislunar space	FN-A-201 L						
Enable crew lunar surface extravehicular activity in sunlit areas and non-PSRs	FN-M-101 L	Crew identification of surface samples in sunlit areas and non-PSRs in the south pole region on the lunar surface	UC-U-103 L				
Provide communications and data exchange between the lunar surface and Earth	FN-C-101 L						

Functions		Use Cases		Characteristics/Needs		Objectives	
Provide position, navigation, and timing services at the south pole region on the lunar surface	**FN-C-201 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						
Capture imagery on the lunar surface	**FN-U-102 L**						
Enable crew lunar surface extravehicular activity in sunlit areas and non-PSRs	**FN-M-101 L**	Collection, recovery, and packaging of deep sub-surface 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-302 L**				
Provide position, navigation, and timing services at the south pole region on the lunar surface	**FN-C-201 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						
Capture imagery on the lunar surface	**FN-U-102 L**						
Provide capability to recover and package deep sub-surface samples, including drill cores, maintaining scientific integrity of the samples, from non-PSRs and sunlit regions on the lunar surface	**FN-U-305 L**						
Enable crew lunar surface extravehicular activity in sunlit areas and non-PSRs	**FN-M-101 L**	Collection, recovery, and packaging of deep sub-surface samples, maintaining scientific integrity of the samples, from non-PSRs and other sunlit areas in distributed sites on the lunar surface	**UC-U-307 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-202 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						
Capture imagery on the lunar surface	**FN-U-102 L**						
Provide capability to recover and package deep sub-surface samples, including drill cores, maintaining scientific integrity of the samples, from non-PSRs and sunlit regions on the lunar surface	**FN-U-305 L**						
Enable crew lunar surface extravehicular activity in sunlit areas and non-PSRs	**FN-M-101 L**	Collection, recovery, and packaging of deep sub-surface samples, maintaining scientific integrity of the samples, from non-PSRs and other sunlit areas in the far side on the lunar surface	**UC-U-308 L**				
Provide position, navigation, and timing services at the far side and outside the south pole region on the lunar surface	**FN-C-203 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						
Capture imagery on the lunar surface	**FN-U-102 L**						
Provide capability to recover and package deep sub-surface samples, including drill cores, maintaining scientific integrity of the samples, from non-PSRs and sunlit regions on the lunar surface	**FN-U-305 L**						
Enable crew lunar surface extravehicular activity in PSRs	**FN-M-102 L**	Conduct of crew excursions in PSRs around landing site at the south pole region	**UC-M-303 L**	Identify, collect, and document deep-surface samples from key destinations in PSRs on the lunar surface, while maintaining scientific integrity of the samples.	**CN-U-302 L**		
Enable local unpressurized surface mobility in PSRs at the south pole region of the lunar surface	**FN-M-304 L**						
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 L**						
Provide communications and data exchange between assets on the lunar surface	**FN-C-103 L**						
Provide position, navigation, and timing services at the south pole region on the lunar surface	**FN-C-201 L**						

Functions		Use Cases		Characteristics/Needs		Objectives	
Provide a coordinated lunar time scale	**FN-C-205 L**						
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 L**	Robotic surveillance of PSRs near potential crewed landing and exploration sites to identify locations of interest	**UC-A-106 L**				
Control robotic system(s) in PSRs on the lunar surface from Earth and/or cislunar space	**FN-A-202 L**						
Enable crew lunar surface extravehicular activity in PSRs	**FN-M-102 L**	Crew identification of surface samples in PSRs	**UC-U-104 L**				
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 L**						
Provide position, navigation, and timing services at the south pole region on the lunar surface	**FN-C-201 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						
Capture imagery on the lunar surface	**FN-U-102 L**						
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 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-105 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-202 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						
Provide a robotic system capable of conducting reconnaissance	**FN-A-103 L**						
Control robotic system(s) in sunlit areas and non-PSRs on the lunar surface from Earth and/or cislunar space	**FN-A-201 L**						
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 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-106 L**				
Provide position, navigation, and timing services at the far side and outside the south pole region on the lunar surface	**FN-C-203 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						
Provide a robotic system capable of conducting reconnaissance	**FN-A-103 L**						
Control robotic system(s) in sunlit areas and non-PSRs on the lunar surface from Earth and/or cislunar space	**FN-A-201 L**						
Enable crew lunar surface extravehicular activity in sunlit areas and non-PSRs	**FN-M-101 L**	Crew identification of surface samples in sunlit areas and non-PSRs in distributed sites on the lunar surface	**UC-U-107 L**				
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 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-202 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						
Capture imagery on the lunar surface	**FN-U-102 L**						
Enable crew lunar surface extravehicular activity in sunlit areas and non-PSRs	**FN-M-101 L**	Crew identification of surface samples in sunlit areas and non-	**UC-U-108 L**				

Functions		Use Cases		Characteristics/Needs		Objectives	
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 L**	PSRs in the far side on the lunar surface					
Provide position, navigation, and timing services at the far side and outside the south pole region on the lunar surface	**FN-C-203 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						
Capture imagery on the lunar surface	**FN-U-102 L**						
Enable crew lunar surface extravehicular activity in PSRs	**FN-M-102 L**	Collection, recovery, and packaging of deep sub-surface samples, maintaining scientific integrity of the samples, from PSRs on the lunar surface	**UC-U-304 L**				
Provide position, navigation, and timing services at the south pole region on the lunar surface	**FN-C-201 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						
Capture imagery on the lunar surface	**FN-U-102 L**						
Provide capability to recover and package deep sub-surface samples, including drill cores, maintaining scientific integrity of the samples, from PSRs on the lunar surface	**FN-U-306 L**						
Enable crew lunar surface extravehicular activity in sunlit areas and non-PSRs	**FN-M-101 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-301 L**	Identify, collect, and document surface and shallow subsurface samples from key destinations in non-PSRs and other sunlit areas on the lunar surface, while maintaining scientific integrity of the samples.	**CN-U-303 L**		
Enable local unpressurized surface mobility in sunlit areas and non-PSRs at distributed sites on the lunar surface	**FN-M-303 L**						
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 L**						
Provide communications and data exchange between assets on the lunar surface	**FN-C-103 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-202 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 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-U-102 L**				
Provide position, navigation, and timing services at the south pole region on the lunar surface	**FN-C-201 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						
Provide a robotic system capable of conducting reconnaissance	**FN-A-103 L**						
Control robotic system(s) in sunlit areas and non-PSRs on the lunar surface from Earth and/or cislunar space	**FN-A-201 L**						
Enable crew lunar surface extravehicular activity in sunlit areas and non-PSRs	**FN-M-101 L**	Crew identification of surface samples in sunlit areas and non-PSRs in the south pole region on the lunar surface	**UC-U-103 L**				
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 L**						
Provide position, navigation, and timing services at the south pole region on the lunar surface	**FN-C-201 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						

Functions		Use Cases		Characteristics/Needs		Objectives	
Capture imagery on the lunar surface	**FN-U-102 L**						
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 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-105 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-202 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						
Provide a robotic system capable of conducting reconnaissance	**FN-A-103 L**						
Control robotic system(s) in sunlit areas and non-PSRs on the lunar surface from Earth and/or cislunar space	**FN-A-201 L**						
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 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-106 L**				
Provide position, navigation, and timing services at the far side and outside the south pole region on the lunar surface	**FN-C-203 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						
Provide a robotic system capable of conducting reconnaissance	**FN-A-103 L**						
Control robotic system(s) in sunlit areas and non-PSRs on the lunar surface from Earth and/or cislunar space	**FN-A-201 L**						
Enable crew lunar surface extravehicular activity in sunlit areas and non-PSRs	**FN-M-101 L**	Crew identification of surface samples in sunlit areas and non-PSRs in distributed sites on the lunar surface	**UC-U-107 L**				
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 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-202 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						
Capture imagery on the lunar surface	**FN-U-102 L**						
Enable crew lunar surface extravehicular activity in sunlit areas and non-PSRs	**FN-M-101 L**	Crew identification of surface samples in sunlit areas and non-PSRs in the far side on the lunar surface	**UC-U-108 L**				
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 L**						
Provide position, navigation, and timing services at the far side and outside the south pole region on the lunar surface	**FN-C-203 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						
Capture imagery on the lunar surface	**FN-U-102 L**						
Enable crew lunar surface extravehicular activity in sunlit areas and non-PSRs	**FN-M-101 L**	Collection, documentation, and packaging of surface and/or shallow sub-surface samples, maintaining scientific integrity of the samples, from non-PSRs and sunlit areas in	**UC-U-301 L**				
Provide position, navigation, and timing services at the south pole region on the lunar surface	**FN-C-201 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						

Functions		Use Cases		Characteristics/Needs		Objectives	
Capture imagery on the lunar surface	**FN-U-102 L**	the south pole region on the lunar surface					
Provide capability to recover and package surface and/or shallow sub-surface samples, maintaining scientific integrity of the samples, from non-PSRs and sunlit regions on the lunar surface	**FN-U-303 L**						
Enable crew lunar surface extravehicular activity in sunlit areas and non-PSRs	**FN-M-101 L**	Collection, documentation, and packaging of surface and/or shallow sub-surface samples, maintaining scientific integrity of the samples, from non-PSRs and sunlit areas in distributed locations on the lunar surface	**UC-U-305 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-202 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						
Capture imagery on the lunar surface	**FN-U-102 L**						
Provide capability to recover and package surface and/or shallow sub-surface samples, maintaining scientific integrity of the samples, from non-PSRs and sunlit regions on the lunar surface	**FN-U-303 L**						
Enable crew lunar surface extravehicular activity in sunlit areas and non-PSRs	**FN-M-101 L**	Collection, documentation, and packaging of surface and/or shallow sub-surface samples, maintaining scientific integrity of the samples, from non-PSRs and sunlit areas in the far side on the lunar surface	**UC-U-306 L**				
Provide position, navigation, and timing services at the far side and outside the south pole region on the lunar surface	**FN-C-203 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						
Capture imagery on the lunar surface	**FN-U-102 L**						
Provide capability to recover and package surface and/or shallow sub-surface samples, maintaining scientific integrity of the samples, from non-PSRs and sunlit regions on the lunar surface	**FN-U-303 L**						
Enable crew lunar surface extravehicular activity in PSRs	**FN-M-102 L**	Conduct of crew excursions in PSRs around landing site at the south pole region	**UC-M-303 L**	Identify, collect, and document surface and shallow subsurface samples from key destinations in PSRs on the lunar surface, while maintaining scientific integrity of the samples.	**CN-U-304 L**		
Enable local unpressurized surface mobility in PSRs at the south pole region of the lunar surface	**FN-M-304 L**						
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 L**						
Provide communications and data exchange between assets on the lunar surface	**FN-C-103 L**						
Provide position, navigation, and timing services at the south pole region on the lunar surface	**FN-C-201 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 L**	Robotic surveillance of PSRs near potential crewed landing and exploration sites to identify locations of interest	**UC-A-106 L**				
Control robotic system(s) in PSRs on the lunar surface from Earth and/or cislunar space	**FN-A-202 L**						
Enable crew lunar surface extravehicular activity in PSRs	**FN-M-102 L**	Crew identification of surface samples in PSRs	**UC-U-104 L**				
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 L**						
Provide position, navigation, and timing services at the south pole region on the lunar surface	**FN-C-201 L**						

Functions		Use Cases		Characteristics/Needs		Objectives	
Provide a coordinated lunar time scale	**FN-C-205 L**						
Capture imagery on the lunar surface	**FN-U-102 L**						
Enable crew lunar surface extravehicular activity in PSRs	**FN-M-102 L**	Collection, recovery, and packaging of surface and/or shallow sub-surface samples, maintaining scientific integrity of the samples, from PSRs on the lunar surface	**UC-U-303 L**				
Provide position, navigation, and timing services at the south pole region on the lunar surface	**FN-C-201 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						
Capture imagery on the lunar surface	**FN-U-102 L**						
Provide capability to recover and package surface and/or shallow sub-surface samples, maintaining scientific integrity of the samples, from PSRs on the lunar surface	**FN-U-304 L**						
Transport a limited amount of cargo (100s of kg) from Earth to south pole region sites on the lunar surface	**FN-T-201 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-703 L**	Deploy and operate utilization payload(s) and equipment, related to Solar System volatiles, at distributed sites on the lunar surface.	**CN-U-715 L**		
Transport a moderate amount of cargo (1000s of kg) from Earth to south pole region sites on the lunar surface	**FN-T-202 L**						
Provide power for deployed external surface utilization payloads(s) and/or equipment for long durations (months to years+)	**FN-P-402 L**						
Enable crew lunar surface extravehicular activity in sunlit areas and non-PSRs	**FN-M-101 L**						
Enable crew lunar surface extravehicular activity in PSRs	**FN-M-102 L**						
Enable local unpressurized surface mobility in sunlit areas and non-PSRs in the south pole region on the lunar surface	**FN-M-302 L**						
Enable local unpressurized surface mobility in PSRs at the south pole region of the lunar surface	**FN-M-304 L**						
Unload a limited amount of cargo (100s of kg) on the lunar surface	**FN-M-401 L**						
Unload a moderate amount of cargo (1000s of kg) on the lunar surface	**FN-M-402 L**						
Reposition a limited amount of cargo (100s of kg) in the south pole region on the lunar surface	**FN-M-501 L**						
Reposition a moderate amount of cargo (1000s of kg) at the south pole region on the lunar surface	**FN-M-503 L**						
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 L**						
Perform robotic manipulation of payloads, logistics, and/or equipment on the lunar surface	**FN-A-104 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-203 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-704 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-204 L**						
Provide power for deployed external surface utilization payloads(s) and/or equipment for long durations (months to years+)	**FN-P-402 L**						
Enable crew lunar surface extravehicular activity in sunlit areas and non-PSRs	**FN-M-101 L**						

Functions		Use Cases		Characteristics/Needs		Objectives	
Enable local unpressurized surface mobility in sunlit areas and non-PSRs at distributed sites on the lunar surface	**FN-M-303 L**						
Unload a moderate amount of cargo (1000s of kg) on the lunar surface	**FN-M-402 L**						
Reposition a limited amount of cargo (100s of kg) at distributed sites on the lunar surface	**FN-M-502 L**						
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 L**						
Perform robotic manipulation of payloads, logistics, and/or equipment on the lunar surface	**FN-A-104 L**						
Transport a moderate amount of cargo (1000s of kg) from Earth to south pole region sites on the lunar surface	**FN-T-202 L**	Deployment and operation of Heliophysics utilization payload(s) and/or equipment on the lunar surface with long-term remote operation	**UC-U-705 L**	Deploy and operate utilization payload(s), related to in-space weather, at distributed sites on the lunar surface.	**CN-U-706 L**	Improve understanding of space weather phenomena to enable enhanced observation and prediction of the dynamic environment from space to the surface at the Moon and Mars.	**HS-01 LM**
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-204 L**						
Provide power for deployed external surface utilization payloads(s) and/or equipment for long durations (months to years+)	**FN-P-402 L**						
Enable crew lunar surface extravehicular activity in sunlit areas and non-PSRs	**FN-M-101 L**						
Unload a moderate amount of cargo (1000s of kg) on the lunar surface	**FN-M-402 L**						
Provide high bandwidth, high availability communications and data exchange between the lunar surface and Earth	**FN-C-105 L**						
Perform robotic manipulation of payloads, logistics, and/or equipment on the lunar surface	**FN-A-104 L**						
Control robotic system(s) in sunlit areas and non-PSRs on the lunar surface from Earth and/or cislunar space	**FN-A-201 L**						
Deliver free flying asset(s) from Earth to cislunar space	**FN-T-216 L**	Deployment and operation of free-flying assets long-term in a variety of lunar orbits	**UC-U-203 L**	Deploy and operate utilization payload(s) relevant to assessing space weather phenomena, including ability to conduct long looks at the Sun, in a variety of lunar orbits.	**CN-U-707 L**		
Provide communications and data exchange between Earth and cislunar space	**FN-C-102 L**						
Provide position, navigation, and timing data in cislunar space	**FN-C-204 L**						
Transport cargo from Earth to cislunar space	**FN-T-213 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-707 L**				
Provide communications and data exchange between Earth and cislunar space	**FN-C-102 L**						
Enable repositioning of externally mounted utilization payloads in cislunar space	**FN-A-106 L**						
Provide extravehicular utilization accommodation, interfaces, and resources, operable during crewed and uncrewed increments, in cislunar space	**FN-U-202 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-103 L**	Storage and local processing of space weather data	**UC-D-201 L**	Provide capabilities for local data storage and processing to enable Earth-independent space weather forecasting.	**CN-U-708 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-104 L**						
Process large volumes of data locally on the lunar surface sufficient to perform real time analysis for in situ decision making	**FN-D-203 L**						
Process large volumes of data locally in cislunar space sufficient to perform real time analysis for in situ decision making	**FN-D-204 L**						

Functions		Use Cases		Characteristics/Needs		Objectives	
Transport cargo from Earth to assets in deep space	**FN-T-215 L**	Deployment and operation of utilization payload(s) and/or equipment related to space weather at assets in deep space	**UC-U-708 L**	Deploy and operate utilization payloads that monitor real-time space weather in deep space.	**CN-U-718 L**		
Distribute power to utilization payloads and/or equipment in deep space	**FN-P-304 L**						
Provide communications and data exchange between Earth and deep space	**FN-C-104 L**						
Provide locations to host utilization payload(s) and/or equipment in deep space	**FN-U-201 L**						
Transport crew from cislunar space to lunar surface sites in the south pole region	**FN-T-102 L**	Transportation of crew between cislunar space and lunar south pole region landing sites	**UC-T-105 L**	Visit diverse sites of key scientific interest on the lunar surface, including polar and non-polar destinations to address high priority science goals.	**CN-T-108 L**	Determine the history of the Sun and solar system as recorded in the lunar and Martian regolith.	**HS-02 LM**
Transport crew from the lunar surface to cislunar space	**FN-T-104 L**						
Enable crew habitation during transit from cislunar space to lunar surface sites in the south pole region	**FN-T-108 L**						
Enable crew habitation during transit from the lunar surface to cislunar space	**FN-T-110 L**						
Transport crew from cislunar space to distributed sites outside of the south pole region on the lunar surface	**FN-T-103 L**	Transportation of crew from cislunar space to distributed landing sites outside of the south pole region on the lunar surface	**UC-T-106 L**				
Enable crew habitation during transit from cislunar space to distributed sites outside of the south pole region on the lunar surface	**FN-T-109 L**						
Transport a small amount of cargo (10s of kg) from the lunar surface to Earth	**FN-T-207 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-301 L**	Transfer, return, and curate a small amount (10s of kg) or a large amount (100s of kg) of unconditioned samples and containers from key destinations across the lunar surface and back to Earth, while maintaining scientific integrity of the samples.	**CN-T-302 L**		
Transport a small amount of cargo (10s of kg) from the lunar surface to cislunar space	**FN-T-209 L**						
Transport a small amount of cargo (10s of kg) from cislunar space to Earth	**FN-T-211 L**						
Reposition a small amount of unconditioned samples and containers (10s of kg) on the lunar surface	**FN-M-504 L**						
Stow collected unconditioned samples on exploration assets while on the lunar surface, while maintaining scientific integrity of the samples	**FN-U-401 L**						
Transport a large amount of cargo (100s of kg) from the lunar surface to Earth	**FN-T-208 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-302 L**				
Transport a large amount of cargo (100s of kg) from the lunar surface to cislunar space	**FN-T-210 L**						
Transport a large amount of cargo (100s of kg) from cislunar space to Earth	**FN-T-212 L**						
Reposition a large amount of unconditioned samples and containers (100s of kg) on the lunar surface	**FN-M-505 L**						
Stow collected unconditioned samples on exploration assets while on the lunar surface, while maintaining scientific integrity of the samples	**FN-U-401 L**						
BLANK	**BLANK**	Delivery of collected samples to curation facilities or other appropriate facilities on Earth, while maintaining scientific integrity of the samples	**UC-G-202 L**				
Enable crew lunar surface extravehicular activity in sunlit areas and non-PSRs	**FN-M-101 L**	Conduct of crew excursions to locations in sunlit areas and non-PSRs at distributed locations outside	**UC-M-301 L**	Identify, collect, and document deep subsurface samples from key destinations in non-PSRs	**CN-U-301 L**		
Enable local unpressurized surface mobility in sunlit areas and non-PSRs at distributed sites on the lunar surface	**FN-M-303 L**						

Functions		Use Cases		Characteristics/Needs		Objectives	
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 L**	of the south pole region around landing site		and other sunlit areas on the lunar surface, while maintaining scientific integrity of the samples.			
Provide communications and data exchange between assets on the lunar surface	**FN-C-103 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-202 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 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-U-102 L**				
Provide position, navigation, and timing services at the south pole region on the lunar surface	**FN-C-201 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						
Provide a robotic system capable of conducting reconnaissance	**FN-A-103 L**						
Control robotic system(s) in sunlit areas and non-PSRs on the lunar surface from Earth and/or cislunar space	**FN-A-201 L**						
Enable crew lunar surface extravehicular activity in sunlit areas and non-PSRs	**FN-M-101 L**	Crew identification of surface samples in sunlit areas and non-PSRs in the south pole region on the lunar surface	**UC-U-103 L**				
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 L**						
Provide position, navigation, and timing services at the south pole region on the lunar surface	**FN-C-201 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						
Capture imagery on the lunar surface	**FN-U-102 L**						
Enable crew lunar surface extravehicular activity in sunlit areas and non-PSRs	**FN-M-101 L**	Collection, recovery, and packaging of deep sub-surface 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-302 L**				
Provide position, navigation, and timing services at the south pole region on the lunar surface	**FN-C-201 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						
Capture imagery on the lunar surface	**FN-U-102 L**						
Provide capability to recover and package deep sub-surface samples, including drill cores, maintaining scientific integrity of the samples, from non-PSRs and sunlit regions on the lunar surface	**FN-U-305 L**						
Enable crew lunar surface extravehicular activity in sunlit areas and non-PSRs	**FN-M-101 L**	Collection, recovery, and packaging of deep sub-surface samples, maintaining scientific integrity of the samples, from non-PSRs and other sunlit areas in distributed sites on the lunar surface	**UC-U-307 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-202 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						
Capture imagery on the lunar surface	**FN-U-102 L**						

Functions		Use Cases		Characteristics/Needs		Objectives	
Provide capability to recover and package deep sub-surface samples, including drill cores, maintaining scientific integrity of the samples, from non-PSRs and sunlit regions on the lunar surface	**FN-U-305 L**						
Enable crew lunar surface extravehicular activity in sunlit areas and non-PSRs	**FN-M-101 L**	Collection, recovery, and packaging of deep sub-surface samples, maintaining scientific integrity of the samples, from non-PSRs and other sunlit areas in the far side on the lunar surface	**UC-U-308 L**				
Provide position, navigation, and timing services at the far side and outside the south pole region on the lunar surface	**FN-C-203 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						
Capture imagery on the lunar surface	**FN-U-102 L**						
Provide capability to recover and package deep sub-surface samples, including drill cores, maintaining scientific integrity of the samples, from non-PSRs and sunlit regions on the lunar surface	**FN-U-305 L**						
Enable crew lunar surface extravehicular activity in sunlit areas and non-PSRs	**FN-M-101 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-301 L**	Identify, collect, and document surface and shallow subsurface samples from key destinations in non-PSRs and other sunlit areas on the lunar surface, while maintaining scientific integrity of the samples.	**CN-U-303 L**		
Enable local unpressurized surface mobility in sunlit areas and non-PSRs at distributed sites on the lunar surface	**FN-M-303 L**						
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 L**						
Provide communications and data exchange between assets on the lunar surface	**FN-C-103 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-202 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 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-U-102 L**				
Provide position, navigation, and timing services at the south pole region on the lunar surface	**FN-C-201 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						
Provide a robotic system capable of conducting reconnaissance	**FN-A-103 L**						
Control robotic system(s) in sunlit areas and non-PSRs on the lunar surface from Earth and/or cislunar space	**FN-A-201 L**						
Enable crew lunar surface extravehicular activity in sunlit areas and non-PSRs	**FN-M-101 L**	Crew identification of surface samples in sunlit areas and non-PSRs in the south pole region on the lunar surface	**UC-U-103 L**				
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 L**						
Provide position, navigation, and timing services at the south pole region on the lunar surface	**FN-C-201 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						
Capture imagery on the lunar surface	**FN-U-102 L**						
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 L**	Robotic surveillance of potential crewed landing and exploration sites	**UC-U-105 L**				

Functions		Use Cases		Characteristics/Needs		Objectives	
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-202 L**	in sunlit areas and non-PSRs in distributed sites on the lunar surface to identify locations of interest					
Provide a coordinated lunar time scale	**FN-C-205 L**						
Provide a robotic system capable of conducting reconnaissance	**FN-A-103 L**						
Control robotic system(s) in sunlit areas and non-PSRs on the lunar surface from Earth and/or cislunar space	**FN-A-201 L**						
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 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-106 L**				
Provide position, navigation, and timing services at the far side and outside the south pole region on the lunar surface	**FN-C-203 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						
Provide a robotic system capable of conducting reconnaissance	**FN-A-103 L**						
Control robotic system(s) in sunlit areas and non-PSRs on the lunar surface from Earth and/or cislunar space	**FN-A-201 L**						
Enable crew lunar surface extravehicular activity in sunlit areas and non-PSRs	**FN-M-101 L**	Crew identification of surface samples in sunlit areas and non-PSRs in distributed sites on the lunar surface	**UC-U-107 L**				
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 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-202 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						
Capture imagery on the lunar surface	**FN-U-102 L**						
Enable crew lunar surface extravehicular activity in sunlit areas and non-PSRs	**FN-M-101 L**	Crew identification of surface samples in sunlit areas and non-PSRs in the far side on the lunar surface	**UC-U-108 L**				
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 L**						
Provide position, navigation, and timing services at the far side and outside the south pole region on the lunar surface	**FN-C-203 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						
Capture imagery on the lunar surface	**FN-U-102 L**						
Enable crew lunar surface extravehicular activity in sunlit areas and non-PSRs	**FN-M-101 L**	Collection, documentation, and packaging of surface and/or shallow sub-surface samples, maintaining scientific integrity of the samples, from non-PSRs and sunlit areas in the south pole region on the lunar surface	**UC-U-301 L**				
Provide position, navigation, and timing services at the south pole region on the lunar surface	**FN-C-201 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						
Capture imagery on the lunar surface	**FN-U-102 L**						

Functions		Use Cases		Characteristics/Needs		Objectives	
Provide capability to recover and package surface and/or shallow sub-surface samples, maintaining scientific integrity of the samples, from non-PSRs and sunlit regions on the lunar surface	**FN-U-303 L**						
Enable crew lunar surface extravehicular activity in sunlit areas and non-PSRs	**FN-M-101 L**	Collection, documentation, and packaging of surface and/or shallow sub-surface samples, maintaining scientific integrity of the samples, from non-PSRs and sunlit areas in distributed locations on the lunar surface	**UC-U-305 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-202 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						
Capture imagery on the lunar surface	**FN-U-102 L**						
Provide capability to recover and package surface and/or shallow sub-surface samples, maintaining scientific integrity of the samples, from non-PSRs and sunlit regions on the lunar surface	**FN-U-303 L**						
Enable crew lunar surface extravehicular activity in sunlit areas and non-PSRs	**FN-M-101 L**	Collection, documentation, and packaging of surface and/or shallow sub-surface samples, maintaining scientific integrity of the samples, from non-PSRs and sunlit areas in the far side on the lunar surface	**UC-U-306 L**				
Provide position, navigation, and timing services at the far side and outside the south pole region on the lunar surface	**FN-C-203 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						
Capture imagery on the lunar surface	**FN-U-102 L**						
Provide capability to recover and package surface and/or shallow sub-surface samples, maintaining scientific integrity of the samples, from non-PSRs and sunlit regions on the lunar surface	**FN-U-303 L**						
Transport a small amount of cargo (10s of kg) from the lunar surface to Earth	**FN-T-207 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-301 L**	Transfer, return, and curate a small amount (10s of kg) or a large amount (100s of kg) of unconditioned samples and containers from key destinations across the lunar surface and back to Earth, while maintaining scientific integrity of the samples.	**CN-T-302 L**	Investigate and characterize fundamental plasma processes, including dust-plasma interactions, using the cislunar, near-Mars, and surface environments as laboratories.	**HS-03 LM**
Transport a small amount of cargo (10s of kg) from the lunar surface to cislunar space	**FN-T-209 L**						
Transport a small amount of cargo (10s of kg) from cislunar space to Earth	**FN-T-211 L**						
Reposition a small amount of unconditioned samples and containers (10s of kg) on the lunar surface	**FN-M-504 L**						
Stow collected unconditioned samples on exploration assets while on the lunar surface, while maintaining scientific integrity of the samples	**FN-U-401 L**						
Transport a large amount of cargo (100s of kg) from the lunar surface to Earth	**FN-T-208 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-302 L**				
Transport a large amount of cargo (100s of kg) from the lunar surface to cislunar space	**FN-T-210 L**						
Transport a large amount of cargo (100s of kg) from cislunar space to Earth	**FN-T-212 L**						
Reposition a large amount of unconditioned samples and containers (100s of kg) on the lunar surface	**FN-M-505 L**						
Stow collected unconditioned samples on exploration assets while on the lunar surface, while maintaining scientific integrity of the samples	**FN-U-401 L**						
BLANK	**BLANK**	Delivery of collected samples to curation facilities or other appropriate facilities on Earth, while maintaining scientific integrity of the samples	**UC-G-202 L**				

Functions		Use Cases		Characteristics/Needs		Objectives	
Enable crew lunar surface extravehicular activity in sunlit areas and non-PSRs	**FN-M-101 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-301 L**	Identify, collect, and document surface and shallow subsurface samples from key destinations in non-PSRs and other sunlit areas on the lunar surface, while maintaining scientific integrity of the samples.	**CN-U-303 L**		
Enable local unpressurized surface mobility in sunlit areas and non-PSRs at distributed sites on the lunar surface	**FN-M-303 L**						
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 L**						
Provide communications and data exchange between assets on the lunar surface	**FN-C-103 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-202 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 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-U-102 L**				
Provide position, navigation, and timing services at the south pole region on the lunar surface	**FN-C-201 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						
Provide a robotic system capable of conducting reconnaissance	**FN-A-103 L**						
Control robotic system(s) in sunlit areas and non-PSRs on the lunar surface from Earth and/or cislunar space	**FN-A-201 L**						
Enable crew lunar surface extravehicular activity in sunlit areas and non-PSRs	**FN-M-101 L**	Crew identification of surface samples in sunlit areas and non-PSRs in the south pole region on the lunar surface	**UC-U-103 L**				
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 L**						
Provide position, navigation, and timing services at the south pole region on the lunar surface	**FN-C-201 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						
Capture imagery on the lunar surface	**FN-U-102 L**						
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 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-105 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-202 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						
Provide a robotic system capable of conducting reconnaissance	**FN-A-103 L**						
Control robotic system(s) in sunlit areas and non-PSRs on the lunar surface from Earth and/or cislunar space	**FN-A-201 L**						
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 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-106 L**				
Provide position, navigation, and timing services at the far side and outside the south pole region on the lunar surface	**FN-C-203 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						

Functions		Use Cases		Characteristics/Needs		Objectives	
Provide a robotic system capable of conducting reconnaissance	**FN-A-103 L**						
Control robotic system(s) in sunlit areas and non-PSRs on the lunar surface from Earth and/or cislunar space	**FN-A-201 L**						
Enable crew lunar surface extravehicular activity in sunlit areas and non-PSRs	**FN-M-101 L**	Crew identification of surface samples in sunlit areas and non-PSRs in distributed sites on the lunar surface	**UC-U-107 L**				
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 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-202 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						
Capture imagery on the lunar surface	**FN-U-102 L**						
Enable crew lunar surface extravehicular activity in sunlit areas and non-PSRs	**FN-M-101 L**	Crew identification of surface samples in sunlit areas and non-PSRs in the far side on the lunar surface	**UC-U-108 L**				
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 L**						
Provide position, navigation, and timing services at the far side and outside the south pole region on the lunar surface	**FN-C-203 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						
Capture imagery on the lunar surface	**FN-U-102 L**						
Enable crew lunar surface extravehicular activity in sunlit areas and non-PSRs	**FN-M-101 L**	Collection, documentation, and packaging of surface and/or shallow sub-surface samples, maintaining scientific integrity of the samples, from non-PSRs and sunlit areas in the south pole region on the lunar surface	**UC-U-301 L**				
Provide position, navigation, and timing services at the south pole region on the lunar surface	**FN-C-201 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						
Capture imagery on the lunar surface	**FN-U-102 L**						
Provide capability to recover and package surface and/or shallow sub-surface samples, maintaining scientific integrity of the samples, from non-PSRs and sunlit regions on the lunar surface	**FN-U-303 L**						
Enable crew lunar surface extravehicular activity in sunlit areas and non-PSRs	**FN-M-101 L**	Collection, documentation, and packaging of surface and/or shallow sub-surface samples, maintaining scientific integrity of the samples, from non-PSRs and sunlit areas in distributed locations on the lunar surface	**UC-U-305 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-202 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						
Capture imagery on the lunar surface	**FN-U-102 L**						
Provide capability to recover and package surface and/or shallow sub-surface samples, maintaining scientific integrity of the samples, from non-PSRs and sunlit regions on the lunar surface	**FN-U-303 L**						
Enable crew lunar surface extravehicular activity in sunlit areas and non-PSRs	**FN-M-101 L**	Collection, documentation, and packaging of surface and/or shallow	**UC-U-306 L**				

Functions		Use Cases		Characteristics/Needs		Objectives	
Provide position, navigation, and timing services at the far side and outside the south pole region on the lunar surface	FN-C-203 L	sub-surface samples, maintaining scientific integrity of the samples, from non-PSRs and sunlit areas in the far side on the lunar surface					
Provide a coordinated lunar time scale	FN-C-205 L						
Capture imagery on the lunar surface	FN-U-102 L						
Provide capability to recover and package surface and/or shallow sub-surface samples, maintaining scientific integrity of the samples, from non-PSRs and sunlit regions on the lunar surface	FN-U-303 L						
Deliver free flying asset(s) from Earth to cislunar space	FN-T-216 L	Deployment and operation of free-flying assets long-term in a variety of lunar orbits	UC-U-203 L	Deploy and operate utilization payload(s) relevant to assessing space weather phenomena, including ability to conduct long looks at the Sun, in a variety of lunar orbits.	CN-U-707 L		
Provide communications and data exchange between Earth and cislunar space	FN-C-102 L						
Provide position, navigation, and timing data in cislunar space	FN-C-204 L						
Transport cargo from Earth to cislunar space	FN-T-213 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-707 L				
Provide communications and data exchange between Earth and cislunar space	FN-C-102 L						
Enable repositioning of externally mounted utilization payloads in cislunar space	FN-A-106 L						
Provide extravehicular utilization accommodation, interfaces, and resources, operable during crewed and uncrewed increments, in cislunar space	FN-U-202 L						
Transport cargo from Earth to cislunar space	FN-T-213 L	Deployment and operation of utilization payload(s) and/or equipment at cislunar asset(s)	UC-U-202 L	Deploy and operate utilization payloads, related to fundamental plasma processes, in cislunar space.	CN-U-709 L		
Provide communications and data exchange between Earth and cislunar space	FN-C-102 L						
Enable repositioning of externally mounted utilization payloads in cislunar space	FN-A-106 L						
Provide extravehicular utilization accommodation, interfaces, and resources, operable during crewed and uncrewed increments, in cislunar space	FN-U-202 L						
Deliver free flying asset(s) from Earth to cislunar space	FN-T-216 L	Deployment and operation of free-flying assets long-term in a variety of lunar orbits	UC-U-203 L				
Provide communications and data exchange between Earth and cislunar space	FN-C-102 L						
Provide position, navigation, and timing data in cislunar space	FN-C-204 L						
Transport a limited amount of cargo (100s of kg) from Earth to south pole region sites on the lunar surface	FN-T-201 L	Deployment and operation of plasma utilization payload(s) on the lunar surface with long term remote operation	UC-U-710 L	Deploy and operate utilization payload(s) related to fundamental plasma processes around globally distributed locations on the lunar surface.	CN-U-710 L		
Provide power for deployed external surface utilization payloads(s) and/or equipment for long durations (months to years+)	FN-P-402 L						
Enable crew lunar surface extravehicular activity in sunlit areas and non-PSRs	FN-M-101 L						
Unload a limited amount of cargo (100s of kg) on the lunar surface	FN-M-401 L						
Reposition a limited amount of cargo (100s of kg) in the south pole region on the lunar surface	FN-M-501 L						

Functions		Use Cases		Characteristics/Needs		Objectives	
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 L**						
Perform robotic manipulation of payloads, logistics, and/or equipment on the lunar surface	**FN-A-104 L**						
Deliver free flying asset(s) from Earth to cislunar space	**FN-T-216 L**	Deployment and operation of free-flying assets long-term in a variety of lunar orbits	**UC-U-203 L**	Deploy and operate utilization payload(s), related to the magnetotail and solar wind, in cislunar space, including the ability to conduct long looks at the Sun.	**CN-U-711 L**	Improve understanding of magnetotail and pristine solar wind dynamics in the vicinity of the Moon and around Mars.	**HS-04 LM**
Provide communications and data exchange between Earth and cislunar space	**FN-C-102 L**						
Provide position, navigation, and timing data in cislunar space	**FN-C-204 L**						
Transport cargo from Earth to cislunar space	**FN-T-213 L**	Deployment and operation of Heliophysics utilization payload(s) and/or equipment at cislunar asset(s) with long term remote operation	**UC-U-706 L**				
Provide communications and data exchange between Earth and cislunar space	**FN-C-102 L**						
Enable repositioning of externally mounted utilization payloads in cislunar space	**FN-A-106 L**						
Provide extravehicular utilization accommodation, interfaces, and resources, operable during crewed and uncrewed increments, in cislunar space	**FN-U-202 L**						
Transport a limited amount of cargo (100s of kg) from Earth to south pole region sites on the lunar surface	**FN-T-201 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-709 L**	Deploy and operate utilization payload(s), related to the magnetotail and solar wind, at distributed sites on the lunar surface.	**CN-U-712 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-203 L**						
Provide power for deployed external surface utilization payloads(s) and/or equipment for long durations (months to years+)	**FN-P-402 L**						
Enable crew lunar surface extravehicular activity in sunlit areas and non-PSRs	**FN-M-101 L**						
Unload a limited amount of cargo (100s of kg) on the lunar surface	**FN-M-401 L**						
Reposition a limited amount of cargo (100s of kg) in the south pole region on the lunar surface	**FN-M-501 L**						
Reposition a limited amount of cargo (100s of kg) at distributed sites on the lunar surface	**FN-M-502 L**						
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 L**						
Perform robotic manipulation of payloads, logistics, and/or equipment on the lunar surface	**FN-A-104 L**						
Transport crew from cislunar space to lunar surface sites in the south pole region	**FN-T-102 L**	Transportation of crew between cislunar space and the lunar surface	**UC-T-104 L**	Transition crew from partial gravity environment to micro-gravity environment.	**CN-T-111 L**	Understand the effects of short- and long-duration exposure to the environments of the Moon, Mars, and deep space on biological systems and health, using humans, model organisms, systems of human physiology, and plants.	**HBS-01 LM**
Transport crew from cislunar space to distributed sites outside of the south pole region on the lunar surface	**FN-T-103 L**						
Transport crew from the lunar surface to cislunar space	**FN-T-104 L**						
Enable crew habitation during transit from cislunar space to lunar surface sites in the south pole region	**FN-T-108 L**						
Enable crew habitation during transit from cislunar space to distributed sites outside of the south pole region on the lunar surface	**FN-T-109 L**						
Enable crew habitation during transit from the lunar surface to cislunar space	**FN-T-110 L**						

Functions		Use Cases		Characteristics/Needs		Objectives	
Transport crew from cislunar space to lunar surface sites in the south pole region	FN-T-102 L	Transportation of crew between cislunar space and the lunar surface	UC-T-104 L	Transition crew from micro-gravity environment to partial gravity environment, following a duration in space	CN-T-112 L		
Transport crew from cislunar space to distributed sites outside of the south pole region on the lunar surface	FN-T-103 L						
Transport crew from the lunar surface to cislunar space	FN-T-104 L						
Enable crew habitation during transit from cislunar space to lunar surface sites in the south pole region	FN-T-108 L						
Enable crew habitation during transit from cislunar space to distributed sites outside of the south pole region on the lunar surface	FN-T-109 L						
Enable crew habitation during transit from the lunar surface to cislunar space	FN-T-110 L						
Transport a small amount of cargo (10s of kg) from the lunar surface to Earth	FN-T-207 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-301 L	Transfer, return, and curate a small amount (10s of kg) or a large amount (100s of kg) of unconditioned samples and containers from key destinations across the lunar surface and back to Earth, while maintaining scientific integrity of the samples.	CN-T-302 L		
Transport a small amount of cargo (10s of kg) from the lunar surface to cislunar space	FN-T-209 L						
Transport a small amount of cargo (10s of kg) from cislunar space to Earth	FN-T-211 L						
Reposition a small amount of unconditioned samples and containers (10s of kg) on the lunar surface	FN-M-504 L						
Stow collected unconditioned samples on exploration assets while on the lunar surface, while maintaining scientific integrity of the samples	FN-U-401 L						
Transport a large amount of cargo (100s of kg) from the lunar surface to Earth	FN-T-208 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-302 L				
Transport a large amount of cargo (100s of kg) from the lunar surface to cislunar space	FN-T-210 L						
Transport a large amount of cargo (100s of kg) from cislunar space to Earth	FN-T-212 L						
Reposition a large amount of unconditioned samples and containers (100s of kg) on the lunar surface	FN-M-505 L						
Stow collected unconditioned samples on exploration assets while on the lunar surface, while maintaining scientific integrity of the samples	FN-U-401 L						
BLANK	BLANK	Delivery of collected samples to curation facilities or other appropriate facilities on Earth, while maintaining scientific integrity of the samples	UC-G-202 L				
Transport a small amount of cargo (10s of kg) from the lunar surface to Earth	FN-T-207 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-303 L	Transfer, return and curate a small amount (10s of kg) or a large amount (100s of kg) of refrigerated sample(s), containers, and freezers from key destinations across the lunar surface to Earth while maintaining scientific integrity of the samples.	CN-T-303 L		
Transport a small amount of cargo (10s of kg) from the lunar surface to cislunar space	FN-T-209 L						
Transport a small amount of cargo (10s of kg) from cislunar space to Earth	FN-T-211 L						
Provide resources to condition refrigerated sample containers during transit from the lunar surface to Earth	FN-T-301 L						
Provide resources to condition refrigerated sample containers during transit from the lunar surface to cislunar space	FN-T-304 L						
Provide resources to condition refrigerated sample containers during transit from cislunar space to Earth	FN-T-307 L						

Functions		Use Cases		Characteristics/Needs		Objectives	
Reposition a small amount of refrigerated samples and containers (10s of kg) on the lunar surface	**FN-M-506 L**						
Stow refrigerated samples during transport from the Lunar Surface to Earth, while maintaining scientific integrity of samples	**FN-U-402 L**						
Stow refrigerated samples during transport from the Lunar Surface to cislunar space, while maintaining scientific integrity of samples	**FN-U-405 L**						
Stow refrigerated samples during transport from cislunar space to Earth, while maintaining scientific integrity of samples	**FN-U-408 L**						
Stow collected refrigerated samples on exploration assets while on the lunar surface, while maintaining scientific integrity of the samples	**FN-U-411 L**						
Provide resources to condition refrigerated sample containers on the lunar surface	**FN-U-414 L**						
Transport a large amount of cargo (100s of kg) from the lunar surface to Earth	**FN-T-208 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-304 L**				
Transport a large amount of cargo (100s of kg) from the lunar surface to cislunar space	**FN-T-210 L**						
Transport a large amount of cargo (100s of kg) from cislunar space to Earth	**FN-T-212 L**						
Provide resources to condition refrigerated sample containers during transit from the lunar surface to Earth	**FN-T-301 L**						
Provide resources to condition refrigerated sample containers during transit from the lunar surface to cislunar space	**FN-T-304 L**						
Provide resources to condition refrigerated sample containers during transit from cislunar space to Earth	**FN-T-307 L**						
Reposition a large amount of refrigerated samples and containers (100s of kg) on the lunar surface	**FN-M-507 L**						
Stow refrigerated samples during transport from the Lunar Surface to Earth, while maintaining scientific integrity of samples	**FN-U-402 L**						
Stow refrigerated samples during transport from the Lunar Surface to cislunar space, while maintaining scientific integrity of samples	**FN-U-405 L**						
Stow refrigerated samples during transport from cislunar space to Earth, while maintaining scientific integrity of samples	**FN-U-408 L**						
Stow collected refrigerated samples on exploration assets while on the lunar surface, while maintaining scientific integrity of the samples	**FN-U-411 L**						
Provide resources to condition refrigerated sample containers on the lunar surface	**FN-U-414 L**						
BLANK	**BLANK**	Delivery of conditioned cargo to curation facilities or other appropriate facilities on Earth after landing, while maintaining scientific integrity of the samples	**UC-G-201 L**				
Transport a small amount of cargo (10s of kg) from the lunar surface to Earth	**FN-T-207 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-305 L**	Transfer, return and curate a small amount (10s of kg) or a large amount (100s of kg) of frozen sample(s), containers, and freezers from key destinations across the lunar surface to Earth while maintaining	**CN-T-304 L**		
Transport a small amount of cargo (10s of kg) from the lunar surface to cislunar space	**FN-T-209 L**						
Transport a small amount of cargo (10s of kg) from cislunar space to Earth	**FN-T-211 L**						
Provide resources to condition frozen sample containers during transit from the lunar surface to Earth	**FN-T-302 L**						

Functions		Use Cases		Characteristics/Needs		Objectives	
Provide resources to condition frozen sample containers during transit from the lunar surface to cislunar space	**FN-T-305 L**			scientific integrity of the samples.			
Provide resources to condition frozen sample containers during transit from cislunar space to Earth	**FN-T-308 L**						
Reposition a small amount of frozen samples and containers (10s of kg) on the lunar surface	**FN-M-508 L**						
Stow frozen 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 cislunar space, while maintaining scientific integrity of samples	**FN-U-406 L**						
Stow frozen samples during transport from cislunar space to Earth, while maintaining scientific integrity of samples	**FN-U-409 L**						
Stow collected frozen samples on exploration assets while on the lunar surface, while maintaining scientific integrity of the samples	**FN-U-412 L**						
Provide resources to condition frozen sample containers on the lunar surface	**FN-U-415 L**						
Transport a large amount of cargo (100s of kg) from the lunar surface to Earth	**FN-T-208 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-306 L**				
Transport a large amount of cargo (100s of kg) from the lunar surface to cislunar space	**FN-T-210 L**						
Transport a large amount of cargo (100s of kg) from cislunar space to Earth	**FN-T-212 L**						
Provide resources to condition frozen 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 cislunar space	**FN-T-305 L**						
Provide resources to condition frozen sample containers during transit from cislunar space to Earth	**FN-T-308 L**						
Reposition a large amount of frozen samples and containers (100s of kg) on the lunar surface	**FN-M-509 L**						
Stow frozen 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 cislunar space, while maintaining scientific integrity of samples	**FN-U-406 L**						
Stow frozen samples during transport from cislunar space to Earth, while maintaining scientific integrity of samples	**FN-U-409 L**						
Stow collected frozen samples on exploration assets while on the lunar surface, while maintaining scientific integrity of the samples	**FN-U-412 L**						
Provide resources to condition frozen sample containers on the lunar surface	**FN-U-415 L**						
BLANK	**BLANK**	Delivery of conditioned cargo to curation facilities or other appropriate facilities on Earth after landing, while maintaining scientific integrity of the samples	**UC-G-201 L**				

Functions		Use Cases		Characteristics/Needs		Objectives	
Transport a small amount of cargo (10s of kg) from cislunar space to Earth	**FN-T-211 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-308 L**	Transfer, return and curate a small amount (10s of kg) or a large amount (100s of kg) of unconditioned sample(s) and containers from cislunar assets back to Earth while maintaining scientific integrity of the samples.	**CN-T-307 L**		
Transport a large amount of cargo (100s of kg) from cislunar space to Earth	**FN-T-212 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-309 L**				
BLANK	**BLANK**	Delivery of collected samples to curation facilities or other appropriate facilities on Earth, while maintaining scientific integrity of the samples	**UC-G-202 L**				
Transport a small amount of cargo (10s of kg) from cislunar space to Earth	**FN-T-211 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-310 L**	Transfer, return and curate a small amount (10s of kg) or a large amount (100s of kg) of refrigerated sample(s) and containers from cislunar assets back to Earth while maintaining scientific integrity of the samples.	**CN-T-308 L**		
Provide resources to condition refrigerated sample containers during transit from cislunar space to Earth	**FN-T-307 L**						
Stow refrigerated samples during transport from cislunar space to Earth, while maintaining scientific integrity of samples	**FN-U-408 L**						
Transport a large amount of cargo (100s of kg) from cislunar space to Earth	**FN-T-212 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-311 L**				
Provide resources to condition refrigerated sample containers during transit from cislunar space to Earth	**FN-T-307 L**						
Stow refrigerated samples during transport from cislunar space to Earth, while maintaining scientific integrity of samples	**FN-U-408 L**						
BLANK	**BLANK**	Delivery of conditioned cargo to curation facilities or other appropriate facilities on Earth after landing, while maintaining scientific integrity of the samples	**UC-G-201 L**				
Transport a small amount of cargo (10s of kg) from cislunar space to Earth	**FN-T-211 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-312 L**	Transfer, return and curate a small amount (10s of kg) or a large amount (100s of kg) of frozen sample(s) and containers from cislunar assets back to Earth while maintaining scientific integrity of the samples.	**CN-T-309 L**		
Provide resources to condition frozen sample containers during transit from cislunar space to Earth	**FN-T-308 L**						
Stow frozen samples during transport from cislunar space to Earth, while maintaining scientific integrity of samples	**FN-U-409 L**						
Transport a large amount of cargo (100s of kg) from cislunar space to Earth	**FN-T-212 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-313 L**				
Provide resources to condition frozen sample containers during transit from cislunar space to Earth	**FN-T-308 L**						
Stow frozen samples during transport from cislunar space to Earth, while maintaining scientific integrity of samples	**FN-U-409 L**						
BLANK	**BLANK**	Delivery of conditioned cargo to curation facilities or other appropriate facilities on Earth after landing, while maintaining scientific integrity of the samples	**UC-G-201 L**				

Functions		Use Cases		Characteristics/Needs		Objectives	
Enable a pressurized, habitable environment on the lunar surface for short durations (days to weeks)	**FN-H-101 L**	Crew habitation of assets on the lunar surface for short-durations (days to weeks)	**UC-H-101 L**	Conduct short-duration (days to weeks) to mid-duration (month+) crew exploration mission(s) on the lunar surface.	**CN-H-101 L**		
Operate habitation system(s) in uncrewed mode between crewed missions on the lunar surface	**FN-H-201 L**						
Manage waste from habitable asset(s) on the lunar surface	**FN-L-301 L**						
Enable a pressurized, habitable environment on the lunar surface for moderate duration (month+) use	**FN-H-102 L**	Crew habitation of assets on the lunar surface for mid-durations (month+)	**UC-H-102 L**				
Operate habitation system(s) in uncrewed mode between crewed missions on the lunar surface	**FN-H-201 L**						
Manage waste from habitable asset(s) on the lunar surface	**FN-L-301 L**						
Operate habitation system(s) in uncrewed mode between crewed missions on the lunar surface	**FN-H-201 L**	Reuse of habitation system(s) on the lunar surface	**UC-H-105 L**				
Transport a limited amount of cargo (100s of kg) from Earth to south pole region sites on the lunar surface	**FN-T-201 L**	Resupply of cargo and management of waste to/from habitable assets on the lunar surface	**UC-L-201 L**				
Transport a moderate amount of cargo (1000s of kg) from Earth to south pole region sites on the lunar surface	**FN-T-202 L**						
Mating between pressurized assets on the lunar surface	**FN-L-101 L**						
Transfer pressurized cargo into habitable assets on the lunar surface	**FN-L-201 L**						
Transfer water to habitable assets on the lunar surface	**FN-L-203 L**						
Transfer gases to habitable assets on the lunar surface	**FN-L-205 L**						
Manage waste from habitable asset(s) on the lunar surface	**FN-L-301 L**						
Unload a limited amount of cargo (100s of kg) on the lunar surface	**FN-M-401 L**						
Unload a moderate amount of cargo (1000s of kg) on the lunar surface	**FN-M-402 L**						
Reposition a limited amount of cargo (100s of kg) in the south pole region on the lunar surface	**FN-M-501 L**						
Reposition a moderate amount of cargo (1000s of kg) at the south pole region on the lunar surface	**FN-M-503 L**						
Enable a pressurized, habitable environment on the lunar surface for short durations (days to weeks)	**FN-H-101 L**	Crew habitation of assets on the lunar surface for short-durations (days to weeks)	**UC-H-101 L**	Conduct short-duration (days to weeks), mid-duration (month+), and extended-duration (year+) crew exploration mission(s) in cislunar space	**CN-H-102 L**		
Operate habitation system(s) in uncrewed mode between crewed missions on the lunar surface	**FN-H-201 L**						
Manage waste from habitable asset(s) on the lunar surface	**FN-L-301 L**						
Enable a pressurized, habitable environment in cislunar space for moderate (month+) durations	**FN-H-104 L**	Crew habitation of assets for moderate-duration (month+) mission(s) in cislunar space	**UC-H-103 L**				
Operate habitation system(s) in uncrewed mode between crewed missions in cislunar space	**FN-H-202 L**						
Enable a pressurized, habitable environment in cislunar space for extended (year+) duration	**FN-H-105 L**		**UC-H-104 L**				

Functions		Use Cases		Characteristics/Needs		Objectives	
Operate habitation system(s) in uncrewed mode between crewed missions in cislunar space	**FN-H-202 L**	Crew habitation of assets for extended-duration (year+) mission(s) in cislunar space					
Operate habitation system(s) in uncrewed mode between crewed missions in cislunar space	**FN-H-202 L**	Reuse of habitation system(s) in cislunar space	**UC-H-106 L**				
Rendezvous, proximity operations, mating and unmating of assets in cislunar space	**FN-T-106 L**	Resupply of cargo and management of waste to/from habitable assets in cislunar space	**UC-L-202 L**				
Transport cargo from Earth to cislunar space	**FN-T-213 L**						
Transfer pressurized cargo into habitable assets in cislunar space	**FN-L-202 L**						
Transfer water to habitable assets in cislunar space	**FN-L-204 L**						
Transfer gases to habitable assets in cislunar space	**FN-L-206 L**						
Manage waste from habitable asset(s) in cislunar space	**FN-L-302 L**						
Transport cargo from Earth to cislunar space	**FN-T-213 L**	Intravehicular science and utilization activities on the lunar surface	**UC-U-201 L**	Provide intravehicular activity accommodations (e.g., instruments, racks, stowage, power) on the lunar surface during crewed and uncrewed mission phases to enable biological science analysis and human research.	**CN-U-201 L**		
Distribute power to utilization payloads and/or equipment in cislunar space	**FN-P-303 L**						
Provide communications and data exchange between Earth and cislunar space	**FN-C-102 L**						
Provide high bandwidth, high availability communications and data exchange between the lunar surface and Earth	**FN-C-105 L**						
Provide intravehicular activity facilities, utilization accommodation, and resources, operable during crewed and uncrewed increments, on the lunar surface	**FN-U-204 L**						
Reposition a small amount of unconditioned samples and containers (10s of kg) on the lunar surface	**FN-M-504 L**	Crew conduct of biological science and human research activities on the lunar surface	**UC-U-602 L**				
Reposition a small amount of refrigerated samples and containers (10s of kg) on the lunar surface	**FN-M-506 L**						
Reposition a small amount of frozen samples and containers (10s of kg) on the lunar surface	**FN-M-508 L**						
Provide data capabilities, including protection for communication, and interface to support crew medical care on the lunar surface	**FN-D-105 L**						
Provide extravehicular utilization accommodation, interfaces, and resources, operable during crewed and uncrewed increments, on the lunar surface	**FN-U-203 L**						
Provide intravehicular activity facilities, utilization accommodation, and resources, operable during crewed and uncrewed increments, on the lunar surface	**FN-U-204 L**						
Stow collected unconditioned samples on exploration assets while on the lunar surface, while maintaining scientific integrity of the samples	**FN-U-401 L**						
Stow collected refrigerated samples on exploration assets while on the lunar surface, while maintaining scientific integrity of the samples	**FN-U-411 L**						
Stow collected frozen samples on exploration assets while on the lunar surface, while maintaining scientific integrity of the samples	**FN-U-412 L**						

Functions		Use Cases		Characteristics/Needs		Objectives	
Provide delivery of live, actively growing biological specimens to cislunar space, including late load of cargo prior to launch	FN-T-214 L	Crew conduct of biological science and human research activities in cislunar space	UC-U-601 L	Provide intravehicular activity accommodations (e.g., instruments, racks, stowage, power) in cislunar space to enable biological science analysis and human research.	CN-U-202 L		
Provide data capabilities, including protection for communication, and interface to support crew medical care in cislunar space	FN-D-106 L						
Enable repositioning of externally mounted utilization payloads in cislunar space	FN-A-106 L						
Provide extravehicular utilization accommodation, interfaces, and resources, operable during crewed and uncrewed increments, in cislunar space	FN-U-202 L						
Provide intravehicular activity facilities, utilization accommodation, and resources, operable during crewed and uncrewed increments, in cislunar space	FN-U-205 L						
Provide intravehicular utilization accommodation and resources during crew transit between Earth and cislunar space	FN-U-206 L	Crew conduct of biological science and human research activities during crew transit between Earth and cislunar space	UC-U-603 L	Provide intravehicular utilization accommodation and resources during crew transit between Earth and cislunar space to enable biological science analysis and human research.	CN-U-205 L		
Transport a limited amount of cargo (100s of kg) from Earth to south pole region sites on the lunar surface	FN-T-201 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-719 L	Deploy and operate external utilization payload(s) addressing biological science analysis and human research around globally distributed locations on the lunar surface for a minimum of mid-duration (month+) missions.	CN-U-701 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-203 L						
Provide communications and data exchange between the lunar surface and Earth	FN-C-101 L						
Perform robotic manipulation of payloads, logistics, and/or equipment on the lunar surface	FN-A-104 L						
Provide extravehicular utilization accommodation, interfaces, and resources, operable during crewed and uncrewed increments, on the lunar surface	FN-U-203 L						
Transport a limited amount of cargo (100s of kg) from Earth to south pole region sites on the lunar surface	FN-T-201 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-720 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-203 L						
Enable crew lunar surface extravehicular activity in sunlit areas and non-PSRs	FN-M-101 L						
Provide communications and data exchange between the lunar surface and Earth	FN-C-101 L						
Perform robotic manipulation of payloads, logistics, and/or equipment on the lunar surface	FN-A-104 L						
Provide extravehicular utilization accommodation, interfaces, and resources, operable during crewed and uncrewed increments, on the lunar surface	FN-U-203 L						
Provide delivery of live, actively growing biological specimens to cislunar space, including late load of cargo prior to launch	FN-T-214 L	Crew conduct of biological science and human research activities in cislunar space	UC-U-601 L	Deploy and operate internal and external utilization payload(s) addressing biological science analysis and human research in cislunar space for mid-duration (month+) to extended-duration (year+) missions.	CN-U-705 L		
Provide data capabilities, including protection for communication, and interface to support crew medical care in cislunar space	FN-D-106 L						
Enable repositioning of externally mounted utilization payloads in cislunar space	FN-A-106 L						
Provide extravehicular utilization accommodation, interfaces, and resources, operable during crewed and uncrewed increments, in cislunar space	FN-U-202 L						
Provide intravehicular activity facilities, utilization accommodation, and resources, operable during crewed and uncrewed increments, in cislunar space	FN-U-205 L						

Functions		Use Cases		Characteristics/Needs		Objectives	
Transport crew from cislunar space to lunar surface sites in the south pole region	**FN-T-102 L**	Transportation of crew between cislunar space and the lunar surface	**UC-T-104 L**	Transition crew from partial gravity environment to micro-gravity environment.	**CN-T-111 L**	Evaluate and validate progressively Earth-independent crew health & performance systems and operations with mission durations representative of Mars-class missions.	**HBS-02 LM**
Transport crew from cislunar space to distributed sites outside of the south pole region on the lunar surface	**FN-T-103 L**						
Transport crew from the lunar surface to cislunar space	**FN-T-104 L**						
Enable crew habitation during transit from cislunar space to lunar surface sites in the south pole region	**FN-T-108 L**						
Enable crew habitation during transit from cislunar space to distributed sites outside of the south pole region on the lunar surface	**FN-T-109 L**						
Enable crew habitation during transit from the lunar surface to cislunar space	**FN-T-110 L**						
Transport crew from cislunar space to lunar surface sites in the south pole region	**FN-T-102 L**	Transportation of crew between cislunar space and the lunar surface	**UC-T-104 L**	Transition crew from micro-gravity environment to partial gravity environment, following a duration in space	**CN-T-112 L**		
Transport crew from cislunar space to distributed sites outside of the south pole region on the lunar surface	**FN-T-103 L**						
Transport crew from the lunar surface to cislunar space	**FN-T-104 L**						
Enable crew habitation during transit from cislunar space to lunar surface sites in the south pole region	**FN-T-108 L**						
Enable crew habitation during transit from cislunar space to distributed sites outside of the south pole region on the lunar surface	**FN-T-109 L**						
Enable crew habitation during transit from the lunar surface to cislunar space	**FN-T-110 L**						
Transport a small amount of cargo (10s of kg) from the lunar surface to Earth	**FN-T-207 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-301 L**	Transfer, return, and curate a small amount (10s of kg) or a large amount (100s of kg) of unconditioned samples and containers from key destinations across the lunar surface and back to Earth, while maintaining scientific integrity of the samples.	**CN-T-302 L**		
Transport a small amount of cargo (10s of kg) from the lunar surface to cislunar space	**FN-T-209 L**						
Transport a small amount of cargo (10s of kg) from cislunar space to Earth	**FN-T-211 L**						
Reposition a small amount of unconditioned samples and containers (10s of kg) on the lunar surface	**FN-M-504 L**						
Stow collected unconditioned samples on exploration assets while on the lunar surface, while maintaining scientific integrity of the samples	**FN-U-401 L**						
Transport a large amount of cargo (100s of kg) from the lunar surface to Earth	**FN-T-208 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-302 L**				
Transport a large amount of cargo (100s of kg) from the lunar surface to cislunar space	**FN-T-210 L**						
Transport a large amount of cargo (100s of kg) from cislunar space to Earth	**FN-T-212 L**						
Reposition a large amount of unconditioned samples and containers (100s of kg) on the lunar surface	**FN-M-505 L**						
Stow collected unconditioned samples on exploration assets while on the lunar surface, while maintaining scientific integrity of the samples	**FN-U-401 L**						
BLANK	**BLANK**	Delivery of collected samples to curation facilities or other appropriate facilities on Earth, while maintaining scientific integrity of the samples	**UC-G-202 L**				

Functions		Use Cases		Characteristics/Needs		Objectives	
Transport a small amount of cargo (10s of kg) from the lunar surface to Earth	**FN-T-207 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-303 L**	Transfer, return and curate a small amount (10s of kg) or a large amount (100s of kg) of refrigerated sample(s), containers, and freezers from key destinations across the lunar surface to Earth while maintaining scientific integrity of the samples.	**CN-T-303 L**		
Transport a small amount of cargo (10s of kg) from the lunar surface to cislunar space	**FN-T-209 L**						
Transport a small amount of cargo (10s of kg) from cislunar space to Earth	**FN-T-211 L**						
Provide resources to condition refrigerated sample containers during transit from the lunar surface to Earth	**FN-T-301 L**						
Provide resources to condition refrigerated sample containers during transit from the lunar surface to cislunar space	**FN-T-304 L**						
Provide resources to condition refrigerated sample containers during transit from cislunar space to Earth	**FN-T-307 L**						
Reposition a small amount of refrigerated samples and containers (10s of kg) on the lunar surface	**FN-M-506 L**						
Stow refrigerated samples during transport from the Lunar Surface to Earth, while maintaining scientific integrity of samples	**FN-U-402 L**						
Stow refrigerated samples during transport from the Lunar Surface to cislunar space, while maintaining scientific integrity of samples	**FN-U-405 L**						
Stow refrigerated samples during transport from cislunar space to Earth, while maintaining scientific integrity of samples	**FN-U-408 L**						
Stow collected refrigerated samples on exploration assets while on the lunar surface, while maintaining scientific integrity of the samples	**FN-U-411 L**						
Provide resources to condition refrigerated sample containers on the lunar surface	**FN-U-414 L**						
Transport a large amount of cargo (100s of kg) from the lunar surface to Earth	**FN-T-208 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-304 L**				
Transport a large amount of cargo (100s of kg) from the lunar surface to cislunar space	**FN-T-210 L**						
Transport a large amount of cargo (100s of kg) from cislunar space to Earth	**FN-T-212 L**						
Provide resources to condition refrigerated sample containers during transit from the lunar surface to Earth	**FN-T-301 L**						
Provide resources to condition refrigerated sample containers during transit from the lunar surface to cislunar space	**FN-T-304 L**						
Provide resources to condition refrigerated sample containers during transit from cislunar space to Earth	**FN-T-307 L**						
Reposition a large amount of refrigerated samples and containers (100s of kg) on the lunar surface	**FN-M-507 L**						
Stow refrigerated samples during transport from the Lunar Surface to Earth, while maintaining scientific integrity of samples	**FN-U-402 L**						
Stow refrigerated samples during transport from the Lunar Surface to cislunar space, while maintaining scientific integrity of samples	**FN-U-405 L**						
Stow refrigerated samples during transport from cislunar space to Earth, while maintaining scientific integrity of samples	**FN-U-408 L**						
Stow collected refrigerated samples on exploration assets while on the lunar surface, while maintaining scientific integrity of the samples	**FN-U-411 L**						
Provide resources to condition refrigerated sample containers on the lunar surface	**FN-U-414 L**						

Functions		Use Cases		Characteristics/Needs		Objectives	
BLANK	**BLANK**	Delivery of conditioned cargo to curation facilities or other appropriate facilities on Earth after landing, while maintaining scientific integrity of the samples	**UC-G-201 L**				
Transport a small amount of cargo (10s of kg) from the lunar surface to Earth	**FN-T-207 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-305 L**	Transfer, return and curate a small amount (10s of kg) or a large amount (100s of kg) of frozen sample(s), containers, and freezers from key destinations across the lunar surface to Earth while maintaining scientific integrity of the samples.	**CN-T-304 L**		
Transport a small amount of cargo (10s of kg) from the lunar surface to cislunar space	**FN-T-209 L**						
Transport a small amount of cargo (10s of kg) from cislunar space to Earth	**FN-T-211 L**						
Provide resources to condition frozen 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 cislunar space	**FN-T-305 L**						
Provide resources to condition frozen sample containers during transit from cislunar space to Earth	**FN-T-308 L**						
Reposition a small amount of frozen samples and containers (10s of kg) on the lunar surface	**FN-M-508 L**						
Stow frozen 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 cislunar space, while maintaining scientific integrity of samples	**FN-U-406 L**						
Stow frozen samples during transport from cislunar space to Earth, while maintaining scientific integrity of samples	**FN-U-409 L**						
Stow collected frozen samples on exploration assets while on the lunar surface, while maintaining scientific integrity of the samples	**FN-U-412 L**						
Provide resources to condition frozen sample containers on the lunar surface	**FN-U-415 L**						
Transport a large amount of cargo (100s of kg) from the lunar surface to Earth	**FN-T-208 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-306 L**				
Transport a large amount of cargo (100s of kg) from the lunar surface to cislunar space	**FN-T-210 L**						
Transport a large amount of cargo (100s of kg) from cislunar space to Earth	**FN-T-212 L**						
Provide resources to condition frozen 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 cislunar space	**FN-T-305 L**						
Provide resources to condition frozen sample containers during transit from cislunar space to Earth	**FN-T-308 L**						
Reposition a large amount of frozen samples and containers (100s of kg) on the lunar surface	**FN-M-509 L**						
Stow frozen 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 cislunar space, while maintaining scientific integrity of samples	**FN-U-406 L**						
Stow frozen samples during transport from cislunar space to Earth, while maintaining scientific integrity of samples	**FN-U-409 L**						

Functions		Use Cases		Characteristics/Needs		Objectives	
Stow collected frozen samples on exploration assets while on the lunar surface, while maintaining scientific integrity of the samples	**FN-U-412 L**						
Provide resources to condition frozen sample containers on the lunar surface	**FN-U-415 L**						
BLANK	**BLANK**	Delivery of conditioned cargo to curation facilities or other appropriate facilities on Earth after landing, while maintaining scientific integrity of the samples	**UC-G-201 L**				
Transport a small amount of cargo (10s of kg) from cislunar space to Earth	**FN-T-211 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-308 L**	Transfer, return and curate a small amount (10s of kg) or a large amount (100s of kg) of unconditioned sample(s) and containers from cislunar assets back to Earth while maintaining scientific integrity of the samples.	**CN-T-307 L**		
Transport a large amount of cargo (100s of kg) from cislunar space to Earth	**FN-T-212 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-309 L**				
BLANK	**BLANK**	Delivery of collected samples to curation facilities or other appropriate facilities on Earth, while maintaining scientific integrity of the samples	**UC-G-202 L**				
Transport a small amount of cargo (10s of kg) from cislunar space to Earth	**FN-T-211 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-310 L**	Transfer, return and curate a small amount (10s of kg) or a large amount (100s of kg) of refrigerated sample(s) and containers from cislunar assets back to Earth while maintaining scientific integrity of the samples.	**CN-T-308 L**		
Provide resources to condition refrigerated sample containers during transit from cislunar space to Earth	**FN-T-307 L**						
Stow refrigerated samples during transport from cislunar space to Earth, while maintaining scientific integrity of samples	**FN-U-408 L**						
Transport a large amount of cargo (100s of kg) from cislunar space to Earth	**FN-T-212 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-311 L**				
Provide resources to condition refrigerated sample containers during transit from cislunar space to Earth	**FN-T-307 L**						
Stow refrigerated samples during transport from cislunar space to Earth, while maintaining scientific integrity of samples	**FN-U-408 L**						
BLANK	**BLANK**	Delivery of conditioned cargo to curation facilities or other appropriate facilities on Earth after landing, while maintaining scientific integrity of the samples	**UC-G-201 L**				
Transport a small amount of cargo (10s of kg) from cislunar space to Earth	**FN-T-211 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-312 L**	Transfer, return and curate a small amount (10s of kg) or a large amount (100s of kg) of frozen sample(s) and containers from cislunar assets back to Earth while maintaining scientific integrity of the samples.	**CN-T-309 L**		
Provide resources to condition frozen sample containers during transit from cislunar space to Earth	**FN-T-308 L**						
Stow frozen samples during transport from cislunar space to Earth, while maintaining scientific integrity of samples	**FN-U-409 L**						
Transport a large amount of cargo (100s of kg) from cislunar space to Earth	**FN-T-212 L**	Return of a large amount of frozen samples and containers (100s of kg) from cislunar space to Earth with the	**UC-T-313 L**				
Provide resources to condition frozen sample containers during transit from cislunar space to Earth	**FN-T-308 L**						

Functions		Use Cases		Characteristics/Needs		Objectives	
Stow frozen samples during transport from cislunar space to Earth, while maintaining scientific integrity of samples	**FN-U-409 L**	samples in sealed conditioned sample containers					
BLANK	**BLANK**	Delivery of conditioned cargo to curation facilities or other appropriate facilities on Earth after landing, while maintaining scientific integrity of the samples	**UC-G-201 L**				
Enable a pressurized, habitable environment on the lunar surface for short durations (days to weeks)	**FN-H-101 L**	Crew habitation of assets on the lunar surface for short-durations (days to weeks)	**UC-H-101 L**	Conduct short-duration (days to weeks) to mid-duration (month+) crew exploration mission(s) on the lunar surface.	**CN-H-101 L**		
Operate habitation system(s) in uncrewed mode between crewed missions on the lunar surface	**FN-H-201 L**						
Manage waste from habitable asset(s) on the lunar surface	**FN-L-301 L**						
Enable a pressurized, habitable environment on the lunar surface for moderate duration (month+) use	**FN-H-102 L**	Crew habitation of assets on the lunar surface for mid-durations (month+)	**UC-H-102 L**				
Operate habitation system(s) in uncrewed mode between crewed missions on the lunar surface	**FN-H-201 L**						
Manage waste from habitable asset(s) on the lunar surface	**FN-L-301 L**						
Operate habitation system(s) in uncrewed mode between crewed missions on the lunar surface	**FN-H-201 L**	Reuse of habitation system(s) on the lunar surface	**UC-H-105 L**				
Transport a limited amount of cargo (100s of kg) from Earth to south pole region sites on the lunar surface	**FN-T-201 L**	Resupply of cargo and management of waste to/from habitable assets on the lunar surface	**UC-L-201 L**				
Transport a moderate amount of cargo (1000s of kg) from Earth to south pole region sites on the lunar surface	**FN-T-202 L**						
Mating between pressurized assets on the lunar surface	**FN-L-101 L**						
Transfer pressurized cargo into habitable assets on the lunar surface	**FN-L-201 L**						
Transfer water to habitable assets on the lunar surface	**FN-L-203 L**						
Transfer gases to habitable assets on the lunar surface	**FN-L-205 L**						
Manage waste from habitable asset(s) on the lunar surface	**FN-L-301 L**						
Unload a limited amount of cargo (100s of kg) on the lunar surface	**FN-M-401 L**						
Unload a moderate amount of cargo (1000s of kg) on the lunar surface	**FN-M-402 L**						
Reposition a limited amount of cargo (100s of kg) in the south pole region on the lunar surface	**FN-M-501 L**						
Reposition a moderate amount of cargo (1000s of kg) at the south pole region on the lunar surface	**FN-M-503 L**						
Enable a pressurized, habitable environment on the lunar surface for short durations (days to weeks)	**FN-H-101 L**	Crew habitation of assets on the lunar surface for short-durations (days to weeks)	**UC-H-101 L**	Conduct short-duration (days to weeks), mid-duration (month+), and extended-duration (year+) crew exploration mission(s) in cislunar space	**CN-H-102 L**		
Operate habitation system(s) in uncrewed mode between crewed missions on the lunar surface	**FN-H-201 L**						
Manage waste from habitable asset(s) on the lunar surface	**FN-L-301 L**						

Functions		Use Cases		Characteristics/Needs		Objectives	
Enable a pressurized, habitable environment in cislunar space for moderate (month+) durations	**FN-H-104 L**	Crew habitation of assets for moderate-duration (month+) mission(s) in cislunar space	**UC-H-103 L**				
Operate habitation system(s) in uncrewed mode between crewed missions in cislunar space	**FN-H-202 L**						
Enable a pressurized, habitable environment in cislunar space for extended (year+) duration	**FN-H-105 L**	Crew habitation of assets for extended-duration (year+) mission(s) in cislunar space	**UC-H-104 L**				
Operate habitation system(s) in uncrewed mode between crewed missions in cislunar space	**FN-H-202 L**						
Operate habitation system(s) in uncrewed mode between crewed missions in cislunar space	**FN-H-202 L**	Reuse of habitation system(s) in cislunar space	**UC-H-106 L**				
Rendezvous, proximity operations, mating and unmating of assets in cislunar space	**FN-T-106 L**	Resupply of cargo and management of waste to/from habitable assets in cislunar space	**UC-L-202 L**				
Transport cargo from Earth to cislunar space	**FN-T-213 L**						
Transfer pressurized cargo into habitable assets in cislunar space	**FN-L-202 L**						
Transfer water to habitable assets in cislunar space	**FN-L-204 L**						
Transfer gases to habitable assets in cislunar space	**FN-L-206 L**						
Manage waste from habitable asset(s) in cislunar space	**FN-L-302 L**						
Transport cargo from Earth to cislunar space	**FN-T-213 L**	Intravehicular science and utilization activities on the lunar surface	**UC-U-201 L**	Provide intravehicular activity accommodations (e.g., instruments, racks, stowage, power) on the lunar surface during crewed and uncrewed mission phases to enable biological science analysis and human research.	**CN-U-201 L**		
Distribute power to utilization payloads and/or equipment in cislunar space	**FN-P-303 L**						
Provide communications and data exchange between Earth and cislunar space	**FN-C-102 L**						
Provide high bandwidth, high availability communications and data exchange between the lunar surface and Earth	**FN-C-105 L**						
Provide intravehicular activity facilities, utilization accommodation, and resources, operable during crewed and uncrewed increments, on the lunar surface	**FN-U-204 L**						
Reposition a small amount of unconditioned samples and containers (10s of kg) on the lunar surface	**FN-M-504 L**	Crew conduct of biological science and human research activities on the lunar surface	**UC-U-602 L**				
Reposition a small amount of refrigerated samples and containers (10s of kg) on the lunar surface	**FN-M-506 L**						
Reposition a small amount of frozen samples and containers (10s of kg) on the lunar surface	**FN-M-508 L**						
Provide data capabilities, including protection for communication, and interface to support crew medical care on the lunar surface	**FN-D-105 L**						
Provide extravehicular utilization accommodation, interfaces, and resources, operable during crewed and uncrewed increments, on the lunar surface	**FN-U-203 L**						
Provide intravehicular activity facilities, utilization accommodation, and resources, operable during crewed and uncrewed increments, on the lunar surface	**FN-U-204 L**						
Stow collected unconditioned samples on exploration assets while on the lunar surface, while maintaining scientific integrity of the samples	**FN-U-401 L**						
Stow collected refrigerated samples on exploration assets while on the lunar surface, while maintaining scientific integrity of the samples	**FN-U-411 L**						

Functions		Use Cases		Characteristics/Needs		Objectives	
Stow collected frozen samples on exploration assets while on the lunar surface, while maintaining scientific integrity of the samples	FN-U-412 L						
Provide delivery of live, actively growing biological specimens to cislunar space, including late load of cargo prior to launch	FN-T-214 L	Crew conduct of biological science and human research activities in cislunar space	UC-U-601 L	Provide intravehicular activity accommodations (e.g., instruments, racks, stowage, power) in cislunar space to enable biological science analysis and human research.	CN-U-202 L		
Provide data capabilities, including protection for communication, and interface to support crew medical care in cislunar space	FN-D-106 L	Crew conduct of biological science and human research activities in cislunar space	UC-U-601 L	Provide intravehicular activity accommodations (e.g., instruments, racks, stowage, power) in cislunar space to enable biological science analysis and human research.	CN-U-202 L		
Enable repositioning of externally mounted utilization payloads in cislunar space	FN-A-106 L	Crew conduct of biological science and human research activities in cislunar space	UC-U-601 L	Provide intravehicular activity accommodations (e.g., instruments, racks, stowage, power) in cislunar space to enable biological science analysis and human research.	CN-U-202 L		
Provide extravehicular utilization accommodation, interfaces, and resources, operable during crewed and uncrewed increments, in cislunar space	FN-U-202 L	Crew conduct of biological science and human research activities in cislunar space	UC-U-601 L	Provide intravehicular activity accommodations (e.g., instruments, racks, stowage, power) in cislunar space to enable biological science analysis and human research.	CN-U-202 L		
Provide intravehicular activity facilities, utilization accommodation, and resources, operable during crewed and uncrewed increments, in cislunar space	FN-U-205 L	Crew conduct of biological science and human research activities in cislunar space	UC-U-601 L	Provide intravehicular activity accommodations (e.g., instruments, racks, stowage, power) in cislunar space to enable biological science analysis and human research.	CN-U-202 L		
Provide intravehicular utilization accommodation and resources during crew transit between Earth and cislunar space	FN-U-206 L	Crew conduct of biological science and human research activities during crew transit between Earth and cislunar space	UC-U-603 L	Provide intravehicular utilization accommodation and resources during crew transit between Earth and cislunar space to enable biological science analysis and human research.	CN-U-205 L		
Transport a limited amount of cargo (100s of kg) from Earth to south pole region sites on the lunar surface	FN-T-201 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-719 L	Deploy and operate external utilization payload(s) addressing biological science analysis and human research around globally distributed locations on the lunar surface for a minimum of mid-duration (month+) missions.	CN-U-701 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-203 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-719 L	Deploy and operate external utilization payload(s) addressing biological science analysis and human research around globally distributed locations on the lunar surface for a minimum of mid-duration (month+) missions.	CN-U-701 L		
Provide communications and data exchange between the lunar surface and Earth	FN-C-101 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-719 L	Deploy and operate external utilization payload(s) addressing biological science analysis and human research around globally distributed locations on the lunar surface for a minimum of mid-duration (month+) missions.	CN-U-701 L		
Perform robotic manipulation of payloads, logistics, and/or equipment on the lunar surface	FN-A-104 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-719 L	Deploy and operate external utilization payload(s) addressing biological science analysis and human research around globally distributed locations on the lunar surface for a minimum of mid-duration (month+) missions.	CN-U-701 L		
Provide extravehicular utilization accommodation, interfaces, and resources, operable during crewed and uncrewed increments, on the lunar surface	FN-U-203 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-719 L	Deploy and operate external utilization payload(s) addressing biological science analysis and human research around globally distributed locations on the lunar surface for a minimum of mid-duration (month+) missions.	CN-U-701 L		
Transport a limited amount of cargo (100s of kg) from Earth to south pole region sites on the lunar surface	FN-T-201 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-720 L	Deploy and operate external utilization payload(s) addressing biological science analysis and human research around globally distributed locations on the lunar surface for a minimum of mid-duration (month+) missions.	CN-U-701 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-203 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-720 L	Deploy and operate external utilization payload(s) addressing biological science analysis and human research around globally distributed locations on the lunar surface for a minimum of mid-duration (month+) missions.	CN-U-701 L		
Enable crew lunar surface extravehicular activity in sunlit areas and non-PSRs	FN-M-101 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-720 L	Deploy and operate external utilization payload(s) addressing biological science analysis and human research around globally distributed locations on the lunar surface for a minimum of mid-duration (month+) missions.	CN-U-701 L		
Provide communications and data exchange between the lunar surface and Earth	FN-C-101 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-720 L	Deploy and operate external utilization payload(s) addressing biological science analysis and human research around globally distributed locations on the lunar surface for a minimum of mid-duration (month+) missions.	CN-U-701 L		
Perform robotic manipulation of payloads, logistics, and/or equipment on the lunar surface	FN-A-104 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-720 L	Deploy and operate external utilization payload(s) addressing biological science analysis and human research around globally distributed locations on the lunar surface for a minimum of mid-duration (month+) missions.	CN-U-701 L		
Provide extravehicular utilization accommodation, interfaces, and resources, operable during crewed and uncrewed increments, on the lunar surface	FN-U-203 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-720 L	Deploy and operate external utilization payload(s) addressing biological science analysis and human research around globally distributed locations on the lunar surface for a minimum of mid-duration (month+) missions.	CN-U-701 L		
Provide delivery of live, actively growing biological specimens to cislunar space, including late load of cargo prior to launch	FN-T-214 L	Crew conduct of biological science and human research activities in cislunar space	UC-U-601 L	Deploy and operate internal and external utilization payload(s) addressing biological science analysis and human research in cislunar space for mid-duration (month+) to extended-duration (year+) missions.	CN-U-705 L		
Provide data capabilities, including protection for communication, and interface to support crew medical care in cislunar space	FN-D-106 L	Crew conduct of biological science and human research activities in cislunar space	UC-U-601 L	Deploy and operate internal and external utilization payload(s) addressing biological science analysis and human research in cislunar space for mid-duration (month+) to extended-duration (year+) missions.	CN-U-705 L		
Enable repositioning of externally mounted utilization payloads in cislunar space	FN-A-106 L	Crew conduct of biological science and human research activities in cislunar space	UC-U-601 L	Deploy and operate internal and external utilization payload(s) addressing biological science analysis and human research in cislunar space for mid-duration (month+) to extended-duration (year+) missions.	CN-U-705 L		
Provide extravehicular utilization accommodation, interfaces, and resources, operable during crewed and uncrewed increments, in cislunar space	FN-U-202 L	Crew conduct of biological science and human research activities in cislunar space	UC-U-601 L	Deploy and operate internal and external utilization payload(s) addressing biological science analysis and human research in cislunar space for mid-duration (month+) to extended-duration (year+) missions.	CN-U-705 L		

Functions		Use Cases		Characteristics/Needs		Objectives	
Provide intravehicular activity facilities, utilization accommodation, and resources, operable during crewed and uncrewed increments, in cislunar space	**FN-U-205 L**						
Transport crew from cislunar space to lunar surface sites in the south pole region	**FN-T-102 L**	Transportation of crew between cislunar space and the lunar surface	**UC-T-104 L**	Transition crew from partial gravity environment to micro-gravity environment.	**CN-T-111 L**	Characterize and evaluate how the interaction of exploration systems and the deep space environment affect human health, performance, and space human factors to inform future exploration-class missions.	**HBS-03 LM**
Transport crew from cislunar space to distributed sites outside of the south pole region on the lunar surface	**FN-T-103 L**						
Transport crew from the lunar surface to cislunar space	**FN-T-104 L**						
Enable crew habitation during transit from cislunar space to lunar surface sites in the south pole region	**FN-T-108 L**						
Enable crew habitation during transit from cislunar space to distributed sites outside of the south pole region on the lunar surface	**FN-T-109 L**						
Enable crew habitation during transit from the lunar surface to cislunar space	**FN-T-110 L**						
Transport crew from cislunar space to lunar surface sites in the south pole region	**FN-T-102 L**	Transportation of crew between cislunar space and the lunar surface	**UC-T-104 L**	Transition crew from micro-gravity environment to partial gravity environment, following a duration in space	**CN-T-112 L**		
Transport crew from cislunar space to distributed sites outside of the south pole region on the lunar surface	**FN-T-103 L**						
Transport crew from the lunar surface to cislunar space	**FN-T-104 L**						
Enable crew habitation during transit from cislunar space to lunar surface sites in the south pole region	**FN-T-108 L**						
Enable crew habitation during transit from cislunar space to distributed sites outside of the south pole region on the lunar surface	**FN-T-109 L**						
Enable crew habitation during transit from the lunar surface to cislunar space	**FN-T-110 L**						
Transport a small amount of cargo (10s of kg) from the lunar surface to Earth	**FN-T-207 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-301 L**	Transfer, return, and curate a small amount (10s of kg) or a large amount (100s of kg) of unconditioned samples and containers from key destinations across the lunar surface and back to Earth, while maintaining scientific integrity of the samples.	**CN-T-302 L**		
Transport a small amount of cargo (10s of kg) from the lunar surface to cislunar space	**FN-T-209 L**						
Transport a small amount of cargo (10s of kg) from cislunar space to Earth	**FN-T-211 L**						
Reposition a small amount of unconditioned samples and containers (10s of kg) on the lunar surface	**FN-M-504 L**						
Stow collected unconditioned samples on exploration assets while on the lunar surface, while maintaining scientific integrity of the samples	**FN-U-401 L**						
Transport a large amount of cargo (100s of kg) from the lunar surface to Earth	**FN-T-208 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-302 L**				
Transport a large amount of cargo (100s of kg) from the lunar surface to cislunar space	**FN-T-210 L**						
Transport a large amount of cargo (100s of kg) from cislunar space to Earth	**FN-T-212 L**						
Reposition a large amount of unconditioned samples and containers (100s of kg) on the lunar surface	**FN-M-505 L**						
Stow collected unconditioned samples on exploration assets while on the lunar surface, while maintaining scientific integrity of the samples	**FN-U-401 L**						
BLANK	**BLANK**	Delivery of collected samples to curation facilities or other appropriate	**UC-G-202 L**				

Functions		Use Cases		Characteristics/Needs		Objectives	
		facilities on Earth, while maintaining scientific integrity of the samples					
Transport a small amount of cargo (10s of kg) from the lunar surface to Earth	**FN-T-207 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-303 L**	Transfer, return and curate a small amount (10s of kg) or a large amount (100s of kg) of refrigerated sample(s), containers, and freezers from key destinations across the lunar surface to Earth while maintaining scientific integrity of the samples.	**CN-T-303 L**		
Transport a small amount of cargo (10s of kg) from the lunar surface to cislunar space	**FN-T-209 L**						
Transport a small amount of cargo (10s of kg) from cislunar space to Earth	**FN-T-211 L**						
Provide resources to condition refrigerated sample containers during transit from the lunar surface to Earth	**FN-T-301 L**						
Provide resources to condition refrigerated sample containers during transit from the lunar surface to cislunar space	**FN-T-304 L**						
Provide resources to condition refrigerated sample containers during transit from cislunar space to Earth	**FN-T-307 L**						
Reposition a small amount of refrigerated samples and containers (10s of kg) on the lunar surface	**FN-M-506 L**						
Stow refrigerated samples during transport from the Lunar Surface to Earth, while maintaining scientific integrity of samples	**FN-U-402 L**						
Stow refrigerated samples during transport from the Lunar Surface to cislunar space, while maintaining scientific integrity of samples	**FN-U-405 L**						
Stow refrigerated samples during transport from cislunar space to Earth, while maintaining scientific integrity of samples	**FN-U-408 L**						
Stow collected refrigerated samples on exploration assets while on the lunar surface, while maintaining scientific integrity of the samples	**FN-U-411 L**						
Provide resources to condition refrigerated sample containers on the lunar surface	**FN-U-414 L**						
Transport a large amount of cargo (100s of kg) from the lunar surface to Earth	**FN-T-208 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-304 L**				
Transport a large amount of cargo (100s of kg) from the lunar surface to cislunar space	**FN-T-210 L**						
Transport a large amount of cargo (100s of kg) from cislunar space to Earth	**FN-T-212 L**						
Provide resources to condition refrigerated sample containers during transit from the lunar surface to Earth	**FN-T-301 L**						
Provide resources to condition refrigerated sample containers during transit from the lunar surface to cislunar space	**FN-T-304 L**						
Provide resources to condition refrigerated sample containers during transit from cislunar space to Earth	**FN-T-307 L**						
Reposition a large amount of refrigerated samples and containers (100s of kg) on the lunar surface	**FN-M-507 L**						
Stow refrigerated samples during transport from the Lunar Surface to Earth, while maintaining scientific integrity of samples	**FN-U-402 L**						
Stow refrigerated samples during transport from the Lunar Surface to cislunar space, while maintaining scientific integrity of samples	**FN-U-405 L**						
Stow refrigerated samples during transport from cislunar space to Earth, while maintaining scientific integrity of samples	**FN-U-408 L**						
Stow collected refrigerated samples on exploration assets while on the lunar surface, while maintaining scientific integrity of the samples	**FN-U-411 L**						

Functions		Use Cases		Characteristics/Needs		Objectives	
Provide resources to condition refrigerated sample containers on the lunar surface	**FN-U-414 L**						
BLANK	**BLANK**	Delivery of conditioned cargo to curation facilities or other appropriate facilities on Earth after landing, while maintaining scientific integrity of the samples	**UC-G-201 L**				
Transport a small amount of cargo (10s of kg) from the lunar surface to Earth	**FN-T-207 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-305 L**	Transfer, return and curate a small amount (10s of kg) or a large amount (100s of kg) of frozen sample(s), containers, and freezers from key destinations across the lunar surface to Earth while maintaining scientific integrity of the samples.	**CN-T-304 L**		
Transport a small amount of cargo (10s of kg) from the lunar surface to cislunar space	**FN-T-209 L**						
Transport a small amount of cargo (10s of kg) from cislunar space to Earth	**FN-T-211 L**						
Provide resources to condition frozen 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 cislunar space	**FN-T-305 L**						
Provide resources to condition frozen sample containers during transit from cislunar space to Earth	**FN-T-308 L**						
Reposition a small amount of frozen samples and containers (10s of kg) on the lunar surface	**FN-M-508 L**						
Stow frozen 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 cislunar space, while maintaining scientific integrity of samples	**FN-U-406 L**						
Stow frozen samples during transport from cislunar space to Earth, while maintaining scientific integrity of samples	**FN-U-409 L**						
Stow collected frozen samples on exploration assets while on the lunar surface, while maintaining scientific integrity of the samples	**FN-U-412 L**						
Provide resources to condition frozen sample containers on the lunar surface	**FN-U-415 L**						
Transport a large amount of cargo (100s of kg) from the lunar surface to Earth	**FN-T-208 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-306 L**				
Transport a large amount of cargo (100s of kg) from the lunar surface to cislunar space	**FN-T-210 L**						
Transport a large amount of cargo (100s of kg) from cislunar space to Earth	**FN-T-212 L**						
Provide resources to condition frozen 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 cislunar space	**FN-T-305 L**						
Provide resources to condition frozen sample containers during transit from cislunar space to Earth	**FN-T-308 L**						
Reposition a large amount of frozen samples and containers (100s of kg) on the lunar surface	**FN-M-509 L**						
Stow frozen 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 cislunar space, while maintaining scientific integrity of samples	**FN-U-406 L**						

Functions		Use Cases		Characteristics/Needs		Objectives	
Stow frozen samples during transport from cislunar space to Earth, while maintaining scientific integrity of samples	**FN-U-409 L**						
Stow collected frozen samples on exploration assets while on the lunar surface, while maintaining scientific integrity of the samples	**FN-U-412 L**						
Provide resources to condition frozen sample containers on the lunar surface	**FN-U-415 L**						
BLANK	**BLANK**	Delivery of conditioned cargo to curation facilities or other appropriate facilities on Earth after landing, while maintaining scientific integrity of the samples	**UC-G-201 L**				
Transport a small amount of cargo (10s of kg) from cislunar space to Earth	**FN-T-211 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-308 L**	Transfer, return and curate a small amount (10s of kg) or a large amount (100s of kg) of unconditioned sample(s) and containers from cislunar assets back to Earth while maintaining scientific integrity of the samples.	**CN-T-307 L**		
Transport a large amount of cargo (100s of kg) from cislunar space to Earth	**FN-T-212 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-309 L**				
BLANK	**BLANK**	Delivery of collected samples to curation facilities or other appropriate facilities on Earth, while maintaining scientific integrity of the samples	**UC-G-202 L**				
Transport a small amount of cargo (10s of kg) from cislunar space to Earth	**FN-T-211 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-310 L**	Transfer, return and curate a small amount (10s of kg) or a large amount (100s of kg) of refrigerated sample(s) and containers from cislunar assets back to Earth while maintaining scientific integrity of the samples.	**CN-T-308 L**		
Provide resources to condition refrigerated sample containers during transit from cislunar space to Earth	**FN-T-307 L**						
Stow refrigerated samples during transport from cislunar space to Earth, while maintaining scientific integrity of samples	**FN-U-408 L**						
Transport a large amount of cargo (100s of kg) from cislunar space to Earth	**FN-T-212 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-311 L**				
Provide resources to condition refrigerated sample containers during transit from cislunar space to Earth	**FN-T-307 L**						
Stow refrigerated samples during transport from cislunar space to Earth, while maintaining scientific integrity of samples	**FN-U-408 L**						
BLANK	**BLANK**	Delivery of conditioned cargo to curation facilities or other appropriate facilities on Earth after landing, while maintaining scientific integrity of the samples	**UC-G-201 L**				
Transport a small amount of cargo (10s of kg) from cislunar space to Earth	**FN-T-211 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-312 L**	Transfer, return and curate a small amount (10s of kg) or a large amount (100s of kg) of frozen sample(s) and containers from cislunar assets back to Earth while maintaining scientific integrity of the samples.	**CN-T-309 L**		
Provide resources to condition frozen sample containers during transit from cislunar space to Earth	**FN-T-308 L**						
Stow frozen samples during transport from cislunar space to Earth, while maintaining scientific integrity of samples	**FN-U-409 L**						
Transport a large amount of cargo (100s of kg) from cislunar space to Earth	**FN-T-212 L**	Return of a large amount of frozen samples and containers (100s of kg)	**UC-T-313 L**				

Functions		Use Cases		Characteristics/Needs		Objectives	
Provide resources to condition frozen sample containers during transit from cislunar space to Earth	FN-T-308 L	from cislunar space to Earth with the samples in sealed conditioned sample containers					
Stow frozen samples during transport from cislunar space to Earth, while maintaining scientific integrity of samples	FN-U-409 L						
BLANK	**BLANK**	Delivery of conditioned cargo to curation facilities or other appropriate facilities on Earth after landing, while maintaining scientific integrity of the samples	**UC-G-201 L**				
Enable a pressurized, habitable environment on the lunar surface for short durations (days to weeks)	**FN-H-101 L**	Crew habitation of assets on the lunar surface for short-durations (days to weeks)	**UC-H-101 L**	Conduct short-duration (days to weeks) to mid-duration (month+) crew exploration mission(s) on the lunar surface.	**CN-H-101 L**		
Operate habitation system(s) in uncrewed mode between crewed missions on the lunar surface	**FN-H-201 L**						
Manage waste from habitable asset(s) on the lunar surface	**FN-L-301 L**						
Enable a pressurized, habitable environment on the lunar surface for moderate duration (month+) use	**FN-H-102 L**	Crew habitation of assets on the lunar surface for mid-durations (month+)	**UC-H-102 L**				
Operate habitation system(s) in uncrewed mode between crewed missions on the lunar surface	**FN-H-201 L**						
Manage waste from habitable asset(s) on the lunar surface	**FN-L-301 L**						
Operate habitation system(s) in uncrewed mode between crewed missions on the lunar surface	**FN-H-201 L**	Reuse of habitation system(s) on the lunar surface	**UC-H-105 L**				
Transport a limited amount of cargo (100s of kg) from Earth to south pole region sites on the lunar surface	**FN-T-201 L**	Resupply of cargo and management of waste to/from habitable assets on the lunar surface	**UC-L-201 L**				
Transport a moderate amount of cargo (1000s of kg) from Earth to south pole region sites on the lunar surface	**FN-T-202 L**						
Mating between pressurized assets on the lunar surface	**FN-L-101 L**						
Transfer pressurized cargo into habitable assets on the lunar surface	**FN-L-201 L**						
Transfer water to habitable assets on the lunar surface	**FN-L-203 L**						
Transfer gases to habitable assets on the lunar surface	**FN-L-205 L**						
Manage waste from habitable asset(s) on the lunar surface	**FN-L-301 L**						
Unload a limited amount of cargo (100s of kg) on the lunar surface	**FN-M-401 L**						
Unload a moderate amount of cargo (1000s of kg) on the lunar surface	**FN-M-402 L**						
Reposition a limited amount of cargo (100s of kg) in the south pole region on the lunar surface	**FN-M-501 L**						
Reposition a moderate amount of cargo (1000s of kg) at the south pole region on the lunar surface	**FN-M-503 L**						

Functions		Use Cases		Characteristics/Needs		Objectives	
Enable a pressurized, habitable environment on the lunar surface for short durations (days to weeks)	FN-H-101 L	Crew habitation of assets on the lunar surface for short-durations (days to weeks)	UC-H-101 L	Conduct short-duration (days to weeks), mid-duration (month+), and extended-duration (year+) crew exploration mission(s) in cislunar space	CN-H-102 L		
Operate habitation system(s) in uncrewed mode between crewed missions on the lunar surface	FN-H-201 L						
Manage waste from habitable asset(s) on the lunar surface	FN-L-301 L						
Enable a pressurized, habitable environment in cislunar space for moderate (month+) durations	FN-H-104 L	Crew habitation of assets for moderate-duration (month+) mission(s) in cislunar space	UC-H-103 L				
Operate habitation system(s) in uncrewed mode between crewed missions in cislunar space	FN-H-202 L						
Enable a pressurized, habitable environment in cislunar space for extended (year+) duration	FN-H-105 L	Crew habitation of assets for extended-duration (year+) mission(s) in cislunar space	UC-H-104 L				
Operate habitation system(s) in uncrewed mode between crewed missions in cislunar space	FN-H-202 L						
Operate habitation system(s) in uncrewed mode between crewed missions in cislunar space	FN-H-202 L	Reuse of habitation system(s) in cislunar space	UC-H-106 L				
Rendezvous, proximity operations, mating and unmating of assets in cislunar space	FN-T-106 L	Resupply of cargo and management of waste to/from habitable assets in cislunar space	UC-L-202 L				
Transport cargo from Earth to cislunar space	FN-T-213 L						
Transfer pressurized cargo into habitable assets in cislunar space	FN-L-202 L						
Transfer water to habitable assets in cislunar space	FN-L-204 L						
Transfer gases to habitable assets in cislunar space	FN-L-206 L						
Manage waste from habitable asset(s) in cislunar space	FN-L-302 L						
Transport cargo from Earth to cislunar space	FN-T-213 L	Intravehicular science and utilization activities on the lunar surface	UC-U-201 L	Provide intravehicular activity accommodations (e.g., instruments, racks, stowage, power) on the lunar surface during crewed and uncrewed mission phases to enable biological science analysis and human research.	CN-U-201 L		
Distribute power to utilization payloads and/or equipment in cislunar space	FN-P-303 L						
Provide communications and data exchange between Earth and cislunar space	FN-C-102 L						
Provide high bandwidth, high availability communications and data exchange between the lunar surface and Earth	FN-C-105 L						
Provide intravehicular activity facilities, utilization accommodation, and resources, operable during crewed and uncrewed increments, on the lunar surface	FN-U-204 L						
Reposition a small amount of unconditioned samples and containers (10s of kg) on the lunar surface	FN-M-504 L	Crew conduct of biological science and human research activities on the lunar surface	UC-U-602 L				
Reposition a small amount of refrigerated samples and containers (10s of kg) on the lunar surface	FN-M-506 L						
Reposition a small amount of frozen samples and containers (10s of kg) on the lunar surface	FN-M-508 L						
Provide data capabilities, including protection for communication, and interface to support crew medical care on the lunar surface	FN-D-105 L						
Provide extravehicular utilization accommodation, interfaces, and resources, operable during crewed and uncrewed increments, on the lunar surface	FN-U-203 L						

Functions		Use Cases		Characteristics/Needs		Objectives	
Provide intravehicular activity facilities, utilization accommodation, and resources, operable during crewed and uncrewed increments, on the lunar surface	**FN-U-204 L**						
Stow collected unconditioned samples on exploration assets while on the lunar surface, while maintaining scientific integrity of the samples	**FN-U-401 L**						
Stow collected refrigerated samples on exploration assets while on the lunar surface, while maintaining scientific integrity of the samples	**FN-U-411 L**						
Stow collected frozen samples on exploration assets while on the lunar surface, while maintaining scientific integrity of the samples	**FN-U-412 L**						
Provide delivery of live, actively growing biological specimens to cislunar space, including late load of cargo prior to launch	**FN-T-214 L**	Crew conduct of biological science and human research activities in cislunar space	**UC-U-601 L**	Provide intravehicular activity accommodations (e.g., instruments, racks, stowage, power) in cislunar space to enable biological science analysis and human research.	**CN-U-202 L**		
Provide data capabilities, including protection for communication, and interface to support crew medical care in cislunar space	**FN-D-106 L**						
Enable repositioning of externally mounted utilization payloads in cislunar space	**FN-A-106 L**						
Provide extravehicular utilization accommodation, interfaces, and resources, operable during crewed and uncrewed increments, in cislunar space	**FN-U-202 L**						
Provide intravehicular activity facilities, utilization accommodation, and resources, operable during crewed and uncrewed increments, in cislunar space	**FN-U-205 L**						
Provide intravehicular utilization accommodation and resources during crew transit between Earth and cislunar space	**FN-U-206 L**	Crew conduct of biological science and human research activities during crew transit between Earth and cislunar space	**UC-U-603 L**	Provide intravehicular utilization accommodation and resources during crew transit between Earth and cislunar space to enable biological science analysis and human research.	**CN-U-205 L**		
Transport a limited amount of cargo (100s of kg) from Earth to south pole region sites on the lunar surface	**FN-T-201 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-719 L**	Deploy and operate external utilization payload(s) addressing biological science analysis and human research around globally distributed locations on the lunar surface for a minimum of mid-duration (month+) missions.	**CN-U-701 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-203 L**						
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 L**						
Perform robotic manipulation of payloads, logistics, and/or equipment on the lunar surface	**FN-A-104 L**						
Provide extravehicular utilization accommodation, interfaces, and resources, operable during crewed and uncrewed increments, on the lunar surface	**FN-U-203 L**						
Transport a limited amount of cargo (100s of kg) from Earth to south pole region sites on the lunar surface	**FN-T-201 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-720 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-203 L**						
Enable crew lunar surface extravehicular activity in sunlit areas and non-PSRs	**FN-M-101 L**						
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 L**						
Perform robotic manipulation of payloads, logistics, and/or equipment on the lunar surface	**FN-A-104 L**						
Provide extravehicular utilization accommodation, interfaces, and resources, operable during crewed and uncrewed increments, on the lunar surface	**FN-U-203 L**						

Functions		Use Cases		Characteristics/Needs		Objectives	
Provide delivery of live, actively growing biological specimens to cislunar space, including late load of cargo prior to launch	**FN-T-214 L**	Crew conduct of biological science and human research activities in cislunar space	**UC-U-601 L**	Deploy and operate internal and external utilization payload(s) addressing biological science analysis and human research in cislunar space for mid-duration (month+) to extended-duration (year+) missions.	**CN-U-705 L**		
Provide data capabilities, including protection for communication, and interface to support crew medical care in cislunar space	**FN-D-106 L**						
Enable repositioning of externally mounted utilization payloads in cislunar space	**FN-A-106 L**						
Provide extravehicular utilization accommodation, interfaces, and resources, operable during crewed and uncrewed increments, in cislunar space	**FN-U-202 L**						
Provide intravehicular activity facilities, utilization accommodation, and resources, operable during crewed and uncrewed increments, in cislunar space	**FN-U-205 L**						
Transport a limited amount of cargo (100s of kg) from Earth to the far side of the lunar surface	**FN-T-205 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-711 L**	Deploy and operate astrophysics and fundamental physics utilization payload(s) on the far side of the lunar surface.	**CN-U-716 L**	Conduct astrophysics and fundamental physics investigations of space and time from the radio quiet environment of the lunar far side.	**PPS-01 L**
Provide power for deployed external surface utilization payloads(s) and/or equipment for long durations (months to years+)	**FN-P-402 L**						
Enable crew surface extravehicular activities at the lunar far side region	**FN-M-103 L**						
Unload a limited amount of cargo (100s of kg) on the lunar surface	**FN-M-401 L**						
Reposition a limited amount of cargo (100s of kg) in the south pole region on the lunar surface	**FN-M-501 L**						
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 L**						
BLANK	**BLANK**	Preservation of lunar far side environment to ensure scientific data integrity	**UC-U-801 L**				
Transport a small amount of cargo (10s of kg) from the lunar surface to Earth	**FN-T-207 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-301 L**	Transfer, return, and curate a small amount (10s of kg) of unconditioned samples, containers, and freezers from key destinations across the lunar surface back to Earth while maintaining scientific integrity of the samples.	**CN-T-306 L**	Advance understanding of physical systems and fundamental physics by utilizing the unique environments of the Moon, Mars, and deep space.	**PPS-02 LM**
Transport a small amount of cargo (10s of kg) from the lunar surface to cislunar space	**FN-T-209 L**						
Transport a small amount of cargo (10s of kg) from cislunar space to Earth	**FN-T-211 L**						
Reposition a small amount of unconditioned samples and containers (10s of kg) on the lunar surface	**FN-M-504 L**						
Stow collected unconditioned samples on exploration assets while on the lunar surface, while maintaining scientific integrity of the samples	**FN-U-401 L**						
BLANK	**BLANK**	Delivery of collected samples to curation facilities or other appropriate facilities on Earth, while maintaining scientific integrity of the samples	**UC-G-202 L**				
Transport a small amount of cargo (10s of kg) from cislunar space to Earth	**FN-T-211 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-308 L**	Transfer, return and curate a small amount (10s of kg) of unconditioned sample(s) and containers from cislunar assets back to Earth while maintaining scientific integrity of the samples.	**CN-T-310 L**		
BLANK	**BLANK**	Delivery of collected samples to curation facilities or other appropriate facilities on Earth, while maintaining scientific integrity of the samples	**UC-G-202 L**				

Functions		Use Cases		Characteristics/Needs		Objectives	
Transport a limited amount of cargo (100s of kg) from Earth to south pole region sites on the lunar surface	**FN-T-201 L**	Conduct of fundamental physics and astrophysics experiments on the lunar surface	**UC-U-712 L**	Provide intravehicular activity accommodations (e.g., instruments, racks, stowage, power) on the lunar surface to enable fundamental physics experiments.	**CN-U-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-203 L**						
Enable crew lunar surface extravehicular activity in sunlit areas and non-PSRs	**FN-M-101 L**						
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 L**						
Perform robotic manipulation of payloads, logistics, and/or equipment on the lunar surface	**FN-A-104 L**						
Provide extravehicular utilization accommodation, interfaces, and resources, operable during crewed and uncrewed increments, on the lunar surface	**FN-U-203 L**						
Transport cargo from Earth to cislunar space	**FN-T-213 L**	Conduct of fundamental physics and astrophysics experiments in cislunar space	**UC-U-713 L**	Provide intravehicular activity accommodations (e.g., instruments, racks, stowage, power) in cislunar space to enable fundamental physics experiments.	**CN-U-204 L**		
Provide communications and data exchange between Earth and cislunar space	**FN-C-102 L**						
Enable repositioning of externally mounted utilization payloads in cislunar space	**FN-A-106 L**						
Provide extravehicular utilization accommodation, interfaces, and resources, operable during crewed and uncrewed increments, in cislunar space	**FN-U-202 L**						
Provide intravehicular utilization accommodation and resources during crew transit between Earth and cislunar space	**FN-U-206 L**	Crew conduct of fundamental physics and astrophysics experiments during crew transit between Earth and cislunar space	**UC-U-714 L**	Provide intravehicular utilization accommodation and resources during crew transit between Earth and cislunar space to enable fundamental physics experiments.	**CN-U-206 L**		
Transport cargo from Earth to cislunar space	**FN-T-213 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-715 L**	Deploy and operate utilization payload(s), related to the physical systems and fundamental physics, in cislunar space.	**CN-U-703 L**		
Deliver free flying asset(s) from Earth to cislunar space	**FN-T-216 L**						
Provide communications and data exchange between Earth and cislunar space	**FN-C-102 L**						
Enable repositioning of externally mounted utilization payloads in cislunar space	**FN-A-106 L**						
Provide extravehicular utilization accommodation, interfaces, and resources, operable during crewed and uncrewed increments, in cislunar space	**FN-U-202 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-203 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-716 L**	Deploy and operate utilization payload(s), related to the physical systems and fundamental physics, at areas of key scientific interest on the lunar surface, including polar and non-polar destinations.	**CN-U-704 L**		
Provide power for deployed external surface utilization payloads(s) and/or equipment for long durations (months to years+)	**FN-P-402 L**						
Enable crew lunar surface extravehicular activity in sunlit areas and non-PSRs	**FN-M-101 L**						
Enable crew lunar surface extravehicular activity in PSRs	**FN-M-102 L**						
Unload a limited amount of cargo (100s of kg) on the lunar surface	**FN-M-401 L**						
Reposition a limited amount of cargo (100s of kg) in the south pole region on the lunar surface	**FN-M-501 L**						

Functions		Use Cases		Characteristics/Needs		Objectives	
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 L**						
BLANK	**BLANK**	Provision of advanced geology training, integrated geology and EVA ops training, as well as detailed objective-specific training to astronauts for science activities	**UC-G-301 L**	Train astronauts to be field scientists and to perform additional science tasks during crewed missions, through integrated geology, field and EVA ops and classroom training.	**CN-X-202 L**	Provide in-depth, mission-specific science training for astronauts to enable crew to perform high-priority or transformational science on the surface of the Moon, and Mars, and in deep space.	**SE-01 LM**
Provide in-mission crew training on the lunar surface	**FN-X-201 L**	Provision of in-situ training to astronauts for science tasks during mission(s) on the lunar surface	**UC-X-203 L**				
Provide high bandwidth, high availability communications and data exchange between the lunar surface and Earth	**FN-C-105 L**						
BLANK	**BLANK**	BLANK	**BLANK**	Train Earth-based scientists to support crew activities in real time.	**CN-X-203 L**	Enable Earth-based scientists to remotely support astronaut surface and deep space activities using advanced techniques and tools.	**SE-02 LM**
Provide high bandwidth, high availability communications and data exchange between the lunar surface and Earth	**FN-C-105 L**	Communications and data exchange with high bandwidth and high availability between assets on the lunar surface and the Earth	**UC-C-101 L**	Provide scalable communication system(s) to enable high bandwidth, high availability communications between Earth-based personnel, surface crew, and assets on the surface.	**CN-C-101 L**		
Collect, store, and locally distribute data on the lunar surface	**FN-D-101 L**	Aggregation and storage of data on the lunar surface until it is able to be transmitted and confirmed received	**UC-D-101 L**				
Process data locally on the lunar surface	**FN-D-201 L**						
Provide high bandwidth, high availability communications and data exchange between cislunar space and the Earth	**FN-C-106 L**	Communications and data exchange with high bandwidth and high availability between assets in cislunar space and the Earth	**UC-C-103 L**	Provide scalable communication system(s) to enable high bandwidth, high availability communications between Earth-based personnel, in-space crew, and in-space assets.	**CN-C-102 L**		
Collect, store, and locally distribute data in cislunar space	**FN-D-102 L**	Aggregation and storage of data in cislunar space until it is able to be transmitted and confirmed received	**UC-D-102 L**				
Process data locally in cislunar space	**FN-D-202 L**						
Transport a large amount of cargo (100s of kg) from the lunar surface to Earth	**FN-T-208 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-T-307 L**	Transfer, return, and curate a large amount (100s of kg) of cryogenic samples, containers, and freezers from key destinations across the lunar surface back to Earth while maintaining scientific integrity of the samples.	**CN-T-305 L**	Develop the capability to retrieve core samples of frozen volatiles from permanently shadowed regions on the Moon and volatile-bearing sites on Mars and to deliver them in pristine states to modern curation facilities on Earth.	**SE-03 LM**
Transport a large amount of cargo (100s of kg) from the lunar surface to cislunar space	**FN-T-210 L**						
Transport a large amount of cargo (100s of kg) from cislunar space to Earth	**FN-T-212 L**						
Provide resources to condition cryogenic 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 cislunar space	**FN-T-306 L**						
Provide resources to condition cryogenic sample containers during transit from cislunar space to Earth	**FN-T-309 L**						
Reposition a large amount of cryogenic samples and containers (100s of kg) on the lunar surface	**FN-M-510 L**						
Stow cryogenic samples during transport from the Lunar Surface to Earth, while maintaining scientific integrity of samples	**FN-U-404 L**						

Functions		Use Cases		Characteristics/Needs		Objectives	
Stow cryogenic 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 cislunar space to Earth, while maintaining scientific integrity of samples	**FN-U-410 L**						
Stow collected cryogenic samples on exploration assets while on the lunar surface, while maintaining scientific integrity of the samples	**FN-U-413 L**						
Provide resources to condition cryogenic sample containers on the lunar surface	**FN-U-416 L**						
BLANK	**BLANK**	Delivery of conditioned cargo to curation facilities or other appropriate facilities on Earth after landing, while maintaining scientific integrity of the samples	**UC-G-201 L**				
BLANK	**BLANK**	BLANK	**BLANK**	Provide curation or other appropriate facilities on Earth equipped for preserving acquired samples in their pristine state.	**CN-G-201 L**		
Enable crew lunar surface extravehicular activity in PSRs	**FN-M-102 L**	Conduct of crew excursions in PSRs around landing site at the south pole region	**UC-M-303 L**	Identify, collect, and document deep-surface samples from key destinations in PSRs on the lunar surface, while maintaining scientific integrity of the samples.	**CN-U-302 L**		
Enable local unpressurized surface mobility in PSRs at the south pole region of the lunar surface	**FN-M-304 L**						
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 L**						
Provide communications and data exchange between assets on the lunar surface	**FN-C-103 L**						
Provide position, navigation, and timing services at the south pole region on the lunar surface	**FN-C-201 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 L**	Robotic surveillance of PSRs near potential crewed landing and exploration sites to identify locations of interest	**UC-A-106 L**				
Control robotic system(s) in PSRs on the lunar surface from Earth and/or cislunar space	**FN-A-202 L**						
Enable crew lunar surface extravehicular activity in PSRs	**FN-M-102 L**	Crew identification of surface samples in PSRs	**UC-U-104 L**				
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 L**						
Provide position, navigation, and timing services at the south pole region on the lunar surface	**FN-C-201 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						
Capture imagery on the lunar surface	**FN-U-102 L**						
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 L**	Robotic surveillance of potential crewed landing and exploration sites	**UC-U-105 L**				

Functions		Use Cases		Characteristics/Needs		Objectives	
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-202 L**	in sunlit areas and non-PSRs in distributed sites on the lunar surface to identify locations of interest					
Provide a coordinated lunar time scale	**FN-C-205 L**						
Provide a robotic system capable of conducting reconnaissance	**FN-A-103 L**						
Control robotic system(s) in sunlit areas and non-PSRs on the lunar surface from Earth and/or cislunar space	**FN-A-201 L**						
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 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-106 L**				
Provide position, navigation, and timing services at the far side and outside the south pole region on the lunar surface	**FN-C-203 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						
Provide a robotic system capable of conducting reconnaissance	**FN-A-103 L**						
Control robotic system(s) in sunlit areas and non-PSRs on the lunar surface from Earth and/or cislunar space	**FN-A-201 L**						
Enable crew lunar surface extravehicular activity in sunlit areas and non-PSRs	**FN-M-101 L**	Crew identification of surface samples in sunlit areas and non-PSRs in distributed sites on the lunar surface	**UC-U-107 L**				
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 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-202 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						
Capture imagery on the lunar surface	**FN-U-102 L**						
Enable crew lunar surface extravehicular activity in sunlit areas and non-PSRs	**FN-M-101 L**	Crew identification of surface samples in sunlit areas and non-PSRs in the far side on the lunar surface	**UC-U-108 L**				
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 L**						
Provide position, navigation, and timing services at the far side and outside the south pole region on the lunar surface	**FN-C-203 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						
Capture imagery on the lunar surface	**FN-U-102 L**						
Enable crew lunar surface extravehicular activity in PSRs	**FN-M-102 L**	Collection, recovery, and packaging of deep sub-surface samples, maintaining scientific integrity of the samples, from PSRs on the lunar surface	**UC-U-304 L**				
Provide position, navigation, and timing services at the south pole region on the lunar surface	**FN-C-201 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						
Capture imagery on the lunar surface	**FN-U-102 L**						
Provide capability to recover and package deep sub-surface samples, including drill cores, maintaining scientific integrity of the samples, from PSRs on the lunar surface	**FN-U-306 L**						

Functions		Use Cases		Characteristics/Needs		Objectives	
Transport crew from cislunar space to lunar surface sites in the south pole region	FN-T-102 L	Transportation of crew between cislunar space and lunar south pole region landing sites	UC-T-105 L	Provide capabilities to visit geographically diverse sites on the lunar surface, including the south polar region, and non-polar destinations.	CN-T-107 L	Return representative samples from multiple locations across the surface of the Moon and Mars, with sample mass commensurate with mission-specific science priorities.	SE-04 LM
Transport crew from the lunar surface to cislunar space	FN-T-104 L						
Enable crew habitation during transit from cislunar space to lunar surface sites in the south pole region	FN-T-108 L						
Enable crew habitation during transit from the lunar surface to cislunar space	FN-T-110 L						
Transport crew from cislunar space to distributed sites outside of the south pole region on the lunar surface	FN-T-103 L	Transportation of crew from cislunar space to distributed landing sites outside of the south pole region on the lunar surface	UC-T-106 L				
Enable crew habitation during transit from cislunar space to distributed sites outside of the south pole region on the lunar surface	FN-T-109 L						
Provide communications and data exchange between the lunar surface and Earth	FN-C-101 L	Robotic surveillance of PSRs near potential crewed landing and exploration sites to identify locations of interest	UC-A-106 L				
Control robotic system(s) in PSRs on the lunar surface from Earth and/or cislunar space	FN-A-202 L						
Provide communications and data exchange between the lunar surface and Earth	FN-C-101 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-U-102 L				
Provide position, navigation, and timing services at the south pole region on the lunar surface	FN-C-201 L						
Provide a coordinated lunar time scale	FN-C-205 L						
Provide a robotic system capable of conducting reconnaissance	FN-A-103 L						
Control robotic system(s) in sunlit areas and non-PSRs on the lunar surface from Earth and/or cislunar space	FN-A-201 L						
Provide communications and data exchange between the lunar surface and Earth	FN-C-101 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-105 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-202 L						
Provide a coordinated lunar time scale	FN-C-205 L						
Provide a robotic system capable of conducting reconnaissance	FN-A-103 L						
Control robotic system(s) in sunlit areas and non-PSRs on the lunar surface from Earth and/or cislunar space	FN-A-201 L						
Provide communications and data exchange between the lunar surface and Earth	FN-C-101 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-106 L				
Provide position, navigation, and timing services at the far side and outside the south pole region on the lunar surface	FN-C-203 L						
Provide a coordinated lunar time scale	FN-C-205 L						
Provide a robotic system capable of conducting reconnaissance	FN-A-103 L						
Control robotic system(s) in sunlit areas and non-PSRs on the lunar surface from Earth and/or cislunar space	FN-A-201 L						

Functions		Use Cases		Characteristics/Needs		Objectives	
Transport crew from cislunar space to lunar surface sites in the south pole region	**FN-T-102 L**	Transportation of crew between cislunar space and lunar south pole region landing sites	**UC-T-105 L**	Visit diverse sites of key scientific interest on the lunar surface, including polar and non-polar destinations to address high priority science goals.	**CN-T-108 L**		
Transport crew from the lunar surface to cislunar space	**FN-T-104 L**						
Enable crew habitation during transit from cislunar space to lunar surface sites in the south pole region	**FN-T-108 L**						
Enable crew habitation during transit from the lunar surface to cislunar space	**FN-T-110 L**						
Transport crew from cislunar space to distributed sites outside of the south pole region on the lunar surface	**FN-T-103 L**	Transportation of crew from cislunar space to distributed landing sites outside of the south pole region on the lunar surface	**UC-T-106 L**				
Enable crew habitation during transit from cislunar space to distributed sites outside of the south pole region on the lunar surface	**FN-T-109 L**						
Transport a small amount of cargo (10s of kg) from the lunar surface to Earth	**FN-T-207 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-301 L**	Transfer, return, and curate a small amount (10s of kg) or a large amount (100s of kg) of unconditioned samples and containers from key destinations across the lunar surface and back to Earth, while maintaining scientific integrity of the samples.	**CN-T-302 L**		
Transport a small amount of cargo (10s of kg) from the lunar surface to cislunar space	**FN-T-209 L**						
Transport a small amount of cargo (10s of kg) from cislunar space to Earth	**FN-T-211 L**						
Reposition a small amount of unconditioned samples and containers (10s of kg) on the lunar surface	**FN-M-504 L**						
Stow collected unconditioned samples on exploration assets while on the lunar surface, while maintaining scientific integrity of the samples	**FN-U-401 L**						
Transport a large amount of cargo (100s of kg) from the lunar surface to Earth	**FN-T-208 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-302 L**				
Transport a large amount of cargo (100s of kg) from the lunar surface to cislunar space	**FN-T-210 L**						
Transport a large amount of cargo (100s of kg) from cislunar space to Earth	**FN-T-212 L**						
Reposition a large amount of unconditioned samples and containers (100s of kg) on the lunar surface	**FN-M-505 L**						
Stow collected unconditioned samples on exploration assets while on the lunar surface, while maintaining scientific integrity of the samples	**FN-U-401 L**						
BLANK	**BLANK**	Delivery of collected samples to curation facilities or other appropriate facilities on Earth, while maintaining scientific integrity of the samples	**UC-G-202 L**				
Transport a small amount of cargo (10s of kg) from the lunar surface to Earth	**FN-T-207 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-305 L**	Transfer, return and curate a small amount (10s of kg) or a large amount (100s of kg) of frozen sample(s), containers, and freezers from key destinations across the lunar surface to Earth while maintaining scientific integrity of the samples.	**CN-T-304 L**		
Transport a small amount of cargo (10s of kg) from the lunar surface to cislunar space	**FN-T-209 L**						
Transport a small amount of cargo (10s of kg) from cislunar space to Earth	**FN-T-211 L**						
Provide resources to condition frozen 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 cislunar space	**FN-T-305 L**						
Provide resources to condition frozen sample containers during transit from cislunar space to Earth	**FN-T-308 L**						

Functions		Use Cases		Characteristics/Needs		Objectives	
Reposition a small amount of frozen samples and containers (10s of kg) on the lunar surface	**FN-M-508 L**						
Stow frozen 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 cislunar space, while maintaining scientific integrity of samples	**FN-U-406 L**						
Stow frozen samples during transport from cislunar space to Earth, while maintaining scientific integrity of samples	**FN-U-409 L**						
Stow collected frozen samples on exploration assets while on the lunar surface, while maintaining scientific integrity of the samples	**FN-U-412 L**						
Provide resources to condition frozen sample containers on the lunar surface	**FN-U-415 L**						
Transport a large amount of cargo (100s of kg) from the lunar surface to Earth	**FN-T-208 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-306 L**				
Transport a large amount of cargo (100s of kg) from the lunar surface to cislunar space	**FN-T-210 L**						
Transport a large amount of cargo (100s of kg) from cislunar space to Earth	**FN-T-212 L**						
Provide resources to condition frozen 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 cislunar space	**FN-T-305 L**						
Provide resources to condition frozen sample containers during transit from cislunar space to Earth	**FN-T-308 L**						
Reposition a large amount of frozen samples and containers (100s of kg) on the lunar surface	**FN-M-509 L**						
Stow frozen 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 cislunar space, while maintaining scientific integrity of samples	**FN-U-406 L**						
Stow frozen samples during transport from cislunar space to Earth, while maintaining scientific integrity of samples	**FN-U-409 L**						
Stow collected frozen samples on exploration assets while on the lunar surface, while maintaining scientific integrity of the samples	**FN-U-412 L**						
Provide resources to condition frozen sample containers on the lunar surface	**FN-U-415 L**						
BLANK	**BLANK**	Delivery of conditioned cargo to curation facilities or other appropriate facilities on Earth after landing, while maintaining scientific integrity of the samples	**UC-G-201 L**				
Transport a large amount of cargo (100s of kg) from the lunar surface to Earth	**FN-T-208 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-T-307 L**	Transfer, return, and curate a large amount (100s of kg) of cryogenic samples, containers, and freezers from key destinations across the lunar surface back to Earth while maintaining scientific integrity of the samples.	**CN-T-305 L**		
Transport a large amount of cargo (100s of kg) from the lunar surface to cislunar space	**FN-T-210 L**						
Transport a large amount of cargo (100s of kg) from cislunar space to Earth	**FN-T-212 L**						
Provide resources to condition cryogenic sample containers during transit from the lunar surface to Earth	**FN-T-303 L**						

Functions		Use Cases		Characteristics/Needs		Objectives	
Provide resources to condition cryogenic 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 cislunar space to Earth	**FN-T-309 L**						
Reposition a large amount of cryogenic samples and containers (100s of kg) on the lunar surface	**FN-M-510 L**						
Stow cryogenic 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 cislunar space, while maintaining scientific integrity of samples	**FN-U-407 L**						
Stow cryogenic samples during transport from cislunar space to Earth, while maintaining scientific integrity of samples	**FN-U-410 L**						
Stow collected cryogenic samples on exploration assets while on the lunar surface, while maintaining scientific integrity of the samples	**FN-U-413 L**						
Provide resources to condition cryogenic sample containers on the lunar surface	**FN-U-416 L**						
BLANK	**BLANK**	Delivery of conditioned cargo to curation facilities or other appropriate facilities on Earth after landing, while maintaining scientific integrity of the samples	**UC-G-201 L**				
BLANK	**BLANK**	BLANK	**BLANK**	Provide curation or other appropriate facilities on Earth equipped for preserving acquired samples in their pristine state.	**CN-G-201 L**		
Enable crew lunar surface extravehicular activity in PSRs	**FN-M-102 L**	Conduct of crew excursions in PSRs around landing site at the south pole region	**UC-M-303 L**	Identify, collect, and document deep-surface samples from key destinations in PSRs on the lunar surface, while maintaining scientific integrity of the samples.	**CN-U-302 L**		
Enable local unpressurized surface mobility in PSRs at the south pole region of the lunar surface	**FN-M-304 L**						
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 L**						
Provide communications and data exchange between assets on the lunar surface	**FN-C-103 L**						
Provide position, navigation, and timing services at the south pole region on the lunar surface	**FN-C-201 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 L**	Robotic surveillance of PSRs near potential crewed landing and exploration sites to identify locations of interest	**UC-A-106 L**				
Control robotic system(s) in PSRs on the lunar surface from Earth and/or cislunar space	**FN-A-202 L**						
Enable crew lunar surface extravehicular activity in PSRs	**FN-M-102 L**	Crew identification of surface samples in PSRs	**UC-U-104 L**				
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 L**						

Functions		Use Cases		Characteristics/Needs		Objectives	
Provide position, navigation, and timing services at the south pole region on the lunar surface	**FN-C-201 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						
Capture imagery on the lunar surface	**FN-U-102 L**						
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 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-105 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-202 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						
Provide a robotic system capable of conducting reconnaissance	**FN-A-103 L**						
Control robotic system(s) in sunlit areas and non-PSRs on the lunar surface from Earth and/or cislunar space	**FN-A-201 L**						
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 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-106 L**				
Provide position, navigation, and timing services at the far side and outside the south pole region on the lunar surface	**FN-C-203 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						
Provide a robotic system capable of conducting reconnaissance	**FN-A-103 L**						
Control robotic system(s) in sunlit areas and non-PSRs on the lunar surface from Earth and/or cislunar space	**FN-A-201 L**						
Enable crew lunar surface extravehicular activity in sunlit areas and non-PSRs	**FN-M-101 L**	Crew identification of surface samples in sunlit areas and non-PSRs in distributed sites on the lunar surface	**UC-U-107 L**				
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 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-202 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						
Capture imagery on the lunar surface	**FN-U-102 L**						
Enable crew lunar surface extravehicular activity in sunlit areas and non-PSRs	**FN-M-101 L**	Crew identification of surface samples in sunlit areas and non-PSRs in the far side on the lunar surface	**UC-U-108 L**				
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 L**						
Provide position, navigation, and timing services at the far side and outside the south pole region on the lunar surface	**FN-C-203 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						
Capture imagery on the lunar surface	**FN-U-102 L**						
Enable crew lunar surface extravehicular activity in PSRs	**FN-M-102 L**	Collection, recovery, and packaging of deep sub-surface samples,	**UC-U-304 L**				

Functions		Use Cases		Characteristics/Needs		Objectives	
Provide position, navigation, and timing services at the south pole region on the lunar surface	**FN-C-201 L**	maintaining scientific integrity of the samples, from PSRs on the lunar surface					
Provide a coordinated lunar time scale	**FN-C-205 L**						
Capture imagery on the lunar surface	**FN-U-102 L**						
Provide capability to recover and package deep sub-surface samples, including drill cores, maintaining scientific integrity of the samples, from PSRs on the lunar surface	**FN-U-306 L**						
Enable crew lunar surface extravehicular activity in sunlit areas and non-PSRs	**FN-M-101 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-301 L**	Identify, collect, and document surface and shallow subsurface samples from key destinations in non-PSRs and other sunlit areas on the lunar surface, while maintaining scientific integrity of the samples.	**CN-U-303 L**		
Enable local unpressurized surface mobility in sunlit areas and non-PSRs at distributed sites on the lunar surface	**FN-M-303 L**						
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 L**						
Provide communications and data exchange between assets on the lunar surface	**FN-C-103 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-202 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 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-U-102 L**				
Provide position, navigation, and timing services at the south pole region on the lunar surface	**FN-C-201 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						
Provide a robotic system capable of conducting reconnaissance	**FN-A-103 L**						
Control robotic system(s) in sunlit areas and non-PSRs on the lunar surface from Earth and/or cislunar space	**FN-A-201 L**						
Enable crew lunar surface extravehicular activity in sunlit areas and non-PSRs	**FN-M-101 L**	Crew identification of surface samples in sunlit areas and non-PSRs in the south pole region on the lunar surface	**UC-U-103 L**				
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 L**						
Provide position, navigation, and timing services at the south pole region on the lunar surface	**FN-C-201 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						
Capture imagery on the lunar surface	**FN-U-102 L**						
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 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-105 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-202 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						
Provide a robotic system capable of conducting reconnaissance	**FN-A-103 L**						

Functions		Use Cases		Characteristics/Needs		Objectives	
Control robotic system(s) in sunlit areas and non-PSRs on the lunar surface from Earth and/or cislunar space	**FN-A-201 L**						
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 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-106 L**				
Provide position, navigation, and timing services at the far side and outside the south pole region on the lunar surface	**FN-C-203 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						
Provide a robotic system capable of conducting reconnaissance	**FN-A-103 L**						
Control robotic system(s) in sunlit areas and non-PSRs on the lunar surface from Earth and/or cislunar space	**FN-A-201 L**						
Enable crew lunar surface extravehicular activity in sunlit areas and non-PSRs	**FN-M-101 L**	Crew identification of surface samples in sunlit areas and non-PSRs in distributed sites on the lunar surface	**UC-U-107 L**				
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 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-202 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						
Capture imagery on the lunar surface	**FN-U-102 L**						
Enable crew lunar surface extravehicular activity in sunlit areas and non-PSRs	**FN-M-101 L**	Crew identification of surface samples in sunlit areas and non-PSRs in the far side on the lunar surface	**UC-U-108 L**				
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 L**						
Provide position, navigation, and timing services at the far side and outside the south pole region on the lunar surface	**FN-C-203 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						
Capture imagery on the lunar surface	**FN-U-102 L**						
Enable crew lunar surface extravehicular activity in sunlit areas and non-PSRs	**FN-M-101 L**	Collection, documentation, and packaging of surface and/or shallow sub-surface samples, maintaining scientific integrity of the samples, from non-PSRs and sunlit areas in the south pole region on the lunar surface	**UC-U-301 L**				
Provide position, navigation, and timing services at the south pole region on the lunar surface	**FN-C-201 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						
Capture imagery on the lunar surface	**FN-U-102 L**						
Provide capability to recover and package surface and/or shallow sub-surface samples, maintaining scientific integrity of the samples, from non-PSRs and sunlit regions on the lunar surface	**FN-U-303 L**						
Enable crew lunar surface extravehicular activity in sunlit areas and non-PSRs	**FN-M-101 L**	Collection, documentation, and packaging of surface and/or shallow sub-surface samples, maintaining scientific integrity of the samples,	**UC-U-305 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-202 L**						

Functions		Use Cases		Characteristics/Needs		Objectives	
Provide a coordinated lunar time scale	FN-C-205 L	from non-PSRs and sunlit areas in distributed locations on the lunar surface					
Capture imagery on the lunar surface	FN-U-102 L						
Provide capability to recover and package surface and/or shallow sub-surface samples, maintaining scientific integrity of the samples, from non-PSRs and sunlit regions on the lunar surface	FN-U-303 L						
Enable crew lunar surface extravehicular activity in sunlit areas and non-PSRs	FN-M-101 L	Collection, documentation, and packaging of surface and/or shallow sub-surface samples, maintaining scientific integrity of the samples, from non-PSRs and sunlit areas in the far side on the lunar surface	UC-U-306 L				
Provide position, navigation, and timing services at the far side and outside the south pole region on the lunar surface	FN-C-203 L						
Provide a coordinated lunar time scale	FN-C-205 L						
Capture imagery on the lunar surface	FN-U-102 L						
Provide capability to recover and package surface and/or shallow sub-surface samples, maintaining scientific integrity of the samples, from non-PSRs and sunlit regions on the lunar surface	FN-U-303 L						
Enable crew lunar surface extravehicular activity in PSRs	FN-M-102 L	Conduct of crew excursions in PSRs around landing site at the south pole region	UC-M-303 L	Identify, collect, and document surface and shallow subsurface samples from key destinations in PSRs on the lunar surface, while maintaining scientific integrity of the samples.	CN-U-304 L		
Enable local unpressurized surface mobility in PSRs at the south pole region of the lunar surface	FN-M-304 L						
Provide communications and data exchange between the lunar surface and Earth	FN-C-101 L						
Provide communications and data exchange between assets on the lunar surface	FN-C-103 L						
Provide position, navigation, and timing services at the south pole region on the lunar surface	FN-C-201 L						
Provide a coordinated lunar time scale	FN-C-205 L						
Provide communications and data exchange between the lunar surface and Earth	FN-C-101 L	Robotic surveillance of PSRs near potential crewed landing and exploration sites to identify locations of interest	UC-A-106 L				
Control robotic system(s) in PSRs on the lunar surface from Earth and/or cislunar space	FN-A-202 L						
Enable crew lunar surface extravehicular activity in PSRs	FN-M-102 L	Crew identification of surface samples in PSRs	UC-U-104 L				
Provide communications and data exchange between the lunar surface and Earth	FN-C-101 L						
Provide position, navigation, and timing services at the south pole region on the lunar surface	FN-C-201 L						
Provide a coordinated lunar time scale	FN-C-205 L						
Capture imagery on the lunar surface	FN-U-102 L						
Enable crew lunar surface extravehicular activity in PSRs	FN-M-102 L	Collection, recovery, and packaging of surface and/or shallow sub-surface samples, maintaining	UC-U-303 L				
Provide position, navigation, and timing services at the south pole region on the lunar surface	FN-C-201 L						

Functions		Use Cases		Characteristics/Needs		Objectives	
Provide a coordinated lunar time scale	**FN-C-205 L**	scientific integrity of the samples, from PSRs on the lunar surface					
Capture imagery on the lunar surface	**FN-U-102 L**						
Provide capability to recover and package surface and/or shallow sub-surface samples, maintaining scientific integrity of the samples, from PSRs on the lunar surface	**FN-U-304 L**						
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 L**	Robotic surveillance of PSRs near potential crewed landing and exploration sites to identify locations of interest	**UC-A-106 L**	Conduct robotic surveys of potential landing sites, including video and in situ measurements.	**CN-A-105 L**	Use robotic techniques to survey sites, conduct in-situ measurements, and identify/stockpile samples in advance of and concurrent with astronaut arrival, to optimize astronaut time on the lunar and Martian surface and maximize science return.	**SE-05 LM**
Control robotic system(s) in PSRs on the lunar surface from Earth and/or cislunar space	**FN-A-202 L**						
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 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-U-102 L**				
Provide position, navigation, and timing services at the south pole region on the lunar surface	**FN-C-201 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						
Provide a robotic system capable of conducting reconnaissance	**FN-A-103 L**						
Control robotic system(s) in sunlit areas and non-PSRs on the lunar surface from Earth and/or cislunar space	**FN-A-201 L**						
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 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-105 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-202 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						
Provide a robotic system capable of conducting reconnaissance	**FN-A-103 L**						
Control robotic system(s) in sunlit areas and non-PSRs on the lunar surface from Earth and/or cislunar space	**FN-A-201 L**						
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 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-106 L**				
Provide position, navigation, and timing services at the far side and outside the south pole region on the lunar surface	**FN-C-203 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						
Provide a robotic system capable of conducting reconnaissance	**FN-A-103 L**						
Control robotic system(s) in sunlit areas and non-PSRs on the lunar surface from Earth and/or cislunar space	**FN-A-201 L**						
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 L**	Robotic assistance of crew exploration, site surveying, sample and resource locating, documentation, and sample retrieval from PSRs	**UC-A-101 L**	Provide appropriate robotic tools to support acquisition of samples, including dust, soil, pebbles, hand-sized rock samples, and drill cores, manufactured in accordance with science requirements to minimize sample contamination.	**CN-A-106 L**		
Provide robotic systems to assist crew in PSRs on the lunar surface	**FN-A-102 L**						
Control robotic system(s) in PSRs on the lunar surface from Earth and/or cislunar space	**FN-A-202 L**						
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 L**	Robotic assistance of crew exploration, site surveying, sample	**UC-A-104 L**				

Functions		Use Cases		Characteristics/Needs		Objectives	
Provide robotic systems to assist crew in sunlit areas and non-PSRs on the lunar surface	**FN-A-101 L**	and resource locating, documentation, and sample retrieval from sunlit areas and non- PSRs					
Perform robotic manipulation of payloads, logistics, and/or equipment on the lunar surface	**FN-A-104 L**						
Control robotic system(s) in sunlit areas and non-PSRs on the lunar surface from Earth and/or 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-201 L**	Remote management of robotic system(s) during surface operation as necessary	**UC-A-201 L**				
Control robotic system(s) in PSRs on the lunar surface from Earth and/or cislunar space	**FN-A-202 L**						
Monitor robotic system(s) performance and health	**FN-A-301 L**						
Transport cargo from Earth to cislunar space	**FN-T-213 L**	Deployment and operation of utilization payload(s) and/or equipment at cislunar asset(s)	**UC-U-202 L**	Deploy and operate utilization payloads, related to fundamental plasma processes, in cislunar space.	**CN-U-709 L**	Enable long-term, planet-wide research by delivering science instruments to multiple science-relevant orbits and surface locations at the Moon and Mars.	**SE-06 LM**
Provide communications and data exchange between Earth and cislunar space	**FN-C-102 L**						
Enable repositioning of externally mounted utilization payloads in cislunar space	**FN-A-106 L**						
Provide extravehicular utilization accommodation, interfaces, and resources, operable during crewed and uncrewed increments, in cislunar space	**FN-U-202 L**						
Deliver free flying asset(s) from Earth to cislunar space	**FN-T-216 L**	Deployment and operation of free-flying assets long-term in a variety of lunar orbits	**UC-U-203 L**				
Provide communications and data exchange between Earth and cislunar space	**FN-C-102 L**						
Provide position, navigation, and timing data in cislunar space	**FN-C-204 L**						
Transport a limited amount of cargo (100s of kg) from Earth to south pole region sites on the lunar surface	**FN-T-201 L**	Setup of utilization payload(s) and/or equipment on the lunar surface with long-term remote operation	**UC-U-204 L**	Deploy and operate utilization payload(s) around globally distributed locations on the lunar surface relevant to addressing associated science objectives.	**CN-U-717 L**		
Transport a moderate amount of cargo (1000s of kg) from Earth to south pole region sites on the lunar surface	**FN-T-202 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-203 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-204 L**						
Provide power for deployed external surface utilization payloads(s) and/or equipment for long durations (months to years+)	**FN-P-402 L**						
Enable crew lunar surface extravehicular activity in sunlit areas and non-PSRs	**FN-M-101 L**						
Unload a limited amount of cargo (100s of kg) on the lunar surface	**FN-M-401 L**						
Unload a moderate amount of cargo (1000s of kg) on the lunar surface	**FN-M-402 L**						
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 L**						
Provide communications and data exchange between assets on the lunar surface	**FN-C-103 L**						

Functions		Use Cases		Characteristics/Needs		Objectives	
BLANK	**BLANK**	BLANK	**BLANK**	Coordinate delivery and deployment of utilization payloads in cislunar space and on the lunar surface to address associated science objectives.	**CN-U-801 L**		
BLANK	**BLANK**	Reduction of blast ejecta to limit the migration of ejecta across the lunar surface	**UC-U-802 L**	Limit contamination of PSRs.	**CN-U-802 L**	Preserve and protect representative features of special interest, including lunar permanently shadowed regions and the radio quiet far side as well as Martian recurring slope lineae, to enable future high-priority science investigations.	**SE-07 LM**
BLANK	**BLANK**	Reduction of path erosion, dust lofting, and sample contamination	**UC-U-803 L**				
BLANK	**BLANK**	Limitation of the spread of dust raised by lunar surface operations	**UC-U-804 L**				
BLANK	**BLANK**	Preservation of lunar far side environment to ensure scientific data integrity	**UC-U-801 L**	Preserve radio free environment on the far side of the Moon.	**CN-U-803 L**		
BLANK	**BLANK**	Landing of exploration missions at sites removed from sites of historic significance	**UC-U-805 L**	Protect sites of historic significance.	**CN-U-804 L**		
BLANK	**BLANK**	BLANK	**BLANK**	Minimize environmental impacts on the lunar surface to preserve scientific integrity for future exploration.	**CN-U-805 L**		
Transport a limited amount of cargo (100s of kg) from Earth to south pole region sites on the lunar surface	**FN-T-201 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-719 L**	Provide system(s) to monitor cislunar space and lunar surface natural environments, including space weather, meteoroids, cosmic weather, thermal conditions, and plasma environments, and provide early warnings to in-space and surface assets and crew.	**CN-U-102 L**	Characterize and monitor the contemporary environments of the lunar and Martian surfaces and orbits, including investigations of micrometeorite flux, atmospheric weather, space weather, space weathering, and dust, to plan, support, and monitor safety of crewed operations in these locations.	**AS-01 LM**
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-203 L**						
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 L**						
Perform robotic manipulation of payloads, logistics, and/or equipment on the lunar surface	**FN-A-104 L**						
Provide extravehicular utilization accommodation, interfaces, and resources, operable during crewed and uncrewed increments, on the lunar surface	**FN-U-203 L**						
Transport cargo from Earth to cislunar space	**FN-T-213 L**	Monitoring, characterization, and advance warning for natural environmental threats in cislunar space, e.g., high energy debris,	**UC-U-721 L**				
Provide communications and data exchange between Earth and cislunar space	**FN-C-102 L**						

Functions		Use Cases		Characteristics/Needs		Objectives	
Enable repositioning of externally mounted utilization payloads in cislunar space	**FN-A-106 L**	natural radiation level, thermal conditions, plasma environments, and electrostatic charges					
Provide extravehicular utilization accommodation, interfaces, and resources, operable during crewed and uncrewed increments, in cislunar space	**FN-U-202 L**						
Transport a limited amount of cargo (100s of kg) from Earth to south pole region sites on the lunar surface	**FN-T-201 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-719 L**	Deploy and operate external utilization payload(s) addressing biological science analysis and human research around globally distributed locations on the lunar surface for a minimum of mid-duration (month+) missions.	**CN-U-701 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-203 L**						
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 L**						
Perform robotic manipulation of payloads, logistics, and/or equipment on the lunar surface	**FN-A-104 L**						
Provide extravehicular utilization accommodation, interfaces, and resources, operable during crewed and uncrewed increments, on the lunar surface	**FN-U-203 L**						
Transport a limited amount of cargo (100s of kg) from Earth to south pole region sites on the lunar surface	**FN-T-201 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-720 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-203 L**						
Enable crew lunar surface extravehicular activity in sunlit areas and non-PSRs	**FN-M-101 L**						
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 L**						
Perform robotic manipulation of payloads, logistics, and/or equipment on the lunar surface	**FN-A-104 L**						
Provide extravehicular utilization accommodation, interfaces, and resources, operable during crewed and uncrewed increments, on the lunar surface	**FN-U-203 L**						
BLANK	**BLANK**	BLANK	**BLANK**	Coordinate delivery and deployment of utilization payloads in cislunar space and on the lunar surface to address associated science objectives.	**CN-U-801 L**	Coordinate on-going and future science measurements from orbital and surface platforms to optimize human-led science campaigns on the Moon and Mars.	**AS-02 LM**
Transport crew from cislunar space to lunar surface sites in the south pole region	**FN-T-102 L**	Transportation of crew between cislunar space and lunar south pole region landing sites	**UC-T-105 L**	Visit diverse sites of key scientific interest on the lunar surface, including polar and non-polar destinations to address high priority science goals.	**CN-T-108 L**	Characterize accessible lunar and Martian resources, gather scientific research data, and analyze potential reserves to satisfy science and technology objectives and enable In-Situ Resource Utilization (ISRU) on successive missions.	**AS-03 LM**
Transport crew from the lunar surface to cislunar space	**FN-T-104 L**						
Enable crew habitation during transit from cislunar space to lunar surface sites in the south pole region	**FN-T-108 L**						
Enable crew habitation during transit from the lunar surface to cislunar space	**FN-T-110 L**						
Transport crew from cislunar space to distributed sites outside of the south pole region on the lunar surface	**FN-T-103 L**	Transportation of crew from cislunar space to distributed landing sites outside of the south pole region on the lunar surface	**UC-T-106 L**				
Enable crew habitation during transit from cislunar space to distributed sites outside of the south pole region on the lunar surface	**FN-T-109 L**						

Functions		Use Cases		Characteristics/Needs		Objectives	
Transport a small amount of cargo (10s of kg) from the lunar surface to Earth	**FN-T-207 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-301 L**	Transfer, return, and curate a small amount (10s of kg) or a large amount (100s of kg) of unconditioned samples and containers from key destinations across the lunar surface and back to Earth, while maintaining scientific integrity of the samples.	**CN-T-302 L**		
Transport a small amount of cargo (10s of kg) from the lunar surface to cislunar space	**FN-T-209 L**						
Transport a small amount of cargo (10s of kg) from cislunar space to Earth	**FN-T-211 L**						
Reposition a small amount of unconditioned samples and containers (10s of kg) on the lunar surface	**FN-M-504 L**						
Stow collected unconditioned samples on exploration assets while on the lunar surface, while maintaining scientific integrity of the samples	**FN-U-401 L**						
Transport a large amount of cargo (100s of kg) from the lunar surface to Earth	**FN-T-208 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-302 L**				
Transport a large amount of cargo (100s of kg) from the lunar surface to cislunar space	**FN-T-210 L**						
Transport a large amount of cargo (100s of kg) from cislunar space to Earth	**FN-T-212 L**						
Reposition a large amount of unconditioned samples and containers (100s of kg) on the lunar surface	**FN-M-505 L**						
Stow collected unconditioned samples on exploration assets while on the lunar surface, while maintaining scientific integrity of the samples	**FN-U-401 L**						
BLANK	**BLANK**	Delivery of collected samples to curation facilities or other appropriate facilities on Earth, while maintaining scientific integrity of the samples	**UC-G-202 L**				
Transport a small amount of cargo (10s of kg) from the lunar surface to Earth	**FN-T-207 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-305 L**	Transfer, return and curate a small amount (10s of kg) or a large amount (100s of kg) of frozen sample(s), containers, and freezers from key destinations across the lunar surface to Earth while maintaining scientific integrity of the samples.	**CN-T-304 L**		
Transport a small amount of cargo (10s of kg) from the lunar surface to cislunar space	**FN-T-209 L**						
Transport a small amount of cargo (10s of kg) from cislunar space to Earth	**FN-T-211 L**						
Provide resources to condition frozen 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 cislunar space	**FN-T-305 L**						
Provide resources to condition frozen sample containers during transit from cislunar space to Earth	**FN-T-308 L**						
Reposition a small amount of frozen samples and containers (10s of kg) on the lunar surface	**FN-M-508 L**						
Stow frozen 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 cislunar space, while maintaining scientific integrity of samples	**FN-U-406 L**						
Stow frozen samples during transport from cislunar space to Earth, while maintaining scientific integrity of samples	**FN-U-409 L**						
Stow collected frozen samples on exploration assets while on the lunar surface, while maintaining scientific integrity of the samples	**FN-U-412 L**						
Provide resources to condition frozen sample containers on the lunar surface	**FN-U-415 L**						

Functions		Use Cases		Characteristics/Needs		Objectives	
Transport a large amount of cargo (100s of kg) from the lunar surface to Earth	**FN-T-208 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-306 L**				
Transport a large amount of cargo (100s of kg) from the lunar surface to cislunar space	**FN-T-210 L**						
Transport a large amount of cargo (100s of kg) from cislunar space to Earth	**FN-T-212 L**						
Provide resources to condition frozen 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 cislunar space	**FN-T-305 L**						
Provide resources to condition frozen sample containers during transit from cislunar space to Earth	**FN-T-308 L**						
Reposition a large amount of frozen samples and containers (100s of kg) on the lunar surface	**FN-M-509 L**						
Stow frozen 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 cislunar space, while maintaining scientific integrity of samples	**FN-U-406 L**						
Stow frozen samples during transport from cislunar space to Earth, while maintaining scientific integrity of samples	**FN-U-409 L**						
Stow collected frozen samples on exploration assets while on the lunar surface, while maintaining scientific integrity of the samples	**FN-U-412 L**						
Provide resources to condition frozen sample containers on the lunar surface	**FN-U-415 L**						
BLANK	**BLANK**	Delivery of conditioned cargo to curation facilities or other appropriate facilities on Earth after landing, while maintaining scientific integrity of the samples	**UC-G-201 L**				
Enable crew lunar surface extravehicular activity in sunlit areas and non-PSRs	**FN-M-101 L**	Conduct of crew extravehicular operations on the lunar surface	**UC-M-101 L**	Provide mobility capabilities to conduct prospecting traverses with appropriate scientific instrumentation and drill capabilities over sites of interest.	**CN-M-301 L**		
Enable crew lunar surface extravehicular activity in PSRs	**FN-M-102 L**						
Enable maintaining and servicing of the EVA system in a habitable environment	**FN-M-202 L**						
Ingress/egress from habitable asset(s) to lunar surface vacuum	**FN-M-203 L**						
Enable crew lunar surface extravehicular activity in sunlit areas and non-PSRs	**FN-M-101 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-301 L**				
Enable local unpressurized surface mobility in sunlit areas and non-PSRs at distributed sites on the lunar surface	**FN-M-303 L**						
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 L**						
Provide communications and data exchange between assets on the lunar surface	**FN-C-103 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-202 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						

Functions		Use Cases		Characteristics/Needs		Objectives	
Enable crew lunar surface extravehicular activity in sunlit areas and non-PSRs	**FN-M-101 L**	Conduct of crew excursions to locations around landing site in sunlit areas and non-PSRs in the south pole region	**UC-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-302 L**						
Enable pressurized surface mobility in sunlit areas and non-PSRs	**FN-M-305 L**						
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 L**						
Provide communications and data exchange between assets on the lunar surface	**FN-C-103 L**						
Provide position, navigation, and timing services at the south pole region on the lunar surface	**FN-C-201 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						
Enable crew lunar surface extravehicular activity in sunlit areas and non-PSRs	**FN-M-101 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-301 L**	Identify, collect, and document deep subsurface samples from key destinations in non-PSRs and other sunlit areas on the lunar surface, while maintaining scientific integrity of the samples.	**CN-U-301 L**		
Enable local unpressurized surface mobility in sunlit areas and non-PSRs at distributed sites on the lunar surface	**FN-M-303 L**						
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 L**						
Provide communications and data exchange between assets on the lunar surface	**FN-C-103 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-202 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 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-U-102 L**				
Provide position, navigation, and timing services at the south pole region on the lunar surface	**FN-C-201 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						
Provide a robotic system capable of conducting reconnaissance	**FN-A-103 L**						
Control robotic system(s) in sunlit areas and non-PSRs on the lunar surface from Earth and/or cislunar space	**FN-A-201 L**						
Enable crew lunar surface extravehicular activity in sunlit areas and non-PSRs	**FN-M-101 L**	Crew identification of surface samples in sunlit areas and non-PSRs in the south pole region on the lunar surface	**UC-U-103 L**				
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 L**						
Provide position, navigation, and timing services at the south pole region on the lunar surface	**FN-C-201 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						
Capture imagery on the lunar surface	**FN-U-102 L**						
Enable crew lunar surface extravehicular activity in sunlit areas and non-PSRs	**FN-M-101 L**	Collection, recovery, and packaging of deep sub-surface samples,	**UC-U-302 L**				

Functions		Use Cases		Characteristics/Needs		Objectives	
Provide position, navigation, and timing services at the south pole region on the lunar surface	**FN-C-201 L**	maintaining scientific integrity of the samples, from non-PSRs and other sunlit areas in the south pole region on the lunar surface					
Provide a coordinated lunar time scale	**FN-C-205 L**						
Capture imagery on the lunar surface	**FN-U-102 L**						
Provide capability to recover and package deep sub-surface samples, including drill cores, maintaining scientific integrity of the samples, from non-PSRs and sunlit regions on the lunar surface	**FN-U-305 L**						
Enable crew lunar surface extravehicular activity in sunlit areas and non-PSRs	**FN-M-101 L**	Collection, recovery, and packaging of deep sub-surface samples, maintaining scientific integrity of the samples, from non-PSRs and other sunlit areas in distributed sites on the lunar surface	**UC-U-307 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-202 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						
Capture imagery on the lunar surface	**FN-U-102 L**						
Provide capability to recover and package deep sub-surface samples, including drill cores, maintaining scientific integrity of the samples, from non-PSRs and sunlit regions on the lunar surface	**FN-U-305 L**						
Enable crew lunar surface extravehicular activity in sunlit areas and non-PSRs	**FN-M-101 L**	Collection, recovery, and packaging of deep sub-surface samples, maintaining scientific integrity of the samples, from non-PSRs and other sunlit areas in the far side on the lunar surface	**UC-U-308 L**				
Provide position, navigation, and timing services at the far side and outside the south pole region on the lunar surface	**FN-C-203 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						
Capture imagery on the lunar surface	**FN-U-102 L**						
Provide capability to recover and package deep sub-surface samples, including drill cores, maintaining scientific integrity of the samples, from non-PSRs and sunlit regions on the lunar surface	**FN-U-305 L**						
Enable crew lunar surface extravehicular activity in PSRs	**FN-M-102 L**	Conduct of crew excursions in PSRs around landing site at the south pole region	**UC-M-303 L**	Identify, collect, and document deep-surface samples from key destinations in PSRs on the lunar surface, while maintaining scientific integrity of the samples.	**CN-U-302 L**		
Enable local unpressurized surface mobility in PSRs at the south pole region of the lunar surface	**FN-M-304 L**						
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 L**						
Provide communications and data exchange between assets on the lunar surface	**FN-C-103 L**						
Provide position, navigation, and timing services at the south pole region on the lunar surface	**FN-C-201 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 L**	Robotic surveillance of PSRs near potential crewed landing and exploration sites to identify locations of interest	**UC-A-106 L**				
Control robotic system(s) in PSRs on the lunar surface from Earth and/or cislunar space	**FN-A-202 L**						
Enable crew lunar surface extravehicular activity in PSRs	**FN-M-102 L**	Crew identification of surface samples in PSRs	**UC-U-104 L**				

Functions		Use Cases		Characteristics/Needs		Objectives	
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 L**						
Provide position, navigation, and timing services at the south pole region on the lunar surface	**FN-C-201 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						
Capture imagery on the lunar surface	**FN-U-102 L**						
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 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-105 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-202 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						
Provide a robotic system capable of conducting reconnaissance	**FN-A-103 L**						
Control robotic system(s) in sunlit areas and non-PSRs on the lunar surface from Earth and/or cislunar space	**FN-A-201 L**						
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 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-106 L**				
Provide position, navigation, and timing services at the far side and outside the south pole region on the lunar surface	**FN-C-203 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						
Provide a robotic system capable of conducting reconnaissance	**FN-A-103 L**						
Control robotic system(s) in sunlit areas and non-PSRs on the lunar surface from Earth and/or cislunar space	**FN-A-201 L**						
Enable crew lunar surface extravehicular activity in sunlit areas and non-PSRs	**FN-M-101 L**	Crew identification of surface samples in sunlit areas and non-PSRs in distributed sites on the lunar surface	**UC-U-107 L**				
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 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-202 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						
Capture imagery on the lunar surface	**FN-U-102 L**						
Enable crew lunar surface extravehicular activity in sunlit areas and non-PSRs	**FN-M-101 L**	Crew identification of surface samples in sunlit areas and non-PSRs in the far side on the lunar surface	**UC-U-108 L**				
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 L**						
Provide position, navigation, and timing services at the far side and outside the south pole region on the lunar surface	**FN-C-203 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						
Capture imagery on the lunar surface	**FN-U-102 L**						

Functions		Use Cases		Characteristics/Needs		Objectives	
Enable crew lunar surface extravehicular activity in PSRs	**FN-M-102 L**	Collection, recovery, and packaging of deep sub-surface samples, maintaining scientific integrity of the samples, from PSRs on the lunar surface	**UC-U-304 L**				
Provide position, navigation, and timing services at the south pole region on the lunar surface	**FN-C-201 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						
Capture imagery on the lunar surface	**FN-U-102 L**						
Provide capability to recover and package deep sub-surface samples, including drill cores, maintaining scientific integrity of the samples, from PSRs on the lunar surface	**FN-U-306 L**						
Enable crew lunar surface extravehicular activity in sunlit areas and non-PSRs	**FN-M-101 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-301 L**	Identify, collect, and document surface and shallow subsurface samples from key destinations in non-PSRs and other sunlit areas on the lunar surface, while maintaining scientific integrity of the samples.	**CN-U-303 L**		
Enable local unpressurized surface mobility in sunlit areas and non-PSRs at distributed sites on the lunar surface	**FN-M-303 L**						
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 L**						
Provide communications and data exchange between assets on the lunar surface	**FN-C-103 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-202 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 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-U-102 L**				
Provide position, navigation, and timing services at the south pole region on the lunar surface	**FN-C-201 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						
Provide a robotic system capable of conducting reconnaissance	**FN-A-103 L**						
Control robotic system(s) in sunlit areas and non-PSRs on the lunar surface from Earth and/or cislunar space	**FN-A-201 L**						
Enable crew lunar surface extravehicular activity in sunlit areas and non-PSRs	**FN-M-101 L**	Crew identification of surface samples in sunlit areas and non-PSRs in the south pole region on the lunar surface	**UC-U-103 L**				
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 L**						
Provide position, navigation, and timing services at the south pole region on the lunar surface	**FN-C-201 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						
Capture imagery on the lunar surface	**FN-U-102 L**						
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 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-105 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-202 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						

Functions		Use Cases		Characteristics/Needs		Objectives	
Provide a robotic system capable of conducting reconnaissance	**FN-A-103 L**						
Control robotic system(s) in sunlit areas and non-PSRs on the lunar surface from Earth and/or cislunar space	**FN-A-201 L**						
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 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-106 L**				
Provide position, navigation, and timing services at the far side and outside the south pole region on the lunar surface	**FN-C-203 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						
Provide a robotic system capable of conducting reconnaissance	**FN-A-103 L**						
Control robotic system(s) in sunlit areas and non-PSRs on the lunar surface from Earth and/or cislunar space	**FN-A-201 L**						
Enable crew lunar surface extravehicular activity in sunlit areas and non-PSRs	**FN-M-101 L**	Crew identification of surface samples in sunlit areas and non-PSRs in distributed sites on the lunar surface	**UC-U-107 L**				
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 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-202 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						
Capture imagery on the lunar surface	**FN-U-102 L**						
Enable crew lunar surface extravehicular activity in sunlit areas and non-PSRs	**FN-M-101 L**	Crew identification of surface samples in sunlit areas and non-PSRs in the far side on the lunar surface	**UC-U-108 L**				
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 L**						
Provide position, navigation, and timing services at the far side and outside the south pole region on the lunar surface	**FN-C-203 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						
Capture imagery on the lunar surface	**FN-U-102 L**						
Enable crew lunar surface extravehicular activity in sunlit areas and non-PSRs	**FN-M-101 L**	Collection, documentation, and packaging of surface and/or shallow sub-surface samples, maintaining scientific integrity of the samples, from non-PSRs and sunlit areas in the south pole region on the lunar surface	**UC-U-301 L**				
Provide position, navigation, and timing services at the south pole region on the lunar surface	**FN-C-201 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						
Capture imagery on the lunar surface	**FN-U-102 L**						
Provide capability to recover and package surface and/or shallow sub-surface samples, maintaining scientific integrity of the samples, from non-PSRs and sunlit regions on the lunar surface	**FN-U-303 L**						
Enable crew lunar surface extravehicular activity in sunlit areas and non-PSRs	**FN-M-101 L**	Collection, documentation, and packaging of surface and/or shallow	**UC-U-305 L**				

Functions		Use Cases		Characteristics/Needs		Objectives	
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-202 L**	sub-surface samples, maintaining scientific integrity of the samples, from non-PSRs and sunlit areas in distributed locations on the lunar surface					
Provide a coordinated lunar time scale	**FN-C-205 L**						
Capture imagery on the lunar surface	**FN-U-102 L**						
Provide capability to recover and package surface and/or shallow sub-surface samples, maintaining scientific integrity of the samples, from non-PSRs and sunlit regions on the lunar surface	**FN-U-303 L**						
Enable crew lunar surface extravehicular activity in sunlit areas and non-PSRs	**FN-M-101 L**	Collection, documentation, and packaging of surface and/or shallow sub-surface samples, maintaining scientific integrity of the samples, from non-PSRs and sunlit areas in the far side on the lunar surface	**UC-U-306 L**				
Provide position, navigation, and timing services at the far side and outside the south pole region on the lunar surface	**FN-C-203 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						
Capture imagery on the lunar surface	**FN-U-102 L**						
Provide capability to recover and package surface and/or shallow sub-surface samples, maintaining scientific integrity of the samples, from non-PSRs and sunlit regions on the lunar surface	**FN-U-303 L**						
Enable crew lunar surface extravehicular activity in PSRs	**FN-M-102 L**	Conduct of crew excursions in PSRs around landing site at the south pole region	**UC-M-303 L**	Identify, collect, and document surface and shallow subsurface samples from key destinations in PSRs on the lunar surface, while maintaining scientific integrity of the samples.	**CN-U-304 L**		
Enable local unpressurized surface mobility in PSRs at the south pole region of the lunar surface	**FN-M-304 L**						
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 L**						
Provide communications and data exchange between assets on the lunar surface	**FN-C-103 L**						
Provide position, navigation, and timing services at the south pole region on the lunar surface	**FN-C-201 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 L**	Robotic surveillance of PSRs near potential crewed landing and exploration sites to identify locations of interest	**UC-A-106 L**				
Control robotic system(s) in PSRs on the lunar surface from Earth and/or cislunar space	**FN-A-202 L**						
Enable crew lunar surface extravehicular activity in PSRs	**FN-M-102 L**	Crew identification of surface samples in PSRs	**UC-U-104 L**				
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 L**						
Provide position, navigation, and timing services at the south pole region on the lunar surface	**FN-C-201 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						
Capture imagery on the lunar surface	**FN-U-102 L**						
Enable crew lunar surface extravehicular activity in PSRs	**FN-M-102 L**	Collection, recovery, and packaging of surface and/or shallow sub-	**UC-U-303 L**				

Functions		Use Cases		Characteristics/Needs		Objectives	
Provide position, navigation, and timing services at the south pole region on the lunar surface	**FN-C-201 L**	surface samples, maintaining scientific integrity of the samples, from PSRs on the lunar surface					
Provide a coordinated lunar time scale	**FN-C-205 L**						
Capture imagery on the lunar surface	**FN-U-102 L**						
Provide capability to recover and package surface and/or shallow sub-surface samples, maintaining scientific integrity of the samples, from PSRs on the lunar surface	**FN-U-304 L**						
Transport a limited amount of cargo (100s of kg) from Earth to south pole region sites on the lunar surface	**FN-T-201 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-U-717 L**	Deploy and operate exploration asset(s), related to available resources, at distributed and south polar region sites on the lunar surface.	**CN-U-702 L**		
Transport a moderate amount of cargo (1000s of kg) from Earth to south pole region sites on the lunar surface	**FN-T-202 L**						
Provide power for deployed external surface utilization payloads(s) and/or equipment for long durations (months to years+)	**FN-P-402 L**						
Enable crew lunar surface extravehicular activity in sunlit areas and non-PSRs	**FN-M-101 L**						
Enable crew lunar surface extravehicular activity in PSRs	**FN-M-102 L**						
Enable local unpressurized surface mobility in sunlit areas and non-PSRs in the south pole region on the lunar surface	**FN-M-302 L**						
Enable local unpressurized surface mobility in PSRs at the south pole region of the lunar surface	**FN-M-304 L**						
Unload a limited amount of cargo (100s of kg) on the lunar surface	**FN-M-401 L**						
Unload a moderate amount of cargo (1000s of kg) on the lunar surface	**FN-M-402 L**						
Reposition a limited amount of cargo (100s of kg) in the south pole region on the lunar surface	**FN-M-501 L**						
Reposition a moderate amount of cargo (1000s of kg) at the south pole region on the lunar surface	**FN-M-503 L**						
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 L**						
Perform robotic manipulation of payloads, logistics, and/or equipment on the lunar surface	**FN-A-104 L**						
Conduct resource identification utilization payload and/or equipment operations on the lunar surface	**FN-U-103 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-203 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-718 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-204 L**						
Provide power for deployed external surface utilization payloads(s) and/or equipment for long durations (months to years+)	**FN-P-402 L**						
Enable crew lunar surface extravehicular activity in sunlit areas and non-PSRs	**FN-M-101 L**						
Enable local unpressurized surface mobility in sunlit areas and non-PSRs at distributed sites on the lunar surface	**FN-M-303 L**						
Unload a moderate amount of cargo (1000s of kg) on the lunar surface	**FN-M-402 L**						

Functions		Use Cases		Characteristics/Needs		Objectives	
Reposition a limited amount of cargo (100s of kg) at distributed sites on the lunar surface	**FN-M-502 L**						
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 L**						
Perform robotic manipulation of payloads, logistics, and/or equipment on the lunar surface	**FN-A-104 L**						
Conduct resource identification utilization payload and/or equipment operations on the lunar surface	**FN-U-103 L**						
Transport cargo from Earth to cislunar space	**FN-T-213 L**	Deployment and operation of utilization payload(s) and/or equipment related to bioregenerative oxygen and water recovery at assets in cislunar space	**UC-U-723 L**	Demonstrate operation of bioregenerative ECLSS sub-systems in LEO and/or deep space.	**CN-U-601 LM**	Conduct applied scientific investigations essential for the development of bioregenerative-based, ecological life support systems.	**AS-04 LM**
Distribute power to utilization payloads and/or equipment in cislunar space	**FN-P-303 L**						
Provide intravehicular activity facilities, utilization accommodation, and resources, operable during crewed and uncrewed increments, in cislunar space	**FN-U-205 L**						
Conduct bioregenerative ECLSS utilization payload and/or equipment operations in space	**FN-U-601 L**						
Transport cargo from Earth to cislunar space	**FN-T-213 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-724 L**				
Distribute power to utilization payloads and/or equipment in cislunar space	**FN-P-303 L**						
Provide communications and data exchange between Earth and cislunar space	**FN-C-102 L**						
Provide intravehicular activity facilities, utilization accommodation, and resources, operable during crewed and uncrewed increments, in cislunar space	**FN-U-205 L**						
Transport cargo from Earth to cislunar space	**FN-T-213 L**	Deployment and operation of utilization payload(s) and/or equipment related to plant growth at assets in cislunar asset(s)	**UC-U-725 L**	Demonstrate operation of plant based ECLSS sub-systems in LEO and/or deep space.	**CN-U-602 LM**	Define crop plant species, including methods for their productive growth, capable of providing sustainable and nutritious food sources for lunar, Deep Space transit, and Mars habitation.	**AS-05 LM**
Distribute power to utilization payloads and/or equipment in cislunar space	**FN-P-303 L**						
Provide communications and data exchange between Earth and cislunar space	**FN-C-102 L**						
Provide intravehicular activity facilities, utilization accommodation, and resources, operable during crewed and uncrewed increments, in cislunar space	**FN-U-205 L**						
Conduct plant growth utilization payload and/or equipment operations in space	**FN-U-602 L**						
Transport cargo from Earth to cislunar space	**FN-T-213 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-715 L**	Deploy and operate utilization payload(s), related to the physical systems and fundamental physics, in cislunar space.	**CN-U-703 L**	Advance understanding of how physical systems and fundamental physical phenomena are affected by partial gravity, microgravity, and general environment of the Moon, Mars, and deep space transit.	**AS-06 LM**
Deliver free flying asset(s) from Earth to cislunar space	**FN-T-216 L**						
Provide communications and data exchange between Earth and cislunar space	**FN-C-102 L**						
Enable repositioning of externally mounted utilization payloads in cislunar space	**FN-A-106 L**						
Provide extravehicular utilization accommodation, interfaces, and resources, operable during crewed and uncrewed increments, in cislunar space	**FN-U-202 L**						

Functions		Use Cases		Characteristics/Needs		Objectives	
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-203 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-716 L**	Deploy and operate utilization payload(s), related to the physical systems and fundamental physics, at areas of key scientific interest on the lunar surface, including polar and non-polar destinations.	**CN-U-704 L**		
Provide power for deployed external surface utilization payloads(s) and/or equipment for long durations (months to years+)	**FN-P-402 L**						
Enable crew lunar surface extravehicular activity in sunlit areas and non-PSRs	**FN-M-101 L**						
Enable crew lunar surface extravehicular activity in PSRs	**FN-M-102 L**						
Unload a limited amount of cargo (100s of kg) on the lunar surface	**FN-M-401 L**						
Reposition a limited amount of cargo (100s of kg) in the south pole region on the lunar surface	**FN-M-501 L**						
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 L**						
Generate power in the south pole region on the lunar surface	**FN-P-101 L**	Power generation and energy storage at south pole region on the lunar surface	**UC-P-101 L**	Provide scalable power generation, energy storage, and power distribution system(s) on the lunar surface to support large exploration assets.	**CN-P-101 L**	Develop an incremental lunar power generation and distribution system that is evolvable to support continuous robotic/human operation and is capable of scaling to global power utilization and industrial power levels.	**LI-01 L**
Store energy in the south pole region on the lunar surface	**FN-P-202 L**						
Distribute power in the south pole region on the lunar surface	**FN-P-301 L**	Power distribution around power generation and energy storage system(s) in the south pole region on the lunar surface	**UC-P-301 L**				
Provide bi-directional power exchange capability	**FN-P-305 L**						
Generate power at multiple distributed locations outside of the south pole region on the lunar surface	**FN-P-102 L**	Power generation and energy storage at multiple distributed locations outside of the south pole region on the lunar surface	**UC-P-102 L**	Provide scalable power generation, energy storage, and power distribution system(s) on the lunar surface to allow power utilization to support assets at multiple distributed locations around exploration sites.	**CN-P-102 L**		
Store energy at multiple distributed locations outside of the south pole region on the lunar surface	**FN-P-201 L**						
Distribute power at multiple distributed locations outside of the south pole region on the lunar surface	**FN-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-302 L**				
Provide bi-directional power exchange capability	**FN-P-305 L**						
BLANK	**BLANK**	Continuous power provision to assets during mission critical activities	**UC-P-501 L**	Provide power generation, energy storage, and power distribution system(s) on the lunar surface that are able to supply continuous power availability during crew safety critical mission operation and are able to support contingency operations.	**CN-P-103 L**		
BLANK	**BLANK**	Continuous power provision to assets in off-nominal conditions	**UC-P-502 L**				
Provide high bandwidth, high availability communications and data exchange between the lunar surface and Earth	**FN-C-105 L**	Communications and data exchange with high bandwidth and high availability between assets on the lunar surface and the Earth	**UC-C-101 L**	Provide scalable communication system(s) to enable high bandwidth, high availability communications between Earth-based personnel, surface crew, and assets on the surface.	**CN-C-101 L**	Develop a lunar surface, orbital, and Moon-to-Earth communications architecture capable of scaling to support long term science, exploration, and industrial needs.	**LI-02 L**
Collect, store, and locally distribute data on the lunar surface	**FN-D-101 L**	Aggregation and storage of data on the lunar surface until it is able to be transmitted and confirmed received	**UC-D-101 L**				
Process data locally on the lunar surface	**FN-D-201 L**						

Functions		Use Cases		Characteristics/Needs		Objectives	
Provide high bandwidth, high availability communications and data exchange between cislunar space and the Earth	**FN-C-106 L**	Communications and data exchange with high bandwidth and high availability between assets in cislunar space and the Earth	**UC-C-103 L**	Provide scalable communication system(s) to enable high bandwidth, high availability communications between Earth-based personnel, in-space crew, and in-space assets.	**CN-C-102 L**		
Collect, store, and locally distribute data in cislunar space	**FN-D-102 L**	Aggregation and storage of data in cislunar space until it is able to be transmitted and confirmed received	**UC-D-102 L**				
Process data locally in cislunar space	**FN-D-202 L**						
Provide high bandwidth, high availability communications and data exchange between cislunar space and the lunar surface	**FN-C-108 L**	Communications and data exchange with high bandwidth and high availability between assets in cislunar space and the lunar surface	**UC-C-104 L**	Provide scalable communication system(s) to enable high bandwidth, high availability communications between In-space personnel, surface crew, and assets on the surface.	**CN-C-103 L**		
Collect, store, and locally distribute data on the lunar surface	**FN-D-101 L**	Aggregation and storage of data on the lunar surface until it is able to be transmitted and confirmed received	**UC-D-101 L**				
Process data locally on the lunar surface	**FN-D-201 L**						
Collect, store, and locally distribute data in cislunar space	**FN-D-102 L**	Aggregation and storage of data in cislunar space until it is able to be transmitted and confirmed received	**UC-D-102 L**				
Process data locally in cislunar space	**FN-D-202 L**						
Provide high bandwidth, high availability communications and data exchange between the lunar surface and Earth	**FN-C-105 L**	Communications and data exchange with high bandwidth and high availability between assets on the lunar surface and the Earth	**UC-C-101 L**	Provide communication capabilities to allow NASA to inspire and inform the general public, students, and teachers by enabling them to interact, learn about, and experience missions in a direct and tangible way.	**CN-C-104 L**		
Provide high bandwidth, high availability communications and data exchange between cislunar space and the Earth	**FN-C-106 L**	Communications and data exchange with high bandwidth and high availability between assets in cislunar space and the Earth	**UC-C-103 L**				
Provide high bandwidth, high availability communications and data exchange between assets on the lunar surface	**FN-C-107 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-102 L**	Provide scalable communication system(s) to enable high bandwidth, high availability communications between different crew and assets on the lunar surface.	**CN-C-105 L**		
Collect, store, and locally distribute data on the lunar surface	**FN-D-101 L**	Aggregation and storage of data on the lunar surface until it is able to be transmitted and confirmed received	**UC-D-101 L**				
Process data locally on the lunar surface	**FN-D-201 L**						
Provide position, navigation, and timing data in cislunar space	**FN-C-204 L**	Determination of position, navigation, and timing by crew and assets in cislunar space	**UC-C-201 L**	Provide scalable navigation, positioning, and timing system(s) to enable high availability navigation and tracking in cislunar space.	**CN-C-201 L**	Develop a lunar position, navigation and timing architecture capable of scaling to support long term science, exploration, and industrial needs.	**LI-03 L**
Provide position, navigation, and timing services at the south pole region on the lunar surface	**FN-C-201 L**	Determination of position, navigation, and timing by crew and assets at the south pole region on the lunar surface	**UC-C-202 L**	Provide scalable navigation, positioning, and timing system(s) to enable high availability navigation and tracking on the lunar surface.	**CN-C-202 L**		
Provide a coordinated lunar time scale	**FN-C-205 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-202 L**		**UC-C-204 L**				

Functions		Use Cases		Characteristics/Needs		Objectives	
Provide a coordinated lunar time scale	**FN-C-205 L**	Determination of position, navigation, and timing by crew and assets at distributed sites on the lunar surface					
Provide position, navigation, and timing services at the far side and outside the south pole region on the lunar surface	**FN-C-203 L**	Determination of position, navigation, and timing by crew and assets at the far side on the lunar surface	**UC-C-206 L**				
Provide a coordinated lunar time scale	**FN-C-205 L**						
Provide position, navigation, and timing services at the south pole region on the lunar surface	**FN-C-201 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-203 L**	Provide system(s) to enable accurate location identification, tracking, and documentation of collected surface samples.	**CN-C-203 L**		
Provide a coordinated lunar time scale	**FN-C-205 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-202 L**	Crew or robotics utilization of position, navigation, and timing for accurate sample tracking at distributed sites on the lunar surface	**UC-C-205 L**				
Provide a coordinated lunar time scale	**FN-C-205 L**						
Provide position, navigation, and timing services at the far side and outside the south pole region on the lunar surface	**FN-C-203 L**	Crew or robotics utilization of position, navigation, and timing for accurate sample tracking at the far side on the lunar surface	**UC-C-207 L**				
Provide a coordinated lunar time scale	**FN-C-205 L**						
Transport a moderate amount of cargo (1000s of kg) from Earth to south pole region sites on the lunar surface	**FN-T-202 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-201 L**	Deploy and operate autonomous construction demonstration asset(s) to the lunar surface, including partial-scale demonstrations of regolith manipulation and construction of structures, to demonstrate scalable capabilities and applications.	**CN-I-201 L**	Demonstrate advanced manufacturing and autonomous construction capabilities in support of continuous human lunar presence and a robust lunar economy.	**LI-04 L**
Provide power for deployed external surface utilization payloads(s) and/or equipment for long durations (months to years+)	**FN-P-402 L**						
Unload a moderate amount of cargo (1000s of kg) on the lunar surface	**FN-M-402 L**						
Reposition a moderate amount of cargo (1000s of kg) at the south pole region on the lunar surface	**FN-M-503 L**						
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 L**						
Process and refine scalable quantities of in-situ feedstock resources on the lunar surface	**FN-I-204 L**						
Conduct autonomous construction utilization payload and/or equipment operations on the lunar surface	**FN-I-205 L**						
Transport a limited amount of cargo (100s of kg) from Earth to south pole region sites on the lunar surface	**FN-T-201 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-I-204 L**	Deploy and operate advanced manufacturing demonstration asset(s) to the lunar surface, including scaled demonstration of additive/subtractive/joining manufacturing techniques and inspection/certification processes, to demonstrate scalable capabilities and applications to create a wide variety or products with metallic/polymer/composites materials.	**CN-I-202 L**		
Provide power for deployed external surface utilization payloads(s) and/or equipment for long durations (months to years+)	**FN-P-402 L**						
Unload a limited amount of cargo (100s of kg) on the lunar surface	**FN-M-401 L**						
Reposition a limited amount of cargo (100s of kg) in the south pole region on the lunar surface	**FN-M-501 L**						
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 L**						
Conduct advanced manufacturing utilization payload and/or equipment operations on the lunar surface	**FN-I-206 L**						

Functions		Use Cases		Characteristics/Needs		Objectives	
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-203 L**	Transportation of small cargo from Earth to distributed locations outside of the south pole region on the lunar surface	**UC-T-201 L**	Demonstrate the capability for lunar landers to reliably and safely land within a defined radius around an intended location.	**CN-T-401 L**	Demonstrate precision landing capabilities in support of continuous human lunar presence and a robust lunar economy.	**LI-05 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-204 L**						
Provide precision landing for cargo transport to the lunar surface	**FN-T-402 L**						
Enable landing on the lunar surface under all lighting conditions	**FN-T-403 L**						
Transport large exploration asset(s) from Earth to the lunar surface	**FN-T-206 L**	Transportation of large cargo from Earth to the lunar surface	**UC-T-202 L**				
Provide precision landing for cargo transport to the lunar surface	**FN-T-402 L**						
Enable landing on the lunar surface under all lighting conditions	**FN-T-403 L**						
Provide precision landing for crew transport to the lunar surface	**FN-T-401 L**	Landing of crew lander(s) at specific pre-defined locations	**UC-T-401 L**				
Enable landing on the lunar surface under all lighting conditions	**FN-T-403 L**						
Provide precision landing for cargo transport to the lunar surface	**FN-T-402 L**	Landing of cargo lander(s) at specific pre-defined locations	**UC-T-402 L**				
Enable landing on the lunar surface under all lighting conditions	**FN-T-403 L**						
Provide position, navigation, and timing services at the south pole region on the lunar surface	**FN-C-201 L**	Determination of position, navigation, and timing by crew and assets at the south pole region on the lunar surface	**UC-C-202 L**				
Provide a coordinated lunar time scale	**FN-C-205 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-202 L**	Determination of position, navigation, and timing by crew and assets at distributed sites on the lunar surface	**UC-C-204 L**				
Provide a coordinated lunar time scale	**FN-C-205 L**						
Provide position, navigation, and timing services at the far side and outside the south pole region on the lunar surface	**FN-C-203 L**	Determination of position, navigation, and timing by crew and assets at the far side on the lunar surface	**UC-C-206 L**				
Provide a coordinated lunar time scale	**FN-C-205 L**						
Transport crew from cislunar space to lunar surface sites in the south pole region	**FN-T-102 L**	Transportation of crew between cislunar space and lunar south pole region landing sites	**UC-T-105 L**	Demonstrate the capability for crew to access surface assets at different potential locations distributed across the lunar globe.	**CN-T-109 L**	Demonstrate local, regional, and global surface transportation and mobility capabilities in support of continuous human lunar presence and a robust lunar economy.	**LI-06 L**
Transport crew from the lunar surface to cislunar space	**FN-T-104 L**						
Enable crew habitation during transit from cislunar space to lunar surface sites in the south pole region	**FN-T-108 L**						
Enable crew habitation during transit from the lunar surface to cislunar space	**FN-T-110 L**						
Transport crew from cislunar space to distributed sites outside of the south pole region on the lunar surface	**FN-T-103 L**	Transportation of crew from cislunar space to distributed landing sites outside of the south pole region on the lunar surface	**UC-T-106 L**				
Enable crew habitation during transit from cislunar space to distributed sites outside of the south pole region on the lunar surface	**FN-T-109 L**						
Provide precision landing for crew transport to the lunar surface	**FN-T-401 L**	Landing of crew lander(s) at specific pre-defined locations	**UC-T-401 L**				

Functions		Use Cases		Characteristics/Needs		Objectives	
Enable landing on the lunar surface under all lighting conditions	**FN-T-403 L**						
Enable crew lunar surface extravehicular activity in sunlit areas and non-PSRs	**FN-M-101 L**	Conduct of crew extravehicular operations on the lunar surface	**UC-M-101 L**	Demonstrate the capability to allow crew to move locally around landing sites to visit multiple locations of interest.	**CN-M-302 L**		
Enable crew lunar surface extravehicular activity in PSRs	**FN-M-102 L**	Conduct of crew extravehicular operations on the lunar surface	**UC-M-101 L**	Demonstrate the capability to allow crew to move locally around landing sites to visit multiple locations of interest.	**CN-M-302 L**		
Enable maintaining and servicing of the EVA system in a habitable environment	**FN-M-202 L**	Conduct of crew extravehicular operations on the lunar surface	**UC-M-101 L**	Demonstrate the capability to allow crew to move locally around landing sites to visit multiple locations of interest.	**CN-M-302 L**		
Ingress/egress from habitable asset(s) to lunar surface vacuum	**FN-M-203 L**	Conduct of crew extravehicular operations on the lunar surface	**UC-M-101 L**	Demonstrate the capability to allow crew to move locally around landing sites to visit multiple locations of interest.	**CN-M-302 L**		
Enable crew lunar surface extravehicular activity in sunlit areas and non-PSRs	**FN-M-101 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-301 L**	Demonstrate the capability to allow crew to move locally around landing sites to visit multiple locations of interest.	**CN-M-302 L**		
Enable local unpressurized surface mobility in sunlit areas and non-PSRs at distributed sites on the lunar surface	**FN-M-303 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-301 L**	Demonstrate the capability to allow crew to move locally around landing sites to visit multiple locations of interest.	**CN-M-302 L**		
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 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-301 L**	Demonstrate the capability to allow crew to move locally around landing sites to visit multiple locations of interest.	**CN-M-302 L**		
Provide communications and data exchange between assets on the lunar surface	**FN-C-103 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-301 L**	Demonstrate the capability to allow crew to move locally around landing sites to visit multiple locations of interest.	**CN-M-302 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-202 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-301 L**	Demonstrate the capability to allow crew to move locally around landing sites to visit multiple locations of interest.	**CN-M-302 L**		
Provide a coordinated lunar time scale	**FN-C-205 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-301 L**	Demonstrate the capability to allow crew to move locally around landing sites to visit multiple locations of interest.	**CN-M-302 L**		
Enable crew lunar surface extravehicular activity in sunlit areas and non-PSRs	**FN-M-101 L**	Conduct of crew excursions to locations around landing site in sunlit areas and non-PSRs in the south pole region	**UC-M-302 L**	Demonstrate the capability to allow crew to move locally around landing sites to visit multiple locations of interest.	**CN-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-302 L**	Conduct of crew excursions to locations around landing site in sunlit areas and non-PSRs in the south pole region	**UC-M-302 L**	Demonstrate the capability to allow crew to move locally around landing sites to visit multiple locations of interest.	**CN-M-302 L**		
Enable pressurized surface mobility in sunlit areas and non-PSRs	**FN-M-305 L**	Conduct of crew excursions to locations around landing site in sunlit areas and non-PSRs in the south pole region	**UC-M-302 L**	Demonstrate the capability to allow crew to move locally around landing sites to visit multiple locations of interest.	**CN-M-302 L**		
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 L**	Conduct of crew excursions to locations around landing site in sunlit areas and non-PSRs in the south pole region	**UC-M-302 L**	Demonstrate the capability to allow crew to move locally around landing sites to visit multiple locations of interest.	**CN-M-302 L**		
Provide communications and data exchange between assets on the lunar surface	**FN-C-103 L**	Conduct of crew excursions to locations around landing site in sunlit areas and non-PSRs in the south pole region	**UC-M-302 L**	Demonstrate the capability to allow crew to move locally around landing sites to visit multiple locations of interest.	**CN-M-302 L**		
Provide position, navigation, and timing services at the south pole region on the lunar surface	**FN-C-201 L**	Conduct of crew excursions to locations around landing site in sunlit areas and non-PSRs in the south pole region	**UC-M-302 L**	Demonstrate the capability to allow crew to move locally around landing sites to visit multiple locations of interest.	**CN-M-302 L**		
Provide a coordinated lunar time scale	**FN-C-205 L**	Conduct of crew excursions to locations around landing site in sunlit areas and non-PSRs in the south pole region	**UC-M-302 L**	Demonstrate the capability to allow crew to move locally around landing sites to visit multiple locations of interest.	**CN-M-302 L**		
Relocation of exploration assets at lunar surface polar locations	**FN-M-601 L**	Demonstration of uncrewed relocation of exploration assets to sites around the lunar south pole region	**UC-M-601 L**	Demonstrate the capability to regionally relocate exploration assets.	**CN-M-601 L**		
Operate mobility system(s) in uncrewed mode between crew surface missions	**FN-M-701 L**	Demonstration of uncrewed relocation of exploration assets to sites around the lunar south pole region	**UC-M-601 L**	Demonstrate the capability to regionally relocate exploration assets.	**CN-M-601 L**		
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 L**	Demonstration of uncrewed relocation of exploration assets to sites around the lunar south pole region	**UC-M-601 L**	Demonstrate the capability to regionally relocate exploration assets.	**CN-M-601 L**		
Provide position, navigation, and timing services at the south pole region on the lunar surface	**FN-C-201 L**	Demonstration of uncrewed relocation of exploration assets to sites around the lunar south pole region	**UC-M-601 L**	Demonstrate the capability to regionally relocate exploration assets.	**CN-M-601 L**		
Provide a coordinated lunar time scale	**FN-C-205 L**	Demonstration of uncrewed relocation of exploration assets to sites around the lunar south pole region	**UC-M-601 L**	Demonstrate the capability to regionally relocate exploration assets.	**CN-M-601 L**		
Relocation of exploration assets at distributed locations outside of the south pole region on the lunar surface	**FN-M-602 L**	Demonstration of uncrewed relocation of exploration assets to	**UC-M-602 L**	Demonstrate the capability to regionally relocate exploration assets.	**CN-M-601 L**		

Functions		Use Cases		Characteristics/Needs		Objectives	
Operate mobility system(s) in uncrewed mode between crew surface missions	FN-M-701 L	sites at distributed locations outside of the south pole region on the lunar surface					
Provide communications and data exchange between the lunar surface and Earth	FN-C-101 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-202 L						
Provide a coordinated lunar time scale	FN-C-205 L						
Transport a moderate amount of cargo (1000s of kg) from Earth to south pole region sites on the lunar surface	FN-T-202 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-101 L	Deploy scalable demonstration ISRU exploration asset(s) on the lunar surface.	CN-I-102 LM	Demonstrate industrial scale ISRU capabilities in support of continuous human lunar presence and a robust lunar economy.	LI-07 L
Provide power for deployed external surface utilization payloads(s) and/or equipment for long durations (months to years+)	FN-P-402 L						
Enable crew lunar surface extravehicular activity in sunlit areas and non-PSRs	FN-M-101 L						
Unload a moderate amount of cargo (1000s of kg) on the lunar surface	FN-M-402 L						
Reposition a moderate amount of cargo (1000s of kg) at the south pole region on the lunar surface	FN-M-503 L						
Provide communications and data exchange between the lunar surface and Earth	FN-C-101 L						
Conduct ISRU utilization payload and/or equipment operations on the lunar surface	FN-I-104 L						
Conduct resource identification utilization payload and/or equipment operations on the lunar surface	FN-U-103 L						
Transport a moderate amount of cargo (1000s of kg) from Earth to south pole region sites on the lunar surface	FN-T-202 L	Deployment and operation of utilization payload(s) and/or equipment related to demonstration of oxygen recovery from lunar regolith	UC-I-102 L	Operate demonstration exploration asset(s) on the lunar surface to collect, produce, store, and transfer commodities, including water, oxygen, and/or construction feedstock, for potential use.	CN-I-103 LM		
Provide power for deployed surface utilization payloads(s) and/or equipment	FN-P-401 L						
Enable crew lunar surface extravehicular activity in sunlit areas and non-PSRs	FN-M-101 L						
Unload a moderate amount of cargo (1000s of kg) on the lunar surface	FN-M-402 L						
Reposition a moderate amount of cargo (1000s of kg) at the south pole region on the lunar surface	FN-M-503 L						
Provide communications and data exchange between the lunar surface and Earth	FN-C-101 L						
Produce scalable quantities of oxygen from lunar regolith	FN-I-102 L						
Store oxygen on the lunar surface	FN-I-105 L						
Transport scalable quantities of oxygen produced to exploration elements	FN-I-107 L						
Collect regolith at sub-scale to support demonstration using scalable capability	FN-I-201 L						
Provide storage for collected regolith	FN-I-203 L						
Conduct resource identification utilization payload and/or equipment operations on the lunar surface	FN-U-103 L						

Functions		Use Cases		Characteristics/Needs		Objectives	
Transport a moderate amount of cargo (1000s of kg) from Earth to south pole region sites on the lunar surface	**FN-T-202 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-103 L**				
Provide power for deployed surface utilization payloads(s) and/or equipment	**FN-P-401 L**						
Enable crew lunar surface extravehicular activity in sunlit areas and non-PSRs	**FN-M-101 L**						
Unload a moderate amount of cargo (1000s of kg) on the lunar surface	**FN-M-402 L**						
Reposition a moderate amount of cargo (1000s of kg) at the south pole region on the lunar surface	**FN-M-503 L**						
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 L**						
Collect water/ice from the polar region of the lunar surface	**FN-I-101 L**						
Produce scalable quantities of water from in-situ materials on the lunar surface	**FN-I-103 L**						
Store collected water/ice on the lunar surface	**FN-I-106 L**						
Transport scalable quantities of water produced to exploration elements	**FN-I-108 L**						
Conduct resource identification utilization payload and/or equipment operations on the lunar surface	**FN-U-103 L**						
Transport a moderate amount of cargo (1000s of kg) from Earth to south pole region sites on the lunar surface	**FN-T-202 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-104 L**				
Transfer water to habitable assets on the lunar surface	**FN-L-203 L**						
Transport a moderate amount of cargo (1000s of kg) from Earth to south pole region sites on the lunar surface	**FN-T-202 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-105 L**				
Transfer gases to habitable assets on the lunar surface	**FN-L-205 L**						
Transport a moderate amount of cargo (1000s of kg) from Earth to south pole region sites on the lunar surface	**FN-T-202 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-106 L**				
Provide power for deployed surface utilization payloads(s) and/or equipment	**FN-P-401 L**						
Enable crew lunar surface extravehicular activity in sunlit areas and non-PSRs	**FN-M-101 L**						
Unload a moderate amount of cargo (1000s of kg) on the lunar surface	**FN-M-402 L**						
Reposition a moderate amount of cargo (1000s of kg) at the south pole region on the lunar surface	**FN-M-503 L**						
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 L**						
Collect regolith at sub-scale to support demonstration using scalable capability	**FN-I-201 L**						
Conduct regolith recovery demonstration utilization payload and/or equipment operations on the lunar surface	**FN-I-202 L**						

Functions		Use Cases		Characteristics/Needs		Objectives	
Process and refine scalable quantities of in-situ feedstock resources on the lunar surface	**FN-I-204 L**						
Conduct resource identification utilization payload and/or equipment operations on the lunar surface	**FN-U-103 L**						
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 L**	Robotic surveillance of PSRs near potential crewed landing and exploration sites to identify locations of interest	**UC-A-106 L**	Demonstrate the capability to identify and locate potential site(s) for resource utilization.	**CN-U-101 L**		
Control robotic system(s) in PSRs on the lunar surface from Earth and/or cislunar space	**FN-A-202 L**						
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 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-U-102 L**				
Provide position, navigation, and timing services at the south pole region on the lunar surface	**FN-C-201 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						
Provide a robotic system capable of conducting reconnaissance	**FN-A-103 L**						
Control robotic system(s) in sunlit areas and non-PSRs on the lunar surface from Earth and/or cislunar space	**FN-A-201 L**						
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 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-105 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-202 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						
Provide a robotic system capable of conducting reconnaissance	**FN-A-103 L**						
Control robotic system(s) in sunlit areas and non-PSRs on the lunar surface from Earth and/or cislunar space	**FN-A-201 L**						
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 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-106 L**				
Provide position, navigation, and timing services at the far side and outside the south pole region on the lunar surface	**FN-C-203 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						
Provide a robotic system capable of conducting reconnaissance	**FN-A-103 L**						
Control robotic system(s) in sunlit areas and non-PSRs on the lunar surface from Earth and/or cislunar space	**FN-A-201 L**						
BLANK	**BLANK**	Reduction of blast ejecta to limit the migration of ejecta across the lunar surface	**UC-U-802 L**	Limit contamination of PSRs.	**CN-U-802 L**		
BLANK	**BLANK**	Reduction of path erosion, dust lofting, and sample contamination	**UC-U-803 L**				
BLANK	**BLANK**	Limitation of the spread of dust raised by lunar surface operations	**UC-U-804 L**				

Functions		Use Cases		Characteristics/Needs		Objectives	
Transport a moderate amount of cargo (1000s of kg) from Earth to south pole region sites on the lunar surface	**FN-T-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-202 L**	Deploy and operate autonomous demonstration construction exploration asset(s) that are reliant on surface-borne feedstock to demonstrate scalable capabilities and applications, such as additive manufacturing and autonomous construction of structures.	**CN-I-203 L**	Demonstrate technologies supporting cislunar orbital/surface depots, construction and manufacturing maximizing the use of in-situ resources, and support systems needed for continuous human/robotic presence.	**LI-08 L**
Provide power for deployed surface utilization payloads(s) and/or equipment	**FN-P-401 L**						
Unload a moderate amount of cargo (1000s of kg) on the lunar surface	**FN-M-402 L**						
Reposition a moderate amount of cargo (1000s of kg) at the south pole region on the lunar surface	**FN-M-503 L**						
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 L**						
Collect regolith at sub-scale to support demonstration using scalable capability	**FN-I-201 L**						
Process and refine scalable quantities of in-situ feedstock resources on the lunar surface	**FN-I-204 L**						
Conduct autonomous construction utilization payload and/or equipment operations on the lunar surface	**FN-I-205 L**						
Transport a limited amount of cargo (100s of kg) from Earth to south pole region sites on the lunar surface	**FN-T-201 L**	Deployment and operation of utilization payload(s) and/or equipment related to demonstration of regolith based additive/subtractive manufacturing techniques	**UC-I-203 L**				
Provide power for deployed surface utilization payloads(s) and/or equipment	**FN-P-401 L**						
Unload a limited amount of cargo (100s of kg) on the lunar surface	**FN-M-401 L**						
Reposition a limited amount of cargo (100s of kg) in the south pole region on the lunar surface	**FN-M-501 L**						
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 L**						
Collect regolith at sub-scale to support demonstration using scalable capability	**FN-I-201 L**						
Process and refine scalable quantities of in-situ feedstock resources on the lunar surface	**FN-I-204 L**						
Conduct additive/subtractive manufacturing utilization payload and/or equipment operations on the lunar surface	**FN-I-207 L**						
Rendezvous, proximity operations, mating and unmating of assets in cislunar space	**FN-T-106 L**	Aggregation and physical assembly of spacecraft components in cislunar space	**UC-T-103 L**	Demonstrate the capability to transfer propellant from one spacecraft to another in space (including interfaces for non-cryogenic propellants, cryogenic propellants, power, data, commands, and buffer gases).	**CN-U-501 L**		
Transport exploration asset(s) from Earth to cislunar space	**FN-T-217 L**						
Provide communications and data exchange between assets on the lunar surface	**FN-C-103 L**						
Transport cargo from Earth to cislunar space	**FN-T-213 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-502 L**				
Transfer propellant/fluids between assets in space	**FN-U-508 L**						

Functions		Use Cases		Characteristics/Needs		Objectives	
Transport a limited amount of cargo (100s of kg) from Earth to south pole region sites on the lunar surface	**FN-T-201 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-501 L**	Demonstrate the capability to transfer propellant from one asset to another on the lunar surface (including interfaces for non-cryogenic propellants, cryogenic propellants, power, data, commands, and buffer gases).	**CN-U-502 L**		
Provide power for deployed surface utilization payloads(s) and/or equipment	**FN-P-401 L**						
Enable crew lunar surface extravehicular activity in sunlit areas and non-PSRs	**FN-M-101 L**						
Unload a limited amount of cargo (100s of kg) on the lunar surface	**FN-M-401 L**						
Reposition a limited amount of cargo (100s of kg) in the south pole region on the lunar surface	**FN-M-501 L**						
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 L**						
Conduct fluid and propellant transfer utilization payload and/or equipment operations on the lunar surface	**FN-U-507 L**						
Transport cargo from Earth to cislunar space	**FN-T-213 L**	Deployment and operation of exploration assets, including utilization payload(s) and/or equipment, related to demonstration of propellant storage for extended-duration (year+) in space	**UC-U-503 L**	Demonstrate the capability to store propellant for extended-durations (year+) in space (including cryogenic propellant, leak management, and mass gauging).	**CN-U-503 L**		
Provide storage of cryogenic propellant in space	**FN-U-504 L**						
Provide storage of non-cryogenic propellant in space	**FN-U-505 L**						
Provide propellant management system(s) in microgravity environment	**FN-U-510 L**						
Transport a moderate amount of cargo (1000s of kg) from Earth to south pole region sites on the lunar surface	**FN-T-202 L**	Deployment and operation of exploration assets, including utilization payload(s) and/or equipment, related to demonstration of propellant storage for extended-duration (year+) on the lunar surface	**UC-U-504 L**	Demonstrate the capability to store propellant for extended-durations (year+) on the lunar surface (including cryogenic propellant, leak management, and mass gauging).	**CN-U-504 L**		
Provide power for deployed external surface utilization payloads(s) and/or equipment for long durations (months to years+)	**FN-P-402 L**						
Unload a moderate amount of cargo (1000s of kg) on the lunar surface	**FN-M-402 L**						
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 L**						
Provide storage of cryogenic propellant on the lunar surface	**FN-U-503 L**						
Provide storage of non-cryogenic propellant on the lunar surface	**FN-U-506 L**						
Provide propellant management system(s) in partial gravity environment	**FN-U-509 L**						
Transport a limited amount of cargo (100s of kg) from Earth to south pole region sites on the lunar surface	**FN-T-201 L**	Resupply of cargo and management of waste to/from habitable assets on the lunar surface	**UC-L-201 L**	Demonstrate technologies for support systems needed for continuous human/robotic presence including mobility repair and outfitting facilities, logistics facilities, and recycling plants.	**CN-A-101 LM**	Develop environmental monitoring, situational awareness, and early warning capabilities to support a resilient, continuous human/robotic lunar presence.	**LI-09 L**
Transport a moderate amount of cargo (1000s of kg) from Earth to south pole region sites on the lunar surface	**FN-T-202 L**						
Mating between pressurized assets on the lunar surface	**FN-L-101 L**						
Transfer pressurized cargo into habitable assets on the lunar surface	**FN-L-201 L**						
Transfer water to habitable assets on the lunar surface	**FN-L-203 L**						
Transfer gases to habitable assets on the lunar surface	**FN-L-205 L**						

Functions		Use Cases		Characteristics/Needs		Objectives	
Manage waste from habitable asset(s) on the lunar surface	**FN-L-301 L**						
Unload a limited amount of cargo (100s of kg) on the lunar surface	**FN-M-401 L**						
Unload a moderate amount of cargo (1000s of kg) on the lunar surface	**FN-M-402 L**						
Reposition a limited amount of cargo (100s of kg) in the south pole region on the lunar surface	**FN-M-501 L**						
Reposition a moderate amount of cargo (1000s of kg) at the south pole region on the lunar surface	**FN-M-503 L**						
BLANK	**BLANK**	Deployment and operation of utilization payload(s) and/or equipment related to demonstration of maintenance and repair of asset(s)	**UC-U-726 L**				
Transport a limited amount of cargo (100s of kg) from Earth to south pole region sites on the lunar surface	**FN-T-201 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-719 L**	Provide system(s) to monitor cislunar space and lunar surface natural environments, including space weather, meteoroids, cosmic weather, thermal conditions, and plasma environments, and provide early warnings to in-space and surface assets and crew.	**CN-U-102 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-203 L**						
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 L**						
Perform robotic manipulation of payloads, logistics, and/or equipment on the lunar surface	**FN-A-104 L**						
Provide extravehicular utilization accommodation, interfaces, and resources, operable during crewed and uncrewed increments, on the lunar surface	**FN-U-203 L**						
Transport cargo from Earth to cislunar space	**FN-T-213 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-721 L**				
Provide communications and data exchange between Earth and cislunar space	**FN-C-102 L**						
Enable repositioning of externally mounted utilization payloads in cislunar space	**FN-A-106 L**						
Provide extravehicular utilization accommodation, interfaces, and resources, operable during crewed and uncrewed increments, in cislunar space	**FN-U-202 L**						
Transport a limited amount of cargo (100s of kg) from Earth to south pole region sites on the lunar surface	**FN-T-201 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-720 L**	Provide system(s) to monitor cislunar space and lunar surface induced environments, including radiation, thermal conditions, dust, high-energy debris, contamination, electrostatics, and acoustics, and provide early warnings to in-space and surface assets and crew.	**CN-U-103 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-203 L**						
Enable crew lunar surface extravehicular activity in sunlit areas and non-PSRs	**FN-M-101 L**						
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 L**						
Perform robotic manipulation of payloads, logistics, and/or equipment on the lunar surface	**FN-A-104 L**						
Provide extravehicular utilization accommodation, interfaces, and resources, operable during crewed and uncrewed increments, on the lunar surface	**FN-U-203 L**						
Transport cargo from Earth to cislunar space	**FN-T-213 L**	Monitoring, characterization, and advance warning for induced environmental threats in cislunar space, e.g., induced radiation level,	**UC-U-722 L**				
Provide communications and data exchange between Earth and cislunar space	**FN-C-102 L**						

Functions		Use Cases		Characteristics/Needs		Objectives	
Enable repositioning of externally mounted utilization payloads in cislunar space	**FN-A-106 L**	thermal conditions, high-energy debris, contamination, electrostatic, and acoustics					
Provide extravehicular utilization accommodation, interfaces, and resources, operable during crewed and uncrewed increments, in cislunar space	**FN-U-202 L**						
BLANK	**BLANK**	BLANK	**BLANK**	Implement stable transportation capabilities, which minimize required upgrades over time, to support lunar missions.	**CN-T-101 L**	Develop cislunar systems that crew can routinely operate to and from lunar orbit and the lunar surface for extended durations.	**TH-01 L**
BLANK	**BLANK**	BLANK	**BLANK**	Implement robust transportation capabilities, where systems can perform a variety of design reference missions, to support lunar missions.	**CN-T-102 L**		
BLANK	**BLANK**	BLANK	**BLANK**	Enable routine access to the lunar surface.	**CN-T-103 L**		
BLANK	**BLANK**	BLANK	**BLANK**	Enable routine access to cislunar space.	**CN-T-104 L**		
Transport crew from Earth to cislunar space	**FN-T-101 L**	Transportation of crew from Earth to cislunar space	**UC-T-101 L**	Provide capabilities to transport crew from Earth to cislunar space.	**CN-T-105 L**		
Enable crew habitation during transit from Earth to cislunar space	**FN-T-107 L**						
Enable abort(s) to safety	**FN-T-112 L**						
Provide ground services on Earth	**FN-G-101 L**						
Stack and integrate system(s) on Earth	**FN-G-102 L**						
Manage consumables and propellant	**FN-G-103 L**						
Enable vehicle launch(es)	**FN-G-104 L**						
Enable multiple launch attempts for vehicle(s)	**FN-G-105 L**						

Functions		Use Cases		Characteristics/Needs		Objectives	
Rendezvous, proximity operations, mating and unmating of assets in cislunar space	**FN-T-106 L**	Staging of crewed lunar surface missions from cislunar space	**UC-T-102 L**	Provide capabilities to transport crew between stable lunar orbit, including NRHO, and the lunar surface.	**CN-T-106 L**		
Enable a pressurized, habitable environment in cislunar space	**FN-H-103 L**						
Provide position, navigation, and timing data in cislunar space	**FN-C-204 L**						
Transport crew from cislunar space to lunar surface sites in the south pole region	**FN-T-102 L**	Transportation of crew between cislunar space and the lunar surface	**UC-T-104 L**				
Transport crew from cislunar space to distributed sites outside of the south pole region on the lunar surface	**FN-T-103 L**						
Transport crew from the lunar surface to cislunar space	**FN-T-104 L**						
Enable crew habitation during transit from cislunar space to lunar surface sites in the south pole region	**FN-T-108 L**						
Enable crew habitation during transit from cislunar space to distributed sites outside of the south pole region on the lunar surface	**FN-T-109 L**						
Enable crew habitation during transit from the lunar surface to cislunar space	**FN-T-110 L**						
Provide precision landing for crew transport to the lunar surface	**FN-T-401 L**	Landing of crew lander(s) at specific pre-defined locations	**UC-T-401 L**				
Enable landing on the lunar surface under all lighting conditions	**FN-T-403 L**						
Observe and sense the lunar surface from lunar orbit	**FN-U-101 L**	Orbital survey(s) of lunar surface before, during, and after crew mission	**UC-U-101 L**				
Rendezvous, proximity operations, mating and unmating of assets in cislunar space	**FN-T-106 L**	Staging of crewed lunar surface missions from cislunar space	**UC-T-102 L**	Provide capabilities to enable staging and/or assembly operations of crew and cargo system(s) in cislunar space with accessibility to both Earth and the lunar surface, including the lunar South Polar region.	**CN-T-110 L**		
Enable a pressurized, habitable environment in cislunar space	**FN-H-103 L**						
Provide position, navigation, and timing data in cislunar space	**FN-C-204 L**						
Rendezvous, proximity operations, mating and unmating of assets in cislunar space	**FN-T-106 L**	Aggregation and physical assembly of spacecraft components in cislunar space	**UC-T-103 L**				
Transport exploration asset(s) from Earth to cislunar space	**FN-T-217 L**						
Provide communications and data exchange between assets on the lunar surface	**FN-C-103 L**						
Command and control of asset(s) from Earth in cislunar space during uncrewed periods	**FN-A-402 L**	Operation of transportation assets(s) in cislunar space from Earth during uncrewed segments	**UC-A-401 L**	Provide capabilities to operate crew transportation system(s) in uncrewed mode for mid-durations (month+) to extended-durations (year+) in cislunar space and on the lunar surface.	**CN-T-113 L**		
Transition assets between crewed and uncrewed mode in cislunar space	**FN-A-404 L**						
Command and control asset(s) from Earth on the lunar surface during uncrewed periods	**FN-A-401 L**	Operation of transportation assets(s) on the lunar surface from Earth during uncrewed segments	**UC-A-402 L**				
Transition assets between crewed and uncrewed mode on the lunar surface	**FN-A-403 L**						

Functions		Use Cases		Characteristics/Needs		Objectives	
Rendezvous, proximity operations, mating and unmating of assets in cislunar space	FN-T-106 L	Staging of crewed lunar surface missions from cislunar space	UC-T-102 L	Provide capabilities to safely return crew and system(s) to Earth from lunar surface and cislunar space.	CN-T-114 L		
Enable a pressurized, habitable environment in cislunar space	FN-H-103 L						
Provide position, navigation, and timing data in cislunar space	FN-C-204 L						
Transport crew from the lunar surface to cislunar space	FN-T-104 L	Transportation of crew from the lunar surface to cislunar space	UC-T-107 L				
Enable crew habitation during transit from the lunar surface to cislunar space	FN-T-110 L						
Transport crew from cislunar space to Earth	FN-T-105 L	Transportation of crew from cislunar space to Earth	UC-T-108 L				
Enable crew habitation during transit from cislunar space to Earth	FN-T-111 L						
Recover crew after Earth landing	FN-G-201 L						
BLANK	BLANK	BLANK	BLANK	Enable routine access to the lunar surface.	CN-T-103 L	Develop system(s) that can routinely deliver a range of elements to the lunar surface.	TH-02 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-203 L	Transportation of small cargo from Earth to distributed locations outside of the south pole region on the lunar surface	UC-T-201 L	Provide capabilities to deliver system(s) from Earth to the lunar surface.	CN-T-201 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-204 L						
Provide precision landing for cargo transport to the lunar surface	FN-T-402 L						
Enable landing on the lunar surface under all lighting conditions	FN-T-403 L						
Transport large exploration asset(s) from Earth to the lunar surface	FN-T-206 L	Transportation of large cargo from Earth to the lunar surface	UC-T-202 L				
Provide precision landing for cargo transport to the lunar surface	FN-T-402 L						
Enable landing on the lunar surface under all lighting conditions	FN-T-403 L						
Unload large exploration assets on the lunar surface	FN-M-403 L	Unloading of large cargo on the lunar surface	UC-M-401 L	Provide capabilities to unload cargo from delivery system(s).	CN-M-401 L		
Unload a limited amount of cargo (100s of kg) on the lunar surface	FN-M-401 L	Unloading of small cargo on the lunar surface	UC-M-402 L				
Unload a moderate amount of cargo (1000s of kg) on the lunar surface	FN-M-402 L						
BLANK	BLANK	Conduct of end-of-life operations	UC-U-807 L	Implement end-of-life strategies for transportation systems to ensure future viable usage of exploration sites on the lunar surface.	CN-U-808 L		

Functions		Use Cases		Characteristics/Needs		Objectives	
Enable a pressurized, habitable environment on the lunar surface for short durations (days to weeks)	**FN-H-101 L**	Crew habitation of assets on the lunar surface for short-durations (days to weeks)	**UC-H-101 L**	Provide capabilities to conduct short-duration (days to weeks) crew exploration mission(s) on the lunar surface.	**CN-H-105 L**	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.	**TH-03 L**
Operate habitation system(s) in uncrewed mode between crewed missions on the lunar surface	**FN-H-201 L**						
Manage waste from habitable asset(s) on the lunar surface	**FN-L-301 L**						
Operate habitation system(s) in uncrewed mode between crewed missions on the lunar surface	**FN-H-201 L**	Reuse of habitation system(s) on the lunar surface	**UC-H-105 L**				
Transport a limited amount of cargo (100s of kg) from Earth to south pole region sites on the lunar surface	**FN-T-201 L**	Resupply of cargo and management of waste to/from habitable assets on the lunar surface	**UC-L-201 L**				
Transport a moderate amount of cargo (1000s of kg) from Earth to south pole region sites on the lunar surface	**FN-T-202 L**						
Mating between pressurized assets on the lunar surface	**FN-L-101 L**						
Transfer pressurized cargo into habitable assets on the lunar surface	**FN-L-201 L**						
Transfer water to habitable assets on the lunar surface	**FN-L-203 L**						
Transfer gases to habitable assets on the lunar surface	**FN-L-205 L**						
Manage waste from habitable asset(s) on the lunar surface	**FN-L-301 L**						
Unload a limited amount of cargo (100s of kg) on the lunar surface	**FN-M-401 L**						
Unload a moderate amount of cargo (1000s of kg) on the lunar surface	**FN-M-402 L**						
Reposition a limited amount of cargo (100s of kg) in the south pole region on the lunar surface	**FN-M-501 L**						
Reposition a moderate amount of cargo (1000s of kg) at the south pole region on the lunar surface	**FN-M-503 L**						
Enable a pressurized, habitable environment on the lunar surface for moderate duration (month+) use	**FN-H-102 L**	Crew habitation of assets on the lunar surface for mid-durations (month+)	**UC-H-102 L**	Provide capabilities to conduct mid-duration (month+) crew exploration mission(s) on the lunar surface.	**CN-H-106 L**		
Operate habitation system(s) in uncrewed mode between crewed missions on the lunar surface	**FN-H-201 L**						
Manage waste from habitable asset(s) on the lunar surface	**FN-L-301 L**						
Operate habitation system(s) in uncrewed mode between crewed missions on the lunar surface	**FN-H-201 L**	Reuse of habitation system(s) on the lunar surface	**UC-H-105 L**				
Transport a limited amount of cargo (100s of kg) from Earth to south pole region sites on the lunar surface	**FN-T-201 L**	Resupply of cargo and management of waste to/from habitable assets on the lunar surface	**UC-L-201 L**				
Transport a moderate amount of cargo (1000s of kg) from Earth to south pole region sites on the lunar surface	**FN-T-202 L**						
Mating between pressurized assets on the lunar surface	**FN-L-101 L**						
Transfer pressurized cargo into habitable assets on the lunar surface	**FN-L-201 L**						
Transfer water to habitable assets on the lunar surface	**FN-L-203 L**						

Functions		Use Cases		Characteristics/Needs		Objectives	
Transfer gases to habitable assets on the lunar surface	**FN-L-205 L**						
Manage waste from habitable asset(s) on the lunar surface	**FN-L-301 L**						
Unload a limited amount of cargo (100s of kg) on the lunar surface	**FN-M-401 L**						
Unload a moderate amount of cargo (1000s of kg) on the lunar surface	**FN-M-402 L**						
Reposition a limited amount of cargo (100s of kg) in the south pole region on the lunar surface	**FN-M-501 L**						
Reposition a moderate amount of cargo (1000s of kg) at the south pole region on the lunar surface	**FN-M-503 L**						
Generate power in the south pole region on the lunar surface	**FN-P-101 L**	Power generation and energy storage at south pole region on the lunar surface	**UC-P-101 L**				
Store energy in the south pole region on the lunar surface	**FN-P-202 L**						
Generate power at multiple distributed locations outside of the south pole region on the lunar surface	**FN-P-102 L**	Power generation and energy storage at multiple distributed locations outside of the south pole region on the lunar surface	**UC-P-102 L**				
Store energy at multiple distributed locations outside of the south pole region on the lunar surface	**FN-P-201 L**						
Distribute power in the south pole region on the lunar surface	**FN-P-301 L**	Power distribution around power generation and energy storage system(s) in the south pole region on the lunar surface	**UC-P-301 L**				
Provide bi-directional power exchange capability	**FN-P-305 L**						
Distribute power at multiple distributed locations outside of the south pole region on the lunar surface	**FN-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-302 L**				
Provide bi-directional power exchange capability	**FN-P-305 L**						
Enable a pressurized, habitable environment in cislunar space for moderate (month+) durations	**FN-H-104 L**	Crew habitation of assets for moderate-duration (month+) mission(s) in cislunar space	**UC-H-103 L**	Provide capabilities to conduct moderate durations (months) to extended-duration (year+) crew exploration mission(s) in cislunar and deep space.	**CN-H-107 L**		
Operate habitation system(s) in uncrewed mode between crewed missions in cislunar space	**FN-H-202 L**						
Enable a pressurized, habitable environment in cislunar space for extended (year+) duration	**FN-H-105 L**	Crew habitation of assets for extended-duration (year+) mission(s) in cislunar space	**UC-H-104 L**				
Operate habitation system(s) in uncrewed mode between crewed missions in cislunar space	**FN-H-202 L**						
Operate habitation system(s) in uncrewed mode between crewed missions in cislunar space	**FN-H-202 L**	Reuse of habitation system(s) in cislunar space	**UC-H-106 L**				
Rendezvous, proximity operations, mating and unmating of assets in cislunar space	**FN-T-106 L**	Resupply of cargo and management of waste to/from habitable assets in cislunar space	**UC-L-202 L**				
Transport cargo from Earth to cislunar space	**FN-T-213 L**						
Transfer pressurized cargo into habitable assets in cislunar space	**FN-L-202 L**						
Transfer water to habitable assets in cislunar space	**FN-L-204 L**						
Transfer gases to habitable assets in cislunar space	**FN-L-206 L**						

Functions		Use Cases		Characteristics/Needs		Objectives	
Manage waste from habitable asset(s) in cislunar space	**FN-L-302 L**						
BLANK	**BLANK**	BLANK	**BLANK**	Implement stable habitation capabilities, which minimize required upgrades over time, to support lunar missions.	**CN-H-108 L**		
BLANK	**BLANK**	BLANK	**BLANK**	Implement robust habitation capabilities, where systems can support all design reference missions, to support lunar missions.	**CN-H-109 L**		
Enable crew lunar surface extravehicular activity in sunlit areas and non-PSRs	**FN-M-101 L**	Conduct of crew extravehicular operations on the lunar surface	**UC-M-101 L**	Provide capabilities to enable crew transition in/out of habitable space to conduct EVA activities.	**CN-M-102 L**		
Enable crew lunar surface extravehicular activity in PSRs	**FN-M-102 L**						
Enable maintaining and servicing of the EVA system in a habitable environment	**FN-M-202 L**						
Ingress/egress from habitable asset(s) to lunar surface vacuum	**FN-M-203 L**						
Enable crew extravehicular activity in cislunar space	**FN-M-104 L**	Conduct of crew extravehicular operations in cislunar space	**UC-M-102 L**				
Ingress/egress from habitable asset(s) to cislunar vacuum	**FN-M-301 L**						
Rendezvous, proximity operations, mating and unmating of assets in cislunar space	**FN-T-106 L**	Staging of crewed lunar surface missions from cislunar space	**UC-T-102 L**	Provide capabilities to enable staging and/or assembly operations of crew and cargo system(s) in cislunar space with accessibility to both Earth and the lunar surface, including the lunar South Polar region.	**CN-T-110 L**	Develop in-space and surface habitation system(s) for crew to live in deep space for extended durations, enabling future missions to Mars.	**TH-04 LM**
Enable a pressurized, habitable environment in cislunar space	**FN-H-103 L**						
Provide position, navigation, and timing data in cislunar space	**FN-C-204 L**						
Rendezvous, proximity operations, mating and unmating of assets in cislunar space	**FN-T-106 L**	Aggregation and physical assembly of spacecraft components in cislunar space	**UC-T-103 L**				
Transport exploration asset(s) from Earth to cislunar space	**FN-T-217 L**						
Provide communications and data exchange between assets on the lunar surface	**FN-C-103 L**						
Enable a pressurized, habitable environment on the lunar surface for short durations (days to weeks)	**FN-H-101 L**	Crew habitation of assets on the lunar surface for short-durations (days to weeks)	**UC-H-101 L**	Provide capabilities to conduct short-duration (days to weeks) crew exploration mission(s) on the lunar surface.	**CN-H-105 L**		
Operate habitation system(s) in uncrewed mode between crewed missions on the lunar surface	**FN-H-201 L**						
Manage waste from habitable asset(s) on the lunar surface	**FN-L-301 L**						
Operate habitation system(s) in uncrewed mode between crewed missions on the lunar surface	**FN-H-201 L**	Reuse of habitation system(s) on the lunar surface	**UC-H-105 L**				
Transport a limited amount of cargo (100s of kg) from Earth to south pole region sites on the lunar surface	**FN-T-201 L**		**UC-L-201 L**				

Functions		Use Cases		Characteristics/Needs		Objectives	
Transport a moderate amount of cargo (1000s of kg) from Earth to south pole region sites on the lunar surface	**FN-T-202 L**	Resupply of cargo and management of waste to/from habitable assets on the lunar surface					
Mating between pressurized assets on the lunar surface	**FN-L-101 L**						
Transfer pressurized cargo into habitable assets on the lunar surface	**FN-L-201 L**						
Transfer water to habitable assets on the lunar surface	**FN-L-203 L**						
Transfer gases to habitable assets on the lunar surface	**FN-L-205 L**						
Manage waste from habitable asset(s) on the lunar surface	**FN-L-301 L**						
Unload a limited amount of cargo (100s of kg) on the lunar surface	**FN-M-401 L**						
Unload a moderate amount of cargo (1000s of kg) on the lunar surface	**FN-M-402 L**						
Reposition a limited amount of cargo (100s of kg) in the south pole region on the lunar surface	**FN-M-501 L**						
Reposition a moderate amount of cargo (1000s of kg) at the south pole region on the lunar surface	**FN-M-503 L**						
Enable a pressurized, habitable environment on the lunar surface for moderate duration (month+) use	**FN-H-102 L**	Crew habitation of assets on the lunar surface for mid-durations (month+)	**UC-H-102 L**	Provide capabilities to conduct mid-duration (month+) crew exploration mission(s) on the lunar surface.	**CN-H-106 L**		
Operate habitation system(s) in uncrewed mode between crewed missions on the lunar surface	**FN-H-201 L**						
Manage waste from habitable asset(s) on the lunar surface	**FN-L-301 L**						
Operate habitation system(s) in uncrewed mode between crewed missions on the lunar surface	**FN-H-201 L**	Reuse of habitation system(s) on the lunar surface	**UC-H-105 L**				
Transport a limited amount of cargo (100s of kg) from Earth to south pole region sites on the lunar surface	**FN-T-201 L**	Resupply of cargo and management of waste to/from habitable assets on the lunar surface	**UC-L-201 L**				
Transport a moderate amount of cargo (1000s of kg) from Earth to south pole region sites on the lunar surface	**FN-T-202 L**						
Mating between pressurized assets on the lunar surface	**FN-L-101 L**						
Transfer pressurized cargo into habitable assets on the lunar surface	**FN-L-201 L**						
Transfer water to habitable assets on the lunar surface	**FN-L-203 L**						
Transfer gases to habitable assets on the lunar surface	**FN-L-205 L**						
Manage waste from habitable asset(s) on the lunar surface	**FN-L-301 L**						
Unload a limited amount of cargo (100s of kg) on the lunar surface	**FN-M-401 L**						
Unload a moderate amount of cargo (1000s of kg) on the lunar surface	**FN-M-402 L**						
Reposition a limited amount of cargo (100s of kg) in the south pole region on the lunar surface	**FN-M-501 L**						

Functions		Use Cases		Characteristics/Needs		Objectives	
Reposition a moderate amount of cargo (1000s of kg) at the south pole region on the lunar surface	**FN-M-503 L**						
Generate power in the south pole region on the lunar surface	**FN-P-101 L**	Power generation and energy storage at south pole region on the lunar surface	**UC-P-101 L**				
Store energy in the south pole region on the lunar surface	**FN-P-202 L**						
Generate power at multiple distributed locations outside of the south pole region on the lunar surface	**FN-P-102 L**	Power generation and energy storage at multiple distributed locations outside of the south pole region on the lunar surface	**UC-P-102 L**				
Store energy at multiple distributed locations outside of the south pole region on the lunar surface	**FN-P-201 L**						
Distribute power in the south pole region on the lunar surface	**FN-P-301 L**	Power distribution around power generation and energy storage system(s) in the south pole region on the lunar surface	**UC-P-301 L**				
Provide bi-directional power exchange capability	**FN-P-305 L**						
Distribute power at multiple distributed locations outside of the south pole region on the lunar surface	**FN-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-302 L**				
Provide bi-directional power exchange capability	**FN-P-305 L**						
Enable a pressurized, habitable environment in cislunar space for moderate (month+) durations	**FN-H-104 L**	Crew habitation of assets for moderate-duration (month+) mission(s) in cislunar space	**UC-H-103 L**	Provide capabilities to conduct moderate durations (months) to extended-duration (year+) crew exploration mission(s) in cislunar and deep space.	**CN-H-107 L**		
Operate habitation system(s) in uncrewed mode between crewed missions in cislunar space	**FN-H-202 L**						
Enable a pressurized, habitable environment in cislunar space for extended (year+) duration	**FN-H-105 L**	Crew habitation of assets for extended-duration (year+) mission(s) in cislunar space	**UC-H-104 L**				
Operate habitation system(s) in uncrewed mode between crewed missions in cislunar space	**FN-H-202 L**						
Operate habitation system(s) in uncrewed mode between crewed missions in cislunar space	**FN-H-202 L**	Reuse of habitation system(s) in cislunar space	**UC-H-106 L**				
Rendezvous, proximity operations, mating and unmating of assets in cislunar space	**FN-T-106 L**	Resupply of cargo and management of waste to/from habitable assets in cislunar space	**UC-L-202 L**				
Transport cargo from Earth to cislunar space	**FN-T-213 L**						
Transfer pressurized cargo into habitable assets in cislunar space	**FN-L-202 L**						
Transfer water to habitable assets in cislunar space	**FN-L-204 L**						
Transfer gases to habitable assets in cislunar space	**FN-L-206 L**						
Manage waste from habitable asset(s) in cislunar space	**FN-L-302 L**						
Provide hardware for crew medical care on the lunar surface	**FN-X-101 L**	Medical capabilities on the lunar surface	**UC-X-101 L**	Provide appropriate medical capabilities (including behavioral health) that allow for autonomous crew health decision making and care, and are preparatory of a mission to Mars.	**CN-X-101 LM**	Develop systems that monitor and maintain crew health and performance throughout all mission phases, including during communication delays to Earth, and in an environment that does not allow emergency evacuation	**TH-08 LM**
Provide data capabilities, including protection for communication, and interface to support crew medical care on the lunar surface	**FN-D-105 L**						
Provide hardware for crew medical care in cislunar space	**FN-X-102 L**	Medical capabilities in cislunar space	**UC-X-102 L**				
Provide data capabilities, including protection for communication, and interface to support crew medical care in cislunar space	**FN-D-106 L**						

Functions		Use Cases		Characteristics/Needs		Objectives	
Provide crew countermeasure system(s) to support the crew for moderate durations (month+) on the lunar surface	**FN-X-103 L**	Crew countermeasure capabilities to support the crew for moderate durations (month+) on the lunar surface	**UC-X-103 L**	Provide countermeasures capabilities that are commensurate in scope with the human system needs for the mission.	**CN-X-102 L**	or terrestrial medical assistance.	
Provide crew countermeasure system(s) to support the crew for moderate (month+) to long (year+) durations in cislunar space	**FN-X-104 L**	Crew countermeasure capabilities to support the crew for moderate (month+) to long (year+) durations in cislunar space	**UC-X-104 L**				
BLANK	**BLANK**	BLANK	**BLANK**	Demonstrate crew survival capabilities in cislunar space and on the lunar surface, including safe havens, system supportability, and/or aborts, for nominal and off-nominal scenarios to prepare for future Mars missions.	**CN-X-103 L**		
Transport a limited amount of cargo (100s of kg) from Earth to south pole region sites on the lunar surface	**FN-T-201 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-719 L**	Provide appropriate environmental monitoring capabilities that enables inflight crew health decision making and mitigation of relevant system/vehicle hazards.	**CN-U-104 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-203 L**						
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 L**						
Perform robotic manipulation of payloads, logistics, and/or equipment on the lunar surface	**FN-A-104 L**						
Provide extravehicular utilization accommodation, interfaces, and resources, operable during crewed and uncrewed increments, on the lunar surface	**FN-U-203 L**						
Transport cargo from Earth to cislunar space	**FN-T-213 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-721 L**				
Provide communications and data exchange between Earth and cislunar space	**FN-C-102 L**						
Enable repositioning of externally mounted utilization payloads in cislunar space	**FN-A-106 L**						
Provide extravehicular utilization accommodation, interfaces, and resources, operable during crewed and uncrewed increments, in cislunar space	**FN-U-202 L**						
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 L**	Robotic assistance of crew exploration, site surveying, sample and resource locating, documentation, and sample retrieval from PSRs	**UC-A-101 L**	Provide appropriate robotic system(s) that can conduct or assist in tasks that would otherwise be performed by the crew alone on the lunar surface.	**CN-A-102 L**	Develop integrated human and robotic systems with inter-relationships that enable maximum science and exploration during lunar missions.	**TH-09 L**
Provide robotic systems to assist crew in PSRs on the lunar surface	**FN-A-102 L**						
Control robotic system(s) in PSRs on the lunar surface from Earth and/or cislunar space	**FN-A-202 L**						
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 L**	Robotic assistance of crew exploration, site surveying, sample and resource locating, documentation, and sample retrieval from sunlit areas and non- PSRs	**UC-A-104 L**				
Provide robotic systems to assist crew in sunlit areas and non-PSRs on the lunar surface	**FN-A-101 L**						
Perform robotic manipulation of payloads, logistics, and/or equipment on the lunar surface	**FN-A-104 L**						
Control robotic system(s) in sunlit areas and non-PSRs on the lunar surface from Earth and/or cislunar space	**FN-A-201 L**						

Functions		Use Cases		Characteristics/Needs		Objectives	
Provide communications and data exchange between the lunar surface and Earth	FN-C-101 L	Robotic surveillance of PSRs near potential crewed landing and exploration sites to identify locations of interest	UC-A-106 L				
Control robotic system(s) in PSRs on the lunar surface from Earth and/or cislunar space	FN-A-202 L						
Provide communications and data exchange between the lunar surface and Earth	FN-C-101 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-U-102 L				
Provide position, navigation, and timing services at the south pole region on the lunar surface	FN-C-201 L						
Provide a coordinated lunar time scale	FN-C-205 L						
Provide a robotic system capable of conducting reconnaissance	FN-A-103 L						
Control robotic system(s) in sunlit areas and non-PSRs on the lunar surface from Earth and/or cislunar space	FN-A-201 L						
Provide communications and data exchange between the lunar surface and Earth	FN-C-101 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-105 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-202 L						
Provide a coordinated lunar time scale	FN-C-205 L						
Provide a robotic system capable of conducting reconnaissance	FN-A-103 L						
Control robotic system(s) in sunlit areas and non-PSRs on the lunar surface from Earth and/or cislunar space	FN-A-201 L						
Provide communications and data exchange between the lunar surface and Earth	FN-C-101 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-106 L				
Provide position, navigation, and timing services at the far side and outside the south pole region on the lunar surface	FN-C-203 L						
Provide a coordinated lunar time scale	FN-C-205 L						
Provide a robotic system capable of conducting reconnaissance	FN-A-103 L						
Control robotic system(s) in sunlit areas and non-PSRs on the lunar surface from Earth and/or cislunar space	FN-A-201 L						
Control robotic system(s) in cislunar space from Earth and/or cislunar space	FN-A-203 L	Robotic assistance of activities in space	UC-A-107 L	Provide appropriate robotic system(s) that can conduct or assist in tasks that would otherwise be performed by the crew alone in cislunar or deep space.	CN-A-107 L		
Control robotic system(s) in cislunar space by in-situ crew	FN-A-204 L						
Control robotic system(s) in cislunar space from Earth and/or cislunar space	FN-A-203 L	Remote management of robotic system(s) during in space operation as necessary	UC-A-202 L				
Monitor robotic system(s) performance and health	FN-A-301 L						
Transport a small amount of cargo (10s of kg) from the lunar surface to cislunar space	FN-T-209 L	Transportation of cargo from the lunar surface to cislunar space	UC-T-204 L	Provide capabilities to return cargo from the lunar surface back to cislunar space.	CN-T-202 L	Develop systems capable of returning a range of cargo mass from the lunar surface to Earth, including the capabilities necessary to	TH-11 L
Transport a large amount of cargo (100s of kg) from the lunar surface to cislunar space	FN-T-210 L						

Functions		Use Cases		Characteristics/Needs		Objectives	
Transport a small amount of cargo (10s of kg) from cislunar space to Earth	**FN-T-211 L**	Transportation of cargo from cislunar space back to Earth	**UC-T-203 L**	Provide capabilities to return cargo from cislunar space back to Earth-based facilities.	**CN-T-301 L**	meet scientific and utilization objectives.	
Transport a large amount of cargo (100s of kg) from cislunar space to Earth	**FN-T-212 L**						
Recover cargo after Earth landing	**FN-G-202 L**						
Transport a small amount of cargo (10s of kg) from the lunar surface to Earth	**FN-T-207 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-301 L**	Transfer, return, and curate a small amount (10s of kg) or a large amount (100s of kg) of unconditioned samples and containers from key destinations across the lunar surface and back to Earth, while maintaining scientific integrity of the samples.	**CN-T-302 L**		
Transport a small amount of cargo (10s of kg) from the lunar surface to cislunar space	**FN-T-209 L**						
Transport a small amount of cargo (10s of kg) from cislunar space to Earth	**FN-T-211 L**						
Reposition a small amount of unconditioned samples and containers (10s of kg) on the lunar surface	**FN-M-504 L**						
Stow collected unconditioned samples on exploration assets while on the lunar surface, while maintaining scientific integrity of the samples	**FN-U-401 L**						
Transport a large amount of cargo (100s of kg) from the lunar surface to Earth	**FN-T-208 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-302 L**				
Transport a large amount of cargo (100s of kg) from the lunar surface to cislunar space	**FN-T-210 L**						
Transport a large amount of cargo (100s of kg) from cislunar space to Earth	**FN-T-212 L**						
Reposition a large amount of unconditioned samples and containers (100s of kg) on the lunar surface	**FN-M-505 L**						
Stow collected unconditioned samples on exploration assets while on the lunar surface, while maintaining scientific integrity of the samples	**FN-U-401 L**						
BLANK	**BLANK**	Delivery of collected samples to curation facilities or other appropriate facilities on Earth, while maintaining scientific integrity of the samples	**UC-G-202 L**				
Transport a small amount of cargo (10s of kg) from the lunar surface to Earth	**FN-T-207 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-303 L**	Transfer, return and curate a small amount (10s of kg) or a large amount (100s of kg) of refrigerated sample(s), containers, and freezers from key destinations across the lunar surface to Earth while maintaining scientific integrity of the samples.	**CN-T-303 L**		
Transport a small amount of cargo (10s of kg) from the lunar surface to cislunar space	**FN-T-209 L**						
Transport a small amount of cargo (10s of kg) from cislunar space to Earth	**FN-T-211 L**						
Provide resources to condition refrigerated sample containers during transit from the lunar surface to Earth	**FN-T-301 L**						
Provide resources to condition refrigerated sample containers during transit from the lunar surface to cislunar space	**FN-T-304 L**						
Provide resources to condition refrigerated sample containers during transit from cislunar space to Earth	**FN-T-307 L**						
Reposition a small amount of refrigerated samples and containers (10s of kg) on the lunar surface	**FN-M-506 L**						
Stow refrigerated samples during transport from the Lunar Surface to Earth, while maintaining scientific integrity of samples	**FN-U-402 L**						
Stow refrigerated samples during transport from the Lunar Surface to cislunar space, while maintaining scientific integrity of samples	**FN-U-405 L**						

Functions		Use Cases		Characteristics/Needs		Objectives	
Stow refrigerated samples during transport from cislunar space to Earth, while maintaining scientific integrity of samples	**FN-U-408 L**						
Stow collected refrigerated samples on exploration assets while on the lunar surface, while maintaining scientific integrity of the samples	**FN-U-411 L**						
Provide resources to condition refrigerated sample containers on the lunar surface	**FN-U-414 L**						
Transport a large amount of cargo (100s of kg) from the lunar surface to Earth	**FN-T-208 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-304 L**				
Transport a large amount of cargo (100s of kg) from the lunar surface to cislunar space	**FN-T-210 L**						
Transport a large amount of cargo (100s of kg) from cislunar space to Earth	**FN-T-212 L**						
Provide resources to condition refrigerated sample containers during transit from the lunar surface to Earth	**FN-T-301 L**						
Provide resources to condition refrigerated sample containers during transit from the lunar surface to cislunar space	**FN-T-304 L**						
Provide resources to condition refrigerated sample containers during transit from cislunar space to Earth	**FN-T-307 L**						
Reposition a large amount of refrigerated samples and containers (100s of kg) on the lunar surface	**FN-M-507 L**						
Stow refrigerated samples during transport from the Lunar Surface to Earth, while maintaining scientific integrity of samples	**FN-U-402 L**						
Stow refrigerated samples during transport from the Lunar Surface to cislunar space, while maintaining scientific integrity of samples	**FN-U-405 L**						
Stow refrigerated samples during transport from cislunar space to Earth, while maintaining scientific integrity of samples	**FN-U-408 L**						
Stow collected refrigerated samples on exploration assets while on the lunar surface, while maintaining scientific integrity of the samples	**FN-U-411 L**						
Provide resources to condition refrigerated sample containers on the lunar surface	**FN-U-414 L**						
BLANK	**BLANK**	Delivery of conditioned cargo to curation facilities or other appropriate facilities on Earth after landing, while maintaining scientific integrity of the samples	**UC-G-201 L**				
Transport a small amount of cargo (10s of kg) from the lunar surface to Earth	**FN-T-207 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-305 L**	Transfer, return and curate a small amount (10s of kg) or a large amount (100s of kg) of frozen sample(s), containers, and freezers from key destinations across the lunar surface to Earth while maintaining scientific integrity of the samples.	**CN-T-304 L**		
Transport a small amount of cargo (10s of kg) from the lunar surface to cislunar space	**FN-T-209 L**						
Transport a small amount of cargo (10s of kg) from cislunar space to Earth	**FN-T-211 L**						
Provide resources to condition frozen 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 cislunar space	**FN-T-305 L**						
Provide resources to condition frozen sample containers during transit from cislunar space to Earth	**FN-T-308 L**						
Reposition a small amount of frozen samples and containers (10s of kg) on the lunar surface	**FN-M-508 L**						

Functions		Use Cases		Characteristics/Needs		Objectives	
Stow frozen 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 cislunar space, while maintaining scientific integrity of samples	**FN-U-406 L**						
Stow frozen samples during transport from cislunar space to Earth, while maintaining scientific integrity of samples	**FN-U-409 L**						
Stow collected frozen samples on exploration assets while on the lunar surface, while maintaining scientific integrity of the samples	**FN-U-412 L**						
Provide resources to condition frozen sample containers on the lunar surface	**FN-U-415 L**						
Transport a large amount of cargo (100s of kg) from the lunar surface to Earth	**FN-T-208 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-306 L**				
Transport a large amount of cargo (100s of kg) from the lunar surface to cislunar space	**FN-T-210 L**						
Transport a large amount of cargo (100s of kg) from cislunar space to Earth	**FN-T-212 L**						
Provide resources to condition frozen 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 cislunar space	**FN-T-305 L**						
Provide resources to condition frozen sample containers during transit from cislunar space to Earth	**FN-T-308 L**						
Reposition a large amount of frozen samples and containers (100s of kg) on the lunar surface	**FN-M-509 L**						
Stow frozen 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 cislunar space, while maintaining scientific integrity of samples	**FN-U-406 L**						
Stow frozen samples during transport from cislunar space to Earth, while maintaining scientific integrity of samples	**FN-U-409 L**						
Stow collected frozen samples on exploration assets while on the lunar surface, while maintaining scientific integrity of the samples	**FN-U-412 L**						
Provide resources to condition frozen sample containers on the lunar surface	**FN-U-415 L**						
BLANK	**BLANK**	Delivery of conditioned cargo to curation facilities or other appropriate facilities on Earth after landing, while maintaining scientific integrity of the samples	**UC-G-201 L**				
Transport a large amount of cargo (100s of kg) from the lunar surface to Earth	**FN-T-208 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-T-307 L**	Transfer, return, and curate a large amount (100s of kg) of cryogenic samples, containers, and freezers from key destinations across the lunar surface back to Earth while maintaining scientific integrity of the samples.	**CN-T-305 L**		
Transport a large amount of cargo (100s of kg) from the lunar surface to cislunar space	**FN-T-210 L**						
Transport a large amount of cargo (100s of kg) from cislunar space to Earth	**FN-T-212 L**						
Provide resources to condition cryogenic 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 cislunar space	**FN-T-306 L**						

Functions		Use Cases		Characteristics/Needs		Objectives	
Provide resources to condition cryogenic sample containers during transit from cislunar space to Earth	**FN-T-309 L**						
Reposition a large amount of cryogenic samples and containers (100s of kg) on the lunar surface	**FN-M-510 L**						
Stow cryogenic 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 cislunar space, while maintaining scientific integrity of samples	**FN-U-407 L**						
Stow cryogenic samples during transport from cislunar space to Earth, while maintaining scientific integrity of samples	**FN-U-410 L**						
Stow collected cryogenic samples on exploration assets while on the lunar surface, while maintaining scientific integrity of the samples	**FN-U-413 L**						
Provide resources to condition cryogenic sample containers on the lunar surface	**FN-U-416 L**						
BLANK	**BLANK**	Delivery of conditioned cargo to curation facilities or other appropriate facilities on Earth after landing, while maintaining scientific integrity of the samples	**UC-G-201 L**				
Transport crew from cislunar space to lunar surface sites in the south pole region	**FN-T-102 L**	Transportation of crew between cislunar space and the lunar surface	**UC-T-104 L**	Transition crew from micro-gravity environment to partial gravity environment, following a duration in space	**CN-T-112 L**	Conduct human research and technology demonstrations on the surface of Earth, low-Earth orbit platforms, cislunar platforms, and on the surface of the moon, to evaluate the effects of extended mission durations on the performance of crew and systems, reduce risk, and shorten the timeframe for system testing and readiness prior to the initial human Mars exploration campaign.	**OP-01 L**
Transport crew from cislunar space to distributed sites outside of the south pole region on the lunar surface	**FN-T-103 L**						
Transport crew from the lunar surface to cislunar space	**FN-T-104 L**						
Enable crew habitation during transit from cislunar space to lunar surface sites in the south pole region	**FN-T-108 L**						
Enable crew habitation during transit from cislunar space to distributed sites outside of the south pole region on the lunar surface	**FN-T-109 L**						
Enable crew habitation during transit from the lunar surface to cislunar space	**FN-T-110 L**						
Enable a pressurized, habitable environment on the lunar surface for short durations (days to weeks)	**FN-H-101 L**	Crew habitation of assets on the lunar surface for short-durations (days to weeks)	**UC-H-101 L**	Conduct short-duration (days to weeks) to mid-duration (month+) crew exploration mission(s) on the lunar surface.	**CN-H-101 L**		
Operate habitation system(s) in uncrewed mode between crewed missions on the lunar surface	**FN-H-201 L**						
Manage waste from habitable asset(s) on the lunar surface	**FN-L-301 L**						
Enable a pressurized, habitable environment on the lunar surface for moderate duration (month+) use	**FN-H-102 L**	Crew habitation of assets on the lunar surface for mid-durations (month+)	**UC-H-102 L**				
Operate habitation system(s) in uncrewed mode between crewed missions on the lunar surface	**FN-H-201 L**						
Manage waste from habitable asset(s) on the lunar surface	**FN-L-301 L**						
Operate habitation system(s) in uncrewed mode between crewed missions on the lunar surface	**FN-H-201 L**	Reuse of habitation system(s) on the lunar surface	**UC-H-105 L**				
Transport a limited amount of cargo (100s of kg) from Earth to south pole region sites on the lunar surface	**FN-T-201 L**	Resupply of cargo and management of waste to/from habitable assets on the lunar surface	**UC-L-201 L**				
Transport a moderate amount of cargo (1000s of kg) from Earth to south pole region sites on the lunar surface	**FN-T-202 L**						

Functions		Use Cases		Characteristics/Needs		Objectives	
Mating between pressurized assets on the lunar surface	**FN-L-101 L**						
Transfer pressurized cargo into habitable assets on the lunar surface	**FN-L-201 L**						
Transfer water to habitable assets on the lunar surface	**FN-L-203 L**						
Transfer gases to habitable assets on the lunar surface	**FN-L-205 L**						
Manage waste from habitable asset(s) on the lunar surface	**FN-L-301 L**						
Unload a limited amount of cargo (100s of kg) on the lunar surface	**FN-M-401 L**						
Unload a moderate amount of cargo (1000s of kg) on the lunar surface	**FN-M-402 L**						
Reposition a limited amount of cargo (100s of kg) in the south pole region on the lunar surface	**FN-M-501 L**						
Reposition a moderate amount of cargo (1000s of kg) at the south pole region on the lunar surface	**FN-M-503 L**						
Enable a pressurized, habitable environment on the lunar surface for short durations (days to weeks)	**FN-H-101 L**	Crew habitation of assets on the lunar surface for short-durations (days to weeks)	**UC-H-101 L**	Conduct short-duration (days to weeks), mid-duration (month+), and extended-duration (year+) crew exploration mission(s) in cislunar space	**CN-H-102 L**		
Operate habitation system(s) in uncrewed mode between crewed missions on the lunar surface	**FN-H-201 L**	Crew habitation of assets on the lunar surface for short-durations (days to weeks)	**UC-H-101 L**	Conduct short-duration (days to weeks), mid-duration (month+), and extended-duration (year+) crew exploration mission(s) in cislunar space	**CN-H-102 L**		
Manage waste from habitable asset(s) on the lunar surface	**FN-L-301 L**	Crew habitation of assets on the lunar surface for short-durations (days to weeks)	**UC-H-101 L**	Conduct short-duration (days to weeks), mid-duration (month+), and extended-duration (year+) crew exploration mission(s) in cislunar space	**CN-H-102 L**		
Enable a pressurized, habitable environment in cislunar space for moderate (month+) durations	**FN-H-104 L**	Crew habitation of assets for moderate-duration (month+) mission(s) in cislunar space	**UC-H-103 L**	Conduct short-duration (days to weeks), mid-duration (month+), and extended-duration (year+) crew exploration mission(s) in cislunar space	**CN-H-102 L**		
Operate habitation system(s) in uncrewed mode between crewed missions in cislunar space	**FN-H-202 L**	Crew habitation of assets for moderate-duration (month+) mission(s) in cislunar space	**UC-H-103 L**	Conduct short-duration (days to weeks), mid-duration (month+), and extended-duration (year+) crew exploration mission(s) in cislunar space	**CN-H-102 L**		
Enable a pressurized, habitable environment in cislunar space for extended (year+) duration	**FN-H-105 L**	Crew habitation of assets for extended-duration (year+) mission(s) in cislunar space	**UC-H-104 L**	Conduct short-duration (days to weeks), mid-duration (month+), and extended-duration (year+) crew exploration mission(s) in cislunar space	**CN-H-102 L**		
Operate habitation system(s) in uncrewed mode between crewed missions in cislunar space	**FN-H-202 L**	Crew habitation of assets for extended-duration (year+) mission(s) in cislunar space	**UC-H-104 L**	Conduct short-duration (days to weeks), mid-duration (month+), and extended-duration (year+) crew exploration mission(s) in cislunar space	**CN-H-102 L**		
Operate habitation system(s) in uncrewed mode between crewed missions in cislunar space	**FN-H-202 L**	Reuse of habitation system(s) in cislunar space	**UC-H-106 L**	Conduct short-duration (days to weeks), mid-duration (month+), and extended-duration (year+) crew exploration mission(s) in cislunar space	**CN-H-102 L**		
Rendezvous, proximity operations, mating and unmating of assets in cislunar space	**FN-T-106 L**	Resupply of cargo and management of waste to/from habitable assets in cislunar space	**UC-L-202 L**	Conduct short-duration (days to weeks), mid-duration (month+), and extended-duration (year+) crew exploration mission(s) in cislunar space	**CN-H-102 L**		
Transport cargo from Earth to cislunar space	**FN-T-213 L**	Resupply of cargo and management of waste to/from habitable assets in cislunar space	**UC-L-202 L**	Conduct short-duration (days to weeks), mid-duration (month+), and extended-duration (year+) crew exploration mission(s) in cislunar space	**CN-H-102 L**		
Transfer pressurized cargo into habitable assets in cislunar space	**FN-L-202 L**	Resupply of cargo and management of waste to/from habitable assets in cislunar space	**UC-L-202 L**	Conduct short-duration (days to weeks), mid-duration (month+), and extended-duration (year+) crew exploration mission(s) in cislunar space	**CN-H-102 L**		
Transfer water to habitable assets in cislunar space	**FN-L-204 L**	Resupply of cargo and management of waste to/from habitable assets in cislunar space	**UC-L-202 L**	Conduct short-duration (days to weeks), mid-duration (month+), and extended-duration (year+) crew exploration mission(s) in cislunar space	**CN-H-102 L**		
Transfer gases to habitable assets in cislunar space	**FN-L-206 L**	Resupply of cargo and management of waste to/from habitable assets in cislunar space	**UC-L-202 L**	Conduct short-duration (days to weeks), mid-duration (month+), and extended-duration (year+) crew exploration mission(s) in cislunar space	**CN-H-102 L**		
Manage waste from habitable asset(s) in cislunar space	**FN-L-302 L**	Resupply of cargo and management of waste to/from habitable assets in cislunar space	**UC-L-202 L**	Conduct short-duration (days to weeks), mid-duration (month+), and extended-duration (year+) crew exploration mission(s) in cislunar space	**CN-H-102 L**		

Functions		Use Cases		Characteristics/Needs		Objectives	
BLANK	**BLANK**	Monitoring of system performance and failures during crewed and uncrewed increments in habitats on the lunar surface	**UC-H-201 L**	Conduct crewed and uncrewed testing of surface habitable system(s).	**CN-H-103 L**		
BLANK	**BLANK**	Monitoring of system performance and failures during crewed and uncrewed increments in habitats in cislunar space	**UC-H-202 L**	Conduct crewed and uncrewed testing of in-space habitable system(s).	**CN-H-104 L**		
BLANK	**BLANK**	Testing, contingency planning, and edge-case analyses of flight systems	**UC-T-501 L**	Operate and gain experience with flight control and mission integration to ensure safety and mission success in nominal and off-nominal conditions.	**CN-T-402 LM**	Optimize operations, training and interaction between the team on Earth, crew members on orbit, and a Martian surface team considering communication delays, autonomy level, and time required for an early return to the Earth.	**OP-02 LM**
Provide in-mission crew training on the lunar surface	**FN-X-201 L**	In-situ crew training on the lunar surface	**UC-X-201 L**	Operate and gain experience with in-situ training and planning capabilities to ensure safety and mission success.	**CN-X-201 LM**		
Provide in-mission crew training in cislunar space	**FN-X-202 L**	In-situ crew training in cislunar space	**UC-X-202 L**				
Provide in-mission crew training on the lunar surface	**FN-X-201 L**	In-situ crew training on the lunar surface	**UC-X-201 L**	Operate and gain experience with onboard autonomous system(s) and crew autonomy to train, plan, and execute safe mission(s) with reduced reliance on Earth based systems.	**CN-A-401 LM**		
Provide in-mission crew training in cislunar space	**FN-X-202 L**	In-situ crew training in cislunar space	**UC-X-202 L**				
Provide safeguards for automated asset(s) operating near crew	**FN-A-302 L**	Safe and effective interaction between crew and autonomous asset(s)	**UC-A-301 L**				
Provide safeguards for automated asset(s) operating near crew	**FN-A-302 L**	Safe and effective interaction between crew and autonomous asset(s)	**UC-A-301 L**	Operate and gain experience with remote & autonomous system(s) to reduce crew workload.	**CN-A-402 LM**		
Transport crew from cislunar space to lunar surface sites in the south pole region	**FN-T-102 L**	Transportation of crew between cislunar space and lunar south pole region landing sites	**UC-T-105 L**	Visit diverse sites of key scientific interest on the lunar surface, including polar and non-polar destinations to address high priority science goals.	**CN-T-108 L**	Characterize accessible resources, gather scientific research data, and analyze potential reserves to satisfy science and technology objectives and enable use of resources on successive missions.	**OP-03 LM**
Transport crew from the lunar surface to cislunar space	**FN-T-104 L**						
Enable crew habitation during transit from cislunar space to lunar surface sites in the south pole region	**FN-T-108 L**						
Enable crew habitation during transit from the lunar surface to cislunar space	**FN-T-110 L**						
Transport crew from cislunar space to distributed sites outside of the south pole region on the lunar surface	**FN-T-103 L**	Transportation of crew from cislunar space to distributed landing sites outside of the south pole region on the lunar surface	**UC-T-106 L**				
Enable crew habitation during transit from cislunar space to distributed sites outside of the south pole region on the lunar surface	**FN-T-109 L**						

Functions		Use Cases		Characteristics/Needs		Objectives	
Transport a small amount of cargo (10s of kg) from the lunar surface to Earth	**FN-T-207 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-301 L**	Transfer, return, and curate a small amount (10s of kg) or a large amount (100s of kg) of unconditioned samples and containers from key destinations across the lunar surface and back to Earth, while maintaining scientific integrity of the samples.	**CN-T-302 L**		
Transport a small amount of cargo (10s of kg) from the lunar surface to cislunar space	**FN-T-209 L**						
Transport a small amount of cargo (10s of kg) from cislunar space to Earth	**FN-T-211 L**						
Reposition a small amount of unconditioned samples and containers (10s of kg) on the lunar surface	**FN-M-504 L**						
Stow collected unconditioned samples on exploration assets while on the lunar surface, while maintaining scientific integrity of the samples	**FN-U-401 L**						
Transport a large amount of cargo (100s of kg) from the lunar surface to Earth	**FN-T-208 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-302 L**				
Transport a large amount of cargo (100s of kg) from the lunar surface to cislunar space	**FN-T-210 L**						
Transport a large amount of cargo (100s of kg) from cislunar space to Earth	**FN-T-212 L**						
Reposition a large amount of unconditioned samples and containers (100s of kg) on the lunar surface	**FN-M-505 L**						
Stow collected unconditioned samples on exploration assets while on the lunar surface, while maintaining scientific integrity of the samples	**FN-U-401 L**						
BLANK	**BLANK**	Delivery of collected samples to curation facilities or other appropriate facilities on Earth, while maintaining scientific integrity of the samples	**UC-G-202 L**				
Transport a small amount of cargo (10s of kg) from the lunar surface to Earth	**FN-T-207 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-305 L**	Transfer, return and curate a small amount (10s of kg) or a large amount (100s of kg) of frozen sample(s), containers, and freezers from key destinations across the lunar surface to Earth while maintaining scientific integrity of the samples.	**CN-T-304 L**		
Transport a small amount of cargo (10s of kg) from the lunar surface to cislunar space	**FN-T-209 L**						
Transport a small amount of cargo (10s of kg) from cislunar space to Earth	**FN-T-211 L**						
Provide resources to condition frozen 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 cislunar space	**FN-T-305 L**						
Provide resources to condition frozen sample containers during transit from cislunar space to Earth	**FN-T-308 L**						
Reposition a small amount of frozen samples and containers (10s of kg) on the lunar surface	**FN-M-508 L**						
Stow frozen 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 cislunar space, while maintaining scientific integrity of samples	**FN-U-406 L**						
Stow frozen samples during transport from cislunar space to Earth, while maintaining scientific integrity of samples	**FN-U-409 L**						
Stow collected frozen samples on exploration assets while on the lunar surface, while maintaining scientific integrity of the samples	**FN-U-412 L**						
Provide resources to condition frozen sample containers on the lunar surface	**FN-U-415 L**						

Functions		Use Cases		Characteristics/Needs		Objectives	
Transport a large amount of cargo (100s of kg) from the lunar surface to Earth	**FN-T-208 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-306 L**				
Transport a large amount of cargo (100s of kg) from the lunar surface to cislunar space	**FN-T-210 L**						
Transport a large amount of cargo (100s of kg) from cislunar space to Earth	**FN-T-212 L**						
Provide resources to condition frozen 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 cislunar space	**FN-T-305 L**						
Provide resources to condition frozen sample containers during transit from cislunar space to Earth	**FN-T-308 L**						
Reposition a large amount of frozen samples and containers (100s of kg) on the lunar surface	**FN-M-509 L**						
Stow frozen 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 cislunar space, while maintaining scientific integrity of samples	**FN-U-406 L**						
Stow frozen samples during transport from cislunar space to Earth, while maintaining scientific integrity of samples	**FN-U-409 L**						
Stow collected frozen samples on exploration assets while on the lunar surface, while maintaining scientific integrity of the samples	**FN-U-412 L**						
Provide resources to condition frozen sample containers on the lunar surface	**FN-U-415 L**						
BLANK	**BLANK**	Delivery of conditioned cargo to curation facilities or other appropriate facilities on Earth after landing, while maintaining scientific integrity of the samples	**UC-G-201 L**				
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 L**	Robotic surveillance of PSRs near potential crewed landing and exploration sites to identify locations of interest	**UC-A-106 L**	Demonstrate the capability to identify and locate potential site(s) for resource utilization.	**CN-U-101 L**		
Control robotic system(s) in PSRs on the lunar surface from Earth and/or cislunar space	**FN-A-202 L**						
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 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-U-102 L**				
Provide position, navigation, and timing services at the south pole region on the lunar surface	**FN-C-201 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						
Provide a robotic system capable of conducting reconnaissance	**FN-A-103 L**						
Control robotic system(s) in sunlit areas and non-PSRs on the lunar surface from Earth and/or cislunar space	**FN-A-201 L**						
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 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-105 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-202 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						

Functions		Use Cases		Characteristics/Needs		Objectives	
Provide a robotic system capable of conducting reconnaissance	**FN-A-103 L**						
Control robotic system(s) in sunlit areas and non-PSRs on the lunar surface from Earth and/or cislunar space	**FN-A-201 L**						
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 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-106 L**				
Provide position, navigation, and timing services at the far side and outside the south pole region on the lunar surface	**FN-C-203 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						
Provide a robotic system capable of conducting reconnaissance	**FN-A-103 L**						
Control robotic system(s) in sunlit areas and non-PSRs on the lunar surface from Earth and/or cislunar space	**FN-A-201 L**						
Enable crew lunar surface extravehicular activity in sunlit areas and non-PSRs	**FN-M-101 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-301 L**	Identify, collect, and document deep subsurface samples from key destinations in non-PSRs and other sunlit areas on the lunar surface, while maintaining scientific integrity of the samples.	**CN-U-301 L**		
Enable local unpressurized surface mobility in sunlit areas and non-PSRs at distributed sites on the lunar surface	**FN-M-303 L**						
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 L**						
Provide communications and data exchange between assets on the lunar surface	**FN-C-103 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-202 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 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-U-102 L**				
Provide position, navigation, and timing services at the south pole region on the lunar surface	**FN-C-201 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						
Provide a robotic system capable of conducting reconnaissance	**FN-A-103 L**						
Control robotic system(s) in sunlit areas and non-PSRs on the lunar surface from Earth and/or cislunar space	**FN-A-201 L**						
Enable crew lunar surface extravehicular activity in sunlit areas and non-PSRs	**FN-M-101 L**	Crew identification of surface samples in sunlit areas and non-PSRs in the south pole region on the lunar surface	**UC-U-103 L**				
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 L**						
Provide position, navigation, and timing services at the south pole region on the lunar surface	**FN-C-201 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						
Capture imagery on the lunar surface	**FN-U-102 L**						
Enable crew lunar surface extravehicular activity in sunlit areas and non-PSRs	**FN-M-101 L**	Collection, recovery, and packaging of deep sub-surface samples,	**UC-U-302 L**				

Functions		Use Cases		Characteristics/Needs		Objectives	
Provide position, navigation, and timing services at the south pole region on the lunar surface	FN-C-201 L	maintaining scientific integrity of the samples, from non-PSRs and other sunlit areas in the south pole region on the lunar surface					
Provide a coordinated lunar time scale	FN-C-205 L						
Capture imagery on the lunar surface	FN-U-102 L						
Provide capability to recover and package deep sub-surface samples, including drill cores, maintaining scientific integrity of the samples, from non-PSRs and sunlit regions on the lunar surface	FN-U-305 L						
Enable crew lunar surface extravehicular activity in sunlit areas and non-PSRs	FN-M-101 L	Collection, recovery, and packaging of deep sub-surface samples, maintaining scientific integrity of the samples, from non-PSRs and other sunlit areas in distributed sites on the lunar surface	UC-U-307 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-202 L						
Provide a coordinated lunar time scale	FN-C-205 L						
Capture imagery on the lunar surface	FN-U-102 L						
Provide capability to recover and package deep sub-surface samples, including drill cores, maintaining scientific integrity of the samples, from non-PSRs and sunlit regions on the lunar surface	FN-U-305 L						
Enable crew lunar surface extravehicular activity in sunlit areas and non-PSRs	FN-M-101 L	Collection, recovery, and packaging of deep sub-surface samples, maintaining scientific integrity of the samples, from non-PSRs and other sunlit areas in the far side on the lunar surface	UC-U-308 L				
Provide position, navigation, and timing services at the far side and outside the south pole region on the lunar surface	FN-C-203 L						
Provide a coordinated lunar time scale	FN-C-205 L						
Capture imagery on the lunar surface	FN-U-102 L						
Provide capability to recover and package deep sub-surface samples, including drill cores, maintaining scientific integrity of the samples, from non-PSRs and sunlit regions on the lunar surface	FN-U-305 L						
Enable crew lunar surface extravehicular activity in PSRs	FN-M-102 L	Conduct of crew excursions in PSRs around landing site at the south pole region	UC-M-303 L	Identify, collect, and document deep-surface samples from key destinations in PSRs on the lunar surface, while maintaining scientific integrity of the samples.	CN-U-302 L		
Enable local unpressurized surface mobility in PSRs at the south pole region of the lunar surface	FN-M-304 L						
Provide communications and data exchange between the lunar surface and Earth	FN-C-101 L						
Provide communications and data exchange between assets on the lunar surface	FN-C-103 L						
Provide position, navigation, and timing services at the south pole region on the lunar surface	FN-C-201 L						
Provide a coordinated lunar time scale	FN-C-205 L						
Provide communications and data exchange between the lunar surface and Earth	FN-C-101 L	Robotic surveillance of PSRs near potential crewed landing and exploration sites to identify locations of interest	UC-A-106 L				
Control robotic system(s) in PSRs on the lunar surface from Earth and/or cislunar space	FN-A-202 L						
Enable crew lunar surface extravehicular activity in PSRs	FN-M-102 L	Crew identification of surface samples in PSRs	UC-U-104 L				

Functions		Use Cases		Characteristics/Needs		Objectives	
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 L**						
Provide position, navigation, and timing services at the south pole region on the lunar surface	**FN-C-201 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						
Capture imagery on the lunar surface	**FN-U-102 L**						
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 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-105 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-202 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						
Provide a robotic system capable of conducting reconnaissance	**FN-A-103 L**						
Control robotic system(s) in sunlit areas and non-PSRs on the lunar surface from Earth and/or cislunar space	**FN-A-201 L**						
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 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-106 L**				
Provide position, navigation, and timing services at the far side and outside the south pole region on the lunar surface	**FN-C-203 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						
Provide a robotic system capable of conducting reconnaissance	**FN-A-103 L**						
Control robotic system(s) in sunlit areas and non-PSRs on the lunar surface from Earth and/or cislunar space	**FN-A-201 L**						
Enable crew lunar surface extravehicular activity in sunlit areas and non-PSRs	**FN-M-101 L**	Crew identification of surface samples in sunlit areas and non-PSRs in distributed sites on the lunar surface	**UC-U-107 L**				
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 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-202 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						
Capture imagery on the lunar surface	**FN-U-102 L**						
Enable crew lunar surface extravehicular activity in sunlit areas and non-PSRs	**FN-M-101 L**	Crew identification of surface samples in sunlit areas and non-PSRs in the far side on the lunar surface	**UC-U-108 L**				
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 L**						
Provide position, navigation, and timing services at the far side and outside the south pole region on the lunar surface	**FN-C-203 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						
Capture imagery on the lunar surface	**FN-U-102 L**						

Functions		Use Cases		Characteristics/Needs		Objectives	
Enable crew lunar surface extravehicular activity in PSRs	**FN-M-102 L**	Collection, recovery, and packaging of deep sub-surface samples, maintaining scientific integrity of the samples, from PSRs on the lunar surface	**UC-U-304 L**				
Provide position, navigation, and timing services at the south pole region on the lunar surface	**FN-C-201 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						
Capture imagery on the lunar surface	**FN-U-102 L**						
Provide capability to recover and package deep sub-surface samples, including drill cores, maintaining scientific integrity of the samples, from PSRs on the lunar surface	**FN-U-306 L**						
Enable crew lunar surface extravehicular activity in sunlit areas and non-PSRs	**FN-M-101 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-301 L**	Identify, collect, and document surface and shallow subsurface samples from key destinations in non-PSRs and other sunlit areas on the lunar surface, while maintaining scientific integrity of the samples.	**CN-U-303 L**		
Enable local unpressurized surface mobility in sunlit areas and non-PSRs at distributed sites on the lunar surface	**FN-M-303 L**						
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 L**						
Provide communications and data exchange between assets on the lunar surface	**FN-C-103 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-202 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 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-U-102 L**				
Provide position, navigation, and timing services at the south pole region on the lunar surface	**FN-C-201 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						
Provide a robotic system capable of conducting reconnaissance	**FN-A-103 L**						
Control robotic system(s) in sunlit areas and non-PSRs on the lunar surface from Earth and/or cislunar space	**FN-A-201 L**						
Enable crew lunar surface extravehicular activity in sunlit areas and non-PSRs	**FN-M-101 L**	Crew identification of surface samples in sunlit areas and non-PSRs in the south pole region on the lunar surface	**UC-U-103 L**				
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 L**						
Provide position, navigation, and timing services at the south pole region on the lunar surface	**FN-C-201 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						
Capture imagery on the lunar surface	**FN-U-102 L**						
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 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-105 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-202 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						

Functions		Use Cases		Characteristics/Needs		Objectives	
Provide a robotic system capable of conducting reconnaissance	**FN-A-103 L**						
Control robotic system(s) in sunlit areas and non-PSRs on the lunar surface from Earth and/or cislunar space	**FN-A-201 L**						
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 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-106 L**				
Provide position, navigation, and timing services at the far side and outside the south pole region on the lunar surface	**FN-C-203 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						
Provide a robotic system capable of conducting reconnaissance	**FN-A-103 L**						
Control robotic system(s) in sunlit areas and non-PSRs on the lunar surface from Earth and/or cislunar space	**FN-A-201 L**						
Enable crew lunar surface extravehicular activity in sunlit areas and non-PSRs	**FN-M-101 L**	Crew identification of surface samples in sunlit areas and non-PSRs in distributed sites on the lunar surface	**UC-U-107 L**				
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 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-202 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						
Capture imagery on the lunar surface	**FN-U-102 L**						
Enable crew lunar surface extravehicular activity in sunlit areas and non-PSRs	**FN-M-101 L**	Crew identification of surface samples in sunlit areas and non-PSRs in the far side on the lunar surface	**UC-U-108 L**				
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 L**						
Provide position, navigation, and timing services at the far side and outside the south pole region on the lunar surface	**FN-C-203 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						
Capture imagery on the lunar surface	**FN-U-102 L**						
Enable crew lunar surface extravehicular activity in sunlit areas and non-PSRs	**FN-M-101 L**	Collection, documentation, and packaging of surface and/or shallow sub-surface samples, maintaining scientific integrity of the samples, from non-PSRs and sunlit areas in the south pole region on the lunar surface	**UC-U-301 L**				
Provide position, navigation, and timing services at the south pole region on the lunar surface	**FN-C-201 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						
Capture imagery on the lunar surface	**FN-U-102 L**						
Provide capability to recover and package surface and/or shallow sub-surface samples, maintaining scientific integrity of the samples, from non-PSRs and sunlit regions on the lunar surface	**FN-U-303 L**						
Enable crew lunar surface extravehicular activity in sunlit areas and non-PSRs	**FN-M-101 L**	Collection, documentation, and packaging of surface and/or shallow	**UC-U-305 L**				

Functions		Use Cases		Characteristics/Needs		Objectives	
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-202 L**	sub-surface samples, maintaining scientific integrity of the samples, from non-PSRs and sunlit areas in distributed locations on the lunar surface					
Provide a coordinated lunar time scale	**FN-C-205 L**						
Capture imagery on the lunar surface	**FN-U-102 L**						
Provide capability to recover and package surface and/or shallow sub-surface samples, maintaining scientific integrity of the samples, from non-PSRs and sunlit regions on the lunar surface	**FN-U-303 L**						
Enable crew lunar surface extravehicular activity in sunlit areas and non-PSRs	**FN-M-101 L**	Collection, documentation, and packaging of surface and/or shallow sub-surface samples, maintaining scientific integrity of the samples, from non-PSRs and sunlit areas in the far side on the lunar surface	**UC-U-306 L**				
Provide position, navigation, and timing services at the far side and outside the south pole region on the lunar surface	**FN-C-203 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						
Capture imagery on the lunar surface	**FN-U-102 L**						
Provide capability to recover and package surface and/or shallow sub-surface samples, maintaining scientific integrity of the samples, from non-PSRs and sunlit regions on the lunar surface	**FN-U-303 L**						
Enable crew lunar surface extravehicular activity in PSRs	**FN-M-102 L**	Conduct of crew excursions in PSRs around landing site at the south pole region	**UC-M-303 L**	Identify, collect, and document surface and shallow subsurface samples from key destinations in PSRs on the lunar surface, while maintaining scientific integrity of the samples.	**CN-U-304 L**		
Enable local unpressurized surface mobility in PSRs at the south pole region of the lunar surface	**FN-M-304 L**						
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 L**						
Provide communications and data exchange between assets on the lunar surface	**FN-C-103 L**						
Provide position, navigation, and timing services at the south pole region on the lunar surface	**FN-C-201 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 L**	Robotic surveillance of PSRs near potential crewed landing and exploration sites to identify locations of interest	**UC-A-106 L**				
Control robotic system(s) in PSRs on the lunar surface from Earth and/or cislunar space	**FN-A-202 L**						
Enable crew lunar surface extravehicular activity in PSRs	**FN-M-102 L**	Crew identification of surface samples in PSRs	**UC-U-104 L**				
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 L**						
Provide position, navigation, and timing services at the south pole region on the lunar surface	**FN-C-201 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						
Capture imagery on the lunar surface	**FN-U-102 L**						
Enable crew lunar surface extravehicular activity in PSRs	**FN-M-102 L**	Collection, recovery, and packaging of surface and/or shallow sub-	**UC-U-303 L**				

Functions		Use Cases		Characteristics/Needs		Objectives	
Provide position, navigation, and timing services at the south pole region on the lunar surface	FN-C-201 L	surface samples, maintaining scientific integrity of the samples, from PSRs on the lunar surface					
Provide a coordinated lunar time scale	FN-C-205 L						
Capture imagery on the lunar surface	FN-U-102 L						
Provide capability to recover and package surface and/or shallow sub-surface samples, maintaining scientific integrity of the samples, from PSRs on the lunar surface	FN-U-304 L						
Transport a limited amount of cargo (100s of kg) from Earth to south pole region sites on the lunar surface	FN-T-201 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-U-717 L	Deploy and operate exploration asset(s), related to available resources, at distributed and south polar region sites on the lunar surface.	CN-U-702 L		
Transport a moderate amount of cargo (1000s of kg) from Earth to south pole region sites on the lunar surface	FN-T-202 L						
Provide power for deployed external surface utilization payloads(s) and/or equipment for long durations (months to years+)	FN-P-402 L						
Enable crew lunar surface extravehicular activity in sunlit areas and non-PSRs	FN-M-101 L						
Enable crew lunar surface extravehicular activity in PSRs	FN-M-102 L						
Enable local unpressurized surface mobility in sunlit areas and non-PSRs in the south pole region on the lunar surface	FN-M-302 L						
Enable local unpressurized surface mobility in PSRs at the south pole region of the lunar surface	FN-M-304 L						
Unload a limited amount of cargo (100s of kg) on the lunar surface	FN-M-401 L						
Unload a moderate amount of cargo (1000s of kg) on the lunar surface	FN-M-402 L						
Reposition a limited amount of cargo (100s of kg) in the south pole region on the lunar surface	FN-M-501 L						
Reposition a moderate amount of cargo (1000s of kg) at the south pole region on the lunar surface	FN-M-503 L						
Provide communications and data exchange between the lunar surface and Earth	FN-C-101 L						
Perform robotic manipulation of payloads, logistics, and/or equipment on the lunar surface	FN-A-104 L						
Conduct resource identification utilization payload and/or equipment operations on the lunar surface	FN-U-103 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-203 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-718 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-204 L						
Provide power for deployed external surface utilization payloads(s) and/or equipment for long durations (months to years+)	FN-P-402 L						
Enable crew lunar surface extravehicular activity in sunlit areas and non-PSRs	FN-M-101 L						
Enable local unpressurized surface mobility in sunlit areas and non-PSRs at distributed sites on the lunar surface	FN-M-303 L						
Unload a moderate amount of cargo (1000s of kg) on the lunar surface	FN-M-402 L						

Functions		Use Cases		Characteristics/Needs		Objectives	
Reposition a limited amount of cargo (100s of kg) at distributed sites on the lunar surface	**FN-M-502 L**						
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 L**						
Perform robotic manipulation of payloads, logistics, and/or equipment on the lunar surface	**FN-A-104 L**						
Conduct resource identification utilization payload and/or equipment operations on the lunar surface	**FN-U-103 L**						
BLANK	**BLANK**	BLANK	**BLANK**	Provide capabilities to integrate networks and mission systems to exchange data between Earth-based systems, in-space exploration assets, and surface exploration assets.	**CN-D-101 L**	Establish command and control processes, common interfaces, and ground systems that will support expanding human missions at the Moon and Mars.	**OP-04 LM**
BLANK	**BLANK**	BLANK	**BLANK**	Provide capabilities to utilize common data interface(s) for exchanges between Earth-based systems, in-space exploration assets, and surface exploration assets.	**CN-D-102 L**		
Collect, store, and locally distribute data on the lunar surface	**FN-D-101 L**	Aggregation and storage of data on the lunar surface until it is able to be transmitted and confirmed received	**UC-D-101 L**	Provide capabilities to store and protect data on exploration assets.	**CN-D-103 L**		
Process data locally on the lunar surface	**FN-D-201 L**						
Collect, store, and locally distribute data in cislunar space	**FN-D-102 L**	Aggregation and storage of data in cislunar space until it is able to be transmitted and confirmed received	**UC-D-102 L**				
Process data locally in cislunar space	**FN-D-202 L**						
Enable crew lunar surface extravehicular activity in sunlit areas and non-PSRs	**FN-M-101 L**	Conduct of crew extravehicular operations on the lunar surface	**UC-M-101 L**	Operate and gain experience with capabilities to conduct extravehicular activities utilizing mobility assets and tools.	**CN-M-101 LM**	Operate surface mobility systems, e.g., extra-vehicular activity (EVA) suits, tools and vehicles.	**OP-05 LM**
Enable crew lunar surface extravehicular activity in PSRs	**FN-M-102 L**						
Enable maintaining and servicing of the EVA system in a habitable environment	**FN-M-202 L**						
Ingress/egress from habitable asset(s) to lunar surface vacuum	**FN-M-203 L**						
Enable the cleaning of EVA equipment and tools	**FN-M-201 L**	Crew use of tools to assist in performing extravehicular activities, sample collection and suit cleaning	**UC-M-103 L**				
Provide capability to recover and package sub-surface samples, maintaining scientific integrity of the samples, from non-PSRs and sunlit regions on the lunar surface	**FN-U-301 L**						
Provide capability to recover and package sub-surface samples, maintaining scientific integrity of the samples, from PSRs on the lunar surface	**FN-U-302 L**						
Provide capability to recover and package surface and/or shallow sub-surface samples, maintaining scientific integrity of the samples, from non-PSRs and sunlit regions on the lunar surface	**FN-U-303 L**						
Provide capability to recover and package surface and/or shallow sub-surface samples, maintaining scientific integrity of the samples, from PSRs on the lunar surface	**FN-U-304 L**						

Functions		Use Cases		Characteristics/Needs		Objectives	
Provide capability to recover and package deep sub-surface samples, including drill cores, maintaining scientific integrity of the samples, from non-PSRs and sunlit regions on the lunar surface	**FN-U-305 L**						
Provide capability to recover and package deep sub-surface samples, including drill cores, maintaining scientific integrity of the samples, from PSRs on the lunar surface	**FN-U-306 L**						
Enable crew lunar surface extravehicular activity in sunlit areas and non-PSRs	**FN-M-101 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-301 L**	Operate and gain experience with capabilities to transport crew and cargo between landing, exploration, and utilization sites at varying distances from assets on the lunar surface.	**CN-M-501 L**		
Enable local unpressurized surface mobility in sunlit areas and non-PSRs at distributed sites on the lunar surface	**FN-M-303 L**						
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 L**						
Provide communications and data exchange between assets on the lunar surface	**FN-C-103 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-202 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						
Enable crew lunar surface extravehicular activity in sunlit areas and non-PSRs	**FN-M-101 L**	Conduct of crew excursions to locations around landing site in sunlit areas and non-PSRs in the south pole region	**UC-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-302 L**						
Enable pressurized surface mobility in sunlit areas and non-PSRs	**FN-M-305 L**						
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 L**						
Provide communications and data exchange between assets on the lunar surface	**FN-C-103 L**						
Provide position, navigation, and timing services at the south pole region on the lunar surface	**FN-C-201 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						
Transport crew from cislunar space to lunar surface sites in the south pole region	**FN-T-102 L**	Transportation of crew between cislunar space and the lunar surface	**UC-T-104 L**	Transition crew from partial gravity environment to micro-gravity environment.	**CN-T-111 L**	Evaluate, understand, and mitigate the impacts on crew health and performance of a long deep space orbital mission, followed by partial gravity surface operations on the Moon.	**OP-06 L**
Transport crew from cislunar space to distributed sites outside of the south pole region on the lunar surface	**FN-T-103 L**						
Transport crew from the lunar surface to cislunar space	**FN-T-104 L**						
Enable crew habitation during transit from cislunar space to lunar surface sites in the south pole region	**FN-T-108 L**						
Enable crew habitation during transit from cislunar space to distributed sites outside of the south pole region on the lunar surface	**FN-T-109 L**						
Enable crew habitation during transit from the lunar surface to cislunar space	**FN-T-110 L**						

Functions		Use Cases		Characteristics/Needs		Objectives	
Transport crew from cislunar space to lunar surface sites in the south pole region	**FN-T-102 L**	Transportation of crew between cislunar space and the lunar surface	**UC-T-104 L**	Transition crew from micro-gravity environment to partial gravity environment, following a duration in space	**CN-T-112 L**		
Transport crew from cislunar space to distributed sites outside of the south pole region on the lunar surface	**FN-T-103 L**						
Transport crew from the lunar surface to cislunar space	**FN-T-104 L**						
Enable crew habitation during transit from cislunar space to lunar surface sites in the south pole region	**FN-T-108 L**						
Enable crew habitation during transit from cislunar space to distributed sites outside of the south pole region on the lunar surface	**FN-T-109 L**						
Enable crew habitation during transit from the lunar surface to cislunar space	**FN-T-110 L**						
Enable a pressurized, habitable environment on the lunar surface for short durations (days to weeks)	**FN-H-101 L**	Crew habitation of assets on the lunar surface for short-durations (days to weeks)	**UC-H-101 L**	Conduct short-duration (days to weeks) to mid-duration (month+) crew exploration mission(s) on the lunar surface.	**CN-H-101 L**		
Operate habitation system(s) in uncrewed mode between crewed missions on the lunar surface	**FN-H-201 L**						
Manage waste from habitable asset(s) on the lunar surface	**FN-L-301 L**						
Enable a pressurized, habitable environment on the lunar surface for moderate duration (month+) use	**FN-H-102 L**	Crew habitation of assets on the lunar surface for mid-durations (month+)	**UC-H-102 L**				
Operate habitation system(s) in uncrewed mode between crewed missions on the lunar surface	**FN-H-201 L**						
Manage waste from habitable asset(s) on the lunar surface	**FN-L-301 L**						
Operate habitation system(s) in uncrewed mode between crewed missions on the lunar surface	**FN-H-201 L**	Reuse of habitation system(s) on the lunar surface	**UC-H-105 L**				
Transport a limited amount of cargo (100s of kg) from Earth to south pole region sites on the lunar surface	**FN-T-201 L**	Resupply of cargo and management of waste to/from habitable assets on the lunar surface	**UC-L-201 L**				
Transport a moderate amount of cargo (1000s of kg) from Earth to south pole region sites on the lunar surface	**FN-T-202 L**						
Mating between pressurized assets on the lunar surface	**FN-L-101 L**						
Transfer pressurized cargo into habitable assets on the lunar surface	**FN-L-201 L**						
Transfer water to habitable assets on the lunar surface	**FN-L-203 L**						
Transfer gases to habitable assets on the lunar surface	**FN-L-205 L**						
Manage waste from habitable asset(s) on the lunar surface	**FN-L-301 L**						
Unload a limited amount of cargo (100s of kg) on the lunar surface	**FN-M-401 L**						
Unload a moderate amount of cargo (1000s of kg) on the lunar surface	**FN-M-402 L**						
Reposition a limited amount of cargo (100s of kg) in the south pole region on the lunar surface	**FN-M-501 L**						
Reposition a moderate amount of cargo (1000s of kg) at the south pole region on the lunar surface	**FN-M-503 L**						

Functions		Use Cases		Characteristics/Needs		Objectives	
Enable a pressurized, habitable environment on the lunar surface for short durations (days to weeks)	**FN-H-101 L**	Crew habitation of assets on the lunar surface for short-durations (days to weeks)	**UC-H-101 L**	Conduct short-duration (days to weeks), mid-duration (month+), and extended-duration (year+) crew exploration mission(s) in cislunar space	**CN-H-102 L**		
Operate habitation system(s) in uncrewed mode between crewed missions on the lunar surface	**FN-H-201 L**						
Manage waste from habitable asset(s) on the lunar surface	**FN-L-301 L**						
Enable a pressurized, habitable environment in cislunar space for moderate (month+) durations	**FN-H-104 L**	Crew habitation of assets for moderate-duration (month+) mission(s) in cislunar space	**UC-H-103 L**				
Operate habitation system(s) in uncrewed mode between crewed missions in cislunar space	**FN-H-202 L**						
Enable a pressurized, habitable environment in cislunar space for extended (year+) duration	**FN-H-105 L**	Crew habitation of assets for extended-duration (year+) mission(s) in cislunar space	**UC-H-104 L**				
Operate habitation system(s) in uncrewed mode between crewed missions in cislunar space	**FN-H-202 L**						
Operate habitation system(s) in uncrewed mode between crewed missions in cislunar space	**FN-H-202 L**	Reuse of habitation system(s) in cislunar space	**UC-H-106 L**				
Rendezvous, proximity operations, mating and unmating of assets in cislunar space	**FN-T-106 L**	Resupply of cargo and management of waste to/from habitable assets in cislunar space	**UC-L-202 L**				
Transport cargo from Earth to cislunar space	**FN-T-213 L**						
Transfer pressurized cargo into habitable assets in cislunar space	**FN-L-202 L**						
Transfer water to habitable assets in cislunar space	**FN-L-204 L**						
Transfer gases to habitable assets in cislunar space	**FN-L-206 L**						
Manage waste from habitable asset(s) in cislunar space	**FN-L-302 L**						
BLANK	**BLANK**	Monitoring of system performance and failures during crewed and uncrewed increments in habitats on the lunar surface	**UC-H-201 L**	Conduct crewed and uncrewed testing of surface habitable system(s).	**CN-H-103 L**	Validate readiness of systems and operations to support crew health and performance for the initial human Mars exploration campaign.	**OP-07 LM**
BLANK	**BLANK**	Monitoring of system performance and failures during crewed and uncrewed increments in habitats in cislunar space	**UC-H-202 L**	Conduct crewed and uncrewed testing of in-space habitable system(s).	**CN-H-104 L**		
Provide hardware for crew medical care on the lunar surface	**FN-X-101 L**	Medical capabilities on the lunar surface	**UC-X-101 L**	Provide appropriate medical capabilities (including behavioral health) that allow for autonomous crew health decision making and care, and are preparatory of a mission to Mars.	**CN-X-101 LM**		
Provide data capabilities, including protection for communication, and interface to support crew medical care on the lunar surface	**FN-D-105 L**						
Provide hardware for crew medical care in cislunar space	**FN-X-102 L**	Medical capabilities in cislunar space	**UC-X-102 L**				
Provide data capabilities, including protection for communication, and interface to support crew medical care in cislunar space	**FN-D-106 L**						

Functions		Use Cases		Characteristics/Needs		Objectives	
Provide crew countermeasure system(s) to support the crew for moderate durations (month+) on the lunar surface	**FN-X-103 L**	Crew countermeasure capabilities to support the crew for moderate durations (month+) on the lunar surface	**UC-X-103 L**	Provide countermeasures capabilities that are commensurate in scope with the human system needs for the mission.	**CN-X-102 L**		
Provide crew countermeasure system(s) to support the crew for moderate (month+) to long (year+) durations in cislunar space	**FN-X-104 L**	Crew countermeasure capabilities to support the crew for moderate (month+) to long (year+) durations in cislunar space	**UC-X-104 L**				
BLANK	**BLANK**	BLANK	**BLANK**	Demonstrate crew survival capabilities in cislunar space and on the lunar surface, including safe havens, system supportability, and/or aborts, for nominal and off-nominal scenarios to prepare for future Mars missions.	**CN-X-103 L**		
BLANK	**BLANK**	Deployment and operation of utilization payload(s) and/or equipment related to demonstration of equipment recovery from surface asset(s)	**UC-U-727 L**	Demonstrate the capabilities to locate, access, and reuse surface assets from previous crewed and uncrewed missions.	**CN-U-105 L**	Demonstrate the capability to find, service, upgrade, or utilize instruments and equipment from robotic landers or previous human missions on the surface of the Moon and Mars.	**OP-08 LM**
BLANK	**BLANK**	Deployment and operation of utilization payload(s) and/or equipment related to demonstration of maintenance and repair of asset(s)	**UC-U-726 L**	Demonstrate the capabilities to service and/or upgrade assets.	**CN-U-806 L**		
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 L**	Robotic assistance of crew exploration, site surveying, sample and resource locating, documentation, and sample retrieval from PSRs	**UC-A-101 L**	Provide appropriate robotic system(s) that can conduct or assist in tasks that would otherwise be performed by the crew alone on the lunar surface.	**CN-A-102 L**	Demonstrate the capability of integrated robotic systems to support and maximize the useful work performed by crewmembers on the surface, and in orbit.	**OP-09 LM**
Provide robotic systems to assist crew in PSRs on the lunar surface	**FN-A-102 L**						
Control robotic system(s) in PSRs on the lunar surface from Earth and/or cislunar space	**FN-A-202 L**						
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 L**	Robotic assistance of crew exploration, site surveying, sample and resource locating, documentation, and sample retrieval from sunlit areas and non- PSRs	**UC-A-104 L**				
Provide robotic systems to assist crew in sunlit areas and non-PSRs on the lunar surface	**FN-A-101 L**						
Perform robotic manipulation of payloads, logistics, and/or equipment on the lunar surface	**FN-A-104 L**						
Control robotic system(s) in sunlit areas and non-PSRs on the lunar surface from Earth and/or cislunar space	**FN-A-201 L**						
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 L**	Robotic surveillance of PSRs near potential crewed landing and exploration sites to identify locations of interest	**UC-A-106 L**				
Control robotic system(s) in PSRs on the lunar surface from Earth and/or cislunar space	**FN-A-202 L**						
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 L**	Robotic surveillance of potential crewed landing and exploration sites	**UC-U-102 L**				

Functions		Use Cases		Characteristics/Needs		Objectives	
Provide position, navigation, and timing services at the south pole region on the lunar surface	**FN-C-201 L**	in sunlit areas and non-PSRs in the south pole region on the lunar surface to identify locations of interest					
Provide a coordinated lunar time scale	**FN-C-205 L**						
Provide a robotic system capable of conducting reconnaissance	**FN-A-103 L**						
Control robotic system(s) in sunlit areas and non-PSRs on the lunar surface from Earth and/or cislunar space	**FN-A-201 L**						
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 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-105 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-202 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						
Provide a robotic system capable of conducting reconnaissance	**FN-A-103 L**						
Control robotic system(s) in sunlit areas and non-PSRs on the lunar surface from Earth and/or cislunar space	**FN-A-201 L**						
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 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-106 L**				
Provide position, navigation, and timing services at the far side and outside the south pole region on the lunar surface	**FN-C-203 L**						
Provide a coordinated lunar time scale	**FN-C-205 L**						
Provide a robotic system capable of conducting reconnaissance	**FN-A-103 L**						
Control robotic system(s) in sunlit areas and non-PSRs on the lunar surface from Earth and/or cislunar space	**FN-A-201 L**						
BLANK	**BLANK**	BLANK	**BLANK**	Demonstrate the capabilities to operate appropriate robotic system(s) that can conduct or assist in tasks that would otherwise be performed by the crew alone on the lunar surface.	**CN-A-103 L**		
BLANK	**BLANK**	BLANK	**BLANK**	Demonstrate the capabilities to operate appropriate robotic system(s) that can conduct or assist in tasks that would otherwise be performed by the crew alone in cislunar space.	**CN-A-104 L**		

Functions		Use Cases		Characteristics/Needs		Objectives	
Control robotic system(s) in cislunar space from Earth and/or cislunar space	**FN-A-203 L**	Maintenance and repair operations using robotic system(s) in cislunar space as appropriate	**UC-A-102 L**	Minimize crew time required for inspection, commissioning, maintenance, and logistics operations to maximize crew time available for science and exploration activities.	**CN-A-108 L**		
Perform robotic manipulation of payloads, logistics, and/or equipment on the lunar surface	**FN-A-104 L**	Robotic support of logistic operations on the lunar surface as necessary	**UC-A-103 L**				
Interface robotic system(s) with logistics carriers on the lunar surface	**FN-A-105 L**						
Control robotic system(s) in sunlit areas and non-PSRs on the lunar surface from Earth and/or 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-201 L**	Maintenance and repair operations using robotic system(s) on the lunar surface as appropriate	**UC-A-105 L**				
BLANK	**BLANK**	BLANK	**BLANK**	Demonstrate capabilities to allow in-space and surface crew to control and command robotic system(s).	**CN-A-201 L**		
BLANK	**BLANK**	BLANK	**BLANK**	Demonstrate the capability for safe and effective interactions between crew and automated/autonomous system(s).	**CN-A-301 L**		
BLANK	**BLANK**	BLANK	**BLANK**	Demonstrate the capability for safe and effective interactions between crew and automated/autonomous system(s).	**CN-A-301 L**	Demonstrate the capability to operate robotic systems that are used to support crew members on the lunar or Martian surface, autonomously or remotely from the Earth or from orbiting platforms.	**OP-10 LM**
Transport a moderate amount of cargo (1000s of kg) from Earth to south pole region sites on the lunar surface	**FN-T-202 L**	Deployment and operation of utilization payload(s) and/or equipment related to demonstration of oxygen recovery from lunar regolith	**UC-I-102 L**	Operate demonstration exploration asset(s) on the lunar surface to collect, produce, store, and transfer commodities, including water, oxygen, and/or construction feedstock, for potential use.	**CN-I-103 LM**	Demonstrate the capability to use commodities produced from planetary surface or in-space resources to reduce the mass required to be transported from Earth.	**OP-11 LM**
Provide power for deployed surface utilization payloads(s) and/or equipment	**FN-P-401 L**						
Enable crew lunar surface extravehicular activity in sunlit areas and non-PSRs	**FN-M-101 L**						
Unload a moderate amount of cargo (1000s of kg) on the lunar surface	**FN-M-402 L**						
Reposition a moderate amount of cargo (1000s of kg) at the south pole region on the lunar surface	**FN-M-503 L**						
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 L**						
Produce scalable quantities of oxygen from lunar regolith	**FN-I-102 L**						
Store oxygen on the lunar surface	**FN-I-105 L**						

Functions		Use Cases		Characteristics/Needs		Objectives	
Transport scalable quantities of oxygen produced to exploration elements	**FN-I-107 L**						
Collect regolith at sub-scale to support demonstration using scalable capability	**FN-I-201 L**						
Provide storage for collected regolith	**FN-I-203 L**						
Conduct resource identification utilization payload and/or equipment operations on the lunar surface	**FN-U-103 L**						
Transport a moderate amount of cargo (1000s of kg) from Earth to south pole region sites on the lunar surface	**FN-T-202 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-103 L**				
Provide power for deployed surface utilization payloads(s) and/or equipment	**FN-P-401 L**						
Enable crew lunar surface extravehicular activity in sunlit areas and non-PSRs	**FN-M-101 L**						
Unload a moderate amount of cargo (1000s of kg) on the lunar surface	**FN-M-402 L**						
Reposition a moderate amount of cargo (1000s of kg) at the south pole region on the lunar surface	**FN-M-503 L**						
Provide communications and data exchange between the lunar surface and Earth	**FN-C-101 L**						
Collect water/ice from the polar region of the lunar surface	**FN-I-101 L**						
Produce scalable quantities of water from in-situ materials on the lunar surface	**FN-I-103 L**						
Store collected water/ice on the lunar surface	**FN-I-106 L**						
Transport scalable quantities of water produced to exploration elements	**FN-I-108 L**						
Conduct resource identification utilization payload and/or equipment operations on the lunar surface	**FN-U-103 L**						
Transport a moderate amount of cargo (1000s of kg) from Earth to south pole region sites on the lunar surface	**FN-T-202 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-104 L**				
Transfer water to habitable assets on the lunar surface	**FN-L-203 L**						
Transport a moderate amount of cargo (1000s of kg) from Earth to south pole region sites on the lunar surface	**FN-T-202 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-105 L**				
Transfer gases to habitable assets on the lunar surface	**FN-L-205 L**						
Transport a moderate amount of cargo (1000s of kg) from Earth to south pole region sites on the lunar surface	**FN-T-202 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-106 L**				
Provide power for deployed surface utilization payloads(s) and/or equipment	**FN-P-401 L**						
Enable crew lunar surface extravehicular activity in sunlit areas and non-PSRs	**FN-M-101 L**						
Unload a moderate amount of cargo (1000s of kg) on the lunar surface	**FN-M-402 L**						

Functions		Use Cases		Characteristics/Needs		Objectives	
Reposition a moderate amount of cargo (1000s of kg) at the south pole region on the lunar surface	FN-M-503 L						
Provide communications and data exchange between the lunar surface and Earth	FN-C-101 L						
Collect regolith at sub-scale to support demonstration using scalable capability	FN-I-201 L						
Conduct regolith recovery demonstration utilization payload and/or equipment operations on the lunar surface	FN-I-202 L						
Process and refine scalable quantities of in-situ feedstock resources on the lunar surface	FN-I-204 L						
Conduct resource identification utilization payload and/or equipment operations on the lunar surface	FN-U-103 L						
Transport a moderate amount of cargo (1000s of kg) from Earth to south pole region sites on the lunar surface	FN-T-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-202 L	Demonstrate the capability to use surface-borne resources for potential construction and/or manufacturing on the lunar surface.	CN-I-204 L		
Provide power for deployed surface utilization payloads(s) and/or equipment	FN-P-401 L						
Unload a moderate amount of cargo (1000s of kg) on the lunar surface	FN-M-402 L						
Reposition a moderate amount of cargo (1000s of kg) at the south pole region on the lunar surface	FN-M-503 L						
Provide communications and data exchange between the lunar surface and Earth	FN-C-101 L						
Collect regolith at sub-scale to support demonstration using scalable capability	FN-I-201 L						
Process and refine scalable quantities of in-situ feedstock resources on the lunar surface	FN-I-204 L						
Conduct autonomous construction utilization payload and/or equipment operations on the lunar surface	FN-I-205 L						
Transport a limited amount of cargo (100s of kg) from Earth to south pole region sites on the lunar surface	FN-T-201 L	Deployment and operation of utilization payload(s) and/or equipment related to demonstration of regolith based additive/subtractive manufacturing techniques	UC-I-203 L				
Provide power for deployed surface utilization payloads(s) and/or equipment	FN-P-401 L						
Unload a limited amount of cargo (100s of kg) on the lunar surface	FN-M-401 L						
Reposition a limited amount of cargo (100s of kg) in the south pole region on the lunar surface	FN-M-501 L						
Provide communications and data exchange between the lunar surface and Earth	FN-C-101 L						
Collect regolith at sub-scale to support demonstration using scalable capability	FN-I-201 L						
Process and refine scalable quantities of in-situ feedstock resources on the lunar surface	FN-I-204 L						
Conduct additive/subtractive manufacturing utilization payload and/or equipment operations on the lunar surface	FN-I-207 L						

Functions		Use Cases		Characteristics/Needs		Objectives	
Transport a moderate amount of cargo (1000s of kg) from Earth to south pole region sites on the lunar surface	FN-T-202 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-104 L	Demonstrate the capabilities to use surface-borne commodities to support exploration assets on the lunar surface.	CN-I-205 L		
Transfer water to habitable assets on the lunar surface	FN-L-203 L						
Transport a moderate amount of cargo (1000s of kg) from Earth to south pole region sites on the lunar surface	FN-T-202 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-105 L				
Transfer gases to habitable assets on the lunar surface	FN-L-205 L						
Transport a limited amount of cargo (100s of kg) from Earth to south pole region sites on the lunar surface	FN-T-201 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-728 L	Demonstrate the capabilities to recovery of excess fluids and gases and separation of products, including propellant residuals, from lunar landers.	CN-I-101 L	Establish procedures and systems that will minimize the disturbance to the local environment, maximize the resources available to future explorers, and allow for reuse/recycling of material transported from Earth (and from the lunar surface in the case of Mars) to be used during exploration.	OP-12 LM
Provide power for deployed surface utilization payloads(s) and/or equipment	FN-P-401 L						
Unload a limited amount of cargo (100s of kg) on the lunar surface	FN-M-401 L						
Reposition a limited amount of cargo (100s of kg) in the south pole region on the lunar surface	FN-M-501 L						
Provide capability to access residual propellant from surface assets	FN-U-501 L						
Transfer propellant between assets on the lunar surface	FN-U-502 L						
BLANK	BLANK	Reduction of blast ejecta to limit the migration of ejecta across the lunar surface	UC-U-802 L	Limit contamination of PSRs.	CN-U-802 L		
BLANK	BLANK	Reduction of path erosion, dust lofting, and sample contamination	UC-U-803 L				
BLANK	BLANK	Limitation of the spread of dust raised by lunar surface operations	UC-U-804 L				
BLANK	BLANK	Preservation of lunar far side environment to ensure scientific data integrity	UC-U-801 L	Preserve radio free environment on the far side of the Moon.	CN-U-803 L		

Functions		Use Cases		Characteristics/Needs		Objectives	
BLANK	**BLANK**	Deployment and operation of utilization payload(s) and/or equipment related to demonstration of equipment recovery from surface asset(s)	**UC-U-727 L**	Demonstrate the capabilities to recover useful equipment from surface assets, where valuable.	**CN-U-807 L**		
BLANK	**BLANK**	Repurposing of hardware and materials brought to the surface for subsequent missions	**UC-U-806 L**				

A.2 Mars Objective Decomposition

Functions		Use Cases		Characteristics/Needs		Objectives	
Generate power on the Martian surface	**FN-P-101 M**	Operation of power generation and energy storage assets on the Martian surface	**UC-P-101 M**	Provide power generation, energy storage, and power distribution system(s) on the Martian surface to support large exploration assets.	**CN-P-101 M**	Develop Mars surface power sufficient for an initial human Mars exploration campaign.	**MI-01 M**
Store energy on the Martian surface	**FN-P-201 M**						
Distribute power to assets on the Martian surface	**FN-P-303 M**	Power distribution around power generation and energy storage assets on the Martian surface	**UC-P-301 M**				
Generate power at multiple distributed locations on the Martian surface	**FN-P-102 M**	Operation of power systems at multiple distributed locations around exploration sites on the Martian surface	**UC-P-102 M**	Provide power generation, energy storage, and power distribution system(s) on the Martian surface to allow power utilization to support assets at multiple distributed locations around exploration sites.	**CN-P-102 M**		
Store energy at multiple distributed locations on the Martian surface	**FN-P-202 M**						
Distribute power to assets on the Martian surface	**FN-P-303 M**	Power distribution around power generation and energy storage assets at multiple distributed locations on the Martian surface	**UC-P-302 M**				
BLANK	**BLANK**	Continuous operation of power generation and energy storage assets during crew safety critical mission operations on the Martian surface	**UC-P-103 M**	Provide power generation, energy storage, and power distribution system(s) on the Martian surface that are able to supply continuous power availability during crew safety critical mission operations and are able to support contingency operations.	**CN-P-103 M**		
BLANK	**BLANK**	Continuous operation of power generation and energy storage assets to support contingency operations on the Martian surface	**UC-P-501 M**				
Provide communications and data exchange between assets on the Martian surface and Earth	**FN-C-102 M**	Communications and data exchange between assets at multiple distributed locations on the Martian surface and Earth	**UC-C-101 M**	Provide communication system(s) to enable high-bandwidth, high-availability communications between Earth-based personnel, surface crew, and assets on the surface.	**CN-C-101 M**	Develop Mars surface, orbital, and Mars-to-Earth communications to support an initial human Mars exploration campaign.	**MI-02 M**
Provide communications and data exchange between assets on the Martian surface	**FN-C-101 M**	Communications and data exchange between assets at multiple distributed locations on the Martian surface	**UC-C-102 M**				
Collect, store, and distribute data on the Martian surface	**FN-D-101 M**	Aggregation and storage of data on the Martian surface until it is able to be transmitted and confirmed received	**UC-C-107 M**				
Provide communications and data exchange between assets in deep space and/or Mars vicinity and Earth	**FN-C-104 M**	Communications and data exchange between assets in deep space and/or Mars vicinity and Earth	**UC-C-104 M**	Provide communication system(s) to enable high-bandwidth, high-availability communications between Earth-based personnel, in-space	**CN-C-102 M**		
Provide communications and data exchange between assets in deep space and/or Mars vicinity	**FN-C-107 M**	Communications and data exchange between assets in deep space and/or Mars vicinity	**UC-C-105 M**				

Functions		Use Cases		Characteristics/Needs		Objectives	
Collect, store, and distribute data in deep space and/or Mars vicinity	**FN-D-102 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-108 M**	crew, and in-space assets.			
Provide communications and data exchange between assets on the Martian surface	**FN-C-101 M**	Communications and data exchange between assets at multiple distributed locations on the Martian surface	**UC-C-102 M**	Provide communication system(s) to enable high-bandwidth, high-availability communications between in-space crew, surface crew, and assets on the surface.	**CN-C-103 M**		
Provide communications and data exchange between assets in deep space and/or Mars vicinity and the Martian surface	**FN-C-103 M**	Communications and data exchange between assets in deep space and/or Mars vicinity and the Martian surface	**UC-C-103 M**				
Collect, store, and distribute data on the Martian surface	**FN-D-101 M**	Aggregation and storage of data on the Martian surface until it is able to be transmitted and confirmed received	**UC-C-107 M**				
Collect, store, and distribute data in deep space and/or Mars vicinity	**FN-D-102 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-108 M**				
BLANK	**BLANK**	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-109 M**	Provide communication capabilities to allow NASA to inspire and inform the general public, students, and teachers by enabling them to interact, learn about, and experience missions in a direct and tangible way.	**CN-C-104 M**		
BLANK	**BLANK**	Asset(s) and/or payload(s) provide communications to inspire and inform the general public, students, and teachers	**UC-C-110 M**				
Provide position, navigation, and timing data on the Martian surface	**FN-C-201 M**	Determination of positioning, navigation, and timing for crew and assets at exploration sites on the Martian surface	**UC-C-202 M**	Demonstrate the capability for Mars landers to safely land within a defined radius around an intended location.	**CN-T-401 M**	Develop Mars position, navigation and timing capabilities to support an initial human Mars exploration campaign.	**MI-03 M**
Provide precision landing for transport of assets to the Martian surface (demonstration)	**FN-C-207 M**	Demonstration of landing within a defined radius around an intended location on the Martian surface	**UC-C-204 M**				
Provide position, navigation, and timing data in deep space and/or Mars vicinity	**FN-C-202 M**	Determination of positioning, navigation, and timing for crew and assets in deep space and Mars vicinity	**UC-C-203 M**	Provide navigation, positioning, and timing system(s) to enable high-availability navigation and tracking in deep space and in Mars vicinity.	**CN-C-201 M**		
Provide position, navigation, and timing data on the Martian surface	**FN-C-201 M**	Determination of positioning, navigation, and timing for crew and assets at exploration sites on the Martian surface	**UC-C-202 M**	Provide navigation, positioning, and timing system(s) to enable high-availability navigation and tracking on the Martian surface.	**CN-C-202 M**		

Functions		Use Cases		Characteristics/Needs		Objectives	
Identify the location(s) of collected Mars surface samples	**FN-U-305 M**	Identification, tracking, and documentation of the location(s) of collected Mars surface samples	**UC-C-201 M**	Provide system(s) to enable accurate location identification, tracking, and documentation of collected surface samples.	**CN-C-203 M**		
Document the Martian surface site location where samples were collected	**FN-U-307 M**						
Distribute power to assets on the Martian surface	**FN-P-303 M**	Deployment of exploration asset(s) for ISRU demonstration on the Martian surface	**UC-M-404 M**	Deploy scalable ISRU demonstration exploration asset(s) on the Martian surface.	**CN-I-102 M**	Demonstrate Mars ISRU capabilities to support an initial human Mars exploration campaign.	**MI-04 M**
Unload asset(s) on the Martian surface	**FN-M-403 M**						
Deploy ISRU demonstration assets into operational configuration on the Martian surface	**FN-M-404 M**						
Transfer assets between sites on the Martian surface	**FN-M-501 M**						
Command and control assets on the Martian surface from a remote location (e.g., Earth-based facilities, other Mars surface locations)	**FN-C-303 M**						
Transition ISRU assets from operation to end-of-life while minimizing impacts to long-term science objectives and sustainability (demonstration)	**FN-I-106 M**						
Collect in situ materials/feedstock on the Martian surface (demonstration)	**FN-I-101 M**	Demonstration of scalable ISRU production, storage, and/or transfer on the Martian surface	**UC-I-102 M**	Operate demonstration exploration asset(s) on the Martian surface to collect, produce, store, and transfer commodities, including water, oxygen and/or fuel, for potential use.	**CN-I-103 M**		
Produce commodities on the Martian surface (demonstration)	**FN-I-102 M**						
Process, refine, and verify the quality of commodities on the Martian surface (demonstration)	**FN-I-103 M**						
Store commodities on the Martian surface (demonstration)	**FN-I-104 M**						
Transfer ISRU commodities between assets and/or sites on the Martian surface (demonstration)	**FN-I-105 M**						
Identify and characterize in-situ material/feedstock on the Martian surface (demonstration)	**FN-I-107 M**						
Document and store data about a Martian surface site location	**FN-D-103 M**	Demonstration of surveying the Martian surface to identify and locate potential site(s) for resource utilization	**UC-U-102 M**	Demonstrate the capability to identify and locate potential site(s) for resource utilization.	**CN-U-101 M**		
Collect data about a Martian surface site location	**FN-U-103 M**						
Identify and characterize resources for potential resource utilization at a given site (demonstration)	**FN-U-202 M**						
Staging of crewed Mars mission(s) in Earth vicinity	**FN-T-101 M**	Staging of crewed Mars mission assets in Earth vicinity	**UC-T-103 M**	Provide capabilities to enable staging and/or assembly operations of crew and cargo system(s) in Earth vicinity with accessibility to Earth and to support departure for Mars missions.	**CN-T-106 M**	Develop in-space and surface habitation system(s) for crew to live in deep space for extended durations, enabling future missions to Mars.	**TH-04 LM**
Enable rendezvous, proximity operation, docking, berthing, and undocking of exploration assets in Earth vicinity	**FN-T-203 M**						
Manage a pressurized habitable environment for crew in Earth vicinity	**FN-H-116 M**						
Manage the transfer and storage of logistics in Earth vicinity	**FN-L-201 M**						
Provide communications and data exchange between Earth and Earth vicinity	**FN-C-108 M**						
Provide position, navigation, and timing data in Earth vicinity	**FN-C-203 M**						

Functions		Use Cases		Characteristics/Needs		Objectives	
Enable rendezvous, proximity operation, docking, berthing, and undocking of exploration assets in Earth vicinity	**FN-T-203 M**	Aggregation and/or physical assembly of assets in Earth vicinity	**UC-T-201 M**				
Provide position, navigation, and timing data in Earth vicinity	**FN-C-203 M**						
Operate exploration asset(s) when uncrewed before and/or between crewed missions in Earth vicinity	**FN-C-304 M**	Operation of exploration asset(s) when uncrewed before and/or between crew missions in Earth vicinity	**UC-H-202 M**				
Provide private areas for crew, including for individual crew members, for crew mission(s) on the Martian surface	**FN-H-107 M**	Habitation for crew exploration missions on the Martian surface	**UC-H-103 M**	Provide capabilities to conduct mid-duration (month+) crew exploration mission(s) on the Martian surface.	**CN-H-101 M**		
Manage and store logistics for crew mission(s) on the Martian surface	**FN-H-108 M**						
Manage a pressurized habitable environment for crew mission(s) on the Martian surface	**FN-H-109 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-110 M**						
Manage crew health and performance for mid-duration (month+) crew mission(s) on the Martian surface	**FN-X-102 M**						
Move logistics and/or cargo into habitable assets for crew mission(s) on the Martian surface	**FN-L-202 M**						
Manage waste/trash and housekeeping for nominal and contingency use for crew mission(s) on the Martian surface	**FN-L-302 M**						
Provide ingress/egress between habitable volumes and external environment that maintain crew health, performance and safety on the Martian surface	**FN-M-202 M**						
Manage crew health and performance for mid-duration (month+) crew mission(s) on the Martian surface	**FN-X-102 M**	Crew living for mid-duration (month+) crew exploration mission(s) on the Martian surface	**UC-H-105 M**				
Enable crew exercise on the Martian surface	**FN-X-105 M**						
Provide nutrition logistics for crew mission(s) on the Martian surface	**FN-X-106 M**						
Manage waste/trash and housekeeping for nominal and contingency use for crew mission(s) on the Martian surface	**FN-L-302 M**						
Control and monitor transfer of Mars environmental contamination into and between habitable assets on the Martian surface	**FN-G-501 M**	Transfer of crew between habitat and external environment on the Martian surface	**UC-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-202 M**						
Provide private areas for crew, including for individual crew members, for extended duration (year+) in deep space and/or Mars vicinity	**FN-H-103 M**	Habitation for extended duration (year+) in deep space and/or Mars vicinity	**UC-H-102 M**	Provide capabilities that allow crew to live in deep space for Mars-duration mission(s).	**CN-H-103 M**		
Manage and store logistics for extended duration (year+) in deep space and/or Mars vicinity	**FN-H-104 M**						
Manage a pressurized habitable environment for crew for extended duration (year+) in deep space and/or Mars vicinity	**FN-H-105 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-H-106 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-101 M**						

Functions		Use Cases		Characteristics/Needs		Objectives	
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-301 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-201 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-101 M	Crew living for extended duration (year+) in deep space and/or Mars vicinity	UC-H-104 M				
Enable crew exercise in deep space and/or Mars vicinity	FN-X-103 M	Crew living for extended duration (year+) in deep space and/or Mars vicinity	UC-H-104 M				
Prepare nutrition logistics for extended duration (year+) in deep space and/or Mars vicinity	FN-X-104 M	Crew living for extended duration (year+) in deep space and/or Mars vicinity	UC-H-104 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-301 M	Crew living for extended duration (year+) in deep space and/or Mars vicinity	UC-H-104 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-201 M	Transfer of crew between habitat and external environment in deep space and/or Mars vicinity	UC-M-201 M				
Transport crew between Earth vicinity and Mars vicinity	FN-T-104 M	Operation of robust Martian transportation systems	UC-T-108 M	Implement robust transportation capabilities, where systems can support all design reference missions, to support Mars missions.	CN-T-101 M	Develop transportation systems that crew can routinely operate between the Earth-Moon vicinity and Mars vicinity, including the Martian surface.	TH-05 M
Transfer propellant into storage system(s) and/or transportation system(s)	FN-T-210 M	Operation of robust Martian transportation systems	UC-T-108 M	Implement robust transportation capabilities, where systems can support all design reference missions, to support Mars missions.	CN-T-101 M	Develop transportation systems that crew can routinely operate between the Earth-Moon vicinity and Mars vicinity, including the Martian surface.	TH-05 M
Maintain necessary environmental conditions for propellant in storage system(s) or transportation system(s)	FN-T-211 M	Operation of robust Martian transportation systems	UC-T-108 M	Implement robust transportation capabilities, where systems can support all design reference missions, to support Mars missions.	CN-T-101 M	Develop transportation systems that crew can routinely operate between the Earth-Moon vicinity and Mars vicinity, including the Martian surface.	TH-05 M
Store propellant	FN-T-212 M	Operation of robust Martian transportation systems	UC-T-108 M	Implement robust transportation capabilities, where systems can support all design reference missions, to support Mars missions.	CN-T-101 M	Develop transportation systems that crew can routinely operate between the Earth-Moon vicinity and Mars vicinity, including the Martian surface.	TH-05 M
Transport cargo between Earth vicinity and Mars vicinity	FN-T-213 M	Operation of robust Martian transportation systems	UC-T-108 M	Implement robust transportation capabilities, where systems can support all design reference missions, to support Mars missions.	CN-T-101 M	Develop transportation systems that crew can routinely operate between the Earth-Moon vicinity and Mars vicinity, including the Martian surface.	TH-05 M
Transition asset in and out of uncrewed mode in Mars vicinity	FN-C-306 M	Operation of robust Martian transportation systems	UC-T-108 M	Implement robust transportation capabilities, where systems can support all design reference missions, to support Mars missions.	CN-T-101 M	Develop transportation systems that crew can routinely operate between the Earth-Moon vicinity and Mars vicinity, including the Martian surface.	TH-05 M
Transport crew from Earth surface to Earth vicinity	FN-T-103 M	Transportation of crew between Earth surface and Earth vicinity	UC-T-104 M	Provide capabilities to transport crew and system(s) between Earth, Earth vicinity, and Mars vicinity.	CN-T-102 M	Develop transportation systems that crew can routinely operate between the Earth-Moon vicinity and Mars vicinity, including the Martian surface.	TH-05 M
Provide ground services	FN-G-101 M	Transportation of crew between Earth surface and Earth vicinity	UC-T-104 M	Provide capabilities to transport crew and system(s) between Earth, Earth vicinity, and Mars vicinity.	CN-T-102 M	Develop transportation systems that crew can routinely operate between the Earth-Moon vicinity and Mars vicinity, including the Martian surface.	TH-05 M
Stack and integrate assets for transportation from Earth surface to Earth vicinity	FN-G-102 M	Transportation of crew between Earth surface and Earth vicinity	UC-T-104 M	Provide capabilities to transport crew and system(s) between Earth, Earth vicinity, and Mars vicinity.	CN-T-102 M	Develop transportation systems that crew can routinely operate between the Earth-Moon vicinity and Mars vicinity, including the Martian surface.	TH-05 M
Enable vehicle launch(es)	FN-G-103 M	Transportation of crew between Earth surface and Earth vicinity	UC-T-104 M	Provide capabilities to transport crew and system(s) between Earth, Earth vicinity, and Mars vicinity.	CN-T-102 M	Develop transportation systems that crew can routinely operate between the Earth-Moon vicinity and Mars vicinity, including the Martian surface.	TH-05 M
Enable multiple launch attempts for transportation from Earth surface to Earth vicinity	FN-G-104 M	Transportation of crew between Earth surface and Earth vicinity	UC-T-104 M	Provide capabilities to transport crew and system(s) between Earth, Earth vicinity, and Mars vicinity.	CN-T-102 M	Develop transportation systems that crew can routinely operate between the Earth-Moon vicinity and Mars vicinity, including the Martian surface.	TH-05 M
Provide position, navigation, and timing data in Earth vicinity	FN-C-203 M	Transportation of crew between Earth surface and Earth vicinity	UC-T-104 M	Provide capabilities to transport crew and system(s) between Earth, Earth vicinity, and Mars vicinity.	CN-T-102 M	Develop transportation systems that crew can routinely operate between the Earth-Moon vicinity and Mars vicinity, including the Martian surface.	TH-05 M
Transport crew between Earth vicinity and Mars vicinity	FN-T-104 M	Transportation of crew between Earth vicinity and Mars vicinity	UC-T-105 M	Provide capabilities to transport crew and system(s) between Earth, Earth vicinity, and Mars vicinity.	CN-T-102 M	Develop transportation systems that crew can routinely operate between the Earth-Moon vicinity and Mars vicinity, including the Martian surface.	TH-05 M
Provide position, navigation, and timing data in deep space and/or Mars vicinity	FN-C-202 M	Transportation of crew between Earth vicinity and Mars vicinity	UC-T-105 M	Provide capabilities to transport crew and system(s) between Earth, Earth vicinity, and Mars vicinity.	CN-T-102 M	Develop transportation systems that crew can routinely operate between the Earth-Moon vicinity and Mars vicinity, including the Martian surface.	TH-05 M
Transport cargo from Earth surface to Earth vicinity	FN-T-204 M	Transportation of cargo between Earth surface and Earth vicinity	UC-T-202 M	Provide capabilities to transport crew and system(s) between Earth, Earth vicinity, and Mars vicinity.	CN-T-102 M	Develop transportation systems that crew can routinely operate between the Earth-Moon vicinity and Mars vicinity, including the Martian surface.	TH-05 M
Provide ground services	FN-G-101 M	Transportation of cargo between Earth surface and Earth vicinity	UC-T-202 M	Provide capabilities to transport crew and system(s) between Earth, Earth vicinity, and Mars vicinity.	CN-T-102 M	Develop transportation systems that crew can routinely operate between the Earth-Moon vicinity and Mars vicinity, including the Martian surface.	TH-05 M

Functions		Use Cases		Characteristics/Needs		Objectives	
Stack and integrate assets for transportation from Earth surface to Earth vicinity	FN-G-102 M						
Enable vehicle launch(es)	FN-G-103 M						
Enable multiple launch attempts for transportation from Earth surface to Earth vicinity	FN-G-104 M						
Provide position, navigation, and timing data in Earth vicinity	FN-C-203 M						
Transport cargo between Earth vicinity and Mars vicinity	FN-T-213 M	Transportation of cargo between Earth vicinity and Mars vicinity	UC-T-203 M				
Provide position, navigation, and timing data in deep space and/or Mars vicinity	FN-C-202 M						
Transport crew from Martian surface to Mars vicinity	FN-T-102 M	Transportation of crew from Martian surface to Mars vicinity	UC-T-101 M	Provide capabilities to transport crew between Mars vicinity and the Martian surface.	CN-T-103 M		
Enable crew habitation during transit from the Martian surface to Mars vicinity	FN-H-120 M						
Provide position, navigation, and timing during Mars ascent	FN-C-205 M						
Transport crew from Mars vicinity to the Martian surface	FN-T-401 M	Transportation of crew from Mars vicinity to the Martian surface	UC-T-102 M				
Enable crew habitation during transit from Mars vicinity to Martian surface	FN-H-102 M						
Provide position, navigation, and timing during Mars ascent	FN-C-205 M						
Staging of crewed Mars mission(s) in Earth vicinity	FN-T-101 M	Staging of crewed Mars mission assets in Earth vicinity	UC-T-103 M	Provide capabilities to enable staging and/or assembly operations of crew and cargo system(s) in space to enable access to deep space and Mars.	CN-T-107 M		
Enable rendezvous, proximity operation, docking, berthing, and undocking of exploration assets in Earth vicinity	FN-T-203 M						
Manage a pressurized habitable environment for crew in Earth vicinity	FN-H-116 M						
Manage the transfer and storage of logistics in Earth vicinity	FN-L-201 M						
Provide communications and data exchange between Earth and Earth vicinity	FN-C-108 M						
Provide position, navigation, and timing data in Earth vicinity	FN-C-203 M						
Enable rendezvous, proximity operation, docking, berthing, and undocking of exploration assets in Mars vicinity	FN-T-205 M	Staging of crewed Mars surface mission assets in Mars vicinity	UC-T-106 M				
Manage a pressurized habitable environment for crew in Mars vicinity	FN-H-117 M						
Provide position, navigation, and timing data in deep space and/or Mars vicinity	FN-C-202 M						
Enable rendezvous, proximity operation, docking, berthing, and undocking of exploration assets in Earth vicinity	FN-T-203 M	Aggregation and/or physical assembly of assets in Earth vicinity	UC-T-201 M				
Provide position, navigation, and timing data in Earth vicinity	FN-C-203 M						
Enable rendezvous, proximity operation, docking, berthing, and undocking of exploration assets in Mars vicinity	FN-T-205 M		UC-T-204 M				

Functions		Use Cases		Characteristics/Needs		Objectives	
Provide position, navigation, and timing data in deep space and/or Mars vicinity	**FN-C-202 M**	Aggregation and/or physical assembly of assets in Mars vicinity					
Unload asset(s) in Earth vicinity	**FN-T-206 M**	Deployment of assets in Earth vicinity	**UC-T-205 M**				
Deploy assets into operational configuration in Earth vicinity	**FN-T-207 M**						
Distribute power to assets in Earth vicinity	**FN-P-301 M**						
Command and control assets in Earth vicinity from a remote location (e.g., Earth-based facilities)	**FN-C-301 M**						
Unload asset(s) in deep space and/or Mars vicinity	**FN-T-208 M**	Deployment of assets in deep space and/or Mars vicinity	**UC-T-206 M**				
Deploy assets into operational configuration in deep space and/or Mars vicinity	**FN-T-209 M**						
Distribute power to assets in deep space and/or Mars vicinity	**FN-P-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-302 M**						
Command and control assets in Earth vicinity from a remote location (e.g., Earth-based facilities)	**FN-C-301 M**	Operation of exploration asset(s) when uncrewed in Earth vicinity	**UC-H-203 M**	Provide capabilities to operate system(s) in uncrewed mode for mid-duration (month+) to extended-duration (year+) in Earth vicinity, Mars vicinity, and/or Martian surface.	**CN-T-112 M**		
Transition asset in and out of uncrewed mode in Earth vicinity	**FN-C-305 M**						
Command and control assets in deep space and/or Mars vicinity from a remote location (e.g., Earth-based facilities) (demonstration)	**FN-C-302 M**	Operation of exploration asset(s) when uncrewed in Mars vicinity	**UC-H-204 M**				
Transition asset in and out of uncrewed mode in Mars vicinity	**FN-C-306 M**						
Command and control assets on the Martian surface from a remote location (e.g., Earth-based facilities, other Mars surface locations)	**FN-C-303 M**	Operation of exploration asset(s) when uncrewed on Mars surface	**UC-H-205 M**				
Transition asset in and out of uncrewed mode on Mars surface	**FN-C-307 M**						
Transport crew between Earth vicinity and Mars vicinity	**FN-T-104 M**	Transportation of crew between Earth vicinity and Mars vicinity	**UC-T-105 M**	Provide capabilities to safely return crew and system(s) to Earth from Mars.	**CN-T-113 M**		
Provide position, navigation, and timing data in deep space and/or Mars vicinity	**FN-C-202 M**						
Transport crew from Earth vicinity to Earth surface	**FN-T-402 M**	Return crew from Earth vicinity to Earth surface	**UC-T-107 M**				
Recover crew and cargo after landing on Earth surface	**FN-G-201 M**						
Provide position, navigation, and timing data in Earth vicinity	**FN-C-203 M**						
Transport crew between Earth vicinity and Mars vicinity	**FN-T-104 M**	Operation of robust Martian transportation systems	**UC-T-108 M**	Implement robust transportation capabilities, where systems can support all design reference	**CN-T-101 M**	Develop transportation systems that can deliver a range of elements to the Martian surface.	**TH-06 M**
Transfer propellant into storage system(s) and/or transportation system(s)	**FN-T-210 M**						
Maintain necessary environmental conditions for propellant in storage system(s) or transportation system(s)	**FN-T-211 M**						

Functions		Use Cases		Characteristics/Needs		Objectives	
Store propellant	**FN-T-212 M**			missions, to support Mars missions.			
Transport cargo between Earth vicinity and Mars vicinity	**FN-T-213 M**						
Transition asset in and out of uncrewed mode in Mars vicinity	**FN-C-306 M**						
Enable rendezvous, proximity operation, docking, berthing, and undocking of exploration assets in Earth vicinity	**FN-T-203 M**	Aggregation and/or physical assembly of assets in Earth vicinity	**UC-T-201 M**	Provide capabilities to deliver system(s) from Earth and Earth vicinity to Mars vicinity and Mars surface.	**CN-T-201 M**		
Provide position, navigation, and timing data in Earth vicinity	**FN-C-203 M**						
Transport cargo from Earth surface to Earth vicinity	**FN-T-204 M**	Transportation of cargo between Earth surface and Earth vicinity	**UC-T-202 M**				
Provide ground services	**FN-G-101 M**						
Stack and integrate assets for transportation from Earth surface to Earth vicinity	**FN-G-102 M**						
Enable vehicle launch(es)	**FN-G-103 M**						
Enable multiple launch attempts for transportation from Earth surface to Earth vicinity	**FN-G-104 M**						
Provide position, navigation, and timing data in Earth vicinity	**FN-C-203 M**						
Transport cargo between Earth vicinity and Mars vicinity	**FN-T-213 M**	Transportation of cargo between Earth vicinity and Mars vicinity	**UC-T-203 M**				
Provide position, navigation, and timing data in deep space and/or Mars vicinity	**FN-C-202 M**						
Transport cargo from Mars vicinity to the Martian surface	**FN-T-202 M**	Transportation of cargo from Mars vicinity to the Martian surface	**UC-T-207 M**				
Provide Mars atmospheric entry for cargo	**FN-T-404 M**						
Provide position, navigation, and timing during Mars entry, descent, and landing	**FN-C-204 M**						
Distribute power to assets on the Martian surface	**FN-P-303 M**	Deployment of assets on the Martian surface	**UC-M-401 M**	Provide capabilities to unload cargo from delivery system(s).	**CN-M-401 M**		
Deploy assets into operational configuration on the Martian surface	**FN-M-402 M**						
Unload asset(s) on the Martian surface	**FN-M-403 M**						
Command and control assets on the Martian surface from a remote location (e.g., Earth-based facilities, other Mars surface locations)	**FN-C-303 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-214 M**	Disposal of assets in a manner that ensures future viable usage of exploration sites on the Martian surface	**UC-U-805 M**	Implement end-of-life strategies for transportation systems to ensure future viable usage of exploration sites on the Martian surface.	**CN-U-807 M**		
Provide position, navigation, and timing data on the Martian surface	**FN-C-201 M**						
Transition assets into end-of-life mode	**FN-C-310 M**						
Enable planetary protection protocols for end-of-life for assets in Mars vicinity	**FN-U-802 M**						

Functions		Use Cases		Characteristics/Needs		Objectives	
Enable planetary protection protocols for end-of-life for assets on the Martian surface	**FN-U-803 M**						
Provide private areas for crew, including for individual crew members, for crew mission(s) on the Martian surface	**FN-H-107 M**	Habitation for crew exploration missions on the Martian surface	**UC-H-103 M**	Provide capabilities to conduct mid-duration (month+) crew exploration mission(s) on the Martian surface.	**CN-H-101 M**	Develop systems for crew to explore, operate, and live on the Martian surface to address key questions with respect to science and resources.	**TH-07 M**
Manage and store logistics for crew mission(s) on the Martian surface	**FN-H-108 M**						
Manage a pressurized habitable environment for crew mission(s) on the Martian surface	**FN-H-109 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-110 M**						
Manage crew health and performance for mid-duration (month+) crew mission(s) on the Martian surface	**FN-X-102 M**						
Move logistics and/or cargo into habitable assets for crew mission(s) on the Martian surface	**FN-L-202 M**						
Manage waste/trash and housekeeping for nominal and contingency use for crew mission(s) on the Martian surface	**FN-L-302 M**						
Provide ingress/egress between habitable volumes and external environment that maintain crew health, performance and safety on the Martian surface	**FN-M-202 M**						
Manage crew health and performance for mid-duration (month+) crew mission(s) on the Martian surface	**FN-X-102 M**	Crew living for mid-duration (month+) crew exploration mission(s) on the Martian surface	**UC-H-105 M**				
Enable crew exercise on the Martian surface	**FN-X-105 M**						
Provide nutrition logistics for crew mission(s) on the Martian surface	**FN-X-106 M**						
Manage waste/trash and housekeeping for nominal and contingency use for crew mission(s) on the Martian surface	**FN-L-302 M**						
Control and monitor transfer of Mars environmental contamination into and between habitable assets on the Martian surface	**FN-G-501 M**	Transfer of crew between habitat and external environment on the Martian surface	**UC-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-202 M**						
Control and monitor transfer of Mars environmental contamination into and between habitable assets on the Martian surface	**FN-G-501 M**	Transfer of crew between habitat and external environment on the Martian surface	**UC-M-202 M**	Provide capabilities to enable crew transition in/out of habitable space to conduct EVA activities.	**CN-M-102 M**		
Provide ingress/egress between habitable volumes and external environment that maintain crew health, performance and safety on the Martian surface	**FN-M-202 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-101 M**	Deployment and operation of crew health monitoring assets in deep space and/or Mars vicinity	**UC-X-107 M**	Provide appropriate medical capabilities (including behavioral health) that allow for autonomous crew health decision making and care, and are preparatory of a mission to Mars.	**CN-X-101 M**	Develop systems that monitor and maintain crew health and performance throughout all mission phases, including during communication delays to Earth, and in an environment that does not allow emergency	**TH-08 LM**
Deploy crew health monitoring assets for extended duration (year+) in deep space and/or Mars vicinity	**FN-X-107 M**						
Manage crew health and performance for mid-duration (month+) crew mission(s) on the Martian surface	**FN-X-102 M**	Deployment and operation of crew health monitoring assets on the Martian surface	**UC-X-108 M**				
Deploy crew health monitoring assets for extended duration (year+) in deep space and/or Mars vicinity	**FN-X-107 M**						

Functions		Use Cases		Characteristics/Needs		Objectives	
Provide private areas for crew, including for individual crew members, for extended duration (year+) in deep space and/or Mars vicinity	**FN-H-103 M**	Habitation for extended duration (year+) in deep space and/or Mars vicinity	**UC-H-102 M**	Provide crew health and performance capabilities in deep space and Mars vicinity, including demonstration of remote and autonomous health care and advanced diagnostics.	**CN-X-102 M**	evacuation or terrestrial medical assistance.	
Manage and store logistics for extended duration (year+) in deep space and/or Mars vicinity	**FN-H-104 M**						
Manage a pressurized habitable environment for crew for extended duration (year+) in deep space and/or Mars vicinity	**FN-H-105 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-H-106 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-101 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-301 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-201 M**						
Provide private areas for crew, including for individual crew members, for crew mission(s) on the Martian surface	**FN-H-107 M**	Habitation for crew exploration missions on the Martian surface	**UC-H-103 M**	Provide crew health and performance capabilities on the Martian surface, including demonstration of remote and autonomous health care and advanced diagnostics.	**CN-X-103 M**		
Manage and store logistics for crew mission(s) on the Martian surface	**FN-H-108 M**						
Manage a pressurized habitable environment for crew mission(s) on the Martian surface	**FN-H-109 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-110 M**						
Manage crew health and performance for mid-duration (month+) crew mission(s) on the Martian surface	**FN-X-102 M**						
Move logistics and/or cargo into habitable assets for crew mission(s) on the Martian surface	**FN-L-202 M**						
Manage waste/trash and housekeeping for nominal and contingency use for crew mission(s) on the Martian surface	**FN-L-302 M**						
Provide ingress/egress between habitable volumes and external environment that maintain crew health, performance and safety on the Martian surface	**FN-M-202 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-101 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-105 M**	Provide countermeasures capabilities that are commensurate in scope with the human system needs for the mission.	**CN-X-104 M**		
Enable crew exercise in deep space and/or Mars vicinity	**FN-X-103 M**						
Manage crew health and performance for mid-duration (month+) crew mission(s) on the Martian surface	**FN-X-102 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-106 M**				
Enable crew exercise on the Martian surface	**FN-X-105 M**						
Enable crew exercise on the Martian surface	**FN-X-105 M**	Operation of crew health and performance countermeasures assets (e.g., exercise, nutrition, sensorimotor, cardiovascular,	**UC-X-109 M**				
Manage crew health and performance for short-duration (less than one month) crewed mission(s) on the Martian surface	**FN-X-108 M**						

Functions		Use Cases		Characteristics/Needs		Objectives	
		immune, radiation) for short-duration (less than one month) crew exploration mission(s) on the Martian surface					
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-404 M**	Commissioning, servicing, maintenance, and upgrades for assets to maintain and restore appropriate performance in deep space and/or Mars vicinity	**UC-G-401 M**	Provide crew survival capabilities in deep space, Mars vicinity, and on the Martian surface, including safe havens, system supportability, and/or aborts, for nominal and off-nominal scenarios.	**CN-X-105 M**		
Inspect assets during extended duration (year+) in deep space and/or Mars vicinity	**FN-G-405 M**						
Detect asset anomalies or off-nominal performance in deep space and/or Mars vicinity	**FN-G-411 M**						
Diagnose asset anomalies or off-nominal performance in deep space and/or Mars vicinity	**FN-G-412 M**						
Determine if asset servicing/maintenance is needed in deep space and/or Mars vicinity	**FN-G-413 M**						
Manage waste/trash from servicing, maintenance, or upgrade activities (demonstration)	**FN-L-203 M**						
Manipulate robotic/EVA/IVA tools and hardware to perform asset servicing, maintenance, upgrades, or replacements on the Martian surface	**FN-G-402 M**	Commissioning, servicing, maintenance, and upgrades for assets to maintain and restore appropriate performance on the Martian surface	**UC-G-402 M**				
Inspect assets on the Martian surface	**FN-G-403 M**						
Inspect performance of servicing, maintenance, upgrade, or replacement activities to evaluate success on the Martian surface	**FN-G-406 M**						
Detect asset anomalies or off-nominal performance on the Martian surface	**FN-G-408 M**						
Diagnose asset anomalies or off-nominal performance on the Martian surface	**FN-G-409 M**						
Determine if asset servicing/maintenance is needed on the Martian surface	**FN-G-410 M**						
Manage waste/trash from servicing, maintenance, or upgrade activities (demonstration)	**FN-L-203 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-123 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-101 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-125 M**						
Demonstrate treatment of emergency crew health conditions for extended duration (year+) crew mission(s) in deep space and/or Mars vicinity	**FN-X-109 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-111 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-301 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-124 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-102 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-126 M**						
Demonstrate treatment of emergency crew health conditions for crew mission(s) on the Martian surface	**FN-X-110 M**						

Functions		Use Cases		Characteristics/Needs		Objectives	
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-112 M**						
Manage waste/trash and housekeeping for nominal and contingency use for crew mission(s) on the Martian surface	**FN-L-302 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-111 M**	Demonstration of operations and emergency response capabilities to enable crew survival in deep space and Mars vicinity	**UC-X-103 M**				
Provide safe haven for extended duration (year+) in deep space and/or Mars vicinity	**FN-H-112 M**						
Demonstrate recovery of habitable environment during extended duration (year+) mission in deep space and/or Mars vicinity	**FN-H-113 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-127 M**						
Provide safe haven for crew mission(s) on the Martian surface	**FN-H-114 M**	Demonstration of operations and emergency response capabilities to enable crew survival on the Martian surface	**UC-X-104 M**				
Demonstrate recovery of habitable environment for crew mission(s) on the Martian surface	**FN-H-115 M**						
Demonstrate use of crew survival equipment and assets for crew mission(s) on the Martian surface	**FN-H-128 M**						
Demonstrate remediation of hazardous conditions within habitable assets for crew mission(s) on the Martian surface	**FN-H-129 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-118 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-106 M**	Provide appropriate environmental monitoring capabilities that enables inflight crew health decision making and mitigation of relevant system/vehicle hazards.	**CN-U-105 M**		
Monitor the pressurized environment and induced environments to detect potential hazards to crew within habitable assets on the Martian surface	**FN-H-119 M**	Monitoring of environment in habitable assets and mitigation of relevant asset hazards to protect crew health on the Martian surface	**UC-H-107 M**				
Deploy robotic assets into operational configuration in deep space and/or Mars vicinity	**FN-T-201 M**	Deployment of robotic assets to assist crew in deep space and/or Mars vicinity	**UC-M-402 M**	Provide appropriate robotic system(s) that can conduct or assist in tasks that would otherwise be performed by the crew alone in Mars vicinity or deep space.	**CN-A-101 M**	Develop integrated human and robotic systems with inter-relationships that enable maximum science and exploration during Martian missions.	**TH-10 M**
Unload asset(s) in deep space and/or Mars vicinity	**FN-T-208 M**						
Distribute power to assets in deep space and/or Mars vicinity	**FN-P-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-302 M**						
Enable robotic assistance of crew in deep space and/or Mars vicinity	**FN-A-116 M**						
Distribute power to assets on the Martian surface	**FN-P-303 M**	Deployment of robotic assets to assist crew on the Martian surface	**UC-M-403 M**	Provide appropriate robotic system(s) that can conduct or assist in tasks that would otherwise be performed by the crew alone on the Martian surface.	**CN-A-102 M**		
Deploy robotic assets into operational configuration on the Martian surface	**FN-M-401 M**						
Unload asset(s) on the Martian surface	**FN-M-403 M**						
Enable robotic assistance of crew on the Martian surface	**FN-A-117 M**						

Functions		Use Cases		Characteristics/Needs		Objectives	
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-201 M**						
Prepare cargo for Earth surface return from Earth vicinity	**FN-T-217 M**	Transportation of cargo from Earth vicinity back to Earth-based facilities	**UC-T-209 M**	Provide capabilities to return cargo from Earth vicinity back to Earth-based facilities.	**CN-T-202 M**	Develop systems capable of returning a range of cargo mass from the Martian surface to Earth, including the capabilities necessary to meet scientific and utilization objectives.	**TH-12 M**
Transport cargo from Earth vicinity to Earth surface	**FN-T-403 M**						
Recover cargo after landing on Earth surface	**FN-G-202 M**						
Relocate cargo in a clean environment, minimizing contamination to/from the container, between sites and facilities on Earth's surface	**FN-G-203 M**						
Provide position, navigation, and timing data in Earth vicinity	**FN-C-203 M**						
Provide precision landing for transport of assets to Earth's surface	**FN-C-206 M**						
Transport cargo between Earth vicinity and Mars vicinity	**FN-T-213 M**	Transportation of cargo between Earth vicinity and Mars vicinity	**UC-T-203 M**	Provide capabilities to return cargo from the Martian surface back to Earth vicinity.	**CN-T-203 M**		
Provide position, navigation, and timing data in deep space and/or Mars vicinity	**FN-C-202 M**						
Transport cargo from Martian surface to Mars vicinity	**FN-T-215 M**	Transportation of cargo from the Martian surface to Mars vicinity	**UC-T-208 M**				
Store cargo during ascent from the Martian surface	**FN-T-216 M**						
Provide position, navigation, and timing during Mars ascent	**FN-C-205 M**						
Transport cargo between Earth vicinity and Mars vicinity	**FN-T-213 M**	Transportation of cargo between Earth vicinity and Mars vicinity	**UC-T-203 M**	Transfer, return, and curate a small amount (10s of kg) or a large amount (100s of kg) of unconditioned samples and containers from key destinations across the Martian surface, while maintaining scientific integrity of the samples.	**CN-T-301 M**		
Provide position, navigation, and timing data in deep space and/or Mars vicinity	**FN-C-202 M**						
Prepare cargo for Earth surface return from Earth vicinity	**FN-T-217 M**	Transportation of cargo from Earth vicinity back to Earth-based facilities	**UC-T-209 M**				
Transport cargo from Earth vicinity to Earth surface	**FN-T-403 M**						
Recover cargo after landing on Earth surface	**FN-G-202 M**						
Relocate cargo in a clean environment, minimizing contamination to/from the container, between sites and facilities on Earth's surface	**FN-G-203 M**						
Provide position, navigation, and timing data in Earth vicinity	**FN-C-203 M**						
Provide precision landing for transport of assets to Earth's surface	**FN-C-206 M**						
Transport cargo between Earth vicinity and Mars vicinity	**FN-T-213 M**	Transportation of collected samples from the Martian surface to Earth vicinity in sealed sample containers	**UC-T-212 M**				
Transport cargo from Martian surface to Mars vicinity	**FN-T-215 M**						
Provide position, navigation, and timing during Mars ascent	**FN-C-205 M**						
Store collected unconditioned samples from the Martian surface in sealed sample containers, while maintaining scientific integrity of the samples	**FN-U-402 M**						

Functions		Use Cases		Characteristics/Needs		Objectives	
Transport cargo between Earth vicinity and Mars vicinity	**FN-T-213 M**	Transportation of cargo between Earth vicinity and Mars vicinity	**UC-T-203 M**	Transfer, return and curate a small amount (10s of kg) or a large amount (100s of kg) of refrigerated sample(s), containers, and freezers from key destinations across the Martian surface, while maintaining scientific integrity of the samples.	**CN-T-302 M**		
Provide position, navigation, and timing data in deep space and/or Mars vicinity	**FN-C-202 M**						
Transport cargo between Earth vicinity and Mars vicinity	**FN-T-213 M**	Transportation of collected surface and sub-surface samples from the Martian surface to Earth vicinity in sealed conditioned sample containers	**UC-T-210 M**				
Transport cargo from Martian surface to Mars vicinity	**FN-T-215 M**						
Prepare conditioned cargo or samples for Earth return	**FN-T-301 M**						
Provide resources to condition sample containers during transfer from Martian surface to Earth vicinity	**FN-T-302 M**						
Provide resources to condition sample containers on the Martian surface	**FN-T-303 M**						
Provide position, navigation, and timing during Mars ascent	**FN-C-205 M**						
Store collected refrigerated surface and sub-surface samples in sealed conditioned sample containers, while maintaining scientific integrity of the samples	**FN-U-401 M**						
Prepare conditioned cargo or samples for Earth return	**FN-T-301 M**	Transportation of conditioned cargo and samples from Earth vicinity to curation facilities on Earth after landing	**UC-T-211 M**				
Provide resources to condition sample containers during transfer from Earth vicinity to curation facilities on Earth	**FN-T-304 M**						
Transport cargo from Earth vicinity to Earth surface	**FN-T-403 M**						
Recover cargo after landing	**FN-G-204 M**						
Recover samples and transport in a clean environment, minimizing contamination to/from the container, to curation facilities after Earth landing	**FN-G-205 M**						
Provide position, navigation, and timing data in Earth vicinity	**FN-C-203 M**						
Provide precision landing for transport of assets to Earth's surface	**FN-C-206 M**						
Store collected refrigerated surface and sub-surface samples in sealed conditioned sample containers, while maintaining scientific integrity of the samples	**FN-U-401 M**						
Transport cargo between Earth vicinity and Mars vicinity	**FN-T-213 M**	Transportation of cargo between Earth vicinity and Mars vicinity	**UC-T-203 M**	Transfer, return and curate a small amount (10s of kg) or a large amount (100s of kg) of frozen sample(s), containers, and freezers from key destinations across the Martian surface, while maintaining scientific integrity of the samples.	**CN-T-303 M**		
Provide position, navigation, and timing data in deep space and/or Mars vicinity	**FN-C-202 M**						
Transport cargo between Earth vicinity and Mars vicinity	**FN-T-213 M**	Transportation of collected surface and sub-surface samples from the Martian surface to Earth vicinity in sealed conditioned sample containers	**UC-T-210 M**				
Transport cargo from Martian surface to Mars vicinity	**FN-T-215 M**						
Prepare conditioned cargo or samples for Earth return	**FN-T-301 M**						
Provide resources to condition sample containers during transfer from Martian surface to Earth vicinity	**FN-T-302 M**						
Provide resources to condition sample containers on the Martian surface	**FN-T-303 M**						

Functions		Use Cases		Characteristics/Needs		Objectives	
Provide position, navigation, and timing during Mars ascent	FN-C-205 M						
Store collected refrigerated surface and sub-surface samples in sealed conditioned sample containers, while maintaining scientific integrity of the samples	FN-U-401 M						
Prepare conditioned cargo or samples for Earth return	FN-T-301 M	Transportation of conditioned cargo and samples from Earth vicinity to curation facilities on Earth after landing	UC-T-211 M				
Provide resources to condition sample containers during transfer from Earth vicinity to curation facilities on Earth	FN-T-304 M						
Transport cargo from Earth vicinity to Earth surface	FN-T-403 M						
Recover cargo after landing	FN-G-204 M						
Recover samples and transport in a clean environment, minimizing contamination to/from the container, to curation facilities after Earth landing	FN-G-205 M						
Provide position, navigation, and timing data in Earth vicinity	FN-C-203 M						
Provide precision landing for transport of assets to Earth's surface	FN-C-206 M						
Store collected refrigerated surface and sub-surface samples in sealed conditioned sample containers, while maintaining scientific integrity of the samples	FN-U-401 M						
Transport cargo between Earth vicinity and Mars vicinity	FN-T-213 M	Transportation of cargo between Earth vicinity and Mars vicinity	UC-T-203 M	Transfer, return, and curate a large amount (100s of kg) of cryogenic samples, containers, and freezers from key destinations across the Martian surface, while maintaining scientific integrity of the samples.	CN-T-304 M		
Provide position, navigation, and timing data in deep space and/or Mars vicinity	FN-C-202 M						
Transport cargo between Earth vicinity and Mars vicinity	FN-T-213 M	Transportation of collected surface and sub-surface samples from the Martian surface to Earth vicinity in sealed conditioned sample containers	UC-T-210 M				
Transport cargo from Martian surface to Mars vicinity	FN-T-215 M						
Prepare conditioned cargo or samples for Earth return	FN-T-301 M						
Provide resources to condition sample containers during transfer from Martian surface to Earth vicinity	FN-T-302 M						
Provide resources to condition sample containers on the Martian surface	FN-T-303 M						
Provide position, navigation, and timing during Mars ascent	FN-C-205 M						
Store collected refrigerated surface and sub-surface samples in sealed conditioned sample containers, while maintaining scientific integrity of the samples	FN-U-401 M						
Prepare conditioned cargo or samples for Earth return	FN-T-301 M	Transportation of conditioned cargo and samples from Earth vicinity to curation facilities on Earth after landing	UC-T-211 M				
Provide resources to condition sample containers during transfer from Earth vicinity to curation facilities on Earth	FN-T-304 M						
Transport cargo from Earth vicinity to Earth surface	FN-T-403 M						
Recover cargo after landing	FN-G-204 M						
Recover samples and transport in a clean environment, minimizing contamination to/from the container, to curation facilities after Earth landing	FN-G-205 M						

Functions		Use Cases		Characteristics/Needs		Objectives	
Provide position, navigation, and timing data in Earth vicinity	**FN-C-203 M**						
Provide precision landing for transport of assets to Earth's surface	**FN-C-206 M**						
Store collected refrigerated surface and sub-surface samples in sealed conditioned sample containers, while maintaining scientific integrity of the samples	**FN-U-401 M**						
Provide Earth-independent decision support for time-critical asset malfunctions on Mars surface (demonstration)	**FN-D-201 M**	Demonstration of response to off-nominal, time-critical events during a mission on the Martian surface with Mars communication latency	**UC-G-501 M**	Operate and gain experience with flight control and mission integration to ensure safety and mission success in nominal and off-nominal conditions.	**CN-T-402 M**	Optimize operations, training and interaction between the team on Earth, crew members on orbit, and a Martian surface team considering communication delays, autonomy level, and time required for an early return to the Earth.	**OP-02 LM**
Provide real-time situational awareness with reduced reliance on ground support on Mars surface (demonstration)	**FN-U-101 M**						
Provide Earth-independent decision support for time-critical asset malfunctions in deep space and/or Mars vicinity (demonstration)	**FN-A-403 M**	Demonstration of response to off-nominal, time-critical events during missions in deep space and/or Mars vicinity with communication latency	**UC-G-502 M**				
Provide real-time situational awareness with reduced reliance on ground support in deep space and/or Mars vicinity (demonstration)	**FN-U-108 M**						
Monitor the performance and health of assets on the Martian surface (demonstration)	**FN-G-401 M**	Flight control and mission integration in nominal and off-nominal scenarios on Mars surface with Mars communication latency	**UC-A-405 M**				
Command and control assets on the Martian surface from a remote location (e.g., Earth-based facilities, other Mars surface locations)	**FN-C-303 M**						
Monitor the performance and health of assets in deep space and/or Mars vicinity (demonstration)	**FN-G-407 M**	Flight control and mission integration in nominal and off-nominal scenarios in deep space and/or Mars vicinity with Mars communication latency	**UC-A-406 M**				
Command and control assets in deep space and/or Mars vicinity from a remote location (e.g., Earth-based facilities) (demonstration)	**FN-C-302 M**						
Enable on-demand, in-situ training of crew in deep space for nominal and contingency procedures	**FN-X-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-201 M**	Operate and gain experience with in-situ training and planning capabilities to ensure safety and mission success.	**CN-X-201 M**		
Enable on-demand, in-situ training of crew on the Martian surface for nominal and contingency procedures	**FN-X-202 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-X-201 M**				
Stabilize and mitigate hazardous conditions autonomously within habitable assets in deep space and/or Mars vicinity	**FN-H-101 M**	Habitable assets response to emergencies autonomously to enable crew survival in deep space and/or Mars vicinity	**UC-H-101 M**	Operate and gain experience with onboard autonomous system(s) and crew autonomy to train, plan, and execute safe mission(s) with reduced reliance on Earth based systems.	**CN-A-401 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-118 M**						
Monitor the pressurized environment and induced environments to detect potential hazards to crew within habitable assets on the Martian surface	**FN-H-119 M**	Habitable assets response to emergencies autonomously to enable crew survival on Mars surface	**UC-H-108 M**				
Stabilize and mitigate hazardous conditions autonomously within habitable assets on Mars surface	**FN-H-121 M**						
Enable on-demand, in-situ training of crew in deep space for nominal and contingency procedures	**FN-X-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-201 M**				

Functions		Use Cases		Characteristics/Needs		Objectives	
Enable on-demand, in-situ training of crew on the Martian surface for nominal and contingency procedures	**FN-X-202 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-X-201 M**				
Provide safety features on robotic and/or autonomous asset(s) operating near crew	**FN-A-301 M**	Safe and effective interaction between crew and autonomous asset(s)	**UC-A-301 M**				
BLANK	**BLANK**	Planning and execution of crew tasks on Mars surface with autonomy and reduced reliance on Earth based systems	**UC-A-401 M**				
BLANK	**BLANK**	Planning and execution of crew tasks in deep space and/or Mars vicinity with autonomy and reduced reliance on Earth based systems	**UC-A-402 M**				
Monitor the performance and health of assets on the Martian surface (demonstration)	**FN-G-401 M**	Demonstration of autonomous operation of assets on Mars surface with reduced commands from crew or Earth-based systems	**UC-A-403 M**				
Monitor the performance and health of assets in deep space and/or Mars vicinity (demonstration)	**FN-G-407 M**						
Execute higher-level commands and make in-situ decisions autonomously for assets on the Martian surface (demonstration)	**FN-A-401 M**						
Monitor the performance and health of assets in deep space and/or Mars vicinity (demonstration)	**FN-G-407 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-404 M**				
Execute higher-level commands and make in-situ decisions autonomously for assets in deep space and/or Mars vicinity (demonstration)	**FN-A-402 M**						
Stabilize and mitigate hazardous conditions autonomously within habitable assets in deep space and/or Mars vicinity	**FN-H-101 M**	Habitable assets response to emergencies autonomously to enable crew survival in deep space and/or Mars vicinity	**UC-H-101 M**	Operate and gain experience with remote & autonomous system(s) to reduce crew workload.	**CN-A-402 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-118 M**						
Monitor the pressurized environment and induced environments to detect potential hazards to crew within habitable assets on the Martian surface	**FN-H-119 M**	Habitable assets response to emergencies autonomously to enable crew survival on Mars surface	**UC-H-108 M**				
Stabilize and mitigate hazardous conditions autonomously within habitable assets on Mars surface	**FN-H-121 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-105 M**	Remote command and control of assets on Mars surface from assets on Earth, Mars vicinity, and/or other Mars surface locations	**UC-C-301 M**				
Command and control assets on the Martian surface from a remote location (e.g., Earth-based facilities, other Mars surface locations)	**FN-C-303 M**						
Provide safety features on robotic and/or autonomous asset(s) operating near crew	**FN-A-301 M**	Safe and effective interaction between crew and autonomous asset(s)	**UC-A-301 M**				
Monitor the performance and health of assets on the Martian surface (demonstration)	**FN-G-401 M**	Demonstration of autonomous operation of assets on Mars surface with reduced commands from crew or Earth-based systems	**UC-A-403 M**				
Monitor the performance and health of assets in deep space and/or Mars vicinity (demonstration)	**FN-G-407 M**						
Execute higher-level commands and make in-situ decisions autonomously for assets on the Martian surface (demonstration)	**FN-A-401 M**						

Functions		Use Cases		Characteristics/Needs		Objectives	
Transport crew from Mars vicinity to the Martian surface	FN-T-401 M	Transportation of crew from Mars vicinity to the Martian surface	UC-T-102 M	Visit diverse sites on the Martian surface to address high priority science and utilization goals.	CN-T-105 M	Characterize accessible resources, gather scientific research data, and analyze potential reserves to satisfy science and technology objectives and enable use of resources on successive missions.	OP-03 LM
Enable crew habitation during transit from Mars vicinity to Martian surface	FN-H-102 M						
Provide position, navigation, and timing during Mars ascent	FN-C-205 M						
Transfer crew between sites on the Martian surface	FN-M-301 M	Transfer of crew between landing site(s) and/or an exploration/utilization site on the Martian surface	UC-M-301 M				
Provide position, navigation, and timing data on the Martian surface	FN-C-201 M						
Transfer assets between sites on the Martian surface	FN-M-501 M	Transfer of assets between landing site(s) and/or exploration/utilization site(s) on Martian surface	UC-M-601 M				
Provide position, navigation, and timing data on the Martian surface	FN-C-201 M						
Document and store data about a Martian surface site location	FN-D-103 M	Surveying of potential exploration sites to identify locations of interest on the Martian surface	UC-U-101 M				
Collect data about a Martian surface site location	FN-U-103 M						
Identify potential exploration sites on the Martian surface	FN-U-106 M						
Transport cargo between Earth vicinity and Mars vicinity	FN-T-213 M	Transportation of cargo between Earth vicinity and Mars vicinity	UC-T-203 M	Transfer, return, and curate a small amount (10s of kg) or a large amount (100s of kg) of unconditioned samples and containers from key destinations across the Martian surface, while maintaining scientific integrity of the samples.	CN-T-301 M		
Provide position, navigation, and timing data in deep space and/or Mars vicinity	FN-C-202 M						
Prepare cargo for Earth surface return from Earth vicinity	FN-T-217 M	Transportation of cargo from Earth vicinity back to Earth-based facilities	UC-T-209 M				
Transport cargo from Earth vicinity to Earth surface	FN-T-403 M						
Recover cargo after landing on Earth surface	FN-G-202 M						
Relocate cargo in a clean environment, minimizing contamination to/from the container, between sites and facilities on Earth's surface	FN-G-203 M						
Provide position, navigation, and timing data in Earth vicinity	FN-C-203 M						
Provide precision landing for transport of assets to Earth's surface	FN-C-206 M						
Transport cargo between Earth vicinity and Mars vicinity	FN-T-213 M	Transportation of collected samples from the Martian surface to Earth vicinity in sealed sample containers	UC-T-212 M				
Transport cargo from Martian surface to Mars vicinity	FN-T-215 M						
Provide position, navigation, and timing during Mars ascent	FN-C-205 M						
Store collected unconditioned samples from the Martian surface in sealed sample containers, while maintaining scientific integrity of the samples	FN-U-402 M						

Functions		Use Cases		Characteristics/Needs		Objectives	
Transport cargo between Earth vicinity and Mars vicinity	**FN-T-213 M**	Transportation of cargo between Earth vicinity and Mars vicinity	**UC-T-203 M**	Transfer, return and curate a small amount (10s of kg) or a large amount (100s of kg) of frozen sample(s), containers, and freezers from key destinations across the Martian surface, while maintaining scientific integrity of the samples.	**CN-T-303 M**		
Provide position, navigation, and timing data in deep space and/or Mars vicinity	**FN-C-202 M**						
Transport cargo between Earth vicinity and Mars vicinity	**FN-T-213 M**	Transportation of collected surface and sub-surface samples from the Martian surface to Earth vicinity in sealed conditioned sample containers	**UC-T-210 M**				
Transport cargo from Martian surface to Mars vicinity	**FN-T-215 M**						
Prepare conditioned cargo or samples for Earth return	**FN-T-301 M**						
Provide resources to condition sample containers during transfer from Martian surface to Earth vicinity	**FN-T-302 M**						
Provide resources to condition sample containers on the Martian surface	**FN-T-303 M**						
Provide position, navigation, and timing during Mars ascent	**FN-C-205 M**						
Store collected refrigerated surface and sub-surface samples in sealed conditioned sample containers, while maintaining scientific integrity of the samples	**FN-U-401 M**						
Prepare conditioned cargo or samples for Earth return	**FN-T-301 M**	Transportation of conditioned cargo and samples from Earth vicinity to curation facilities on Earth after landing	**UC-T-211 M**				
Provide resources to condition sample containers during transfer from Earth vicinity to curation facilities on Earth	**FN-T-304 M**						
Transport cargo from Earth vicinity to Earth surface	**FN-T-403 M**						
Recover cargo after landing	**FN-G-204 M**						
Recover samples and transport in a clean environment, minimizing contamination to/from the container, to curation facilities after Earth landing	**FN-G-205 M**						
Provide position, navigation, and timing data in Earth vicinity	**FN-C-203 M**						
Provide precision landing for transport of assets to Earth's surface	**FN-C-206 M**						
Store collected refrigerated surface and sub-surface samples in sealed conditioned sample containers, while maintaining scientific integrity of the samples	**FN-U-401 M**						
Document and store data about a Martian surface site location	**FN-D-103 M**	Demonstration of surveying the Martian surface to identify and locate potential site(s) for resource utilization	**UC-U-102 M**	Demonstrate the capability to identify and locate potential site(s) for resource utilization.	**CN-U-101 M**		
Collect data about a Martian surface site location	**FN-U-103 M**						
Identify and characterize resources for potential resource utilization at a given site (demonstration)	**FN-U-202 M**						
Identify potential sample collection/extraction locations on the Martian surface	**FN-U-102 M**	Identification, collection, and documentation of deep subsurface samples from site(s) on the Martian surface	**UC-U-303 M**	Identify, collect, and document deep subsurface samples from key destinations on the Martian surface, with the potential to contain volatiles or biologics, while	**CN-U-301 M**		
Document collected Martian samples	**FN-U-302 M**						
Provide capability to recover and package, minimizing contamination to/from the container, Martian deep subsurface samples	**FN-U-306 M**						
Document the Martian surface site location where samples were collected	**FN-U-307 M**						

Functions		Use Cases		Characteristics/Needs		Objectives	
				maintaining scientific integrity of the samples.			
Identify potential sample collection/extraction locations on the Martian surface	**FN-U-102 M**	Identification, collection, and documentation of surface and shallow subsurface samples in special regions from site(s) on the Martian surface	**UC-U-301 M**	Identify, collect, and document surface and shallow subsurface samples from key destinations in special regions on the Martian surface, while maintaining scientific integrity of the samples.	**CN-U-302 M**		
Provide capability to recover and package, minimizing contamination to/from the container, Martian surface and shallow subsurface samples in special regions	**FN-U-301 M**						
Document collected Martian samples	**FN-U-302 M**						
Document the Martian surface site location where samples were collected	**FN-U-307 M**						
Identify potential sample collection/extraction locations on the Martian surface	**FN-U-102 M**	Identification, collection, and documentation of surface and shallow subsurface samples from site(s) on the Martian surface	**UC-U-302 M**	Identify, collect, and document surface and shallow subsurface samples from key destinations on the Martian surface, while maintaining scientific integrity of the samples.	**CN-U-303 M**		
Document collected Martian samples	**FN-U-302 M**						
Provide capability to recover and package, minimizing contamination to/from the container, Martian surface and shallow subsurface samples	**FN-U-303 M**						
Document the Martian surface site location where samples were collected	**FN-U-307 M**						
Distribute power to assets on the Martian surface	**FN-P-303 M**	Deployment of assets on the Martian surface	**UC-M-401 M**	Deploy and operate exploration asset(s), related to available resources, at key destinations across the Martian surface.	**CN-U-704 M**		
Deploy assets into operational configuration on the Martian surface	**FN-M-402 M**						
Unload asset(s) on the Martian surface	**FN-M-403 M**						
Command and control assets on the Martian surface from a remote location (e.g., Earth-based facilities, other Mars surface locations)	**FN-C-303 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-105 M**	Remote command and control of assets on Mars surface from assets on Earth, Mars vicinity, and/or other Mars surface locations	**UC-C-301 M**				
Command and control assets on the Martian surface from a remote location (e.g., Earth-based facilities, other Mars surface locations)	**FN-C-303 M**						
Provide communications and data exchange between assets on the Martian surface	**FN-C-101 M**	Operation of exploration assets for resource utilization on the Martian Surface	**UC-I-101 M**				
Provide communications and data exchange between assets on the Martian surface and Earth	**FN-C-102 M**						
Conduct resource utilization payload and/or equipment operations on the Martian surface	**FN-U-201 M**						
Provide communications and data exchange between assets on the Martian surface and Earth	**FN-C-102 M**	Communications and data exchange between assets at multiple distributed locations on the Martian surface and Earth	**UC-C-101 M**	Provide capabilities to integrate networks and mission systems to exchange data between Earth-based systems, in-space exploration assets, and surface exploration assets.	**CN-D-101 M**	Establish command and control processes, common interfaces, and ground systems that will support expanding human missions at the Moon and Mars.	**OP-04 LM**
Provide communications and data exchange between assets on the Martian surface	**FN-C-101 M**	Communications and data exchange between assets at multiple distributed locations on the Martian surface	**UC-C-102 M**				
Provide communications and data exchange between assets in deep space and/or Mars vicinity and the Martian surface	**FN-C-103 M**	Communications and data exchange between assets in deep space and/or Mars vicinity and the Martian surface	**UC-C-103 M**				

Functions		Use Cases		Characteristics/Needs		Objectives	
Provide communications and data exchange between assets in deep space and/or Mars vicinity and Earth	FN-C-104 M	Communications and data exchange between assets in deep space and/or Mars vicinity and Earth	UC-C-104 M				
Provide communications and data exchange between assets in deep space and/or Mars vicinity	FN-C-107 M	Communications and data exchange between assets in deep space and/or Mars vicinity	UC-C-105 M				
BLANK	BLANK	Utilization of common interface(s) for data transfer and distribution between Mars exploration assets	UC-C-106 M	Provide capabilities to utilize common data interface(s) for exchanges between Earth-based systems, in-space exploration assets, and surface exploration assets.	CN-D-102 M		
Collect, store, and distribute data on the Martian surface	FN-D-101 M	Aggregation and storage of data on the Martian surface until it is able to be transmitted and confirmed received	UC-C-107 M	Provide capabilities to store and protect data on exploration assets.	CN-D-103 M		
Collect, store, and distribute data in deep space and/or Mars vicinity	FN-D-102 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-108 M				
Manipulate robotic/EVA/IVA tools and hardware to perform asset servicing, maintenance, upgrades, or replacements on the Martian surface	FN-G-402 M	Commissioning, servicing, maintenance, and upgrades for assets to maintain and restore appropriate performance on the Martian surface	UC-G-402 M	Operate and gain experience with capabilities to conduct extravehicular activities utilizing mobility assets and tools.	CN-M-101 M	Operate surface mobility systems, e.g., extra-vehicular activity (EVA) suits, tools and vehicles.	OP-05 LM
Inspect assets on the Martian surface	FN-G-403 M						
Inspect performance of servicing, maintenance, upgrade, or replacement activities to evaluate success on the Martian surface	FN-G-406 M						
Detect asset anomalies or off-nominal performance on the Martian surface	FN-G-408 M						
Diagnose asset anomalies or off-nominal performance on the Martian surface	FN-G-409 M						
Determine if asset servicing/maintenance is needed on the Martian surface	FN-G-410 M						
Manage waste/trash from servicing, maintenance, or upgrade activities (demonstration)	FN-L-203 M						
Identify potential utilization locations on the Martian surface	FN-U-107 M	Crew use of mobility assets and tools to conduct exploration and utilization activities on the Martian surface	UC-M-101 M				
Provide capability to recover and package, minimizing contamination to/from the container, Martian surface and shallow subsurface samples in special regions	FN-U-301 M						
Conduct science and collect science data on the Martian surface	FN-U-701 M						
Transfer crew between sites on the Martian surface	FN-M-301 M	Transfer of crew between landing site(s) and/or an exploration/utilization site on the Martian surface	UC-M-301 M	Operate and gain experience with capabilities to transport crew and cargo between landing, exploration, and utilization sites at varying distances from	CN-M-501 M		
Provide position, navigation, and timing data on the Martian surface	FN-C-201 M						
Transfer assets between sites on the Martian surface	FN-M-501 M	Transfer of assets between landing site(s) and/or exploration/utilization site(s) on Martian surface	UC-M-601 M				
Provide position, navigation, and timing data on the Martian surface	FN-C-201 M						

Functions		Use Cases		Characteristics/Needs		Objectives	
				assets on the Martian surface.			
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-101 M**	Deployment and operation of crew health monitoring assets in deep space and/or Mars vicinity	**UC-X-107 M**	Provide appropriate medical capabilities (including behavioral health) that allow for autonomous crew health decision making and care, and are preparatory of a mission to Mars.	**CN-X-101 M**	Validate readiness of systems and operations to support crew health and performance for the initial human Mars exploration campaign.	**OP-07 LM**
Deploy crew health monitoring assets for extended duration (year+) in deep space and/or Mars vicinity	**FN-X-107 M**						
Manage crew health and performance for mid-duration (month+) crew mission(s) on the Martian surface	**FN-X-102 M**	Deployment and operation of crew health monitoring assets on the Martian surface	**UC-X-108 M**				
Deploy crew health monitoring assets for extended duration (year+) in deep space and/or Mars vicinity	**FN-X-107 M**						
Provide private areas for crew, including for individual crew members, for extended duration (year+) in deep space and/or Mars vicinity	**FN-H-103 M**	Habitation for extended duration (year+) in deep space and/or Mars vicinity	**UC-H-102 M**	Provide crew health and performance capabilities in deep space and Mars vicinity, including demonstration of remote and autonomous health care and advanced diagnostics.	**CN-X-102 M**		
Manage and store logistics for extended duration (year+) in deep space and/or Mars vicinity	**FN-H-104 M**						
Manage a pressurized habitable environment for crew for extended duration (year+) in deep space and/or Mars vicinity	**FN-H-105 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-H-106 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-101 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-301 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-201 M**						
Provide private areas for crew, including for individual crew members, for crew mission(s) on the Martian surface	**FN-H-107 M**	Habitation for crew exploration missions on the Martian surface	**UC-H-103 M**	Provide crew health and performance capabilities on the Martian surface, including demonstration of remote and autonomous health care and advanced diagnostics.	**CN-X-103 M**		
Manage and store logistics for crew mission(s) on the Martian surface	**FN-H-108 M**						
Manage a pressurized habitable environment for crew mission(s) on the Martian surface	**FN-H-109 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-110 M**						
Manage crew health and performance for mid-duration (month+) crew mission(s) on the Martian surface	**FN-X-102 M**						
Move logistics and/or cargo into habitable assets for crew mission(s) on the Martian surface	**FN-L-202 M**						
Manage waste/trash and housekeeping for nominal and contingency use for crew mission(s) on the Martian surface	**FN-L-302 M**						
Provide ingress/egress between habitable volumes and external environment that maintain crew health, performance and safety on the Martian surface	**FN-M-202 M**						

Functions		Use Cases		Characteristics/Needs		Objectives	
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-101 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-105 M**	Provide countermeasures capabilities that are commensurate in scope with the human system needs for the mission.	**CN-X-104 M**		
Enable crew exercise in deep space and/or Mars vicinity	**FN-X-103 M**						
Manage crew health and performance for mid-duration (month+) crew mission(s) on the Martian surface	**FN-X-102 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-106 M**				
Enable crew exercise on the Martian surface	**FN-X-105 M**						
Enable crew exercise on the Martian surface	**FN-X-105 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-109 M**				
Manage crew health and performance for short-duration (less than one month) crewed mission(s) on the Martian surface	**FN-X-108 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-404 M**	Commissioning, servicing, maintenance, and upgrades for assets to maintain and restore appropriate performance in deep space and/or Mars vicinity	**UC-G-401 M**	Provide crew survival capabilities in deep space, Mars vicinity, and on the Martian surface, including safe havens, system supportability, and/or aborts, for nominal and off-nominal scenarios.	**CN-X-105 M**		
Inspect assets during extended duration (year+) in deep space and/or Mars vicinity	**FN-G-405 M**						
Detect asset anomalies or off-nominal performance in deep space and/or Mars vicinity	**FN-G-411 M**						
Diagnose asset anomalies or off-nominal performance in deep space and/or Mars vicinity	**FN-G-412 M**						
Determine if asset servicing/maintenance is needed in deep space and/or Mars vicinity	**FN-G-413 M**						
Manage waste/trash from servicing, maintenance, or upgrade activities (demonstration)	**FN-L-203 M**						
Manipulate robotic/EVA/IVA tools and hardware to perform asset servicing, maintenance, upgrades, or replacements on the Martian surface	**FN-G-402 M**	Commissioning, servicing, maintenance, and upgrades for assets to maintain and restore appropriate performance on the Martian surface	**UC-G-402 M**				
Inspect assets on the Martian surface	**FN-G-403 M**						
Inspect performance of servicing, maintenance, upgrade, or replacement activities to evaluate success on the Martian surface	**FN-G-406 M**						
Detect asset anomalies or off-nominal performance on the Martian surface	**FN-G-408 M**						
Diagnose asset anomalies or off-nominal performance on the Martian surface	**FN-G-409 M**						
Determine if asset servicing/maintenance is needed on the Martian surface	**FN-G-410 M**						
Manage waste/trash from servicing, maintenance, or upgrade activities (demonstration)	**FN-L-203 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-123 M**	Demonstration of integrated crew health and performance support assets and medical care for	**UC-X-101 M**				

Functions		Use Cases		Characteristics/Needs		Objectives	
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-125 M**	contingency events or emergency response in deep space and/or Mars vicinity					
Demonstrate treatment of emergency crew health conditions for extended duration (year+) crew mission(s) in deep space and/or Mars vicinity	**FN-X-109 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-111 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-301 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-124 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-102 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-126 M**						
Demonstrate treatment of emergency crew health conditions for crew mission(s) on the Martian surface	**FN-X-110 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-112 M**						
Manage waste/trash and housekeeping for nominal and contingency use for crew mission(s) on the Martian surface	**FN-L-302 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-111 M**	Demonstration of operations and emergency response capabilities to enable crew survival in deep space and Mars vicinity	**UC-X-103 M**				
Provide safe haven for extended duration (year+) in deep space and/or Mars vicinity	**FN-H-112 M**						
Demonstrate recovery of habitable environment during extended duration (year+) mission in deep space and/or Mars vicinity	**FN-H-113 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-127 M**						
Provide safe haven for crew mission(s) on the Martian surface	**FN-H-114 M**	Demonstration of operations and emergency response capabilities to enable crew survival on the Martian surface	**UC-X-104 M**				
Demonstrate recovery of habitable environment for crew mission(s) on the Martian surface	**FN-H-115 M**						
Demonstrate use of crew survival equipment and assets for crew mission(s) on the Martian surface	**FN-H-128 M**						
Demonstrate remediation of hazardous conditions within habitable assets for crew mission(s) on the Martian surface	**FN-H-129 M**						
Transfer assets between sites on the Martian surface	**FN-M-501 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-M-602 M**	Demonstrate the capabilities to locate, access, and reuse surface assets from previous crewed and uncrewed missions.	**CN-U-106 M**	Demonstrate the capability to find, service, upgrade, or utilize instruments and equipment from robotic landers or previous human missions on the surface of the Moon and Mars.	**OP-08 LM**
Provide position, navigation, and timing data on the Martian surface	**FN-C-201 M**						
Identify asset(s) on the Martian surface (demonstration)	**FN-U-104 M**						
Recover propellant from assets on the Martian surface (demonstration)	**FN-U-501 M**	Demonstration of recovery of excess propellant from tanks of previous asset(s) on the Martian surface	**UC-U-501 M**				
Transfer propellant into storage asset(s) and/or transportation asset(s) on the Martian surface (demonstration)	**FN-U-502 M**						
Maintain necessary environmental conditions for propellant in storage asset(s) or transportation asset(s) (demonstration)	**FN-U-503 M**						

Functions		Use Cases		Characteristics/Needs		Objectives	
Store propellant on the Martian surface (demonstration)	FN-U-504 M						
Transition an asset in and out of uncrewed mode on the Martian surface (demonstration)	FN-C-308 M	Demonstration of reuse of assets on the Martian surface	UC-U-803 M				
Operate asset(s) when uncrewed between crewed missions on the Martian surface (demonstration)	FN-C-309 M						
Repurpose and/or recycle asset equipment on the Martian surface (demonstration)	FN-U-801 M	Demonstration of the reuse of hardware and materials brought to the surface during subsequent missions on the Martian surface	UC-U-804 M				
Manipulate robotic/EVA/IVA tools and hardware to perform asset servicing, maintenance, upgrades, or replacements on the Martian surface	FN-G-402 M	Commissioning, servicing, maintenance, and upgrades for assets to maintain and restore appropriate performance on the Martian surface	UC-G-402 M	Demonstrate the capabilities to service and/or upgrade assets.	CN-U-806 M		
Inspect assets on the Martian surface	FN-G-403 M						
Inspect performance of servicing, maintenance, upgrade, or replacement activities to evaluate success on the Martian surface	FN-G-406 M						
Detect asset anomalies or off-nominal performance on the Martian surface	FN-G-408 M						
Diagnose asset anomalies or off-nominal performance on the Martian surface	FN-G-409 M						
Determine if asset servicing/maintenance is needed on the Martian surface	FN-G-410 M						
Manage waste/trash from servicing, maintenance, or upgrade activities (demonstration)	FN-L-203 M						
Conduct utilization activities external to crewed elements with robotic systems on the Martian surface (demonstration)	FN-A-127 M	Demonstration of robotic systems to perform and/or assist in external utilization activities on the Martian surface	UC-A-101 M	Demonstrate the capabilities to operate appropriate robotic system(s) that can conduct or assist in tasks that would otherwise be performed by the crew alone on the Martian surface.	CN-A-103 M	Demonstrate the capability of integrated robotic systems to support and maximize the useful work performed by crewmembers on the surface, and in orbit.	OP-09 LM
Survey areas of interest and identify potential scientific utilization locations with robotic systems on the Martian surface (demonstration)	FN-U-105 M						
Provide capability to recover and package samples with robotic systems on the Martian surface (demonstration)	FN-U-304 M						
Assist crew conducting utilization activities with robotic systems on the Martian surface (demonstration)	FN-A-101 M	Demonstration of robotic systems to perform and/or assist crew conducting EVA activities on the Martian surface	UC-A-102 M				
Assist crew surveying areas of interest and identify potential utilization locations with robotic systems on the Martian surface (demonstration)	FN-A-102 M						
Assist crew recovering and packaging samples with robotic systems on the Martian surface (demonstration)	FN-A-103 M						
Robotic systems operate and/or monitor utilization experiments internal to crewed assets on the Martian surface (demonstration)	FN-A-104 M	Demonstration of robotic systems to perform and/or assist in utilization activities internal to crewed assets on the Martian surface	UC-A-103 M				
Manage waste/trash from servicing, maintenance, or upgrade activities (demonstration)	FN-L-203 M	Demonstration of robotic systems to perform and/or assist in commissioning, servicing, maintenance, and/or upgrades of assets to maintain and restore	UC-A-104 M				
Use robotic systems to assist crew performing system maintenance and upgrades of assets on the Martian surface (demonstration)	FN-A-106 M						
Detect and diagnose asset anomalies or off-nominal performance using robotic systems on the Martian surface (demonstration)	FN-A-121 M						

Functions		Use Cases		Characteristics/Needs		Objectives	
Inspect performance of servicing, maintenance, upgrade, or replacement activities to evaluate success using robotic systems on the Martian surface (demonstration)	**FN-A-122 M**	appropriate performance on the Martian surface					
Robotic systems perform maintenance and upgrades of assets on the Martian surface (demonstration)	**FN-A-123 M**						
Use robotic systems to assist crew moving logistics and/or cargo into habitable elements on the Martian surface (demonstration)	**FN-A-107 M**	Demonstration of robotic systems to perform and/or assist in logistics operations on the Martian surface	**UC-A-105 M**				
Use robotic systems to assist crew organizing logistics and waste/trash on the Martian surface (demonstration)	**FN-A-108 M**						
Use robotic systems to assist managing waste/trash and housekeeping for nominal and continency use on the Martian surface (demonstration)	**FN-A-109 M**						
Use robotic systems to move logistics and/or cargo into habitable elements on the Martian surface (demonstration)	**FN-A-128 M**						
Use robotic systems to organize logistics and waste/trash on the Martian surface (demonstration)	**FN-A-129 M**						
Use robotic systems to manage waste/trash and housekeeping for nominal and contingency use on the Martian surface (demonstration)	**FN-A-130 M**						
Robotic systems assist crew operating and/or monitoring utilization experiments internal to crewed assets on the Martian surface (demonstration)	**FN-A-105 M**	Demonstration of robotic systems to perform and/or assist in utilization activities internal to crewed assets in space	**UC-A-106 M**	Demonstrate the capabilities to operate appropriate robotic system(s) that can conduct or assist in tasks that would otherwise be performed by the crew alone in deep space and/or Mars vicinity.	**CN-A-104 M**		
Use robotic systems to assist crew operating utilization experiments internal to crewed assets in space (demonstration)	**FN-A-110 M**						
Use robotic systems to operate utilization experiments internal to crewed assets in space (demonstration)	**FN-A-124 M**						
Detect and diagnose asset anomalies or off-nominal performance using robotic systems in space (demonstration)	**FN-A-111 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-107 M**				
Use robotic systems to assist crew performing system maintenance and upgrades of assets in space (demonstration)	**FN-A-112 M**						
Inspect performance of servicing, maintenance, upgrade, or replacement activities to evaluate success using robotic systems in space (demonstration)	**FN-A-125 M**						
Operate robotic systems to perform maintenance and upgrades assets in space (demonstration)	**FN-A-126 M**						
Use robotic systems to assist crew moving logistics and/or cargo into habitable elements in space as (demonstration)	**FN-A-113 M**	Demonstration of robotic systems to perform and/or assist in logistics operations in space	**UC-A-108 M**				
Use robotic systems to assist crew organizing logistics and waste/trash in space as (demonstration)	**FN-A-114 M**						
Use robotic systems to assist managing waste/trash and housekeeping for nominal and contingency use in space (demonstration)	**FN-A-115 M**						
Use robotic systems to move logistics and/or cargo into habitable elements in space (demonstration)	**FN-A-118 M**						
Use robotic systems to organize logistics and waste/trash in space (demonstration)	**FN-A-119 M**						
Use robotic systems to manage waste/trash and housekeeping for nominal and contingency use in space (demonstration)	**FN-A-120 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-105 M**	Remote command and control of assets on Mars surface from assets on Earth, Mars vicinity, and/or other Mars surface locations	**UC-C-301 M**	Demonstrate capabilities to allow in-space and surface crew to control and command robotic system(s).	**CN-A-201 M**		
Command and control assets on the Martian surface from a remote location (e.g., Earth-based facilities, other Mars surface locations)	**FN-C-303 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-201 M**	Demonstration of remote command and control of robotic	**UC-C-302 M**				

Functions		Use Cases		Characteristics/Needs		Objectives	
		assets on Mars surface from assets on Earth, Mars vicinity, and/or other Mars surface locations					
Command and control assets in deep space and/or Mars vicinity from a remote location (e.g., Earth-based facilities) (demonstration)	**FN-C-302 M**	Demonstration of remote command and control of robotic assets in-space from assets on Earth, Mars vicinity, and/or Mars surface locations	**UC-C-303 M**				
Monitor the performance and health of assets on the Martian surface (demonstration)	**FN-G-401 M**	Demonstration of safe in-situ crew command and control of robotic asset(s) on the Martian surface	**UC-A-201 M**	Demonstrate the capability for safe and effective interactions between crew and automated/autonomous system(s).	**CN-A-301 M**		
Provide communications and data exchange between assets at a variety of exploration locations on the Martian surface	**FN-C-106 M**						
Enable the control of robotic asset(s) by crew on the Martian surface (demonstration)	**FN-A-202 M**						
Provide safety features on robotic and/or autonomous asset(s) operating near crew	**FN-A-301 M**						
Monitor the performance and health of assets in deep space and/or Mars vicinity (demonstration)	**FN-G-407 M**	Demonstration of safe in-situ crew command and control of robotic asset(s) in deep space and/or Mars vicinity	**UC-A-202 M**				
Provide communications and data exchange between assets in deep space and/or Mars vicinity	**FN-C-107 M**						
Enable the control of robotic asset(s) by crew in deep space and/or Mars vicinity (demonstration)	**FN-A-203 M**						
Provide safety features on robotic and/or autonomous asset(s) operating near crew	**FN-A-301 M**						
Provide safety features on robotic and/or autonomous asset(s) operating near crew	**FN-A-301 M**	Safe and effective interaction between crew and autonomous asset(s)	**UC-A-301 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-201 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-302 M**	Demonstrate autonomous and remote operations of robotic surface systems from external systems, including Earth, orbital, and/or other surface locations.	**CN-A-202 M**	Demonstrate the capability to operate robotic systems that are used to support crew members on the lunar or Martian surface, autonomously or remotely from the Earth or from orbiting platforms.	**OP-10 LM**
Monitor the performance and health of assets on the Martian surface (demonstration)	**FN-G-401 M**	Demonstration of autonomous operation of assets on Mars surface with reduced commands from crew or Earth-based systems	**UC-A-403 M**				
Monitor the performance and health of assets in deep space and/or Mars vicinity (demonstration)	**FN-G-407 M**						
Execute higher-level commands and make in-situ decisions autonomously for assets on the Martian surface (demonstration)	**FN-A-401 M**						
Command and control assets in deep space and/or Mars vicinity from a remote location (e.g., Earth-based facilities) (demonstration)	**FN-C-302 M**	Demonstration of remote command and control of robotic assets in-space from assets on Earth, Mars vicinity, and/or Mars surface locations	**UC-C-303 M**	Demonstrate autonomous and remote operations of in-space robotic systems from external systems, including Earth, orbital,	**CN-A-203 M**		
Monitor the performance and health of assets in deep space and/or Mars vicinity (demonstration)	**FN-G-407 M**	Demonstration of autonomous operation of assets in deep space	**UC-A-404 M**				

Functions		Use Cases		Characteristics/Needs		Objectives	
Execute higher-level commands and make in-situ decisions autonomously for assets in deep space and/or Mars vicinity (demonstration)	**FN-A-402 M**	and/or Mars vicinity with reduced commands from crew or Earth-based systems		and/or other surface locations.			
Monitor the performance and health of assets on the Martian surface (demonstration)	**FN-G-401 M**	Demonstration of safe in-situ crew command and control of robotic asset(s) on the Martian surface	**UC-A-201 M**	Demonstrate the capability for safe and effective interactions between crew and automated/autonomous system(s).	**CN-A-301 M**		
Provide communications and data exchange between assets at a variety of exploration locations on the Martian surface	**FN-C-106 M**						
Enable the control of robotic asset(s) by crew on the Martian surface (demonstration)	**FN-A-202 M**						
Provide safety features on robotic and/or autonomous asset(s) operating near crew	**FN-A-301 M**						
Monitor the performance and health of assets in deep space and/or Mars vicinity (demonstration)	**FN-G-407 M**	Demonstration of safe in-situ crew command and control of robotic asset(s) in deep space and/or Mars vicinity	**UC-A-202 M**				
Provide communications and data exchange between assets in deep space and/or Mars vicinity	**FN-C-107 M**						
Enable the control of robotic asset(s) by crew in deep space and/or Mars vicinity (demonstration)	**FN-A-203 M**						
Provide safety features on robotic and/or autonomous asset(s) operating near crew	**FN-A-301 M**						
Provide safety features on robotic and/or autonomous asset(s) operating near crew	**FN-A-301 M**	Safe and effective interaction between crew and autonomous asset(s)	**UC-A-301 M**				
Collect in situ materials/feedstock on the Martian surface (demonstration)	**FN-I-101 M**	Demonstration of scalable ISRU production, storage, and/or transfer on the Martian surface	**UC-I-102 M**	Operate demonstration exploration asset(s) on the Martian surface to collect, produce, store, and transfer commodities, including water, oxygen and/or fuel, for potential use.	**CN-I-103 M**	Demonstrate the capability to use commodities produced from planetary surface or in-space resources to reduce the mass required to be transported from Earth.	**OP-11 LM**
Produce commodities on the Martian surface (demonstration)	**FN-I-102 M**						
Process, refine, and verify the quality of commodities on the Martian surface (demonstration)	**FN-I-103 M**						
Store commodities on the Martian surface (demonstration)	**FN-I-104 M**						
Transfer ISRU commodities between assets and/or sites on the Martian surface (demonstration)	**FN-I-105 M**						
Identify and characterize in-situ material/feedstock on the Martian surface (demonstration)	**FN-I-107 M**						
Collect in situ materials/feedstock on the Martian surface (demonstration)	**FN-I-101 M**	Demonstration of construction and/or manufacturing using surface-born resources on the Martian surface	**UC-I-201 M**	Demonstrate the capability to use surface-borne resources for potential construction and/or manufacturing on the Martian surface.	**CN-I-104 M**		
Unload or manufacture pieces or parts to support construction and/or manufacturing on the Martian surface (demonstration)	**FN-I-201 M**						
Assemble pieces of a construction project on the Martian surface (demonstration)	**FN-I-202 M**						
Inspect and validate accuracy and performance of manufacturing and/or construction activities on the Martian surface (demonstration)	**FN-I-203 M**						
Transfer assets between sites on the Martian surface	**FN-M-501 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-M-602 M**	Demonstrate the capabilities to recover excess fluids and gases, including propellant residuals, from Mars landers and separation of products.	**CN-I-101 M**	Establish procedures and systems that will minimize the disturbance to the local environment, maximize the resources available to future explorers, and allow for	**OP-12 LM**
Provide position, navigation, and timing data on the Martian surface	**FN-C-201 M**						
Identify asset(s) on the Martian surface (demonstration)	**FN-U-104 M**						

Functions		Use Cases		Characteristics/Needs		Objectives	
BLANK	**BLANK**	Enable reduction of long-term environmental impact of waste and housekeeping	**UC-U-801 M**	Abide by planetary protection protocols, policies, and guidelines.	**CN-U-802 M**	reuse/recycling of material transported from Earth (and from the lunar surface in the case of Mars) to be used during exploration.	
BLANK	**BLANK**	Enable planetary stewardship through sustainable resource utilization, maintaining scientific integrity, and reduction of environmental impact	**UC-U-802 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-214 M**	Disposal of assets in a manner that ensures future viable usage of exploration sites on the Martian surface	**UC-U-805 M**				
Provide position, navigation, and timing data on the Martian surface	**FN-C-201 M**						
Transition assets into end-of-life mode	**FN-C-310 M**						
Enable planetary protection protocols for end-of-life for assets in Mars vicinity	**FN-U-802 M**						
Enable planetary protection protocols for end-of-life for assets on the Martian surface	**FN-U-803 M**						
Control bioburden release from assets to Mars surface and environment	**FN-U-804 M**	Control bioburden release by assets on the Martian surface	**UC-U-806 M**				
Control and monitor transfer of Mars environmental contamination into and between habitable assets on the Martian surface	**FN-G-501 M**	Control transfer of Mars environmental contamination into crewed assets	**UC-U-807 M**				

A.3 List of Lunar Use Cases

ID	Use Cases
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 back 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

ID	Use Cases
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 flight systems
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 moderate-duration (month+) mission(s) in cislunar space
UC-H-104 L	Crew habitation of assets for extended-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

ID	Use Cases
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 moderate durations (month+) on the lunar surface
UC-X-104 L	Crew countermeasure capabilities to support the crew for moderate (month+) to long (year+) durations 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

ID	Use Cases
UC-M-303 L	Conduct of crew excursions in PSRs around landing site at the south pole region
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 on 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

ID	Use Cases
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-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

ID	Use Cases
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-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 sub-surface 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 sub-surface 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 sub-surface samples, maintaining scientific integrity of the samples, from PSRs on the lunar surface
UC-U-304 L	Collection, recovery, and packaging of deep sub-surface 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 sub-surface 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 sub-surface samples, maintaining scientific integrity of the samples, from non-PSRs and sunlit areas in the far side on the lunar surface

ID	Use Cases
UC-U-307 L	Collection, recovery, and packaging of deep sub-surface 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 sub-surface 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 extended-duration (year+) in space
UC-U-504 L	Deployment and operation of exploration assets, including utilization payload(s) and/or equipment, related to demonstration of propellant storage for extended-duration (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

ID	Use Cases
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-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 bioregenerative 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

ID	Use Cases
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

A.4 List of Mars Use Cases

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

ID	Use Cases
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-210 M	Transportation of collected surface and sub-surface samples from the Martian surface to Earth vicinity in sealed conditioned sample containers
UC-T-211 M	Transportation of conditioned cargo and samples from Earth vicinity to curation facilities on Earth after landing
UC-T-212 M	Transportation of collected samples from the Martian surface to Earth vicinity in sealed sample containers
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

ID	Use Cases
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-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

ID	Use Cases
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-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

ID	Use Cases
UC-C-110 M	Asset(s) and/or payload(s) provide communications to inspire and inform the general public, students, and teachers
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-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-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-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

ID	Use Cases
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-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-101 M	Surveying of potential exploration sites to identify locations of interest 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-301 M	Identification, collection, and documentation of surface and shallow subsurface samples in special regions from site(s) on the Martian surface
UC-U-302 M	Identification, collection, and documentation of surface and shallow subsurface samples from site(s) on the Martian surface
UC-U-303 M	Identification, collection, and documentation of deep subsurface samples from site(s) 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-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

ID	Use Cases
UC-U-807 M	Control transfer of Mars environmental contamination into crewed assets

A.5 List of Lunar Functions

ID	Functions
FN-T-101 L	Transport crew from Earth to cislunar space
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 exploration 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

ID	Functions
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-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

ID	Functions
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-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
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 moderate 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 moderate (month+) durations
FN-H-105 L	Enable a pressurized, habitable environment in cislunar space for extended (year+) duration
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 moderate durations (month+) on the lunar surface
FN-X-104 L	Provide crew countermeasure system(s) to support the crew for moderate (month+) to long (year+) durations in cislunar space

ID	Functions
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	Mating between pressurized assets on the lunar surface
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

ID	Functions
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 long durations (months to years+)
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-103 L	Enable crew 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 exploration 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

ID	Functions
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-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	Relocation of exploration assets at lunar surface polar locations
FN-M-602 L	Relocation of 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

ID	Functions
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-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

ID	Functions
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 of asset(s) from Earth in cislunar space during uncrewed periods
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 polar 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

ID	Functions
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 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-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 sub-surface 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 sub-surface 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 sub-surface 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 sub-surface samples, maintaining scientific integrity of the samples, from PSRs on the lunar surface
FN-U-305 L	Provide capability to recover and package deep sub-surface 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 sub-surface 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

ID	Functions
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-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

ID	Functions
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

A.6 List of Mars Functions

ID	Functions
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

ID	Functions
FN-T-216 M	Store cargo during ascent from the Martian surface
FN-T-217 M	Prepare cargo for Earth surface return from Earth vicinity
FN-T-301 M	Prepare conditioned cargo or samples for Earth return
FN-T-302 M	Provide resources to condition sample containers during transfer from Martian surface to Earth vicinity
FN-T-303 M	Provide resources to condition sample containers on the Martian surface
FN-T-304 M	Provide resources to condition sample containers during transfer from Earth vicinity to curation facilities on 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
FN-G-102 M	Stack and integrate assets for transportation from Earth surface to Earth vicinity
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 and cargo after landing on Earth surface
FN-G-202 M	Recover cargo after landing on Earth surface
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-204 M	Recover cargo after landing
FN-G-205 M	Recover samples and transport in a clean environment, minimizing contamination to/from the container, to curation facilities after Earth landing
FN-G-401 M	Monitor the performance and health of assets on the Martian surface (demonstration)

ID	Functions
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-H-107 M	Provide private areas for crew, including for individual crew members, for crew mission(s) on the Martian surface

ID	Functions
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

ID	Functions
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-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

ID	Functions
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-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-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

ID	Functions
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-201 M	Provide position, navigation, and timing data on the Martian surface
FN-C-202 M	Provide position, navigation, and timing data in deep space and/or Mars vicinity
FN-C-203 M	Provide position, navigation, and timing data in Earth vicinity
FN-C-204 M	Provide position, navigation, and timing during Mars entry, descent, and landing
FN-C-205 M	Provide position, navigation, and timing 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-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

ID	Functions
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-201 M	Provide Earth-independent decision support for time-critical asset malfunctions on Mars surface (demonstration)
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-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

ID	Functions
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-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)

ID	Functions
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-102 M	Identify potential sample collection/extraction locations on the Martian surface
FN-U-103 M	Collect data about a Martian surface site location
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-201 M	Conduct resource utilization payload and/or equipment operations on the Martian surface

ID	Functions
FN-U-202 M	Identify and characterize resources for potential resource utilization at a given site (demonstration)
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, minimizing contamination to/from the container, Martian surface and shallow subsurface samples
FN-U-304 M	Provide capability to recover and package samples with robotic systems on the Martian surface (demonstration)
FN-U-305 M	Identify the location(s) of collected Mars surface samples
FN-U-306 M	Provide capability to recover and package, minimizing contamination to/from the container, Martian deep subsurface samples
FN-U-307 M	Document the Martian surface site location where samples were collected
FN-U-401 M	Store collected refrigerated surface and sub-surface samples in sealed conditioned sample containers, while maintaining scientific integrity of the samples
FN-U-402 M	Store collected unconditioned samples from the Martian surface in sealed sample containers, while maintaining scientific integrity of the samples
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-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

APPENDIX B: KEY MOON TO MARS ARCHITECTURE DECISIONS

Key architecture decision – Defined as a decision (i.e., decision definitions and, when available, outcomes) that so profoundly influences the end-to-end architecture that it warrants elevated scrutiny. At one end of the spectrum, deciding how many crew members an architecture must accommodate is obviously a "key" decision because it influences virtually every aspect of the architecture and will involve collaboration between multiple decision authorities. At the other end of the spectrum, deciding handrail color or style — even though it will affect many elements — is best categorized as an engineering decision that does not rise to the same level of management scrutiny. But where to draw the line? For the purpose of sorting through thousands of decisions to determine which have a profound enough impact to be labeled as "key," NASA employs two criteria: high connectivity to other decisions, programs, and projects and high sensitivity of architecture-level and agency values (such as cost, schedule, or risk) to the decision options. This sorting process is subjective but errs on the side of caution: if in doubt, a decision is considered key; it may be reclassified later if further analysis indicates — or a decision authority decides — that the decision could be made at a lower level or does not have a significant technical, cost, schedule, or risk impact.

Once a candidate architecture decision has been identified, defined, traced, and pre-coordinated with internal NASA organizations and relevant decision authorities, it is presented at ACR for consensus for agency workload prioritization. This step provides rationale for relevant organizations to allocate resources for their individual contributions to decision package development, research or analysis, integration, decision making, and implementation.

B.1 PRIORITY MARS ARCHITECTURE KEY DECISIONS

MD-01 Initial Human Mars Segment Science Objective Priorities

The agency's Moon to Mars Strategy identifies science as one of three pillars on which the blueprint for sustained human presence and exploration throughout the solar system is built. The needed decision outcome is a formulation of more specific science objectives — traceable to NASA's high-level "blueprint" science objectives — for missions carried out during the initial human Mars segment and prioritization of these objectives. Decision prerequisites will include inputs from and coordination between affected science communities and organizations such as academia, National Academies, affected NASA Science Advisory Committees, and the Human Research Program. Priority science objectives have substantial flow-down impacts to most architecture and operations decisions. Therefore, the Mars Science Priorities key decision must be placed at the starting point of the Mars decision roadmapping process.

MD-02 Initial Human Mars Segment Target State

To "architect from the right" per the agency's new Moon to Mars Strategy, "the right" must first be defined. A decision outcome is needed on the initial human Mars segment "target state." Specifically, the infrastructure and operational capabilities to be available on or at Mars by the end of the campaign segment must be identified. The vision for the initial Humans to Mars campaign segment must balance the highest-priority science objectives with implementation constraints, which will include pacing human Mars campaign segment investments in the context of the agency's other concurrent science and exploration commitments.

MD-03 Initial Human Mars Segment Mission Cadence

For architecture planning purposes, a decision outcome is needed on the mission cadence for the Initial Humans to Mars campaign segment. This decision outcome should be focused on the desired period of time between missions to Mars (i.e., the “cadence”) and should be based on the general capability build-up that should be targeted during that cadence to reach the Initial Human Mars Target State. This decision outcome is part of defining the “campaign,” which is defined as the combination of the mission cadence, the number of missions, and what operations happen on the way to and at Mars. However, the scope of this decision outcome has been intentionally limited to the cadence — that is, how fast we will achieve the target state. Also, the scope includes only missions to Mars, but it can include both crewed and uncrewed missions in the mission cadence, where the missions’ purposes are to perform operations and capabilities necessary to achieve the Humans to Mars target state. Later decision outcomes will address other aspects of the campaign due to the potential difference in stakeholders and/or decision authorities, the need for further study of the options, and the many dependencies to other key decisions.

MD-04 Mars Architecture Loss-of-Crew Risk Posture

Human spaceflight programs typically develop an understanding of the overall loss-of-crew risk. In order to make risk informed architecture decisions, an architecture loss-of-crew risk posture is needed. A risk posture is defined as an expression of the agreed-upon limits of risk an organization’s leadership team is willing to accept in order to achieve one or more of its objectives. The Mars architecture loss-of-crew risk posture must be expressed as a range for the probability of loss of crew. The probability values should be determined based on candidate initial human Mars segment concept(s) of operation, and the decision outcome should include a comparison with other industry risks of comparable and non-comparable magnitudes.

MD-05 Number of Crew to Mars Surface

Crew complement is the most common study constraint across all architectures and elements. The number of astronauts to support has direct impacts on the volume of habitable elements and other elements’ performance of environmental control and life support systems (ECLSS) and crew support systems (such as for exercise), as well as logistics needs (e.g., for utilization, food, clothing, medical supplies), which drive campaign launches and cadences. Operationally, crew complement selection also sets an upper limit on the crew time and expertise available to carry out planned tasks, such as systems monitoring and maintenance, science, utilization, and public affairs outreach. To feed the initial human Mars segment target state, a decision outcome is needed on the targeted capability for how many crew members will travel to the Martian surface in the initial segment. This needed decision outcome is related to and interdependent with the needed decision outcome on the total number of crew to Mars vicinity per mission.

MD-06 Number of Crew to Mars Vicinity

Crew complement is a key constraint for human exploration architectures, with flow-down impacts to most elements and sub-architectures. The number of astronauts to support has direct impacts on the volume of habitable elements and other elements’ performance of ECLSS and crew support systems (such as for exercise), as well as logistics needs (e.g., for utilization, food, clothing, medical supplies), which drives campaign launches and cadences. Operationally, crew complement selection also sets an upper limit on the crew time and expertise available to carry out planned tasks, such as systems monitoring and maintenance, science, utilization, and public affairs outreach. As a companion decision to the Number of Crew to Mars Surface, a decision outcome is needed on the targeted capability for the number of crew in total that will travel to the vicinity of Mars during crewed missions. To consider the possible needs of orbiting spacecraft in parallel with surface mission objectives, the Crew to the Vicinity decision will also cover whether to split the crew between Mars orbit and surface.

MD-07 Primary Mars Surface Power Generation Technology

The scope of human exploration on Mars will be largely dependent on the amount of energy available to power crew life support systems, provide keep-alive support to surface elements, and to make, move, or environmentally maintain critical ascent vehicle propellants. A decision outcome is needed for the primary Mars surface power generation technology to be used during the missions of the initial human Mars segment. This decision will be a down-select between non-nuclear and nuclear technology types and will determine which type of power generation technology will be carried forward throughout further definition of the initial human segment architecture. Note that the scope of this decision would be limited to the power *generation* technique(s), not power load sizing, distribution, or other implementation technologies or methods. Additionally, the decision scope is limited to *primary* power generation and the outcome will not impact power generation technology for back-up power, mobility systems, or other non-primary power needs.

MD-08 Mars Architecture Loss-of-Mission Risk Posture

Building on the Mars Architecture Loss-of-Crew Risk Posture decision, a decision outcome is also needed about an architecture loss-of-mission risk posture. This decision will have flow-down impacts from several other priority key decisions, such as the decisions on the number of crew to Mars vicinity and to surface (given the need for crew time and expertise to accomplish primary mission objectives) and the decision about maximum crew surface stay duration. A risk posture is defined as an expression of the agreed-upon limits of risk an organization's leadership team is willing to accept in order to achieve one or more of its objectives. The loss-of-mission risk posture must be expressed as a range for the probability of loss-of-mission. The probability values should be determined based on candidate initial human Mars segment concept(s) of operation, and the decision outcome should include a comparison with other industry risks of comparable and non-comparable magnitudes.

MD-09 Maximum Mars Crew Surface Stay Duration

The Mars science objective priorities decision, initial Mars target state decision, and initial Mars mission cadence decision outcomes will together serve as the primary inputs on what is to be accomplished at Mars during the initial Humans to Mars segment. Building on these initial decisions, a decision outcome will be needed on the maximum Mars crew surface stay duration for the initial human Mars segment. This decision outcome should choose the upper limit target for crewed surface missions for the entire segment, but this does not restrict the program from implementing shorter crew surface stays during the segment. The focus should be on the drivers and pinch points for general surface stay duration options needed to accomplish the "what" on the surface of Mars, while not focusing on the exact number of days (something that is reserved for implementation organizations).

MD-10 Forward Contamination Planetary Protection Risk Posture

Forward contamination is terrestrial-origin harmful contamination present on or in a spacecraft during exploration activities (definition derived from NASA-STD-8719.27 Implementing Planetary Protection Requirements for Space Flight). To support compliance with the United Nations' Outer Space Treaty, the Committee on Space Research (COSPAR) maintains a consensus on international Policy on Planetary Protection. NASA supports and is an active partner with COSPAR's Panel on Planetary Protection for developing an international consensus standard for the discipline. NASA also participates in the COSPAR Panel on Planetary Protection for communicating and reporting mission activities from the agency to the international community. COSPAR Planetary Protection Policy, the international consensus standard and guidelines, is then used as one of multiple sources to inform NASA planetary protection policy and implementation. COSPAR policy designates landed Mars missions as Category IV, which triggers additional forward planetary protection as compared to landed missions on Earth's Moon (designated Category II). This means that the forward planetary protection risks — and NASA's risk posture — for human missions to Mars will be different than that for Artemis missions to the Moon. Additionally, NASA interim guidance for human missions to Mars acknowledges that it will not be possible for all human-associated processes and mission operations to be conducted within entirely closed systems.

Therefore, a decision outcome is needed on the Mars architecture forward contamination planetary protection risk posture. A "risk posture" is an expression of the agreed-upon limits of risk an organization's leadership team is willing to accept in order to achieve one or more of its objectives. Given the unique nature of this risk assessment, the Mars architecture forward contamination planetary protection risk posture may be expressed through a combination of quantitative and qualitative measures, which may include a minimum acceptable probability value determined based on candidate initial human Mars segment concept(s) of operation. The decision outcome should include comparison of robotic performance alongside other industry risks of comparable and non-comparable magnitudes.

MD-11 Backward Contamination Planetary Protection Risk Posture

Backward contamination is extraterrestrial harmful contamination that could pose a threat to the Earth's biosphere (definition from NASA-STD-8719.27 Implementing Planetary Protection Requirements for Space Flight). The United Nations' Outer Space Treaty specifies that space exploration should avoid "adverse changes in the environment of the Earth resulting from the introduction of extraterrestrial matter." To support compliance with the treaty, COSPAR maintains a consensus on international Policy on Planetary Protection. NASA's planetary protection policies are informed by the COSPAR policy. This policy designates all Earth return missions as Planetary Protection Category V, and landed missions to Mars are classified as Restricted Earth Return. This means that both the planetary protection risks — and NASA's risk posture — for human exploration of Mars will be different than that for Artemis missions to the Moon.

Although the NASA Interim Directive NID8715.129[18] acknowledges that crewmembers exploring Mars, or their support systems, will inevitably be exposed to Martian materials, NASA principles and guidelines emphasize that safeguarding the Earth from potential back contamination is the highest planetary protection priority in Mars exploration.

Therefore, a decision outcome is needed on the Mars architecture backward contamination planetary protection risk posture. Given the unique nature of this risk assessment, the Mars architecture backward contamination planetary protection risk posture may be addressed through a combination of quantitative and qualitative measures, which may include a minimum acceptable probability, determined based on acceptable metrics applied to candidate initial human Mars segment concept(s) of operation. The decision outcome should include comparison with other industry risks of comparable and non-comparable magnitudes.

MD-12 Maximum Allowable Crew Communication Disruption

[18] NASA Interim Directive NID8715.129, "Biological Planetary Protection for Human Missions to Mars", https://nodis3.gsfc.nasa.gov/OPD_Docs/NID_8715_129_.pdf (2020).

Communication blackouts are a known possibility based on planetary alignment in Mars mission trajectories. Without a means of mitigation (e.g., a communications relay or other communication assets), that blackout period may be unavoidable and of a wide range of durations. A decision outcome is needed on the maximum allowable communication blackout periods (i.e., when there is no communication possible between Earth and the crew) for crewed missions during the initial Humans to Mars segment. This decision outcome must consider the implications of a communications disruption during a crewed mission (future decisions will address contingency scenarios) and consider whether a mitigation might be desired.

B.2 Mars Key Decision Dependencies and Modeling

According to technical report TP-20240003341[19], decisions might be related to each other via a decision refines dependency in a SysML model. This dependency stereotype is customized to be the «MAT.Flows Down» relationship. In the decision model, these flow-down relationships indicate that one decision is thought to follow another for a variety of reasons: perhaps the previous decision may result in some required data products for the subsequent decision, or perhaps the previous decision will reduce the options available for the subsequent decision. The primary purpose of the SysML representation, example shown in Figure B-1, is to capture this notional sense of dependence between the decisions.

[19] "Decision Space Modeling: Trade Space Ontology" https://ntrs.nasa.gov/citations/20240003341

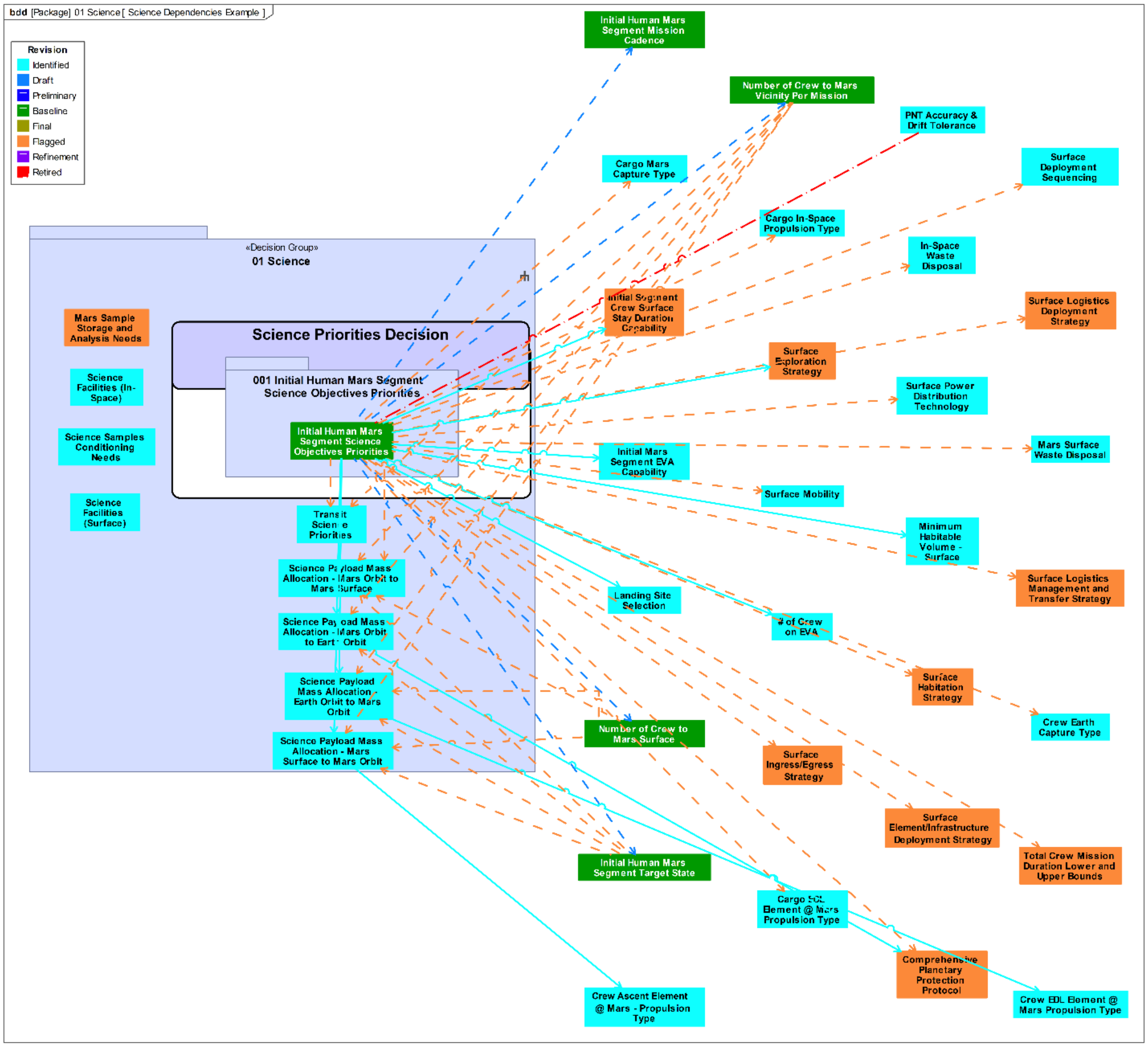


Figure B-1. Illustration of Flowdowns Centered on Science Decisions, Highlighting the Initial Mars Science Priorities

For the purpose of analyzing the resulting network of decisions, flow-downs can be interpreted in a variety of ways. For some kinds of critical path analysis, flow-downs can be taken as precedence constraints with decisions as tasks. However, the notional approach captured in the flow-downs results in many cycles between decisions that must be "cut" somehow for a critical path analysis. On the other hand, certain schedule optimization approaches can represent concurrence[20], and these cycles could be included under some definitions of concurrence. It remains to be formulated exactly how best to support roadmapping through the formulation of appropriate analytical methods. Any analytical method may have additional metadata requirements — information to be tracked alongside the decisions and their flow-downs; this information is being monitored and elicited preliminarily from stakeholders.

[20] "Development and Acquisition Modeling for Space Campaign Architecting" https://hdl.handle.net/1853/75323

B.3 REMAINING MARS KEY DECISIONS

The catalog of Mars architecture key decisions (Table B-2) is still a work in progress, and updates are expected to this document each year as the current decisions continue to be refined (including refinements to title and scope) and as new key decisions are identified.

A maturation process has been implemented to define review “toll gates” for bringing decisions from initial identification to final definition. Figure B--2 depicts this maturation process, consisting of a series of four maturity review gates, A through D. Each gate constitutes a review where criteria related to data completeness, model consistency, and architecture context are checked. If the maturity review gate criteria are satisfied, decisions progress up to the next maturity state. Nominally, the progression flows through the following maturity states: Identified → Draft → Preliminary → Provisional → Final. These maturity states are defined per the following:

- **Identified:** A model object (e.g., decision definition or flow-down relationship) that has been initially identified or suggested by the roadmapping team or a stakeholder. This model element has not yet passed any maturity review gates.

- **Draft:** A model object that has passed Maturity Review A. Review B is performed at the level of the decision roadmapping team. This means that the following metadata have been identified, reviewed during Review A, and documented in the model: decision name, decision scope, and decision context.

- **Preliminary:** A model object that has passed Maturity Review B. Review B is performed at the level of the decision roadmapping team.

- **Provisional:** A model object that has passed Maturity Review C. Review C requires approval from Mars Architecture Team leadership. Generally, decision definitions that have an ongoing decision package tasks will be at a “Provisional” maturity state.

- **Final:** A model object that has passed Maturity Review D. Review D requires approval from the model manager and generally means that a decision outcome has been released.

However, when issues or deficiencies are found during a review, decisions are moved to the Flagged state. Another review is then performed on Flagged decisions to determine whether the decision requires additional Refinement, or if the decision should be Retired. Refinement is the maturity state when a resolution for the issue has been achieved, but not yet implemented. Reasons for a decision being Retired include (but are not limited to):

- Proposed decision represents a metric or option rather than an actual decision
- Decision assumes or implies a particular solution
- Decision already exists, or is too correlated with decisions already existing in the model
- Decision belongs to an implementing project/program rather than the top-level architecture
- Decision is defined at a level that is inappropriate for the scope of the model

It is important to note that all decisions enter the maturation process in the Identified state, even those decisions that have been discussed and studied for many decades. Following the maturation process ensures that the model is able to support the various queries and analyses that will be used in supporting architecture decision-making.

Of the approximately 100 key Mars architecture decisions needed, only 12 have thus far been reviewed for inclusion in the Mars architecture decision roadmapping. These 12 (described in Appendix B.1) are considered sufficiently mature for decision roadmapping purposes, meaning that the needed decision outcome is well-defined, the needed decision outcome has been placed into the proper technical context, decision dependencies have been (or are being) mapped, and at least an initial assessment of supporting data needs has been developed.

The catalog of Mars decisions is still very much in work, but a snapshot of current progress is provided in Table B-1 and Table B-2. More than 70 needed decision outcomes are currently in the Identified state. Based on historical programs and analyses, what needs to be decided is well-defined, but the teams have not yet had a chance to fully analyze and map decision dependencies or assess supporting data needs or gaps to satisfy the maturity review gates. Remaining entries in the architecture decision catalog fall into the Flagged state. This set of needed decision outcomes was identified as potential candidates, but the architecture teams are still working through the maturation process. The list of Mars key decisions is included here for completeness and transparency, but note that some of these decisions may very well be removed from the catalog—i.e., marked as Retired—for various reasons. For example, “International Partnerships” was proposed for the Mars decision roadmapping based on historical precedent, but it remains forward work to define what precisely needs to be decided. Simply asking each partner to decide what they want to contribute would force planners to design a mission around the collection of elements actually contributed, which runs counter to the principles of “architecting from the right,” where the architecture teams identify functions and then develop elements that can provide those functions. Asking partners to decide whether they want to contribute a particular needed element may very well be an implementation decision, not an architecture decision. Whether “International Partnerships” remains in the architecture decision roadmapping or is an implementation decision best managed by the implementing programs is an example of the forward work remaining for the architecture teams in subsequent analysis cycles.

Table B-1. Number of Mars Key Decisions in Each Decision Category and in Each Maturity State

Decision Category	Total Decisions	Total Active (Not Retired)	Number Identified	Number Draft	Number Preliminary	Number Provisional	Number Final	Number Flagged	Number Refined	Number Retired
01 Science	10	9	7	0	0	1	0	1	0	1
02 Overall Strategy	17	15	7	0	0	2	0	6	0	2
03 Overall Risk	11	5	3	0	0	1	0	1	0	6
04 Human Systems & Habitation	27	21	17	0	0	2	0	2	0	6
05 Surface Systems & Infrastructure	12	8	5	0	0	1	0	2	0	4
06 Surface Infrastructure Deployment Strategy	8	6	3	0	0	0	0	3	0	2
07 Surface Operations	6	5	4	0	0	0	0	0	1	1
08 In-Space Systems & Infrastructure	5	2	1	0	0	0	0	1	0	3
09 In-Space Transportation	18	17	15	0	0	0	0	2	0	1

Decision Category	Total Decisions	Total Active (Not Retired)	Number Identified	Number Draft	Number Preliminary	Number Provisional	Number Final	Number Flagged	Number Refined	Number Retired
10 EDLA	10	9	8	0	0	0	0	1	0	1
11 C&PNT	7	6	3	0	0	0	0	2	1	1
12 Robotics & Autonomy	2	2	1	0	0	0	0	1	0	0
13 Inspiration	3	2	2	0	0	0	0	0	0	1
MODEL SUMMARY	**136**	**107**	**76**	**0**	**0**	**7**	**0**	**22**	**2**	**29**

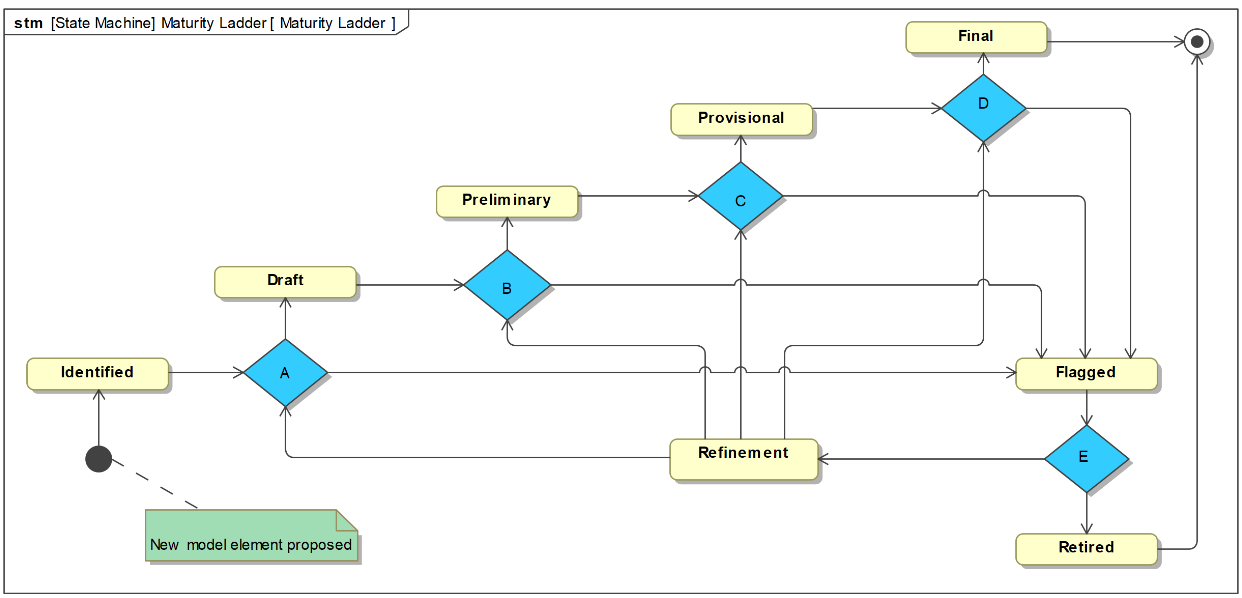


Figure B-2. Architecture Key Decision Maturity State Diagram

Note: Table B-2 below does not reflect a priority-based order; the table is sorted first for whether or not it is categorized as a priority key decision, and then the remaining rows are sorted based on the decision category.

Table B-2. Ongoing Working List of the Needed Mars Architecture Key Decisions

Decision ID Tag	Decision Title	Decision Category	Maturity State
MD-01	Initial Human Mars Segment Science Objectives Priorities	01 Science	Provisional
MD-02	Initial Human Mars Segment Target State	02 Overall Strategy	Provisional
MD-03	Initial Human Mars Segment Mission Cadence	02 Overall Strategy	Provisional

Decision ID Tag	Decision Title	Decision Category	Maturity State
MD-04	Mars Architecture Loss of Crew Risk Posture	03 Overall Risk	Provisional
MD-05	Number of Crew to Mars Surface	04 Human Systems & Habitation	Provisional
MD-06	Number of Crew to Mars Vicinity Per Mission	04 Human Systems & Habitation	Provisional
MD-07	Primary Mars Surface Power Generation Technology	05 Surface Systems & Infrastructure	Final
MD-08	Mars Architecture Loss of Mission Risk Posture	03 Overall Risk	Identified
MD-09	Initial Segment Crew Surface Stay Duration Capability	07 Surface Operations	Identified
MD-10	Mars Forward Contamination Planetary Protection Risk Posture	02 Overall Strategy	Identified
MD-11	Mars Backward Contamination Planetary Protection Risk Posture	02 Overall Strategy	Identified
MD-12	Maximum Allowable Crewed Communications Disruption	11 C&PNT	Identified
TBD	Mars Sample Storage and Analysis Needs	01 Science	Flagged
TBD	Science Facilities (In-Space)	01 Science	Identified
TBD	Science Facilities (Surface)	01 Science	Identified
TBD	Science Payload Mass Allocation - Earth Orbit to Mars Orbit	01 Science	Identified
TBD	Science Payload Mass Allocation - Mars Orbit to Earth Orbit	01 Science	Identified
TBD	Science Payload Mass Allocation - Mars Orbit to Mars Surface	01 Science	Identified
TBD	Science Payload Mass Allocation - Mars Surface to Mars Orbit	01 Science	Identified
TBD	Science Samples Conditioning Needs	01 Science	Identified
TBD	Mars Crew Quarantine for Planetary Protection	02 Overall Strategy	Flagged
TBD	Comprehensive Planetary Protection Protocol[21]	02 Overall Strategy	Flagged
TBD	Element Life and/or Re-Use	02 Overall Strategy	Identified
TBD	High Priority Technology Demonstration Objectives	02 Overall Strategy	Identified
TBD	International Partnerships	02 Overall Strategy	Flagged
TBD	Loss of Crew/Mission Contingency Procedure (Interplanetary)	02 Overall Strategy	Identified
TBD	Loss of Crew/Mission Contingency Procedure (Mars orbit)	02 Overall Strategy	Identified
TBD	Loss of Crew/Mission Contingency Procedure (Mars surface)	02 Overall Strategy	Identified

[21] Comprehensive Planetary Protection Protocol is not actually a unique key decision, but rather a "parent" decision of three separate key decisions: Mars Forward Contamination Planetary Protection Risk Posture, Mars Backward Contamination Planetary Protection Risk Posture, and Mars Crew Quarantine for Planetary Protection.

Decision ID Tag	Decision Title	Decision Category	Maturity State
TBD	Parts and Spares Strategy	02 Overall Strategy	Flagged
TBD	Precursor Missions	02 Overall Strategy	Flagged
TBD	Total Crew Mission Duration Lower and Upper Bounds	02 Overall Strategy	Flagged
TBD	Architecture-Driven Full Scale Demo Needs	03 Overall Risk	Identified
TBD	Human Rating Approach for Elements	03 Overall Risk	Flagged
TBD	Long-Duration Analogs for Mars	03 Overall Risk	Identified
TBD	Acceptable Level of Crew Deconditioning at Earth Return	04 Human Systems & Habitation	Flagged
TBD	Acceptable Level of Crew Deconditioning at Mars Arrival	04 Human Systems & Habitation	Flagged
TBD	Crew Composition	04 Human Systems & Habitation	Identified
TBD	Crew Health and Performance via Nutrition	04 Human Systems & Habitation	Identified
TBD	Crew Microgravity Deconditioning Countermeasures	04 Human Systems & Habitation	Identified
TBD	Crew Mortality Logistics (In Space)	04 Human Systems & Habitation	Identified
TBD	Crew Mortality Logistics (Mars Surface)	04 Human Systems & Habitation	Identified
TBD	Degree of ECLSS Loop Closure (In Space)	04 Human Systems & Habitation	Identified
TBD	Degree of ECLSS Loop Closure (Mars Surface)	04 Human Systems & Habitation	Identified
TBD	Exploration Atmospheres (In Space)	04 Human Systems & Habitation	Identified
TBD	Exploration Atmospheres (Mars Surface)	04 Human Systems & Habitation	Identified
TBD	Food Hydration Percentage	04 Human Systems & Habitation	Identified
TBD	Functional Split for Crew Radiation Mitigation	04 Human Systems & Habitation	Identified
TBD	Medical System Level of Care (In Space)	04 Human Systems & Habitation	Identified
TBD	Medical System Level of Care (Mars Surface)	04 Human Systems & Habitation	Identified
TBD	Waste Disposal (In Space)	04 Human Systems & Habitation	Identified
TBD	Waste Disposal (Mars Surface)	04 Human Systems & Habitation	Identified
TBD	Minimum Habitable Volume (In Space)	04 Human Systems & Habitation	Identified
TBD	Minimum Habitable Volume (Mars Surface)	04 Human Systems & Habitation	Identified
TBD	Asset Relocation Capability	05 Surface Systems & Infrastructure	Flagged
TBD	Degree of Surface Habitation Mobility	05 Surface Systems & Infrastructure	Identified
TBD	Primary Mars Surface Ingress/Egress Technology Type	05 Surface Systems & Infrastructure	Flagged

Decision ID Tag	Decision Title	Decision Category	Maturity State
TBD	Science Payload + Equipment Access and Transfer	05 Surface Systems & Infrastructure	Identified
TBD	Source of Mars Crew Consumables	05 Surface Systems & Infrastructure	Identified
TBD	Surface Logistics Access and Transfer	05 Surface Systems & Infrastructure	Identified
TBD	Surface Mobility	05 Surface Systems & Infrastructure	Identified
TBD	Surface Power Distribution Technology	05 Surface Systems & Infrastructure	Identified
TBD	Surface Power Grid Design	05 Surface Systems & Infrastructure	Flagged
TBD	Pre-Deployment of Infrastructure	06 Surface Infrastructure Deployment Strategy	Flagged
TBD	Surface Construction Materials Source	06 Surface Infrastructure Deployment Strategy	Identified
TBD	Surface Deployment Sequencing	06 Surface Infrastructure Deployment Strategy	Identified
TBD	Surface Logistics Deployment Strategy	06 Surface Infrastructure Deployment Strategy	Flagged
TBD	# of Crew on EVA	07 Surface Operations	Identified
TBD	Initial Mars Segment EVA Capability	07 Surface Operations	Identified
TBD	Landing Site Selection	07 Surface Operations	Identified
TBD	Mars Surface EVA Distance	07 Surface Operations	Identified
TBD	In-Space EVA Repair Capability	08 In-Space Systems & Infrastructure	Flagged
TBD	Primary Mars In-Space Power Generation Technology	08 In-Space Systems & Infrastructure	Identified
TBD	Cargo + Transportation Aggregation Location	09 In-Space Transportation	Identified
TBD	Cargo In-Space Propulsion Type	09 In-Space Transportation	Identified
TBD	Cargo Mars Capture Type	09 In-Space Transportation	Identified
TBD	Crew + Habitat Aggregation Location - Outbound	09 In-Space Transportation	Identified
TBD	Crew Earth Capture Type	09 In-Space Transportation	Identified

Decision ID Tag	Decision Title	Decision Category	Maturity State
TBD	Crew Earth to Mars Allowable Transit Duration	09 In-Space Transportation	Identified
TBD	Crew In-Space Propulsion Type	09 In-Space Transportation	Identified
TBD	Crew In-Space Return Propellant Strategy	09 In-Space Transportation	Flagged
TBD	Crew Mars Capture Type	09 In-Space Transportation	Identified
TBD	Element Delivery Conops	09 In-Space Transportation	Identified
TBD	In-Space Habitat + Transportation Aggregation Location	09 In-Space Transportation	Identified
TBD	In-Space Habitation Outfitting & Checkout Location	09 In-Space Transportation	Identified
TBD	In-Space Transportation Systems Reusability	09 In-Space Transportation	Identified
TBD	Logistics Delivery Conops	09 In-Space Transportation	Identified
TBD	Mars Parking Orbit	09 In-Space Transportation	Flagged
TBD	Science Payload + Equipment Delivery Conops	09 In-Space Transportation	Identified
TBD	Cargo Mars EDL Propulsion Type	10 EDLA	Identified
TBD	Crew Earth Ascent Vehicle	10 EDLA	Identified
TBD	Crew Earth Descent Vehicle	10 EDLA	Identified
TBD	Crew Mars Ascent Availability	10 EDLA	Identified
TBD	Crew Mars Ascent Propulsion Type	10 EDLA	Identified
TBD	Crew Mars Ascent Propellant Strategy	10 EDLA	Flagged
TBD	Crew Mars Descent Availability	10 EDLA	Identified
TBD	Crew Mars EDL Propulsion Type	10 EDLA	Identified
TBD	EDLA and In-Space Transportation Systems Functional Split	10 EDLA	Identified
TBD	EDLA Systems Reusability	10 EDLA	Identified
TBD	Crew Communications Architecture	11 C&PNT	Flagged
TBD	Minimum Crew Communications Capability	11 C&PNT	Flagged
TBD	PNT Accuracy & Drift Tolerance	11 C&PNT	Identified
TBD	Post-Crew Communications Architecture	11 C&PNT	Identified
TBD	Pre-Crew Communications Architecture	11 C&PNT	Identified
TBD	Degree of Autonomy in Systems	12 Robotics & Autonomy	Identified
TBD	Human/Robotic Interaction for Exploration	12 Robotics & Autonomy	Flagged
TBD	Inspiration Payload Allocation - Earth to Mars Surface	13 Inspiration	Identified
TBD	Inspiration Payload Allocation - Return to Earth	13 Inspiration	Identified

B.4 Lunar Architecture Key Decisions

This section is reserved. More information to be provided in a future revision.

APPENDIX C: ARCHITECTURE-DRIVEN TECHNOLOGY GAPS

C.1 TECHNOLOGY GAPS SUMMARIES

This appendix contains a set of gap detail summary tables for each of the architecture-driven technology gaps, which are described in Section 2.5. 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. The specific gap detail fields are defined as follows:

Gap ID	A four-digit unique identifier. The first two digits are determined by the gap's most relevant sub-architecture.
Gap Title	Summary of the needed capability in the Moon to Mars Architecture.
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 Impacts 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.
Sub-Architecture	List of the Moon to Mars sub-architecture(s) with strong relevance to the gap's content and scope.
Segment Mapping	The Moon to Mars Architecture segment(s) for which the capability is needed.
Architecture Traceability: Use Cases and Functions	List of the use cases and functions from which the needed Moon to Mars Architecture capability was derived.
Architecture Traceability: Key Decisions	List of key architecture decisions with strong relevance to the gap. To be considered relevant, the decision 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
Architecture-Driven Child Gaps	List of the titles of the child gaps related to this technology gap, which are also architecture-driven
Priority Bin	Distinct groupings of architecture preference of gap closure based upon prioritized list to show relative priority

Gap ID	Gap Title	
ESDMD #0101	Lunar Surface Positioning, Navigation, and Timing Systems for Extreme Temperature, Radiation, and Dust	Priority

Gap Description

Current positioning, navigation, and timing (PNT) systems for exploration assets and crew provide relative position but lack the ability to determine their absolute location. Long traverses across the lunar surface will require absolute localization to facilitate path planning and execution. There is a need for improvements to current absolute and relative PNT systems and technologies to accurately track crew and mobile surface assets. Additionally, PNT systems should be operable for expected durations and protected from lunar debris, dust, temperature variations, and exposure to radiation or any other space weather/lunar phenomena.

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 Impact 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 Traceability

UC/Fs

- UC-M-601 L -- FN-C-201 L
- UC-C-202 L -- FN-C-201 L
- UC-C-203 L -- FN-C-201 L

Key Decision

Metrics

Current State of the Art

There are no current NASA or ESA rovers on the moon. Current Mars rovers possess state-of-the-art PNT capabilities for mobile assets on another planetary surface.

Performance Target

Achieve absolute localization of crew, mobile, and in-place assets on the order of TBD meters.

Sub-Architecture(s)

Communications and Positioning, Navigation, and Timing Systems

Campaign Segment(s)

Foundational Exploration

Sustained Lunar Evolution

Higher Priority

!

Gap ID	Gap Title	
ESDMD #0102	High-bandwidth, High-reliability Deep Space Communications	Priority

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-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 Impact 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 (including PAO activities). For timing systems, there may be impacts reducing SWaP.

Architecture Traceability

UC/Fs

- UC-C-101 M -- FN-C-102 M
- UC-C-103 M -- FN-C-103 M
- UC-C-104 M -- FN-C-104 M

Key Decision

- Minimum Crew Communications Capability
- Maximum Allowable Crewed Communications Disruption
- Crew Communications Architecture

Metrics

Current State of the Art

Ground-based methods through the Deep Space Network or Mars orbiters.

Performance Target

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 which will drive bandwidth requirements.

Sub-Architecture(s)

Communications and Positioning, Navigation, and Timing Systems

Campaign Segment(s)

Humans to Mars

Higher Priority

!

Gap ID	Gap Title	Priority
ESDMD #0103	High-bandwidth, High-reliability Surface-to-Surface Communications	Higher Priority

Gap Description

Lunar and Mars surface communication technologies and systems 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-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 Impact and Benefits

If advancements are not made toward gap closure, there will be a lack of reliable, high-bandwidth lunar and Mars 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 Traceability

UC/Fs

- UC-C-102 L -- FN-C-107 L
- UC-C-102 M -- FN-C-101 M

Key Decision

- Crew Communications Architecture
- Post-Crew Communications Architecture
- Pre-Crew Communications Architecture

Metrics

Current State of the Art

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 demonstrated on the lunar surface and there are some concerns towards multipath being difficult for UHF-SSCS that may reduce the useable distance.

Performance Target

The 3rd Generation Partnership Project (3GPP) cellular technology (e.g. 4G, 5G) that supports video as well as critical voice. Advanced Wi-Fi technologies that can support critical applications. Communications technologies (e.g., rad-hard cores, user equipment, nodes) that are scalable, secure, and able to support multiple users with voice, video, and data at a high bandwidth. (TBR)

Sub-Architecture(s)

Communications and Positioning, Navigation, and Timing Systems

Campaign Segment(s)

Foundational Exploration; Sustained Lunar Evolution; Humans to Mars

Gap ID	Gap Title	Priority
ESDMD #0104	Earth-Independent Surface Positioning, Navigation, and Timing for Deep Space Missions	Higher Priority

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-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 Impact 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 Traceability

UC/Fs

- UC-C-202 M -- FN-C-201 M
- UC-C-203 M -- FN-C-202 M

Key Decision

- Maximum Allowable Crewed Communications Disruption
- PNT Accuracy & Drift Tolerance

Metrics

Current State of the Art

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.

Performance Target

Earth-independent tracking of spacecraft(s) PNT for 24/7, 365 continued coverage, despite disruptions and/or blackout periods.

Sub-Architecture(s)

Communications and Positioning, Navigation, and Timing Systems

Campaign Segment(s)

Humans to Mars

Gap ID	Gap Title	Priority
ESDMD #0201	Extreme Environment Avionics	! (Higher Priority)

Gap Description

Exploration missions in deep space and planetary environments will expose systems to large aggregate radiation doses and extreme temperatures. In parallel, computing and processing needs for future missions are increasing with system complexity, increased autonomy, in-situ analysis, and other factors. There is a need for systems that are tolerant to radiation, extreme temperature, and dust.

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

Architecture Impact 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 Traceability

UC/Fs

- UC-A-101 L -- FN-A-202 L
- UC-A-201 L -- FN-A-202 L

Key Decision

Metrics

Current State of the Art

Existing spacecraft subsystems operate between -180 and 130 deg C. TBR radiation tolerance with degraded functionality.

Performance Target

Enable high-performance computing capability in extreme environments (temperature, radiation, dust, etc.).

Sub-Architecture(s)

Data Systems and Management

Campaign Segment(s)

Foundational Exploration; Sustained Lunar Evolution; Humans to Mars

Gap ID	Gap Title	Priority
ESDMD #0202	High-Performance Onboard Computing	! (Higher Priority)

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. Flexibility is also needed to adapt power, fault tolerance, processing bandwidth, and I/O bandwidth to mission needs. Future computing systems should support open system avionics architectures that provide interoperability between modules sourced from different vendors.

Architecture-Driven Child Gaps

- 0202-01: High-performance general-purpose processors for deep space missions
- 0202-02: Radiation-hardened data storage to enable autonomous operations

Architecture Impact 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 Traceability

UC/Fs

- UC-D-201 L – All FN
- UC-D-201 L -- FN-D-204 L
- UC-A-403 M -- FN-A-402 M
- UC-A-404 M -- FN-A-402 M

Key Decision

- Degree of Autonomy in Systems

Metrics

Current State of the Art

Redundant COTS processors are used but incur the cost of increased SWaP and complexity.

Performance Target

Enable radiation-tolerant onboard computing operations to support autonomy, navigation, and other high-performance use cases in relevant environments. (TBR)

Sub-Architecture(s)

Data Systems and Management

Campaign Segment(s)

Foundational Exploration; Sustained Lunar Evolution; Humans to Mars

Gap ID	Gap Title	
ESDMD #0301	Systems to Survive and Operate through Extended Periods of Lunar Shadow	Priority

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-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 Impact 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 Traceability

UC/Fs

- UC-H-105 L -- FN-H-201 L

Key Decision

Metrics

Current State of the Art

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.

Performance Target

Survive continuous shadow for 150 (TBR) hours or more several times a year for 10 years.

Sub-Architecture(s)

Habitation Systems · Mobility Systems · Autonomous Systems and Robotics

Campaign Segment(s)

Foundational Exploration · Sustained Lunar Evolution

Higher Priority

Gap ID	Gap Title	
ESDMD #0302	Fire Safety Upgrades for Surviving Exploration Mission Environments	Priority

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-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 Impact and Benefits

If advances are not made in fire safety, exploration missions will have an increased probability of loss of crew or loss of mission/element. 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 Traceability

UC/Fs

- 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

Key Decision

- Mars Architecture Loss of Crew Risk Posture
- Mars Architecture Loss of Mission Risk Posture

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, which may be worst-case environment.

Performance Target

Materials capable of meeting flammability test standards in low- and partial-gravity environments at reduced pressures and higher oxygen levels. Fire detection, suppression, monitoring, and clean-up technologies that perform based on the worst-case fire scenario.

Sub-Architecture(s)

Habitation Systems

Campaign Segment(s)

Foundational Exploration · Sustained Lunar Evolution · Humans to Mars

Higher Priority

Gap ID	Gap Title	Priority
ESDMD #0303	Dormancy Recovery for Habitat Water Storage, Distribution, and Reclamation	

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-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 Impact 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 Traceability

UC/Fs

- UC-H-104 L -- FN-H-105 L
- UC-H-102 L -- FN-H-102 L
- UC-U-720 L -- FN-U-601 L
- UC-H-102 M -- FN-H-104 M
- UC-H-103 M -- FN-H-108 M

Key Decision

- Mars Architecture Loss of Crew Risk Posture
- Mars Architecture Loss of Mission Risk Posture
- Element Life and/or Re-Use
- Degree of ECLSS Loop Closure (In Space)
- Degree of ECLSS Loop Closure (Mars Surface)

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 Target

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. (TBR)

Sub-Architecture(s)

Habitation Systems

Campaign Segment(s)

Foundational Exploration; Sustained Lunar Evolution; Humans to Mars

Gap ID	Gap Title	Priority
ESDMD #0304	Habitat Environmental Monitors Capable of Supporting Deep Space Missions	

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 lunar and Mars mission durations.

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 Impact 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 Traceability

UC/Fs

- UC-H-106 M -- FN-H-118 M
- UC-H-107 M -- FN-H-119 M

Key Decision

- Mars Architecture Loss of Crew Risk Posture
- Mars Forward Contamination Planetary Protection Risk Posture
- Mars Backward Contamination Planetary Protection Risk Posture

Metrics

Current State of the Art

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. ISS flight demonstration of the Airborne Particulate Monitor. ISS Major Constituent Analyzer. ISS handheld acoustic monitors.

Performance Target

Water quality, microbial, airborne particulate monitors, trace contaminant, and acoustic monitoring capable of preventing undesirable crew health and vehicle operation outcomes, operable without Earth return of samples and with minimal consumables and crew time.

Sub-Architecture(s)

Habitation Systems

Campaign Segment(s)

Sustained Lunar Evolution; Humans to Mars

Gap ID	Gap Title	Priority
ESDMD #0305	Food and Nutrition Capabilities for Missions with Long-duration Storage	Higher Priority

Gap Description

Food system shelf life 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.

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

Architecture Impact 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 Traceability

UC/Fs

- 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

Key Decision

- Mars Architecture Loss of Crew Risk Posture
- Crew Health and Performance via Nutrition
- Food Hydration Percentage
- Acceptable Level of Crew Deconditioning at Earth Return
- Degree of ECLSS Loop Closure (In Space)

Metrics

Current State of the Art

ISS is regularly resupplied with a wide variety of shelf stable foods for the crew to choose from minimum 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.

Performance Target

Food system to provide nutritional shelf life, variety, safety, and acceptability for sustained lunar and Mars mission durations and life support closure levels. (TBR)

Sub-Architecture(s)

Habitation Systems

Campaign Segment(s)

Foundational Exploration, Sustained Lunar Evolution, Humans to Mars

Gap ID	Gap Title	Priority
ESDMD #0306	Advanced Structures and Materials to Enable Mass-Efficient Habitats	Higher Priority

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-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 Impact 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 Traceability

UC/Fs

- UC-H-102 L -- FN-H-102 L

Key Decision

- Minimum Habitable Volume (In Space)
- Minimum Habitable Volume (Mars Surface)

Metrics

Current State of the Art

Multiple options for mass and volume savings such as inflatable softgoods, composites, and lightweight metallics.

Performance Target

Solutions that allow habitation structures to meet TBR performance thresholds while complying with TBR mass and volume constraints.

Sub-Architecture(s)

Habitation Systems

Campaign Segment(s)

Sustained Lunar Evolution, Humans to Mars

Gap ID	Gap Title	Priority
ESDMD #0307	Radiation Monitoring and Modeling	! Higher Priority

Gap Description

Lunar 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. Models for predicting Galactic Cosmic Radiation (GCR) intensity from one solar cycle to the next are also needed.

Architecture-Driven Child Gaps

- 0307-01: Forecasting and radiation models for solar particle events
- 0307-02: Space radiation environment characterization systems
- 0307-03: Earth-independent space weather forecasting

Architecture Impact 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 Traceability

UC/Fs

- UC-U-721 L
- UC-U-722 L
- UC-U-719 L
- UC-U-720 L
- UC-H-102 M -- FN-H-106 M
- UC-H-103 M -- FN-H-110 M

Key Decision

- Mars Architecture Loss of Crew Risk Posture
- Total Crew Mission Duration Lower and Upper Bounds

Metrics

Current State of the Art

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. SPE prediction models struggle to understand and capture event onset with high false alarm rates exceeding positive detections. Current models do not forecast the duration, intensity, or how the event will change over time and struggle to predict the most intense and hazardous events.

Performance Target

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.

Sub-Architecture(s)

Habitation Systems

Human Systems

Campaign Segment(s)

Foundational Exploration

Sustained Lunar Evolution

Humans to Mars

Gap ID	Gap Title	Priority
ESDMD #0308	Radiation Countermeasures	

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 are needed to reduce the risk of adverse medical impacts on crew. GCR shielding will also help shield for SPE radiation.

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 Impact 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 Traceability

UC/Fs

- 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

Key Decision

- Mars Architecture Loss of Crew Risk Posture
- Acceptable Crew Radiation Exposure Limit
- Total Crew Mission Duration Lower and Upper Bounds
- In-Space Radiation Mitigation

Metrics

Current State of the Art

Operational and physical mitigation strategies are used to reduce crew doses on ISS. No medical radiation countermeasures have been identified/validated to protect against long-term health effects. Countermeasures exist to protect against acute, high-dose terrestrial exposures and are most likely suitable for protection against an unanticipated exposure to a large SPE.

Performance Target

Develop long-duration, mass-efficient exploration mission-compatible countermeasures performing adequately to reduce adverse crew health outcomes, including a combination of 1) passive shielding 2) active shielding 3) other countermeasures in alignment with NASA-STD-3001 V1 4030 & 4031.

Sub-Architecture(s)

Habitation Systems

Human Systems

Campaign Segment(s)

Sustained Lunar Evolution

Humans to Mars

!

Higher Priority

Gap ID	Gap Title	Priority
ESDMD #0401	Crew Exercise Countermeasures to Support Extended Habitation in Space	Higher Priority

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-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 Impact 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 Traceability

UC/Fs

- 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

Key Decision

- Mars Architecture Loss of Crew Risk Posture
- Crew Microgravity Deconditioning Countermeasures
- Mars Crew Surface Stay Duration Maximum
- Acceptable Level of Crew Deconditioning at Mars Arrival

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 Mars 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 Target

Hardware and software that 1) are sufficient to meet CHP standards for aerobic fitness, muscle strength, bone health for extraterrestrial surface injury risk minimization; 2) require planned maintenance of no more than (TBD); 3) compatible with Mars mission, systems, and operations (TBR); and 4) applicable for in-transit and surface mission phases (TBR).

Sub-Architecture(s)

Human Systems

Campaign Segment(s)

Sustained Lunar Evolution

Humans to Mars

Gap ID	Gap Title	
ESDMD #0402	Sensorimotor Countermeasures to Support Extended Habitation in Space	Priority

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-Driven Child Gaps

- 0402-01: Sensorimotor and disorientation countermeasures and mitigation
- 0402-02: Sensorimotor adaptation assessment tools

Architecture Impact and Benefits

Without gap closure, there is an increased risk of injury from insufficient sensorimotor adaptation.

Architecture Traceability

UC/Fs

- 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

Key Decision

- Mars Architecture Loss of Crew Risk Posture
- Crew Microgravity Deconditioning Countermeasures
- Mars Crew Surface Stay Duration Maximum
- Acceptable Level of Crew Deconditioning at Mars Arrival

Metrics

Current State of the Art

There are no effective sensorimotor countermeasures. Exercise is an inadequate sensorimotor countermeasure. (Current ISS return is example of ineffectiveness).

Performance Target

Hardware and software that are sufficient to meet CHP standards for sensorimotor health to safe completion of assessment within (TBD) of preflight baseline.

Sub-Architecture(s)

Human Systems

Campaign Segment(s)

Sustained Lunar Evolution

Humans to Mars

Higher Priority

Gap ID	Gap Title	
ESDMD #0403	Physiological Countermeasures for Extended Habitation in Space	Priority

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 need to be improved for crew to accurately maintain and monitor physical health and performance during exploration missions.

Architecture-Driven Child Gaps

- 0403-01: Neuro-ocular countermeasures and mitigation
- 0403-02: Microbially-induced disease countermeasures
- 0403-03: Immune system dysregulation countermeasures

Architecture Impact 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 Traceability

UC/Fs

- 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

Key Decision

- Mars Architecture Loss of Crew Risk Posture
- Crew Microgravity Deconditioning Countermeasures

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 Target

Long-duration exploration mission-compatible countermeasures performing adequately to reduce adverse crew health outcomes with communication delay and without resupply.

Sub-Architecture(s)

Human Systems

Campaign Segment(s)

Sustained Lunar Evolution

Humans to Mars

Higher Priority

Gap ID: ESDMD #0404 — Gap Title: Behavioral Countermeasures for Extended Habitation in Space

Priority: Higher Priority !

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 Impact 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

UC/Fs

- 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

Key Decision

- Mars Architecture Loss of Crew Risk Posture
- Mars Architecture Loss of Mission Risk Posture
- Mars Surface Medical System Level of Care

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 Target

Long-duration exploration mission-compatible countermeasures performing adequately to reduce adverse crew health outcomes with communication delays and without resupply.

Sub-Architecture(s)

Human Systems

Campaign Segment(s)

Sustained Lunar Evolution; Humans to Mars

Gap ID: ESDMD #0405 — Gap Title: Exploration Medical Capabilities for Deep Space Missions

Priority: Higher Priority !

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-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

Architecture Impact 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 Traceability

UC/Fs

- 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

Key Decision

- Mars Architecture Loss of Crew Risk Posture
- Mars Architecture Loss of Mission Risk Posture
- Medical System Level of Care (In Space)
- Medical System Level of Care (Mars Surface)

Metrics

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 Target

Dependent upon future integrated risk assessment trades. Medical systems and concepts of operation to reduce risk of adverse crew health outcomes with communication delay, no abort capability, and limited diagnostic and treatment resources.

Sub-Architecture(s)

Human Systems

Campaign Segment(s)

Sustained Lunar Evolution; Humans to Mars

Gap ID	Gap Title	Priority
ESDMD #0406	Spacesuit Physiology for Deep Space Missions	Higher Priority

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 Impact 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

UC/Fs

- UC-M-101-L -- All FN
- UC-M-102-L -- All FN

Key Decision

- Mars Architecture Loss of Crew Risk Posture

Metrics

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 Target

Dependent upon future integrated risk assessment trades, improved spacesuit physiology capabilities capable of supporting lunar and Mars mission EVA strategy with acceptable risk of adverse outcomes.

Sub-Architecture(s)

Human Systems

Campaign Segment(s)

Sustained Lunar Evolution

Humans to Mars

Gap ID	Gap Title	Priority
ESDMD #0501	Robotic and Human-Robot Inspection, Maintenance, and Repair	Higher Priority

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 both perform IM&R activities in the absence of crew and support/assist crew to maximize available time for crew science and exploration priorities. This includes the maturation of robotic systems with the necessary manipulation capabilities, the design and integration of interfaces suited for robotic IM&R, and the development of appropriate methods of human-robot collaboration across these tasks (both when collocated and via remote operation). 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-Driven Child Gaps

- 0806-03: 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
- 1005-01: Situational awareness and safety controls for human-robot interaction

Architecture Impact and Benefits

Closing this gap helps assure in-space and surface assets remain available to achieve mission objectives.

Architecture Traceability

UC/Fs

- 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

Key Decision

- Degree of Autonomy in Systems

Metrics

Current State of the Art

IM&R tasks performed manually by crew only.

Performance Target

Improved system availability (reliability, maintainability, supportability) as well as safety.

Sub-Architecture(s)

Infrastructure Support

Autonomous Systems and Robotics

Campaign Segment(s)

Foundational Exploration

Sustained Lunar Evolution

Humans to Mars

Gap ID: ESDMD #0502 — Gap Title: In-situ Manufacturing of Spares, Repairs, and New Parts

Priority: Higher Priority

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 outfitting, structural components, basic tools, materials for daily crew use, and custom-designed parts for mission-critical 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 Impact 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 Traceability

UC/Fs

- UC-I-204 L -- FN-I-206 L
- UC-I-203 L -- FN-I-207 L
- UC-I-201 M -- All FN

Key Decision

- Parts and Spares Strategy
- Surface Construction Materials Source

Metrics

Current State of the Art

Capability to manufacture new products, spare parts, replacement units, or specialty tools in-situ does not exist beyond small demonstration components fabricated from polymers.

Performance Target

Enable space-based manufacturing techniques allowing repairs and replacement of hardware components in-situ (TBR). Reliance on in-situ manufacturing is subject to ongoing and future decisions.

Sub-Architecture(s)

- Infrastructure Support
- In-situ Resource Utilization (ISRU) Systems
- Logistics Systems

Campaign Segment(s)

- Sustained Lunar Evolution
- Humans to Mars

Gap ID: ESDMD #0503 — Gap Title: In-Space & Surface Transfer of Earth-Storable Propellants

Priority: Higher Priority

Gap Description

Planned lunar and Mars exploration benefits from propellant transfer of hypergolic propellants, including both in-space and lunar/Mars surface operations. This gap captures the required activities to enable efficient propellant transfer with acceptable risk posture.

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

Architecture Impact and Benefits

Without gap closure, the architecture will be unable to transfer storable propellant between elements.

Architecture Traceability

UC/Fs

- UC-U-502 L -- FN-U-508 L
- UC-U-501 L -- FN-U-507 L

Key Decision

- Surface Logistics Access and Transfer

Metrics

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 Target

Enable the transfer of storable propellant and high pressure gases between exploration assets in space and on the surface of the Moon and Mars.

Sub-Architecture(s)

- Infrastructure Support

Campaign Segment(s)

- Sustained Lunar Evolution
- Humans to Mars

Gap ID	Gap Title	
ESDMD #0601	Oxygen Extraction from Lunar Regolith	Priority

Gap Description

Oxygen from lunar regolith has been identified as a primary demonstration target to support sustained lunar presence through ISRU. Long-term operation of these systems has not been demonstrated.

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 Impact 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 Traceability

UC/Fs

- UC-I-102 L -- All FN

Key Decision

Metrics

Current State of the Art

Days of operation under ambient environments with Mare-type regolith simulants at sub-pilot scale. Two processes were developed to TRL 4/5.

Performance Target

The ability to demonstrate the acquisition, processing, storage and transfer of usable ISRU-generated products in the TBR kg class at the moon in a scalable manner.

Sub-Architecture(s)

In-situ Resource Utilization (ISRU) Systems

Campaign Segment(s)

Foundational Exploration

Sustained Lunar Evolution

Higher Priority

!

Gap ID	Gap Title	
ESDMD #0602	In-Situ Resource Identification, Characterization, and Mapping	Priority

Gap Description

Current knowledge of lunar and Martian resources is insufficient to ensure the success of ISRU operations that will support human exploration. New instruments and methods are required to adequately determine presence and abundance of in-situ resources.

Architecture-Driven Child Gaps

- 0602-01: Instruments to determine the mineral/chemical composition of lunar regolith
- 0602-02: Instruments to determine the geotechnical properties of lunar regolith
- 0602-03: Lunar resource mapping, reconnaissance, and predictive modeling
- 0602-04: Mars resource mapping, reconnaissance, and predictive modeling

Architecture Impact and Benefits

Without gap closure, the impacts include reduced ability to select effective ISRU sites near lunar south pole exploration sites. Martian site selection criteria to meet ISRU objectives will need data from orbit remote sensing sources and likely from surface validation.

Architecture Traceability

UC/Fs

- UC-I-101 L -- FN-U-103 L
- UC-U-719 L -- All FN
- UC-U-102 M -- All FN

Key Decision

- Source of Mars Crew Consumables
- Surface Construction Materials Source
- Crew Ascent from Mars Propellant Strategy

Metrics

Current State of the Art

VIPER site selection tools and onboard instruments.

Performance Target

Measure the abundance, form, and mineralogy of resources at sufficient accuracy to ensure reserves can meet use case need.

Sub-Architecture(s)

In-situ Resource Utilization (ISRU) Systems

Campaign Segment(s)

Foundational Exploration

Sustained Lunar Evolution

Humans to Mars

Higher Priority

!

Gap ID	Gap Title	Priority
ESDMD #0603	Water Recovery from Lunar Regolith/Ice	

Gap Description

Water has been identified as a primary demonstration 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-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 Impact 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 Traceability

UC/Fs

- UC-I-103 L -- All FN

Key Decision

Metrics

Current State of the Art

Various methods and low TRL technologies tested with simulant at subscale.

Performance Target

The ability to demonstrate the acquisition, processing, storage, and transfer of usable ISRU generated products in the TBR kg class at the Moon in a scalable manner.

Sub-Architecture(s)

In-situ Resource Utilization (ISRU) Systems

Campaign Segment(s)

Foundational Exploration

Sustained Lunar Evolution

Higher Priority !

Gap ID	Gap Title	Priority
ESDMD #0604	Metal Extraction from Lunar Regolith	

Gap Description

Metals for manufacturing feedstock have been identified as a primary demonstration 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-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 Impact 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 Traceability

UC/Fs

- UC-I-106 L -- All FN

Key Decision

Metrics

Current State of the Art

Proof of concept type lab operations; short durations and small quantities. Terrestrial excavation techniques.

Performance Target

The ability to demonstrate the acquisition, processing, storage and transfer of usable ISRU-generated products in the TBR kg class at the Moon in a scalable manner.

Sub-Architecture(s)

In-situ Resource Utilization (ISRU) Systems

Campaign Segment(s)

Foundational Exploration

Sustained Lunar Evolution

Higher Priority !

Gap ID	Gap Title	Priority
ESDMD #0605	Lunar Regolith Excavation, Manipulation, and Transportation	Higher Priority !

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) demonstrations such as oxygen, water ice, metals, and feedstock. Site preparation requires manipulation of regolith and capabilities are needed with novel implements to provide these functions so that routine operations at landing zones, habitation zones, and pathways can emerge.

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 Impact 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.

Architecture Traceability

UC/Fs

- UC-I-202 L -- All FN

Key Decision

Metrics

Current State of the Art

Lander-mounted Phoenix scoop <10 kg of regolith. Time consuming manual operations contending with unimproved, dusty, unlit terrain without maintained services.

Performance Target

Demand for regolith will depend on the scale of ISRU operations and site preparation. (TBR)

Sub-Architecture(s)

In-situ Resource Utilization (ISRU) Systems; Autonomous Systems and Robotics; Mobility Systems

Campaign Segment(s)

Sustained Lunar Evolution

Gap ID	Gap Title	Priority
ESDMD #0606	Mars ISRU to Support Human Exploration	Higher Priority !

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-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 Impact and Benefits

Without gap closure, Mars mission architectures will be confined to Earth-delivered resources.

Architecture Traceability

UC/Fs

- UC-I-101 M -- All FN
- UC-I-102 M -- All FN
- UC-I-201 M -- All FN

Key Decision

- Source of Mars Crew Consumables
- Surface Construction Materials Source
- Crew Ascent from Mars Propellant Strategy

Metrics

Current State of the Art

Various technologies at TRL 3/4. MOXIE CO2 to O2 demonstration on Mars at subscale with challenges that must be addressed for scaling operations.

Performance Target

Enable the production of commodities, propellant, and other usable materials to support human Mars missions (TBR). Reliance on ISRU is subject to ongoing and future decisions.

Sub-Architecture(s)

In-situ Resource Utilization (ISRU) Systems

Campaign Segment(s)

Humans to Mars

Gap ID	Gap Title	Priority
ESDMD #0701	Packing, Transport, and Use of Conditioned Supplies and Commodities	! Higher Priority

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, human-robotic compatible, transportable, thermally 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

Architecture Impact 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

UC/Fs

- UC-L-201 L -- FN-L-201 L
- UC-H-102 M -- FN-H-104 M
- UC-H-103 M -- FN-H-108 M

Key Decision

- Surface Logistics Access and Transfer
- Logistics Strategy

Metrics

Current State of the Art

Apollo equipment carriers. ISS EVR experience (SPDM, etc.), ISS systems for pressurized cargo (e.g., CTB, ZSR, fluid bags, etc.)

Performance Target

Minimize logistics footprint, system mass, crew handling, and delivery time. Maximize reuse.

Sub-Architecture(s)

Logistics Systems

Campaign Segment(s)

Foundational Exploration · Sustained Lunar Evolution · Humans to Mars

Gap ID	Gap Title	Priority
ESDMD #0702	Waste Management	! Higher Priority

Gap Description

A comprehensive ability to manage waste streams is lacking. Trash disposal can release microbial material, 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 and oxygen) 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-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 Impact 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 Traceability

UC/Fs

- UC-L-201 L -- FN-L-301 L
- UC-L-202 L -- FN-L-302 L
- UC-H-102-L -- FN-L-301 M
- UC-H-103 M -- FN-L-302 M

Key Decision

- Mars Forward Contamination Planetary Protection Risk Posture
- Waste Disposal (In Space)
- Waste Disposal (Mars Surface)

Metrics

Current State of the Art

Abandoning all waste on the surface or in designated orbit.

Performance Target

Solutions that maximize reuse, minimize logistics footprint, and prevent microbial and volatile releases that contaminate the vehicle and planetary surfaces.

Sub-Architecture(s)

Logistics Systems

Campaign Segment(s)

Foundational Exploration · Sustained Lunar Evolution · Humans to Mars

Gap ID	Gap Title	Priority
ESDMD #0801	Lunar Dust-Tolerant Systems and Dust Mitigation	

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-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 Impact and Benefits

Without gap closure, systems may be damaged by dust particles and unable to perform at expected reliabilities or for expected durations.

Architecture Traceability

UC/Fs

- UC-U-804 L
- UC-M-101 L -- FN-M-101 L

Key Decision

Metrics

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 Target

Systems 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 to allow desired operational capability. (TBR)

Sub-Architecture(s)

Mobility Systems, Habitation Systems, Logistics Systems, Power Systems

Campaign Segment(s)

Foundational Exploration, Sustained Lunar Evolution

Higher Priority

Gap ID	Gap Title	Priority
ESDMD #0802	Mars Dust-Tolerant Systems and Dust Mitigation	

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, and surface habitats. Additionally, dust mitigation technologies that can be leveraged to reduce the impact of dust on systems/subsystems are needed.

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 Impact 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 Traceability

UC/Fs

- UC-H-103 M -- FN-H-110 M

Key Decision

- Primary Mars Surface Ingress/Egress Technology Type

Metrics

Current State of the Art

Dust-tolerant systems and mechanisms on the Mars Perseverance rover.

Performance Target

Systems 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 to allow desired operational capability. (TBR)

Sub-Architecture(s)

Mobility Systems, Habitation Systems, Logistics Systems, Power Systems

Campaign Segment(s)

Humans to Mars

Higher Priority

Gap ID: ESDMD #0803

Gap Title: Extravehicular Activity (EVA) and Intravehicular Activity (IVA) Suit System Capabilities for Mars Missions

Priority

Higher Priority

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, mass reductions for the Mars surface suit and systems are necessary for Mars partial gravity. Furthermore, there is unknown material degradation due to radiation beyond LEO that future suits must account for. Human missions to Mars may require radical changes in the approach to EVA suit design.

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 Impact 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 Traceability

UC/Fs

- UC-M-101 M -- All FN

Key Decision

- Initial Mars Segment EVA Capability
- Mars Surface EVA Distance
- Mars Architecture Loss of Crew Risk Posture
- Mars Architecture Loss of Mission Risk Posture

Metrics

Current State of the Art

The xEMU heat rejection and CO2 removal systems are dependent on operating in a vacuum environment as opposed to the Martian atmosphere.

Performance Target

Mars spacesuits must be compatible with the surface gravity environment and the presence of an atmosphere, including CO2 that 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.

Sub-Architecture(s)

Mobility Systems

Human Systems

Campaign Segment(s)

Humans to Mars

Gap ID: ESDMD #0804

Gap Title: Robotic and Mobility Systems in Extreme Cold Environments

Priority

Higher Priority

Gap Description

Access to extreme cold environments including permanently shadowed regions (PSRs) presents several technology challenges. Extreme cold temperature robotic and mobility components such as actuators, wheels, circuits, and other subsystems including robust perception in low or no lighting are critical to enabling access to PSRs.

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 lunar lighting conditions

Architecture Impact 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.

Architecture Traceability

UC/Fs

- UC-A-106 L -- FN-A-202 L
- UC-A-101 L -- FN-A-202 L

Key Decision

Metrics

Current State of the Art

Non-integrated subsystems tested independently between 220 K and 130 K, with limited operational lifetimes.

Performance Target

Enable use cases for surveying and accessing PSRs for sample retrieval. Increasing survey durations and areas with PSRs.

Sub-Architecture(s)

Mobility Systems

Autonomous Systems and Robotics

Campaign Segment(s)

Foundational Exploration

Sustained Lunar Evolution

Gap ID	Gap Title	Priority
ESDMD #0805	Autonomous Surface Mobility and Navigation	! (Higher Priority)

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-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 lunar lighting conditions
- 0805-02: High-performance general purpose processors for deep space missions
- 0805-03: Software for onboard localization, hazard detection, and path planning for surface mobility systems

Architecture Impact 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 Traceability

UC/Fs

- UC-A-201 L -- FN-A-201 L

Key Decision

- PNT Accuracy & Drift Tolerance
- Degree of Autonomy in Systems

Metrics

Current State of the Art

Human-in-the-loop ground control solutions navigating at slow pace over comm delay and data latency. VIPER sensors for determining position and identifying hazards. 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.

Performance Target

Capability for autonomous surface mobility and navigation to enable accurate location estimation and repositioning of surface assets while uncrewed.

Sub-Architecture(s)

Mobility Systems

Autonomous Systems and Robotics

Campaign Segment(s)

Foundational Exploration

Sustained Lunar Evolution

Humans to Mars

Gap ID	Gap Title	Priority
ESDMD #0806	Payload Offloading, Handling, and Manipulation for Surface Assets	Higher Priority (!)

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-Driven Child Gaps

- 1001-01: Robust robotic sensors
- 1001-03: Efficient autonomous object detection, classification, and pose estimation
- 0806-01: Affordance recognition, grasp planning, and execution for autonomous object and interface manipulation
- 1001-02: Adaptable robotic end effectors for fine grasping and manipulation
- 0806-02: Payload maneuvering tools for offloading, positioning, and delivery

Architecture Impact 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 Traceability

UC/Fs

- UC-A-103 L -- All FN
- UC-A-105 M -- All FN

Key Decision

- Surface Logistics Access and Transfer
- Surface Logistics Deployment Strategy

Metrics

Current State of the Art

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.

Performance Target

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.

Sub-Architecture(s)

- Mobility Systems
- Autonomous Systems and Robotics
- Logistics Systems

Campaign Segment(s)

- Foundational Exploration
- Sustained Lunar Evolution
- Humans to Mars

Gap ID	Gap Title	Priority
ESDMD #0807	Docking and Berthing between Surface Elements on the Moon and Mars	Higher Priority (!)

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-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 Impact 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 Traceability

UC/Fs

- UC-L-201 L -- FN-L-101 L
- UC-L-201 L -- FN-L-205 L

Key Decision

- Surface Logistics Access and Transfer

Metrics

Current State of the Art

Heritage ISS docking systems. Surface docking/mating systems for dusty surface environments do not currently exist.

Performance Target

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.

Sub-Architecture(s)

- Mobility Systems
- Logistics Systems
- Habitation Systems

Campaign Segment(s)

- Foundational Exploration
- Sustained Lunar Evolution
- Humans to Mars

Gap ID	Gap Title	Priority
ESDMD #0808	Relocation of Large Assets on the Lunar Surface	Higher Priority

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-Driven Child Gaps

- 0808-01: Robotic offloading and relocation for large-scale payloads

Architecture Impact 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 Traceability

UC/Fs

- UC-M-401 L -- FN-M-403 L
- UC-M-601 L -- FN-M-601 L

Key Decision

Metrics

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 Target

Capability to manipulate and transport >6-metric ton asset over TBR distance.

Sub-Architecture(s)

Mobility Systems

Autonomous Systems and Robotics

Campaign Segment(s)

Foundational Exploration

Sustained Lunar Evolution

Gap ID	Gap Title	Priority
ESDMD #0901	Scalable Lunar Surface Power Generation	Higher Priority

Gap Description

There is a need for scalable lunar surface power generation capabilities to provide continuous electrical energy for large exploration 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 in the lunar polar environment.

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 Impact 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 Traceability

UC/Fs

- UC-P-101 L -- All FN
- UC-P-102 L -- All FN
- UC-P-501 L
- UC-P-502 L

Key Decision

Metrics

Current State of the Art

ISS has ~200 kW of solar arrays with battery energy storage for ~30-minute LEO eclipse. There has been one brief ground test of a kW-scale fission power system intended for space ("KRUSTY" in 2018).

Performance Target

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.

Sub-Architecture(s)

Power Systems

Campaign Segment(s)

Foundational Exploration

Sustained Lunar Evolution

Gap ID	Gap Title	Priority
ESDMD #0902	Scalable Mars Surface Power Generation	Higher Priority

Gap Description

There is a need for scalable Mars surface power generation capabilities to provide electrical energy for the majority of large exploration 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.

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 Impact and Benefits

Without gap closure, the impact is the inability to support more than minimal missions to the Martian surface. Inability to demonstrate in-situ resource utilization described in objective MI-04.

Architecture Traceability

UC/Fs

- UC-P-101 M -- All FN
- UC-P-102 M -- All FN
- UC-P-103 M
- UC-P-501 M

Key Decision

- Primary Mars Surface Power Generation Technology

Metrics

Current State of the Art

Mars surface solar flux is <40% of the Moon and exacerbated by month-long dust storms. NASA experience with long-duration lunar 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 Target

Scalable multi-kWe-scale power generation capable of supporting crew safety in Mars temperatures, dust, and solar availability conditions. (TBR)

Sub-Architecture(s)

Power Systems

Campaign Segment(s)

Humans to Mars

Gap ID	Gap Title	Priority
ESDMD #0903	Power Management and Distribution between Surface Elements	Higher Priority

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-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 Impact 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 Traceability

UC/Fs

- 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

Key Decision

- Surface Power Distribution Technology
- Surface Power Grid Design

Metrics

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 Target

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).

Sub-Architecture(s)

Power Systems

Campaign Segment(s)

Foundational Exploration | Sustained Lunar Evolution | Humans to Mars

Gap ID	Gap Title	Priority
ESDMD #1001	High-performance Actuators, Sensors, and Interfaces	

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-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 Impact 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 Traceability

UC/Fs

- UC-L-202 L -- FN-T-106 L
- UC-A-107 L -- FN-A-204 L

Key Decision

Metrics

Current State of the Art

Heritage robotic missions to Mars have tele-operated actuators, cameras, sensors for limited capture functions.

Performance Target

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. (TBR)

Sub-Architecture(s)

Mobility Systems; Autonomous Systems and Robotics

Campaign Segment(s)

Sustained Lunar Evolution; Humans to Mars

Higher Priority

Gap ID	Gap Title	Priority
ESDMD #1002	Autonomous Monitoring for Exploration Missions	

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-Driven Child Gaps

- 1002-01: Autonomous monitoring software
- 1002-02: High-performance general-purpose processors for deep space missions

Architecture Impact 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 Traceability

UC/Fs

- 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

Key Decision

- Mars Architecture Loss of Crew Risk Posture
- Mars Architecture Loss of Mission Risk Posture
- Degree of Autonomy in Systems
- Mars Maximum Crew Communication Disruption

Metrics

Current State of the Art

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.

Performance Target

Enable autonomous monitoring of systems and crew that support human exploration with Mars-distance communication delays and blackouts.

Sub-Architecture(s)

Autonomous Systems and Robotics; Data Systems and Management

Campaign Segment(s)

Foundational Exploration; Sustained Lunar Evolution; Humans to Mars

Higher Priority

Gap ID	Gap Title	Priority
ESDMD #1003	Integrated System Fault/Anomaly Diagnosis, Decision Support, and Response	Higher Priority

Gap Description

Future missions with long element lifetimes, periods of dormancy, and potential communication delay may require improved software capability to enable system fault/anomaly detection, diagnosis, prognostics, decision support, and automated control. Existing strategies and algorithms currently detect faults/anomalies through physics/statistical models, empirical knowledge, etc.

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 Impact 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 Traceability

UC/Fs

- UC-G-501 M -- FN-D-201 M

Key Decision

- Mars Architecture Loss of Crew Risk Posture
- Mars Architecture Loss of Mission Risk Posture
- Degree of Autonomy in Systems
- Mars Maximum Crew Communication Disruption

Metrics

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 Target

Safe, reliable, autonomous control of systems; autonomous detection and diagnosis of off-nominal conditions and events; automated control and safing sequences.

Sub-Architecture(s)

Autonomous Systems and Robotics; Data Systems and Management

Campaign Segment(s)

Foundational Exploration; Sustained Lunar Evolution; Humans to Mars

Gap ID	Gap Title	Priority
ESDMD #1004	Trustworthy Autonomy for Planning and Decision-making	Higher Priority

Gap Description

Lunar 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-Driven Child Gaps

- 1004-01: High-performance general-purpose 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: Lack of capability to integrate planning resources into commanding tasks

Architecture Impact 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 Traceability

UC/Fs

- UC-A-403 M -- FN-A-401 M
- UC-A-404 M -- FN-A-402 M

Key Decision

- Mars Architecture Loss of Crew Risk Posture
- Mars Architecture Loss of Mission Risk Posture
- Degree of Autonomy in Systems
- Mars Maximum Crew Communication Disruption

Metrics

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 Target

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.

Sub-Architecture(s)

Autonomous Systems and Robotics; Data Systems and Management; Human Systems

Campaign Segment(s)

Sustained Lunar Evolution; Humans to Mars

Gap ID	Gap Title	
ESDMD #1005	Safe Human-Robot Interaction and Teaming	Priority

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-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 Impact 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 Traceability

UC/Fs

- UC-A-301 L -- FN-A-302 L
- UC-A-301 M -- FN-A-301 M

Key Decision

Metrics

Current State of the Art

Increasing commercial use of human-scale robots working alongside humans to move cargo in warehouses.

Performance Target

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.

Sub-Architecture(s)

Autonomous Systems and Robotics
Human Systems

Campaign Segment(s)

Foundational Exploration
Sustained Lunar Evolution
Humans to Mars

Higher Priority

Gap ID	Gap Title	
ESDMD #1101	Lunar Precision Landing and Hazard Avoidance for Human Exploration	Priority

Gap Description

Advancement in precision landing and hazard avoidance (PL&HA) is needed to safely and reliably aggregate surface elements at lunar South Pole explorations sites. PL&HA technologies should enable safe and accurate landings in all visibility conditions (induced plume surface interaction effects, shadow, 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 Impact 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

UC/Fs

- UC-T-401 L -- All FN
- UC-T-402 L -- All FN

Key Decision

Metrics

Current State of the Art

Systems capable of soft-touchdowns on illuminated landing sites at the lunar South Pole.

Performance Target

Enable crew and cargo to be landed at lunar south pole exploration sites in various illumination conditions with TBD accuracy.

Sub-Architecture(s)

Transportation Systems

Campaign Segment(s)

Foundational Exploration
Sustained Lunar Evolution

Higher Priority

Gap ID	Gap Title	
ESDMD #1102	Mars Precision Landing and Hazard Avoidance for Human Exploration	Priority

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.

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 Impact 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 Traceability

UC/Fs

- UC-C-204 M -- FN-C-207 M

Key Decision

- Mars Architecture Loss of Mission Risk Posture
- Cargo Mars EDL Propulsion Type
- Crew Mars EDL Propulsion Type
- EDLA Systems Reusability
- Crew Mars Descent Availability

Metrics

Current State of the Art

Perseverance landing ellipse of 7.7 km x 6.6 km. This EDL architecture does not scale to human-class vehicles.

Performance Target

Landing accuracy on order of 100 m. Detect and avoid obstacles on order of 1 m in diameter/depth.

Sub-Architecture(s)

Transportation Systems

Campaign Segment(s)

Humans to Mars

Higher Priority

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Gap ID	Gap Title	
ESDMD #1103	Mars Entry, Descent, and Landing for Human Exploration	Priority

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-Driven Child Gaps

- 1103-01: Supersonic retropropulsion engines for Mars descent
- 1103-02: Large-scale inflatable decelerators for Mars atmospheric entry
- 1103-03: Mid-L/D systems for Mars atmospheric entry
- 1103-04: Robust modeling and simulation for high-mass Mars atmospheric entry

Architecture Impact 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 Traceability

UC/Fs

- UC-T-102 M -- All FN
- UC-T-207 M -- All FN

Key Decision

- Cargo Mars EDL Propulsion Type
- Crew Mars EDL Propulsion Type
- EDLA Systems Reusability
- Crew Mars Descent Availability

Metrics

Current State of the Art

Perseverance landed approx. 1 metric ton on Mars surface with EDL architecture that does not scale to human-class elements.

Performance Target

Enable the safe, reliable, and precise landing of payloads between 25 and 75+ metric tons.

Sub-Architecture(s)

Transportation Systems

Campaign Segment(s)

Humans to Mars

Higher Priority

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Gap ID	Gap Title	Priority
ESDMD #1104	Mars Transportation Propulsion	Higher Priority

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-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

Architecture Impact 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 Traceability

UC/Fs

- UC-T-105 M -- All FN
- UC-T-203 M -- All FN
- UC-T-108 M -- All FN

Key Decision

- Cargo In-Space Propulsion Type
- Crew In-Space Propulsion Type
- In-Space Transportation Systems Reusability
- Mars Parking Orbit

Metrics

Current State of the Art

Chemical combustion solutions are current state of the art, but aggregation of chemical propellant has not been demonstrated on orbit. NTP, NEP, SEP all in low TRL at human exploration scale.

Performance Target

Enable the transfer of crew and cargo between Earth and Mars. Desired propulsion system performance will be informed by ongoing and future key decisions. (TBR)

Sub-Architecture(s)

Transportation Systems

Campaign Segment(s)

Humans to Mars

Gap ID	Gap Title	Priority
ESDMD #1105	Mars Ascent Propulsion for Human Exploration	Higher Priority

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-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

Architecture Impact 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 Traceability

UC/Fs

- UC-T-208 M -- All FN

Key Decision

- Crew Mars Ascent Propulsion Type
- Crew Mars Ascent Availability
- EDLA Systems Reusability
- Mars Parking Orbit

Metrics

Current State of the Art

Ascent from Mars surface has never been attempted. Current solutions are conventional storable propellant liquid rocket engines.

Performance Target

Enable crew and cargo to ascend to Mars orbit. Desired performance will be informed by ongoing and future key decisions. (TBR)

Sub-Architecture(s)

Transportation Systems

Campaign Segment(s)

Humans to Mars

Gap ID	Gap Title	Priority
ESDMD #1106	Cryogenic Fluid Storage	

Gap Description

There is a need to store certain fluids, such as propellants for propulsion assets, at cryogenic temperatures during long-duration missions. 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 and leakage.

Architecture-Driven Child Gaps

- 1106-01: Thermal management for long-duration cryogenic fluid storage
- 1106-02: Fluid management for long-duration cryogenic fluid storage

Architecture Impact and Benefits

Closing this gap enables long-duration missions using cryogenic propellant systems. Enables long-duration storage with minimal boil-off.

Architecture Traceability

UC/Fs

- UC-U-503 L -- FN-U-504 L
- UC-U-504 L -- FN-U-503 L
- UC-T-108 M -- FN-T-212 M
- UC-U-501 M -- FN-U-504 M

Key Decision

- Crew In-Space Return Propellant Strategy
- Crew Ascent from Mars Propellant Strategy

Metrics

Current State of the Art

Boil-off rate in current storage solutions necessitates additional propellant mass margin of 15%-20%.

Performance Target

System that can efficiently store propellant for long-durations in microgravity and partial gravity environments while minimizing boil-off.

Sub-Architecture(s)

Transportation Systems

Infrastructure Support

Campaign Segment(s)

Foundational Exploration

Sustained Lunar Evolution

Humans to Mars

Higher Priority

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Gap ID	Gap Title	Priority
ESDMD #1107	Cryogenic Fluid Transfer	

Gap Description

There is a need to transfer cryogenic fluids in 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-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

Architecture Impact and Benefits

Closing this gap enables regular transfer of cryogenic fluids across tanks and other interfaces with minimal leakage, reduces propellant margin associated with leak losses, and reduces risks associated with fluid leakage.

Architecture Traceability

UC/Fs

- UC-U-502 L -- FN-U-508 L
- UC-U-501 L -- FN-U-507 L
- UC-U-501 M -- FN-U-502 M
- UC-T-108 M -- FN-T-210 M

Key Decision

- Crew In-Space Return Propellant Strategy
- Crew Ascent from Mars Propellant Strategy

Metrics

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.

Performance Target

System that can enable low-loss cryogenic fluid transfer between spacecraft in microgravity and partial gravity environments.

Sub-Architecture(s)

Transportation Systems

Campaign Segment(s)

Foundational Exploration

Sustained Lunar Evolution

Humans to Mars

Higher Priority

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Gap ID	Gap Title	Priority
ESDMD #1201	In-Situ Sample Storage and Processing	Higher Priority

Gap Description

In-situ samples collected on the Moon and Mars will call for storage at 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-Driven Child Gaps

- 1201-01: Conditioned surface sample storage and return
- 1201-02: High-capacity and high-efficiency cryocoolers for sample conditioning applications

Architecture Impact 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 Traceability

UC/Fs

- UC-T-301 L -- FN-T-207 L
- UC-T-210 M -- FN-U-401 M
- UC-T-305 L -- All FN
- UC-T-306 L -- All FN
- UC-T-307 L -- All FN

Key Decision

- Mars Sample Storage and Analysis Needs
- Science Samples Conditioning Needs

Metrics

Current State of the Art

Active cold storage systems on the ISS (e.g., MERLIN, MELFI, Glacier) and active and passive cold stowage.

Performance Target

Enable storage of geological and biological samples at TBR temperature range for TBR duration.

Sub-Architecture(s)

Utilization Systems

Campaign Segment(s)

Foundational Exploration, Sustained Lunar Evolution, Humans to Mars

Gap ID	Gap Title	Priority
ESDMD #1202	Planetary Protection Technologies for Human Exploration	Higher Priority

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 becomes much more complex. Bioburden management, sample handling, and sensing/monitoring will be key components of effective planetary protection (PP) 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-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 Impact 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 PP 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. PP countermeasures that prevent venting may significantly impact vehicle life, space suit support performance, and vehicle mass.

Architecture Traceability

UC/Fs

- UC-M-202 M -- FN-G-501 M

Key Decision

- Mars Forward Contamination Planetary Protection Risk Posture
- Mars Backward Contamination Planetary Protection Risk Posture

Metrics

Current State of the Art

Pre-launch cleaning methods that enable compliance with PP guidelines and protocols for robotic spacecraft provided in NPR 8715.24, NASA-STD-8719.27 and NASA-HDBK-6022. Life support systems and airlocks vent unfiltered gas to environment, no ability to disinfect equipment or spacesuits exiting vehicle.

Performance Target

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.

Sub-Architecture(s)

Utilization Systems

Campaign Segment(s)

Humans to Mars

C.2 TECHNOLOGY GAPS PRIORITIZED LIST

This appendix section contains the prioritized list of architecture-driven technology gaps described in Section 2.5. The technology gaps are binned by similar levels of preference according to the Moon to Mars Architecture perspective.

Gap ID	Gap Title	Priority Ranking	Priority Bin
0801	Lunar Dust Tolerant Systems and Dust Mitigation	1	1
0301	Systems to Survive and Operate through Extended Periods of Lunar Shadow	2	
0103	High-bandwidth, High-reliability Surface-to-Surface Communications	3	
1104	Mars Transportation Propulsion	4	
0201	Extreme Environment Avionics	5	
0805	Autonomous Surface Mobility and Navigation	6	2
0305	Food and Nutrition Capabilities for Missions with Long-duration Storage	7	
1103	Mars Entry, Descent, and Landing for Human Exploration	8	
0806	Payload Offloading, Handling, and Manipulation for Surface Assets	9	
0304	Habitat Environmental Monitors Capable of Supporting Deep Space Missions	10	
1107	Cryogenic Fluid Transfer	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
0307	Radiation Monitoring and Modeling	17	
1003	Integrated System Fault/Anomaly Diagnosis, Decision Support, and Response	18	
0804	Robotic and Mobility Systems in Extreme Cold Environments	19	
0101	Lunar Surface Position, Navigation, and Timing Systems for Extreme Temperature, Radiation, and Dust	20	
0702	Waste Management	21	
0302	Fire Safety Upgrades for Surviving Exploration Mission Environments	22	
0903	Power Management and Distribution between Surface Elements	23	
0808	Relocation of Large Assets on the Lunar Surface	24	
0202	High-Performance Onboard Computing	25	
0701	Packaging, Transport, and Use of Conditioned Supplies and Commodities	26	
1005	Safe Human-Robot Interaction and Teaming	27	

Gap ID	Gap Title	Priority Ranking	Priority Bin
0803	Extravehicular Activity (EVA) and Intravehicular Activity (IVA) Suit System Capabilities for Mars Missions	28	4
1101	Lunar Precision Landing and Hazard Avoidance for Human Exploration	29	
1004	Trustworthy Autonomy for Planning and Decision-making	30	
1002	Autonomous Monitoring for Exploration Missions	31	
0802	Mars Dust-Tolerant Systems and Dust Mitigation	32	
0501	Robotic and Human-Robot Inspection, Maintenance, and Repair	33	
1102	Mars Precision Landing and Hazard Avoidance for Human Exploration	34	5
1201	In-Situ Sample Storage and Processing	35	
0402	Sensorimotor Countermeasures to Support Extended Habitation in Space	36	
0401	Crew Exercise Countermeasures to Support Extended Habitation in Space	37	
0403	Physiological Countermeasures for Extended Habitation in Space	37	
0404	Behavioral Countermeasures for Extended Habitation in Space	37	
0406	Spacesuit Physiology for Deep Space Missions	40	
1202	Planetary Protection Technologies for Human Exploration	41	
0405	Exploration Medical Capabilities for Deep Space Missions	42	
1106	Cryogenic Fluid Storage	43	
0308	Radiation Countermeasures	44	
0902	Scalable Mars Surface Power Generation	45	
0104	Earth-Independent Surface Positioning, Navigation, and Timing for Deep Space Missions	46	
0306	Advanced Structures and Materials to Enable Mass-Efficient Habitats	47	6
0602	In-Situ Resource Identification, Characterization, and Mapping	48	
0503	In-Space & Surface Transfer of Earth Storable Propellants	49	
0102	High-bandwidth, High-reliability Deep Space Communications	50	
0606	Mars ISRU to Support Human Exploration	51	
0605	Lunar Regolith Excavation, Manipulation, and Transportation	52	
0601	Oxygen Extraction from Lunar Regolith	53	
0603	Water Recovery from Lunar Regolith/Ice	53	
0604	Metal Extraction from Lunar Regolith	55	
0502	In-situ Manufacturing of Spares, Repairs, and New Parts	56	

APPENDIX D: ACRONYMS, ABBREVIATIONS, AND GLOSSARY OF TERMS

D.1 ACRONYMS AND ABBREVIATIONS

ACR	Architecture Concept Review
ADD	Architecture Definition Document
AFS	Augmented Forward Signal
AS	Applied Science
ASA	Australian Space Agency
ASI	Italian Space Agency (Agenzia Spaziale Italiana)
AU	Astronomical Unit
BEO	Beyond Earth Orbit
CAPSTONE	Cislunar Autonomous Positioning System Technology Operations and Navigation Experiment
CLD	Commercial Low Earth Orbit Destinations
CLDP	Commercial Low Earth Orbit Development Program
CLPS	Commercial Lunar Payload Services
CM	Crew Module
CMA	Crew Module Adapter
CNES	Centre National D'Etudes Spatiales
COSMIC	Consortium for Space Mobility and ISAM Capabilities
COSPAR	Committee on Space Research
CPL	Co-manifested Payloads
C&PNT	Communication and Positioning, Navigation, and Timing
CSA	Canadian Space Agency
DLR	German Aerospace Center
DS&M	Data Systems and Management
DSN	Deep Space Network
DST	Deep Space Transport
DTE	Direct-to-Earth
DWE	Direct-with-Earth
ECLS	Environmental Control and Life Support
ECLSS	Environmental Control and Life Support System
EDL	Entry, Descent, and Landing
EDLA	Entry, Descent, Landing, and Ascent
EGS	Exploration Ground Systems
EP	Electric Propulsion
ERM	ESPRIT Refueling Module
ESA	European Space Agency

ESM	European Service Module
ESPRIT	European System Providing Refueling, Infrastructure and Telecommunications
Estrack	European Space Agency's European Space Tracking Network
EUS	Exploration Upper Stage
EVA	Extravehicular Activity
FE	Foundational Exploration
FSP	Fission Surface Power
GCR	Galactic Cosmic Radiation
GERS	Gateway External Robotic System
GLE	Gateway Logistics Element
GNSS	Global Navigation Satellite System
HALO	Habitation and Logistics Outpost
HBS	Human and Biological Science
HDL	Human-class Delivery Lander
HIAD	Hypersonic Inflatable Aerodynamic Decelerator
HLCS	HALO Lunar Communications Systems
HLR	Human Lunar Return
HLS	Human Landing System
HRP	Human Research Program
HS	Heliophysics Science
IADC	Inter-Agency Space Debris Coordination Committee
IAU	International Astronomical Union
ICG	International Committee on Global Navigation Satellite System
ICPS	Interim Cryogenic Propulsion Stage
ICSIS	International Communication System Interoperability Standards
I-Hab	International Habitation Module
IMEWG	International Mars Exploration Working Group
IOAG	Interagency Operations Advisory Group
IoT	Internet of Things
ISA	Israel Space Agency
ISECG	International Space Exploration Coordination Group
ISLSWG	International Space Life Sciences Working Group
ISAM	In-space Servicing, Assembly, and Manufacturing
ISRO	Indian Space Research Organization
ISRU	In-Situ Resource Utilization
ITU	International Telecommunications Union
IVA	Intra-Vehicular Activities
JAXA	Japan Aerospace Exploration Agency
KASA	Korean AeroSpace Agency
KASI	Korea Astronomy and Space Science Institute

KPLO	Korea Pathfinder Lunar Orbiter
LAS	Launch Abort System
LCRNS	Lunar Communication Relay and Navigation System
LEAG	Lunar Exploration Analysis Group
LEAP	Lunar Exploration Accelerator Program
LEGS	Lunar Exploration Ground System
LEO	Low Earth Orbit
LI	Lunar Infrastructure
LNIS	LunaNet Interoperability Specification
LPS	Lunar/Planetary Science
LSIC	Lunar Surface Innovation Consortium
LTV	Lunar Terrain Vehicle
LuPEX	Lunar Polar Exploration
MAV	Mars Ascent Vehicle
MBRSC	Mohammed Bin Rashid Space Centre
MCC	Mission Control Center
MCC-H	Mission Control Center — Houston
MCR	Mission Concept Review
MDS	Mars Descent System
MEPAG	Mars Exploration Program Analysis Group
MEXT	Japan’s Ministry of Education, Culture, Sports, Science and Technology
ML	Mobile Launcher
ML2	Mobile Launcher 2
MSolo	Mass Spectrometer observing lunar operations
NASA	National Aeronautics and Space Administration
NEP	Nuclear Electric Propulsion
NextSTEP	Next Space Technologies for Exploration Partnerships
NPR	NASA Procedural Requirements
NRHO	Near Rectilinear Halo Orbit
NSN	Near Space Network
NTP	Nuclear Thermal Propulsion
NZSA	New Zealand Space Agency
OP	Operations
ORU	Orbital Replaceable Units
PMAD	Power Management and Distribution
PNT	Positioning, Navigation, and Timing
PP	Planetary Protection
PPE	Power Propulsion Element
PPS	Physics and Physical Sciences
PR	Pressurized Rover

PRIME-1	Polar Resources Ice Mining Experiment-1
PRISM	Payload and Research Investigations from the Surface of the Moon
PSR	Permanently Shadowed Regions
RT	Recurring Tenet
RPODU	Rendezvous, Proximity Operations, Docking, and Undocking
SAC	Strategic Analysis Cycles
SANSA	South African National Space Agency
SE	Science-Enabling
SEP	Solar Electric Propulsion
SFCG	Space Frequency Coordination Group
SLE	Sustained Lunar Evolution
SLIM	Smart Lander for Investigating Moon
SLS	Space Launch System
SM	Service Module
SMD	Science Mission Directorate
SPE	Solar Particle Event
SRTs	Safety Reporting Thresholds
SSERVI	Solar System Exploration Research Virtual Institute
STMD	Space Technology Mission Directorate
TH	Transportation and Habitation
TRIDENT	The Regolith and Ice Drill for Exploring New Terrain
UHF	Ultra-High Frequency
UKSA	United Kingdom Space Agency
UTC	Coordinated Universal Time
VAB	Vehicle Assembly Building
VIPER	Volatiles Investigating Polar Exploration Rover
xEVA	Exploration Extra-Vehicular Activity

D.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 Characteristic Decision	Decisions that define an architecture feature or characteristic, where the selection of an alternative option would be considered a different architecture.
Architecture Constraint Decision	Decisions that apply across all possible architecture variants, but do not directly define an architecture characteristic. Options for these types of decisions do not narrow or expand the feasible architecture trade space,
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.

Term	Description
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 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.
Decision Authority	The highest-ranking official or body (such as a control board or executive council) that will sign a formal decision outcome, thus indicating responsibility for—and commitment to implementing—that decision outcome.
Decision Definition	The set of inputs required to reach a decision outcome, which includes a question, options, context, dependencies, and a recommendation that will be deliberated on by a decision authority.
Decision Outcome	A formal judgement of the options as a result of deliberation, culminating in agreement on which option(s) to implement.

Term	Description
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 (DST)	DST 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 DST 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.
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.

Term	Description
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: 1) Human-rating is the process of designing, evaluating, and assuring that the total system can safely conduct the required human missions. 2) Human-rating includes the incorporation of design features and capabilities that accommodate human interaction with the system to enhance overall safety and mission success. 3) 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: SEP/chem, which combines a solar electric propulsion system with a chemical stage, and NEP/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.
Incremental	Building compounding operational capabilities within the constraints of schedule, cost, risk, and access. (Definition from Moon to Mars Strategy and 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.

Term	Description
Key Architecture Decision	A decision 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.
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., PR and SH). 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.
Loss of Crew	Death of or permanently debilitating injury to one or more crew members.

Term	Description
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.
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.

Term	Description
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 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).
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.
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 ADD sub-architectures) and disembodied autonomous systems that lack the capacity for physical interaction are not robotic systems.

Term	Description
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.
Secondary Payloads	Additional cargo carried on a transportation element, currently on an adapter ring, after the primary and CPLs 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.

Term	Description
Stakeholder	An organization with an interest in a particular architecture decision because it can either affect or be affected by the decision. Different architecture decisions may have different stakeholders who are responsible for contributing supporting data and analyses to an architecture decision package. In some cases, stakeholders are decision authorities for prerequisite decisions that feed into a particular architecture decision.
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.
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.)
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.
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.

Term	Description
Utilization Payload and Equipment	Any item that is primarily in support of and attributed to utilization objectives. Utilization payload 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.
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).

D.3 Quantity Descriptors Used in Objective Decomposition

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