National Aeronautics and
Space Administration

NASA's
Moon to Mars Architecture

Architecture White Papers
2024 Architecture Concept Review

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2024 Architecture Concept Review

Exploration Systems Development Mission Directorate
National Aeronautics and Space Administration

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White Papers

NASA white papers highlight key results from the annual Architecture Concept Review and complement the Architecture Definition Document. They provide deep dives into specific topics within the architecture and explain NASA's latest thinking. Below are brief summaries for the 2024 Moon to Mars Architecture white papers:

LUNAR SURFACE CARGO
Analyzes projected needs and capability gaps for transportation of cargo to the lunar surface.

LUNAR MOBILITY DRIVERS AND NEEDS
Discusses the need to move cargo and assets on the lunar surface and factors that will significantly impact mobility systems.

PRIORITY SCIENCE ENABLED THROUGH ARCHITECTURE
Surveys landmark studies that inform NASA's science goals and how the Artemis campaign is realizing those goals.

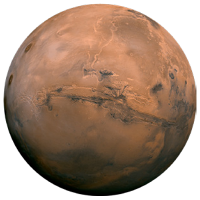
LUNAR REFERENCE FRAMES
Offers considerations for developing an architecture that supports multiple reference frames to meet diverse positioning, navigation, and timing needs.

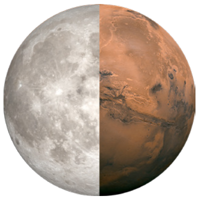
MARS CREW COMPLEMENT CONSIDERATIONS
Weighs the factors, risks, and opportunities that affect how many astronauts NASA will send to the Red Planet during the first human missions.

MARS SURFACE POWER TECHNOLOGY DECISION
Presents NASA's selection of nuclear fission power as the primary surface power generation technology for initial missions to Mars.

MARS ENTRY, DESCENT, AND LANDING CHALLENGES
Examines the challenges of landing on the Red Planet and considerations for crewed entry, descent, and landing capabilities.

MARS ASCENT PROPELLANT CONSIDERATIONS
Explores the challenges of transport, or in-situ manufacture, of fuel needed to ascend to Mars orbit after a surface mission.





ARCHITECTURE-DRIVEN TECHNOLOGY GAPS
Explains how NASA identifies technology gaps for needed architecture capabilities and encourages innovation to close them.

HUMANS IN SPACE TO ACCOMPLISH SCIENCE OBJECTIVES
Describes unique capabilities of human explorers and how humans and robots can work together to maximize scientific returns.

INTERNATIONAL PARTNERSHIPS
Policies, Opportunities, and Engagement: Elaborates on how NASA engages and collaborates with space agencies from around the world.

RESPONSIBLE EXPLORATION
Dives into the ethical, legal, and societal implications of space exploration and how NASA explores in the interest of all humanity.

MOON-FOCUSED

White Papers

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2024
Moon to Mars
Architecture

white paper

Lunar Surface Cargo

Introduction

The exploration of the lunar surface, as described in NASA's Moon to Mars Architecture Definition Document (ADD), will require a wide variety of landed systems, including scientific instruments, habitats, mobility systems, infrastructure, and more. Given diverse cargo needs of varying size, mass, cadence, delivery locations, and end users, access to a range of cargo lander capabilities offers strategic benefit.

While current cargo lander development activities will contribute to meeting some cargo delivery demands, a substantial gap in lander capability remains. This paper characterizes lunar surface cargo delivery needs, compares those needs with projected in-work cargo lander capabilities, and outlines strategic considerations for fulfilling this architectural capability gap.

> **Note:** *Cargo deliveries to Gateway are already instantiated in the Moon to Mars Architecture through the Gateway Logistics Element (GLE). GLE flights will supply Gateway with critical deliveries that maximize the length of crew stays on Gateway. While use of the Gateway as a logistics cache for lunar exploration could be considered, this paper does not attempt to speculate on concepts of operation. Instead, it specifically addresses architectural gaps for cargo deliveries to the lunar surface. The specific functions fulfilled by GLE may be found in Table 3-6 of ADD Revision A.*[1]

Cargo Lander Architecture

Lunar surface exploration will require the delivery of assets, equipment, and supplies to the lunar surface.[1] While some limited supplies and equipment may be delivered alongside crew on NASA's Human Landing System (HLS), the breadth and scale of logistical needs for deep space exploration require additional surface cargo lander capabilities.

NASA has developed a conceptual reference mission for cargo lander delivery that will be added to the ADD in revision B. This reference mission:

- Delivers non-offloaded and/or offloaded cargo to the lunar surface.
- Provides all services necessary to maintain cargo from in-space transit through landing on the lunar surface until the cargo is either offloaded from the lander or in an operational state where these services from the lander are no longer needed, in accordance with cargo lander provider agreements.
- Ensures successful landing at an accessible and useable location on the lunar surface with sufficient precision.
- Establishes safe conditions on the lunar surface for the crew to approach the lander.
- Verifies health and functionality of non-offloaded and/or offloaded cargo.
- Performs any lander end-of-life operations — including potential relocation — ensuring that the cargo or other surface assets are not adversely affected by the lander after landing operations.

As noted above, cargo deliveries will need support service interfaces to ensure safe delivery of cargo to the surface. Service interfaces may support the offloading of cargo, compatibility to surface mobility system interactions, and/or providing resources to the cargo, such as power, communications, data, and/or thermal dissipation. Services may be needed from landing to until the cargo is fully operational, including before or after the cargo is offloaded to the surface.

Landers and cargo may also need additional, crew-focused lander interfaces such as extravehicular activity (EVA) touch interfaces to support crew interactions. Lastly, given potential crew activity at, with, or near a lander, each lander must have the ability to safe itself after landing so that crew are protected while in the lander's vicinity.

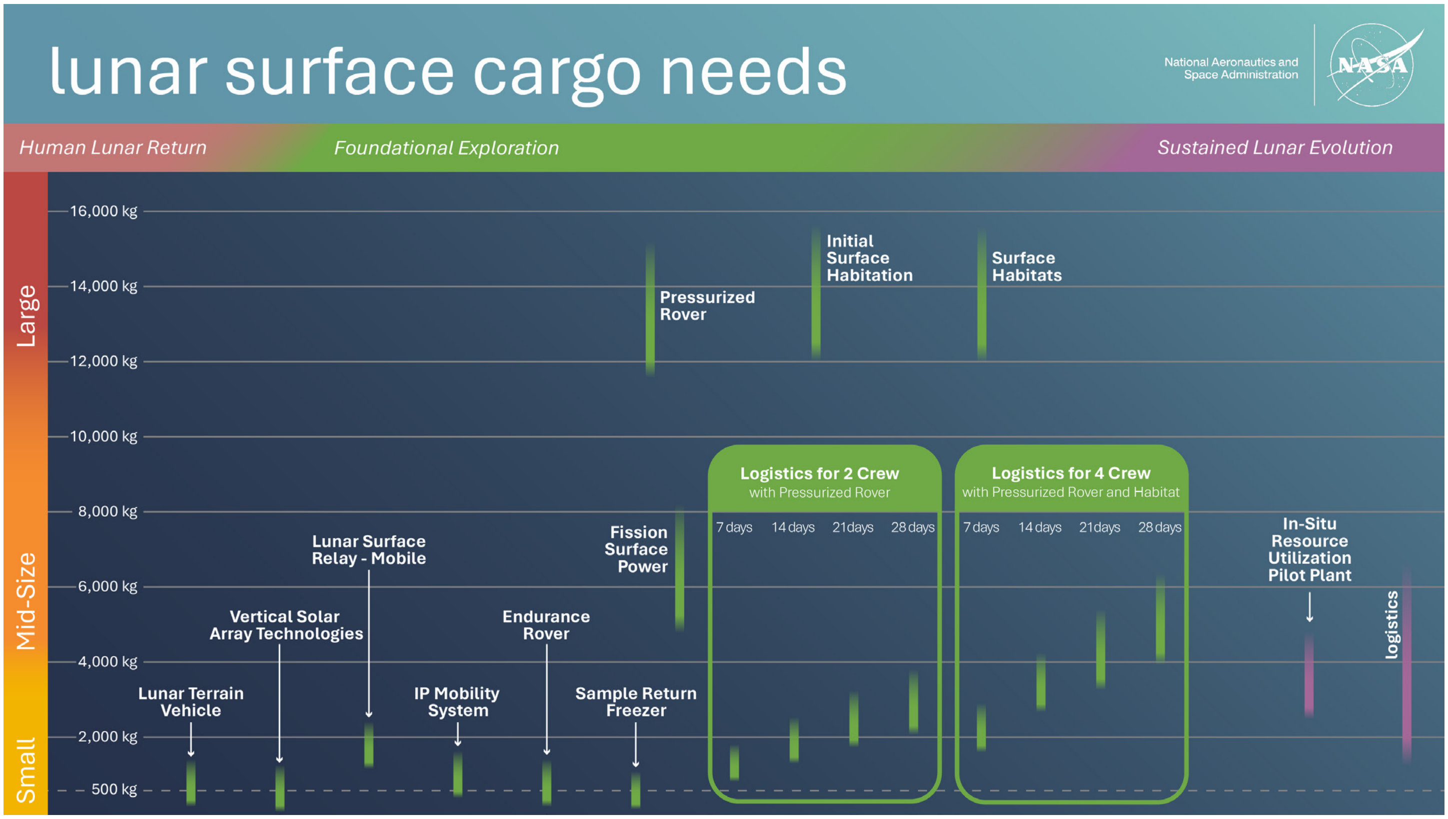

Figure 1: *Planned and potential cargo to the lunar surface. (NASA)*

Note: While contracts are in place for some cargo identified, this figure does not represent agency decisions to fly any item, nor does it reflect the order of flights for any of the items represented.

Lunar Surface Demand vs. Capability

Cargo Demand

To better understand the future demand for lunar landers and transportation systems, NASA assessed a representative sample of planned and potential future surface cargo. **Figure 1** reflects this assessment: each item is represented by a potential mass range and its notional alignment within an exploration campaign segment defined in the ADD.[1]

This cargo includes many one-time delivery missions for habitation, various types of mobility systems, power augmentation, communications relays, and freezers, among many other potential science and technology development payloads. These cargo deliveries — whether of a single item or in aggregate — would each come with a unique set of support service needs (e.g., offloading, manipulation, or surface mobility. For more insight into surface mobility, see the 2024 Moon to Mars Architecture "Lunar Mobility Drivers and Needs" white paper,[2] published concurrently to this paper).

Cargo needs also include recurring logistics delivery missions associated with projected crewed missions (assumed to occur on an annual basis). Logistics items include "food, water, air, spare parts, and other similar products required to sustain life, maintain systems, and allow for productive science and utilization activities."[3]

While initial crewed missions using HLS vehicles will carry the logistics needed for short mission durations, future missions will utilize additional surface elements to expand mission duration, crew member size, and exploration capability (e.g., accessible range). **Figure 1** shows the approximate mass of logistics needed (including carriers) for a range of mission parameters.

To meet the annual crewed mission cadence, the associated logistics delivery for the duration and crew size will be required each year. For more insight on logistics needs, see the 2023 "Lunar Logistics Drivers and Needs" white paper. [3]

In aggregate, **NASA forecasts a cargo demand range of 2,500 to 10,000 kg per year** for annual recurring logistics and some frequency of small to large elements during the Foundational Exploration campaign segment. This includes occasional large cargo deliveries of up to 15,000 kg for elements like rovers or habitation modules.

These cargo deliveries are necessary to meet a variety of exploration, science, and technology development objectives and a robust future cargo delivery demand drives considerable cargo lander capability needs.

Cargo Lander Capability

To meet initial cargo delivery demands, NASA has contracted with U.S. industry for lander development through the Commercial Lunar Payload Services (CLPS) program[4] and the HLS program,[5] which includes crewed landers and cargo lander variants called Human-class Delivery Landers (HDL). [6] International partners, such as the European Space Agency

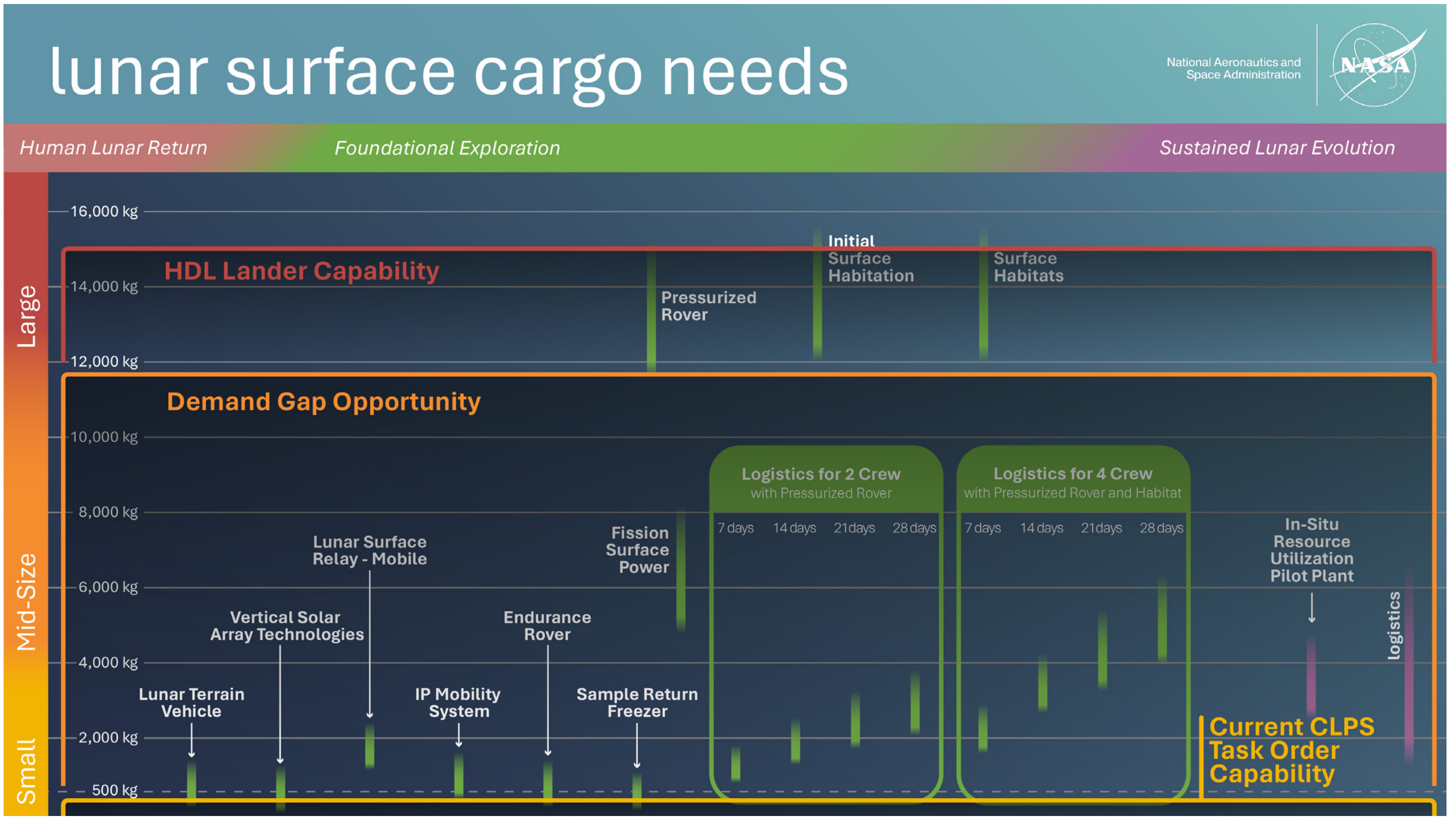

Figure 2: *Planned lander capability compared with lunar surface cargo demand. (NASA)*

(ESA) and Japan Aerospace Exploration Agency (JAXA), are working in collaboration with NASA on potential cargo delivery services.[7] **Table 1** reflects the latest planned and potential cargo lander capabilities.

Despite the capabilities currently in development, a gap in cargo lander delivery has been identified between 500 kg and 12,000 kg, for which significant demand exists. **Figure 2** illustrates the gap between planned lander capability and lunar surface cargo demand.

Strategic Cargo Considerations

Lunar exploration's dynamic mission parameters drive the need for a responsive cargo lander portfolio that covers a range of payloads of various shapes, sizes, and functions. The landers in this portfolio must also provide access to diverse locations across the lunar South Pole region to satisfy exploration objectives. **Figure 3** illustrates this diversity, showing potential landing and exploration regions superimposed over the Washington, DC, area for scale.

Engaging multiple providers from both industry and international partners over time offers many strategic benefits. Leveraging provider diversity in a mixed cargo lander fleet approach addresses some key lessons learned from the International Space Station, including the need for dissimilar redundancy to avoid a situation in which any system becomes a single point of failure.[9] A range of cargo providers also gives NASA the flexibility to manifest cargo efficiently for utilization payloads, technology demonstrations, and logistics delivery.

In addition to the considerations listed above, NASA has identified additional capability gaps for lunar cargo and sample return. The capacity needed to achieve stated objectives greatly exceeds the return capability offered by existing elements. While this paper doesn't seek to address those specific concerns, ongoing NASA analysis is characterizing the driving needs and architectural constraints. Those will be published in an additional ACR24 white paper later this year.

Table 1: *Planned and Potential Cargo Landers*

Lander Type	Mass Delivery Capability (kg)	Provider
CLPS – Current Task Orders[4]	70 – 475	U.S.
HDL Cargo Lander[6]	12,000 to 15,000	U.S.
ESA Argonaut Lander*[7]	Up to 2,100	International
JAXA Cargo Lander Capability[8]	Under Study	International

**Note: Delivered mass represents cargo platform element + payload.*

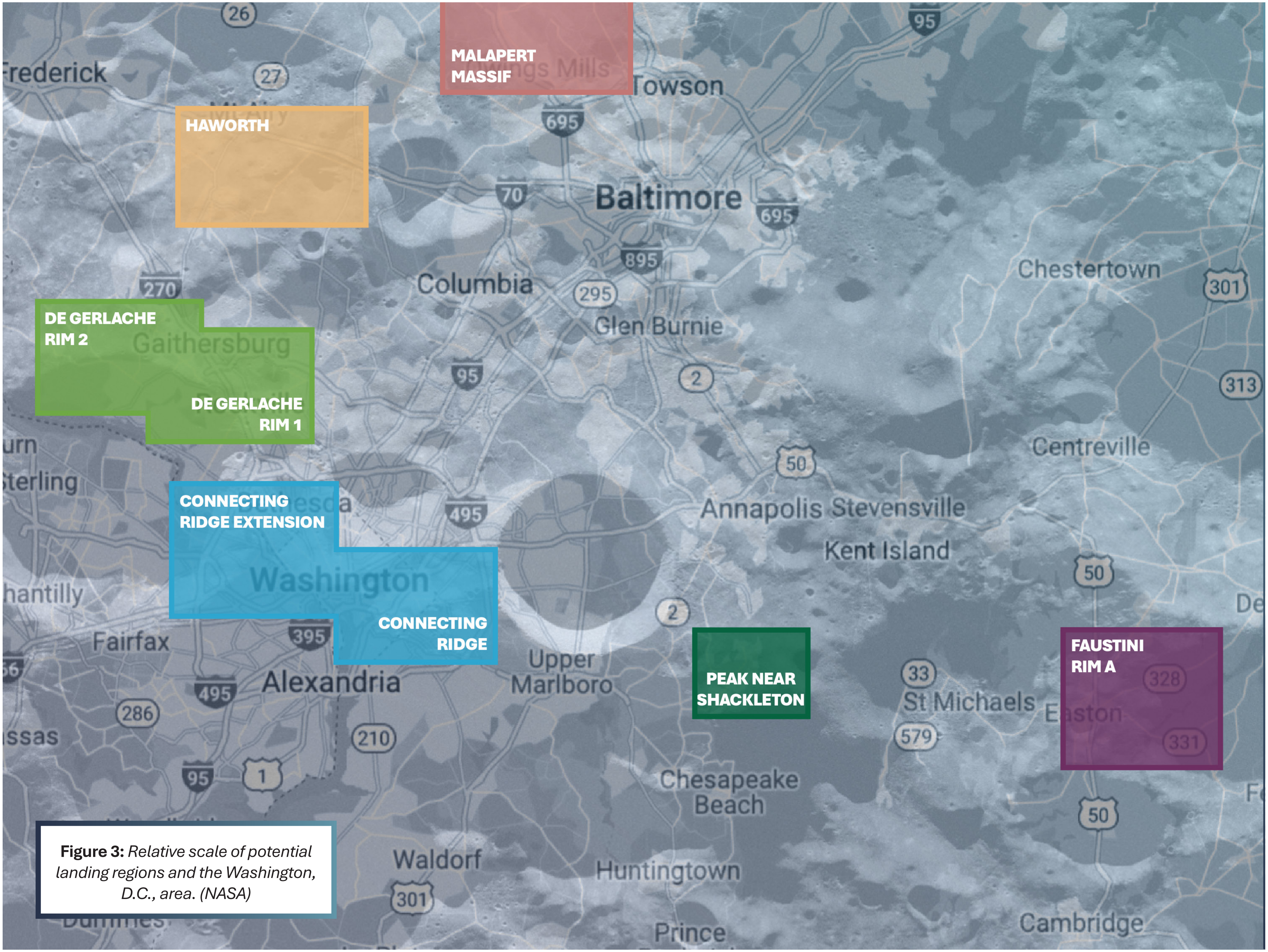

Figure 3: *Relative scale of potential landing regions and the Washington, D.C., area. (NASA)*

Summary

Given diverse cargo needs of varying size, mass, delivery cadence, and operational needs, a diverse portfolio of cargo lander capabilities will be necessary to achieve NASA's Moon to Mars Objectives. While current cargo lander development activities contribute to meeting the Human Lunar Return segment's cargo delivery needs, there is a substantial architectural gap in lander capability for the Foundational Exploration segment and beyond.

Both international partnerships and industry offer opportunities to create a mixed cargo lander fleet that fully meets cargo delivery demands, enables longer missions, sends more crew members to the surface, and empowers a larger exploration footprint. Encouraging the development of varied cargo lander concepts and capabilities will be key to establishing a long-term lunar presence for science and exploration.

More detail on architectural gaps for lunar cargo will be released at the close of the 2024 Architecture Concept Review Cycle, including in white papers on NASA's lunar surface strategy and cargo return needs.

Key Takeaways

Foundational Exploration and Sustained Lunar Exploration segment goals require significant transportation of cargo to the lunar surface.

HDL is the only lander currently expressed in the architecture that can deliver beyond 500 kg to the lunar surface.

NASA anticipates an aggregate demand for lunar surface cargo on the order of 2,000 to 10,000 kg per year.

To mitigate this capability gap, strategic considerations include engaging multiple providers across both international partners and industry over time, offering dissimilar redundancy.

Communication of cargo demand to the exploration community helps enable industry and international engagement.

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Lunar Mobility Drivers and Needs

Introduction

NASA's new campaign of lunar exploration will see astronauts visiting sites of scientific or strategic interest across the lunar surface, with a particular focus on the lunar South Pole region.[1] After landing crew and cargo at these destinations, local mobility around landing sites will be key to movement of cargo, logistics, science payloads, and more to maximize exploration returns.

NASA's Moon to Mars Architecture Definition Document (ADD)[2] articulates the work needed to achieve the agency's human lunar exploration objectives by decomposing needs into use cases and functions. Ongoing analysis of lunar exploration needs reveals demands that will drive future concepts and elements.

Recent analysis of integrated surface operations has shown that the transportation of cargo on the surface from points of delivery to points of use will be particularly important. Exploration systems will often need to support deployment of cargo in close proximity to other surface infrastructure. This cargo can range from the crew logistics and consumables described in the 2023 "Lunar Logistics Drivers and Needs" white paper,[3] to science and technology demonstrations, to large-scale infrastructure that requires precision relocation.

The current defined mobility elements — the Lunar Terrain Vehicle (LTV) and Pressurized Rover (PR) — are primarily for crew transportation, with limited cargo mobility functions. Conversely, planned near-term robotic missions — such as those being delivered through the Commercial Lunar Payload Services (CLPS) program — provide only small-scale mobility. This paper describes the integrated cargo mobility drivers for consideration in future architecture and system studies, with a focus on the human lunar exploration architecture. Scientific and uncrewed, robotic missions could necessitate additional mobility needs beyond those discussed here.

The cadence, mass, and number of cargo lander deliveries will be timed to meet the operational needs of NASA's lunar architecture, based on factors including science objectives, lighting conditions, and safety considerations. In many cases, cargo offloading and manipulation 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. This would require mobility capabilities to transport cargo of varying size and mass for full utilization within the architecture.

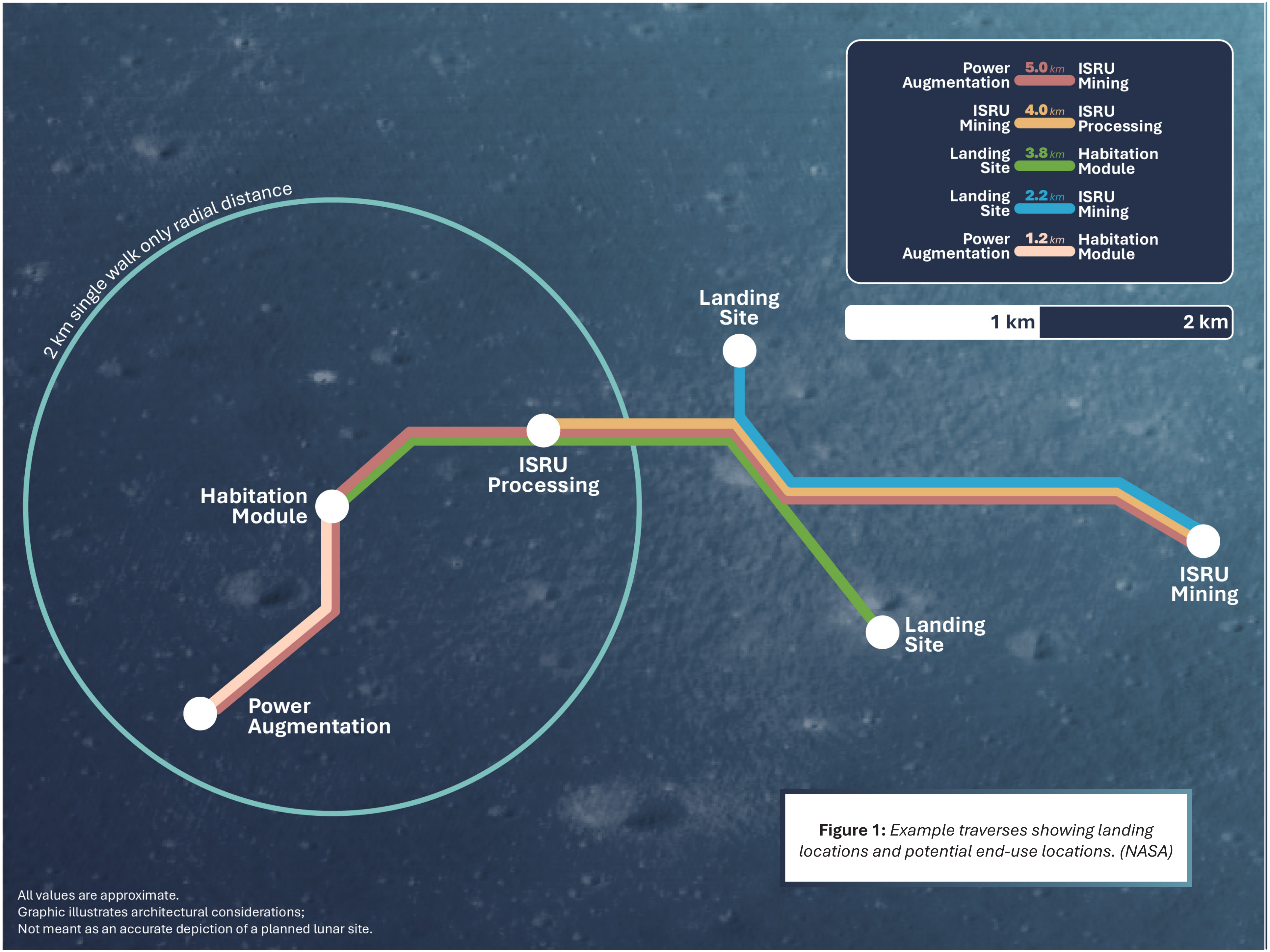
Current capabilities planned for lunar surface operations are limited to transporting approximately 1,500 kg of cargo. However, fulfilling other key exploration objectives could require cargo of sizes and masses beyond of these planned capabilities, creating the need for additional mobility capabilities.

Mobility Needs

One of the largest drivers of mobility needs on the lunar surface is moving cargo from its landing site to its point of use. Numerous factors drive cargo point of use, many of which necessitate separation from landing sites (e.g., darkness caused by a lander's shadow, point of use contamination by landers, or blast ejecta from lander plume surface interactions). These relocation distances can include the following factors:

- Separation from lander shadowing (tens of meters)
- Lander blast ejecta constraints (>1,000 m) due either to separation between the lander and existing infrastructure or lander ascent
- Support for aggregation of elements in ideal habitation zones from available regional landing areas (up to 5,000 m)

For more insight into lunar lighting considerations, see the 2022 Moon to Mars Architecture "Lunar Site Selection" white paper.[4]



All values are approximate.
Graphic illustrates architectural considerations;
Not meant as an accurate depiction of a planned lunar site.

Figure 1: *Example traverses showing landing locations and potential end-use locations. (NASA)*

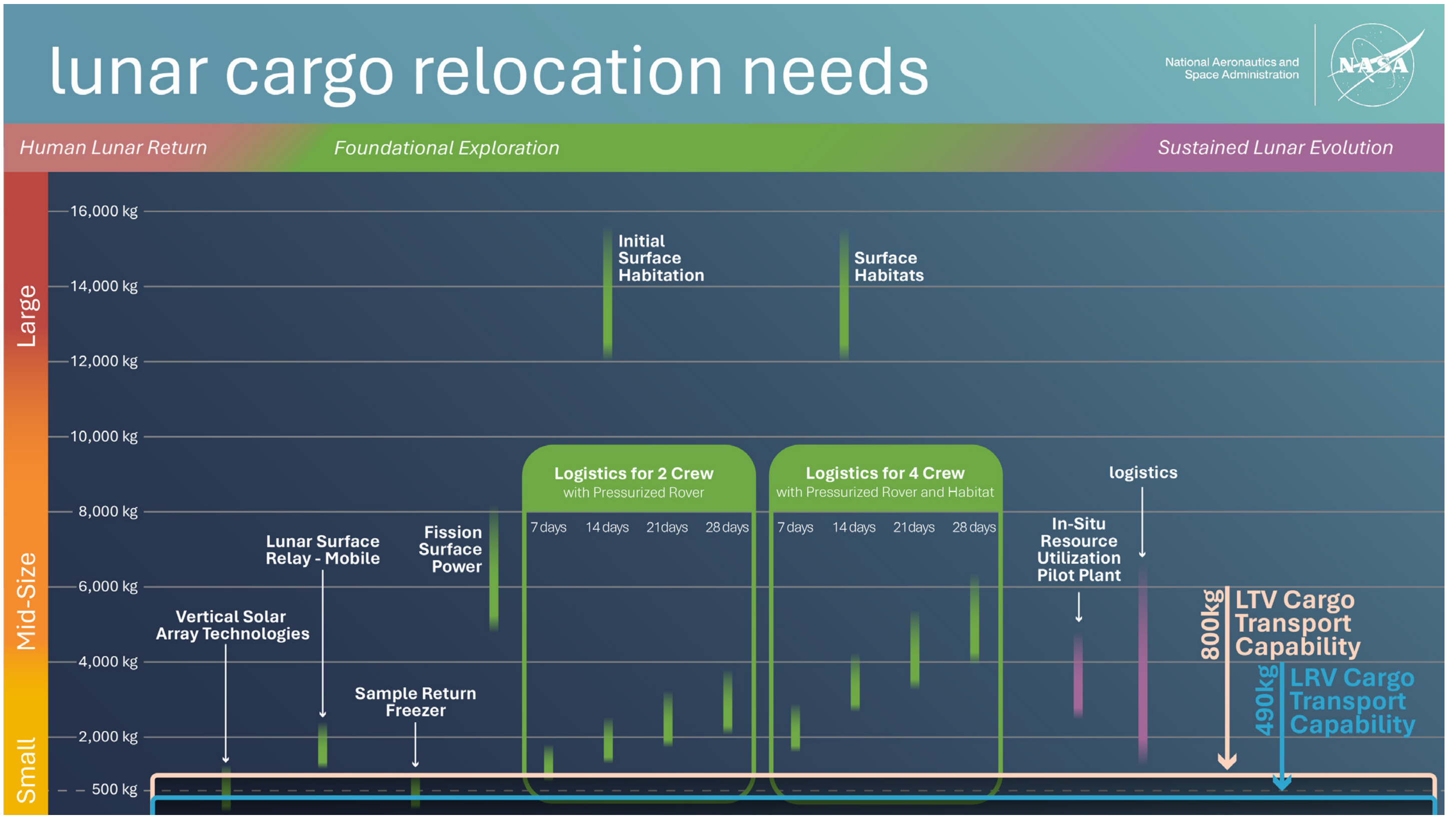


Figure 2: *Mobility demand forecast ranges compared to LTV and LRV transport capabilities. (NASA)*
Note: While contracts are in place for some cargo identified, this figure does not represent agency decisions to fly any item, nor does it reflect the order of flights for any of the items represented.

NASA will select habitation and seasonal hibernation points in the lunar South Pole region to minimize the frequency and length of periods of darkness from shadows caused by local topography and sun inclinations during lunar nights. These conditions are easiest to minimize at higher elevations and on top of ridges, driving elements with high energy needs to higher elevations, or upslope. Traverses from landing zones to habitation zones could encounter slopes of up to 20 degrees. **Figure 1** provides an example of this distribution.

NASA can meet these overlapping mobility challenges by providing capabilities for elements to move away from landers once on the surface. This could be done using independent or integrated mobility systems.

The frequency of traverses between downslope and upslope locations would be driven by the cadence with which landers deliver cargo to the lunar surface and the mass that a given mobility system can carry on each traversal. Integrated architecture operations will necessitate non-trivial relocation and aggregation ranges for cargo and assets.

Cargo and Asset Mass Demands

Currently, NASA expects that the Foundational Exploration segment of the Moon to Mars Architecture would require support for four crew members operating on the lunar surface for approximately 30 days. While this forms the basis for commodity and logistics demand, NASA expects to deploy additional science or technology demonstrations, infrastructure, and elements over time through various cargo lander capabilities. For more insight into lunar cargo landers, see the 2024 Moon to Mars Architecture "Lunar Surface Cargo" white paper published concurrently with this paper.[5]

Operational needs will require NASA to remotely or autonomously deploy many of these cargo deliveries and exploration assets, so they are available prior to crew arrival. This approach optimizes available crew time for tasks that require humans. **Figure 2** shows the mass ranges of potential cargo against transport capabilities.

The Foundational Exploration segment includes a wide range of potential mobility needs across the mass spectrum. Smaller deployed demonstrations are estimated in the 500-to-2,000 kg range. However, logistics elements needed on a recurring basis can total 2,000 to 6,000 kg per crewed surface mission. Further, the ability to aggregate infrastructure will be driven by larger crew elements — such as habitation systems — that could deploy in the 12,000-to-15,000 kg range.

Current mobility elements could provide some portion of cargo relocation capabilities. However, the LTV, for example — developed as a crew transportation element — is limited to 800 kg of uncrewed cargo mass. The Apollo-era Lunar Roving Vehicle (LRV) was designed to hold a payload of an additional 490 kg.[6] Studies indicate a significant near-term mobility demand in the Foundational Exploration segment beyond those capabilities. In total, current demand and mobility capacity are mismatched on the order of 1,000 to 15,000 kg per asset for ranges of 50 to 5,000 m.

The frequency of relocation needs can range from single operations for large elements to multiple trips per year for logistics containers or smaller scientific cargo. To allow for operations at the cadence and speed required to support crew, mobility assets will require sufficient autonomy and/or tele-robotic operation capability to operate throughout the year. Element planning should consider not just mechanical and electrical designs, but also operational paradigms and methods for automation and autonomy.

Mobility Technology and Drivers

Large-scale mobility demands require several considerations in technology and system development, including energy, surface conditions, control paradigms, and terramechanics (specifically the interaction between wheeled or tracked vehicles and lunar regolith). Energy demand for a system can be driven by many factors including operational considerations and payload masses, desired surface traversal speed, and the ability for the system to survive lunar night conditions.

Lunar surface conditions including terrain, lighting, and thermal environments are of extreme importance to mobility. Slopes of more than 10 degrees are common at the lunar South Pole (analogous to unimproved mountain passes), making slope traverses complex. Wheel and soil interactions for large mobility systems do not scale linearly with transported mass or the size of the mobility system. Transportation becomes exponentially more difficult at the upper end of the mass range.

Lunar regolith also poses a significant concern to the durability of autonomous mobility systems alone. Studies should consider regolith mitigation strategies to prevent wheel wear and overall system design should consider effects of lunar regolith and dust accumulation on all electro-mechanical systems.

This combination of factors creates a significant technological gap between existing systems and mobility demands for future exploration.

Mobility System Features

When considering lunar mobility technologies and capabilities, interactions between the mobility system, deployed cargo, and interfacing systems are critical. This can drive features for both interoperability and autonomous capabilities. A stated capability for mass relocation means little if the interfaces between the mobility element and the cargo are incompatible. Establishing shared standards that support autonomy would empower mission planners to better stage cargo and assets prior to crew arrival, increasing available crew utilization time.

The ability of mobility systems to manipulate cargo elements will be a key factor. Access to offload cargo landers, leveling to support surface docking of multiple elements, and support to mated power or other types of connectors could be key drivers for lunar surface mobility as well. The ability of multiple robotic mobility systems to work together may also be an enabling feature for future systems. This type of behavior would be additional motivation for standardization among robotic interfaces.

The operational independence provided by autonomous or semi-autonomous mobility has flow-down impacts on a wide variety of mission parameters. Navigation without human intervention can increase the speed of mobility elements, especially when crossing locations where terrain obscures communication links. Terrain and obstacle recognition, path planning, and mapping capabilities would empower year-round mobility independent of crew, offering increased flexibility for mission planning.

Summary

Mobility needs are driven by the requirement to move cargo and elements from their points of delivery to points of use for deployment in close proximity to other surface infrastructure or optimal locations. This means transporting 500-to-15,000 kg elements or cargo and across distances of up to 5,000 m to support even limited intra-regional operations at varying cadences.

Mobility on the lunar surface will need control paradigms that allow such traversal cadences to be met. Technology and systems development needed to achieve this goal must also consider several challenging environmental conditions. The Moon to Mars Architecture will include significant demand for mobility and relocation operations to provide effective and sustained human surface exploration.

More detail on architectural gaps for lunar mobility will be released at the close of the 2024 Architecture Concept Review Cycle, including in a white paper on NASA's lunar surface strategy.

Key Takeaways

Lunar exploration objectives require significant mobility of cargo and assets across the lunar surface from landing site to point of use at ranges of 5 to 5,000 m.

Currently, the surface mobility capability expressed in the architecture is limited to 800 kg. However, future mobility demands include aggregated logistics and larger elements as massive as 12,000 kg or more.

Large-scale mobility is not simply scaled up small-scale mobility; energy and environmental considerations are crucial to the design process.

Interoperability and autonomous or semi-autonomous capabilities on mobility systems enable mission planning flexibility and increase available crew utilization time.

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Priority Science Objectives Enabled through NASA's Moon to Mars Architecture

Introduction

Crewed lunar exploration, beginning with the Artemis campaign, provides NASA an opportunity to significantly advance humanity's understanding of the origin and evolution of the Moon, the characteristics of cislunar environments, and their impacts on biological systems. **NASA has implemented an objective-based approach to address high-priority and high-impact science questions.**

The agency documented this approach in NASA's Moon to Mars Strategy and Objectives Development document[1] and the objectives in the Moon to Mars Objectives document.[2] The National Academies' decadal reports,[3] which establish science priorities for NASA's Science Mission Directorate, were the source material for the Moon to Mars science objectives and further break down those objectives into strategic investigations and are summarized in Appendix C of the Mars Strategy and Objectives Development document.[1]

Collectively, these documents establish what NASA wants to achieve in exploring the Moon and Mars and why it's important. NASA's Moon to Mars Architecture, as defined in the agency's Architecture Definition Document,[4] outlines how NASA will achieve these aims.

Realizing these ambitions requires a multi-disciplinary approach that integrates the scientific community; NASA's mission directorates, centers, and technical authorities; international partners; academic institutions; and commercial entities. **United under the architecture framework, NASA and its partners can realize a safe and sustained campaign of robotic and human exploration that reveals the secrets of the universe for the benefit of all.**

Science Implementation Strategy

In response to decadal recommendations, NASA's Science Mission Directorate is developing its Implementation Plan for a NASA Integrated Lunar Science Strategy in the Artemis Era.[5] The document — currently in draft — provides a snapshot of how NASA intends to implement the science strategy outlined in the recent decadal survey in planetary science: *Origins, Worlds, and Life: A Decadal Strategy for Planetary Science and Astrobiology 2023–2032* (OWL).[6] While this initial implementation plan focuses on planetary science, the Science Mission Directorate plans to produce an additional document that includes science strategies drawn from SMD directorate-specific science disciplines' decadal surveys and associated Moon to Mars Objectives, as well as Human Research Program goals and objectives.

This white paper focuses on the current implementation plan for the OWL strategy. It overviews how NASA will integrate science discipline areas with architectural elements as they come online.

Science Implementation Challenges

The OWL, Moon to Mars Strategy and Objectives Development document, the National Academies' *The Scientific Context for Exploration of the Moon*,[7] the Lunar Exploration Analysis Group's *Advancing Science of the Moon*,[8] and other community documents identify six primary lunar science challenges shown in **Table 1**. Three are architecture-dependent; three will require the incremental buildup of knowledge over time through investigations across varied lunar surface destinations.

Table 1: *Six primary lunar science challenges. (NASA)*

	Lunar Science Challenges	Associated Lunar/ Planetary Science (LPS) Objective(s)[2]
1	South Pole-Aitken Basin Sample Return	LPS-1, LPS-2
2	Lunar Geophysical Network	LPS-1, LPS-2
3	Cryogenic Volatile Sample Return	LPS-3
4	Lunar Chronology	LPS-1, LPS-2
5	Lunar Formation and Evolution	LPS-1, LPS-2
6	Lunar Volatiles	LPS-3

Architecture-Dependent Challenges

The first three challenges are listed in the priority order established by the planetary science community. These are architecture-dependent challenges, meaning that they require specific architectural functions or elements to conduct scientific investigations that attain specific data.

South Pole-Aitken Basin Sample Return

For example, the OWL strategy recommended the Endurance-A mission concept[9] to accomplish South Pole-Aitken basin sample return. This concept would leverage Artemis sample return capabilities in tandem with a sample collecting rover.

The OWL strategy recommended that this concept "should be implemented as a *strategic medium-class* mission as the *highest priority* of the Lunar Discovery and Exploration Program." Conducting the mission as described requires long-lived, long-distance roving capabilities coupled with robotic sampling and large cargo sample return via crewed Artemis missions.

Lunar Geophysical Network

The OWL also recommended the Lunar Geophysical Network concept[10] as a high-priority mission under the New Frontiers Program.[11] This mission concept would require 6 to 10 years of concurrent operations on the lunar surface at more than four nodes spread across the lunar globe to gather data that would allow the scientific community to better understand the nature of the lunar interior and — more broadly — the geologic processes that evolve planetary bodies.

To enable the Lunar Geophysical Network concept, the lunar architecture would require long-lived surface assets (i.e., power and thermal control), global access, and communications and data transfer to both the near and far sides of the Moon.

Cryogenic Volatile Sample Return

An architecture capable of cryogenic volatile sample return would need to overcome numerous challenges in order to collect, transport, and curate the samples in a manner that closely mimics the environment in which they were collected. It would require cryogenic freezers and sampling techniques, large cargo return, access to permanently shadowed regions, curatorial, and analytical facilities capable of storing, processing, and analyzing cryogenic samples.

Progressive Exploration Challenges

Challenges four to six map directly to the OWL's science themes for lunar exploration (page 572)[6] and Moon to Mars Objectives LPS-1, LPS-2, and LPS-3.[2] These scientific focus areas will build upon themselves as NASA conducts progressively evolved investigations across the lunar surface, including in-situ measurements, geologic field observations, and sample return.

As noted in appendix C of NASA's Moon to Mars Strategy and Objectives Development document (page 46),[1] each science objective may be further decomposed down to strategic research topics and specific investigations. These investigations may create a multitude of architectural needs, including local/global access to diverse locations, sample return, in-situ analyses, deployment of diverse instruments, access to the lunar subsurface, and more.

Architecture Enables Science

NASA's Moon to Mars Architecture can enable all six of these science challenges through a mixture of robotic and human capabilities. While crewed operations and sample return are essential for many of the strategic research investigations identified in the guiding documents discussed above, some investigations may be carried out or supplemented by robotic missions, including NASA's Commercial Lunar Payload Services program,[12] directed or competed missions, or uncrewed human-rated platforms (e.g., Lunar Terrain Vehicle[13]). Thus, as the human architecture capabilities evolve and robotic mission opportunities continue, missions to non-polar destinations will allow science to address objectives that need global access to fully address specific objectives.

As the Moon to Mars Architecture progresses from the Human Lunar Return through the Foundational Exploration and into the Sustained Lunar Evolution segments, it will incorporate new assets on the lunar surface that will enhance mobility (e.g., Pressurized Rover[14]), habitation (e.g., the initial surface habitat element), and surface power. These assets will allow for a more robust scientific campaign in the lunar South Pole region, enabling more comprehensive and long-duration investigations into space biology, fundamental physics, physical sciences, and human research.

Conclusion

The Implementation Plan for a NASA Integrated Lunar Science Strategy in the Artemis Era[5] offers a strategic insight into the planetary science that NASA plans to achieve through robotic and crewed exploration. NASA will augment the implementation plan with an Artemis strategy designed to capture the agency's plans to achieve the science objectives for other scientific disciplines, as laid out in decadal surveys[3] and NASA's Moon to Mars Objectives.[2]

Science continues to drive NASA's architecture definition process. As the architecture evolves, NASA is realizing a strategy that will achieve groundbreaking science and revolutionize our understanding of the Moon, our solar system, and the universe.

Key Takeaways

NASA's robotic and crewed architectures are essential to addressing the scientific community-derived priority science objectives.

NASA's science priorities are established by a variety of sources, including the Moon to Mars Objectives and decadal surveys by the National Academies.

The Science Mission Directorate will produce an overall Artemis strategy document that includes science strategies for all directorate-specific science disciplines, as well as science defined by the Human Research Program.

The specific needs of scientific investigations contributing to NASA's science goals drive architecture definition efforts.

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Lunar Reference Frames

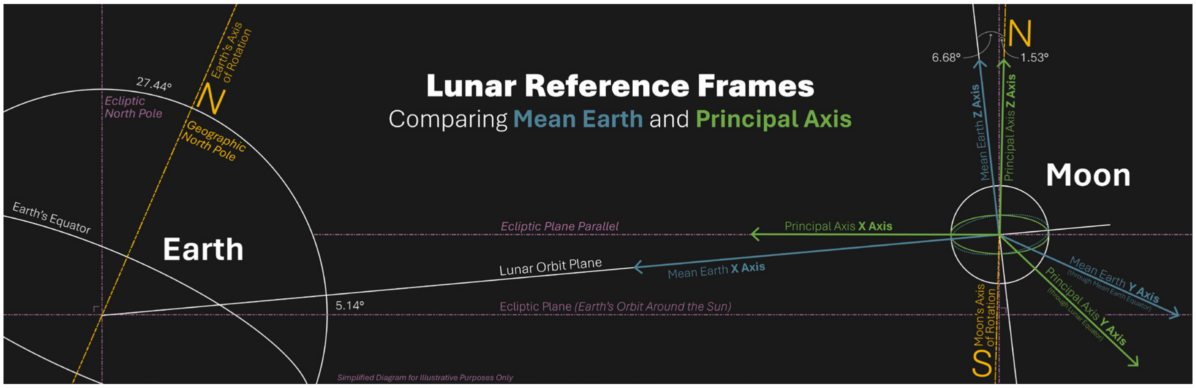
Introduction

As NASA returns to the Moon to establish a long-term presence there, navigation capabilities will be critical to all aspects of science and exploration. **Accurate and precise lunar navigation data improves safety, enhances planning, and enables crewed and robotic missions to achieve agency goals.**

NASA's Moon to Mars Objectives[1] — the agency's vision for crewed, deep space exploration — include a lunar infrastructure goal to "Develop a lunar position, navigation and timing architecture capable of scaling to support long term science, exploration, and industrial needs." Additionally, the National Cislunar Science and Technology Strategy[2] — a 2022 White House Office of Science and Technology Policy product — calls for NASA to lead the development of standards around "a Lunar reference frame tied to the celestial and terrestrial reference frames."

NASA's Moon to Mars Architecture[3] — the agency's roadmap for achieving the Moon to Mars Objectives — includes the Communications and Position, Navigation, and Timing (C&PNT) sub-architecture. NASA documents the architecture, including its C&PNT components, in the agency's Architecture Definition Document,[4] which is updated annually.

To empower sustained exploration of the Moon, NASA must thoughtfully consider the navigation standard it incorporates into the Moon to Mars Architecture. **This white paper identifies key considerations for the selection and implementation of or lunar reference frames for NASA's Artemis campaign.**



Figures 1: *Simplified diagram highlighting differences between lunar reference frames. (NASA)*

What is a Reference Frame?

The International Astronomical Union defines a reference system as the "theoretical concept of a system of coordinates, including time and standards necessary to specify the bases used to define the position and motion of objects in time and space" and a reference frame as "practical realization of a reference system."[5] Simply put, reference frames help mission planners understand where things are in space relative to one another.

Reference frames enable cartography, navigation, and operations on planetary bodies. They also create a shared navigation vernacular for mission planners, empowering cooperation and coordination that transcend boundaries of language or nation.

At the Moon, NASA has historically used two different body-fixed reference frames, each with different applications: **Mean Earth** and **Principal Axis**.

Mean Earth

Mean Earth has been used since the 18th century to observe and map the lunar surface and is still commonly used today. For this frame, the mean direction of Earth defines zero longitude (the x axis) and the mean direction of the Moon's rotation determines latitude (the z axis). The Moon's center of mass is the origin (center) of the Mean Earth coordinate system.[6,7]

The lunar surface science community commonly uses the Mean Earth reference frame for spatial data, to generate terrain and elevation models, and to reference surface features. Even as humanity's knowledge of the Moon improves, updates to the Mean Earth frame remain consistent with previous frames, minimizing changes to the coordinate frame in which surface feature locations are recorded (e.g., Apollo sample locations noted in the Mean Earth coordinate frame remain relatively consistent over time.)

Principal Axis

The Principal Axis frame adopts the principal axes and rotation of the Moon (i.e., the coordinate frame orientation is determined by the Moon's shape and mass distribution and rotates with the Moon). Like Mean Earth, the Moon's center of mass is the origin (center) of the Principal Axis coordinate system. Due to the nature of the Earth-Moon system, the Mean Earth and Principal Axis rotation axes do not coincide (see Figure 1).

Mission operators often use a Principal Axis frame for flight dynamics and navigation for cislunar spacecraft because lunar gravity is commonly computed in this frame, and thus gravitational forces on a spacecraft can be easily derived in that frame. It's also used for studies and modeling concerned with lunar gravity, topography, geodesy, and internal modeling.

Key Considerations

Accuracy and Safety

Equivalent coordinates on the lunar surface for Mean Earth and Principal Axis frames can differ by as much as 875 meters (i.e., a little over half a mile). This discrepancy can pose risks during mission-critical activities (e.g., lunar landings) or introduce errors in scientific investigations.

For the Artemis campaign, NASA has stringent surface location accuracy requirements to ensure the safety of lunar astronauts. Both the Mean Earth and Principal Axis frames are accurate to about the meter level, which is about 10% of the navigation accuracy budget for Artemis missions.

Collaboration and Consensus

Because the Mean Earth and Principal Axis frames are better suited to different applications, their adoption also varies. No single reference frame is ideal for all stakeholders — reference frames are chosen according to intended use case.

Establishing a consensus approach to lunar reference frames requires NASA to consider the needs of individual Artemis exploration assets. These assets will, by necessity of mission and vehicle design optimization, use different reference frames based on mission objectives and destinations. The reference frames used may also vary based on the implementing commercial organization or international partner.

NASA should establish standards, roles, and responsibilities to ensure proper configuration management of reference frame definitions and transformations. Additionally, the agency should ensure dissemination of these products to industry, academic, and international partners.

Backwards Compatibility

As reference frames evolve over time, it will become necessary to document transformations that maintain backwards compatibility with previously used frames in addition to transformations between frames. These calculations will be critical to preserving backwards compatibility with heritage data and systems.

Architectural Flexibility

Receivers of navigation signals should be designed to perform transformations to the reference frame best suited to their mission. This is not an unusual consideration for terrestrial applications, as receivers designed for the Global Navigation Satellite System[8] perform transformations between the reference frames of its component navigation systems (e.g., between the U.S. GPS, which uses the World Geodetic System 1984[9] maintained by the U.S. National Geospatial-Intelligence Agency,[10] and European Galileo,[11] which uses an independent version of the international terrestrial reference frame).[12]

Considering current spectrum allocations and constraints for radio navigation satellite systems — as defined by the Space Frequency Coordination Group[13] and International Telecommunications Union[14] — lunar navigation will likely secure relatively low bandwidth. This will limit satellite systems to broadcasting in a single reference frame (and data to support transformations by users).

Artemis Continuity

Both Mean Earth and Principal Axis user communities have already created science and navigation data within their respective frames. If NASA were to require use of a single reference frame, users would need to spend time and budget reprocessing their data, adding unnecessary processing risk, resource reprioritization from other tasks, and additional workload with little return value.

For the Artemis campaign, NASA is utilizing a Mean Earth frame for site selection and surface analyses. Transitioning to Principal Axis would disrupt progress, shifting focus from time-sensitive Artemis planning activities.

Recommendations

The Artemis campaign will comprise many systems in lunar orbit and on the Moon's surface. To realize a capable and extensible C&PNT sub-architecture, space vehicles and exploration assets must communicate navigation data between one another. To support these complex interactions, NASA must develop standards for reference frames and transformations. This guidance will enable consistency, simplify early mission and systems development, and reduce risk in surface operations.

In 2024, NASA established a working group to begin developing an agency approach to lunar reference frames that could meet the needs of the Artemis campaign and future lunar exploration. **Based on the considerations outlined above, the working group recommended that NASA develop a flexible lunar exploration architecture that supports the use of more than one frame.**

The working group also recommended that NASA work with the international community to establish standards for the exchange of surface location data. Defining these interfaces early in the architecture development process will simplify mission engagements.

The working group endorsed the Mean Earth lunar reference frame as the standard for initial surface operations, including planning and user location data exchange. Mean Earth meets identified needs at the lunar surface with minimum impact to current mission planning with minimal need to change heritage data products. **The working group did not endorse a corresponding orbital standard, understanding the need for mission-driven flexibility.**

In the future, NASA plans to use the Architecture Concept Review[15] as a forum to adopt reference frame updates to support agency stakeholder communities. Working with the community, NASA will also establish processes for the reference frame configuration management and the dissemination of reference frame updates.

Key Takeaways

Accurate and precise lunar navigation data improves safety, enhances planning, and empowers science for crewed and robotic missions; lunar reference frames are a critical component of a navigation architecture.

There are two primary lunar reference frames in use: Mean Earth and Principal Axis. Neither frame meets the needs of every stakeholder; each frame is better suited to a different set of specific disciplines and scientific communities. Availability of relevant transformation data allows for conversion between frames.

Establishing a consensus approach to lunar reference frames requires NASA to consider the needs of individual Artemis exploration assets and its industry, academic, and international partners.

It would be impractical and disruptive to establish a single reference frame for all lunar activities. A flexible architecture supporting multiple, complementary reference frames will benefit diverse users.

Adopting a Mean Earth reference frame for initial surface operations, including planning and user location data exchange, will meet current needs identified for missions while on the lunar surface. The working group did not endorse a corresponding orbital standard, understanding the need for mission-driven flexibility.

NASA will use the Architecture Concept Review cycle to evaluate and implement reference frame updates. This evaluation must include all relevant stakeholders and should quantify impacts to all stakeholders.

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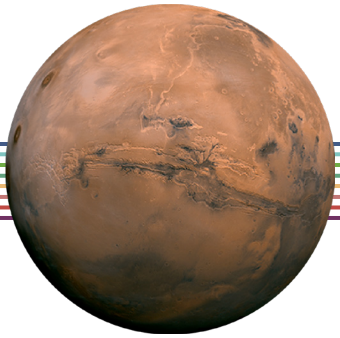

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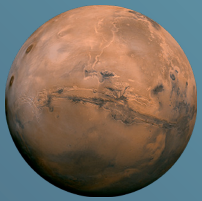

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Mars Surface Power Technology Decision

Introduction

NASA has selected nuclear fission power as the primary surface power generation technology for crewed missions to Mars. The decision was adopted as part of the 2024 Architecture Concept Review cycle and will inform development of the Humans to Mars segment of the Moon to Mars Architecture.

This paper updates a white paper from the 2023 Architecture Concept Review, "Mars Surface Power Generation Challenges and Considerations."[1] It summarizes the drivers and constraints that informed this architecture decision and provides an overview of NASA's decision-making considerations.

Background

As part of the 2023 Architecture Concept Review cycle, NASA began identifying driving decisions needed to define initial human missions to Mars. This effort identified the selection of the primary Mars surface power generation technology as a key decision because of its down-flow impacts on NASA's Mars architecture and Mars-forward considerations for NASA's lunar architecture.

NASA involved numerous internal stakeholder communities (such as technology developers and safety experts) in its assessment process. ESDMD coordinated relevant data and technical expertise across NASA's mission directorates and technical authorities, collating these inputs into a decision package for consideration by agency leadership at the 2024 Architecture Concept Review and subsequent meetings of the executive council. **These bodies reviewed the package and accepted the recommendation that nuclear fission serve as the primary Mars surface power technology.**

Selecting nuclear fission establishes the primary power generation technology for the Humans to Mars architecture segment but does not dictate funding for technology development or restrict other power technologies that could operate on the Martian surface. Instead, it offers an initial assumption for narrowing the architectural trade space and lays the groundwork on which flow-down architectural and implementation decisions may be made.

NASA's selection of nuclear power technology over non-nuclear power technology was driven primarily by the need to mitigate the risk of loss of mission. To make the decision, NASA traded numerous power technologies, ultimately down selecting to nuclear fission systems versus photovoltaic arrays with energy storage (i.e., solar panels with batteries).

Although solar power may have a lower per unit cost, fission power is more robust and better suited to the Martian environment. Fission can provide consistent power generation for a wide range of potential landing sites, around the clock, and during global dust storms. It also offers advantages in landed mass and volume.

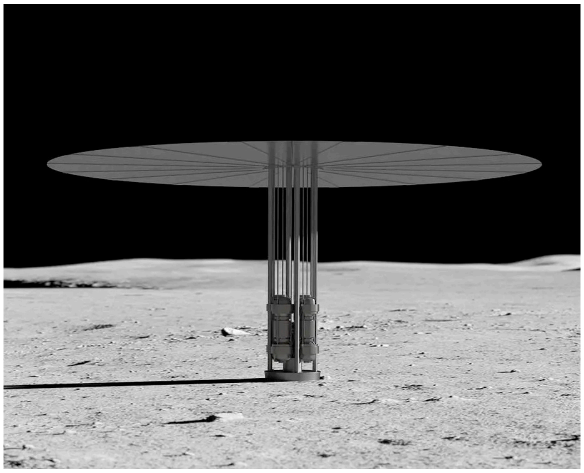


Image 1: *Artist concept of space fission surface power systems. (NASA)*

Note: *This paper is concerned with the primary power generation technology for an initial crewed Mars exploration campaign. The potential for supplementary, backup, and redundant systems remains an open area of architectural analysis.*

Mars Surface Power Considerations

After reaching and landing on the Red Planet, the first human Mars explorers must generate sufficient energy to power the systems they will need for a healthy and productive stay on the surface and their ascent back to orbit. Mars surface power needs may vary from one crewed mission to another depending on how long each crew plans to stay on Mars, surface mission objectives, and the requirements of surface assets and ascent vehicles.

Studies show that a modest mission of two crew members, conducting science and exploring the surface for no more than 30 days while living in a pressurized rover would require at least 10 kilowatts (kW) of surface power. (This includes propellant conditioning for a small crew ascent vehicle).

At the other end of the trade space, a larger crew complement, longer duration, propellant manufacturing, etc., would require hundreds of kW. Some architectures could require megawatt (MW)-class power systems.

Regardless of the architecture, a Mars surface power generation technology must address each of the unique environmental and operational challenges below:

Environmental Challenges

Dust Storms

Martian dust storms range from local dust devils to regional or global storms persisting for weeks or months. Local phenomena can evolve to global events in just a few Martian days. Atmospheric dust can reduce the solar energy that reaches solar arrays and the effectiveness of technologies requiring line of sight for power distribution, (e.g., power beaming). Dust settling out of the atmosphere can also collect on solar arrays, reducing performance. Sufficient accumulation can prevent them from generating keep-alive power, a situation that proved fatal for the solar-powered Opportunity rover.

Reduced Solar Energy Availability

Mars missions must account for reduced solar flux — the amount of solar energy that reaches an area — which is at most 45 percent of typical Earth values and varies significantly by location and season. The Martian day/night cycle also varies by location and season, with mid-latitude missions experiencing a 25-hour cycle and only illuminated for about 50 percent of that time. A Mars solar power system must simultaneously provide power for daylight operations while charging batteries to maintain night operations under this reduced solar energy availability.

Gravity and Wind Loads

Although Mars gravity is only about a third of that on Earth, Mars has about twice the gravity of the Moon. Large solar array structures designed for lunar applications would need higher structural strength for deployment on Mars. The design of very large or vertical solar arrays must also account for Martian winds. While wind is a design consideration, it is insufficient to serve as a primary surface power source (see the trade space section below).

Operational Challenges

Autonomous/Remote Power System Operation

To mitigate landing risks, many proposed Mars architectures would land their crew ascent vehicles with empty or partially full propellant tanks and either transfer staged, Earth-origin propellant or manufacture propellant from Mars resources. Both approaches require abundant surface power to condition, transport, and/or manufacture fuel. Depending on a variety of factors (including the use of delivered versus in-situ propellant and Earth departure windows), power systems may need to be deployed years in advance and support several human missions.

Limited Repair Options

The sheer distance between Earth and Mars means that unplanned replacement units or repair parts will not be readily available unless already staged on or near the Red Planet. The reliability, redundancy, and repairability of a surface power technology will have flow-down impacts on the architecture. To ensure crew safety, a surface power technology must be sufficiently robust, have built-in redundancy, and/or consider maintenance and servicing in its concept of operations.

Plume-Surface Interactions

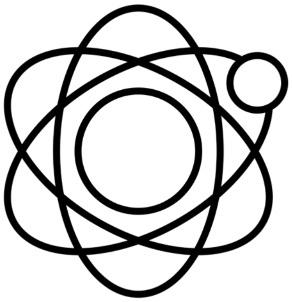
Descent and ascent engines can create plume-surface interactions, a known challenge for lunar landings that is exacerbated by the Martian atmosphere. Power systems must be shielded or separated from debris ejected by arriving or departing vehicles. This could require more extensive power distribution systems (e.g., autonomously deployed cabling) or mobility capabilities. Additionally, plume-surface interactions can loft dust that can cover solar panels a significant distance from a landing site.

Planetary Protection Constraints

Planetary protection refers to "the policy and practice of protecting current and future scientific investigations by limiting biological and relevant molecular contamination of other solar system bodies through exploration activities and protecting the Earth's biosphere by avoiding harmful biological contamination carried on returning spacecraft, as described in the Outer Space Treaty."[2] NASA is developing specific planetary protection guidelines for human missions to Mars; the primary power generation technology selected for Mars must adhere to these constraints.

Mars Surface Power Generation Trade Space

Despite Mars' many challenges, many promising power generation technologies are available or in development. While NASA considered many technologies as part of its surface power decision, two options in the trade space stand out as offering the most value: nuclear power and solar power.

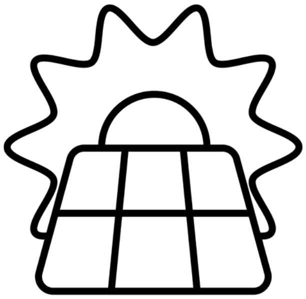


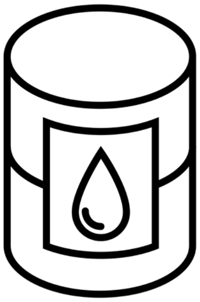
Nuclear Power

High energy density nuclear power — either Curiosity/Perseverance rover-style radioisotope power systems or nuclear fission systems — are unaffected by day/night cycles and reduced solar energy availability. Additionally, nuclear power systems would package well in volume-constrained spacecraft. Although current radioisotope power system designs only offer a few hundred watts, they may be applicable to applications with smaller power loads. For higher power needs (e.g., crew life support or ascent propellant manufacturing), fission surface power is readily scalable.

Solar Power

Solar power could be feasible if designed to address the challenges of dust accumulation and the day/night cycle. To clear accumulated dust from solar panels, NASA could augment them with robotic dust wipers, pressurized gases, mechanical array tilting, or electrodynamic or piezoelectric dust removal. However, surface dust removal would not mitigate the problem of reduced solar availability due to suspended atmospheric dust during lengthy storms. Nighttime power needs would require energy storage and simultaneous daytime charging and power distribution. Additionally, NASA would need to evaluate unique operational considerations — such as radiation keep-out and large array off-loading — for large-scale solar power system deployment on Mars.



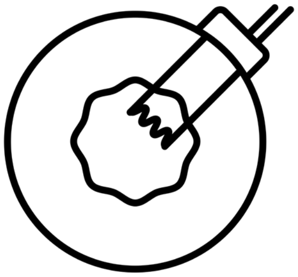


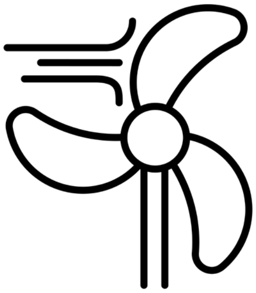
Fuel Cells

Fuel cells — which generate electricity through chemical reactions — are often proposed for Mars missions. In this paradigm, associated chemical fuel would be transported from Earth or generated in-situ on Mars. These systems do not trade well because they require large amounts of landed reactant mass and/or more energy to make reactants in-situ than the fuel cells could provide.

Geothermal Engergy

Geothermal energy has been proposed for use in eventual Martian settlements. However, NASA currently has limited data on local geothermal availability and has not matured geothermal technologies for Mars. Additionally, accessing geothermal energy would require heavy equipment to implement and may be geographically constrained to areas with easy access to geothermal sources. The autonomous robotic drilling and regolith-moving required to access heat sources would also require a separate power source. This makes geothermal energy generation less attractive for early missions.



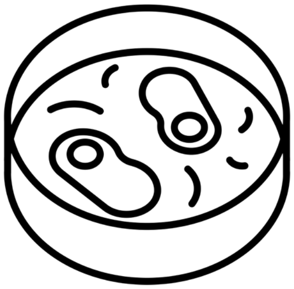


Wind Power

While some have proposed wind turbines as a potential Mars power generation technology, analysis shows that the Red Planet has insufficient sustained winds for reliable power production. While wind is a key design consideration for Mars surface power, it would not suffice for primary power generation for initial crewed missions to Mars.

Biogeneration

Biogeneration relies on microorganisms to convert organic feedstock directly into heat or another commodity, such as methane, that can then be used to generate power. This technology has been proposed as an option for Mars power generation but would be greatly complicated by planetary protection constraints.



Note: While multiple power systems may be integrated to support mission needs, this paper and its associated decision consider *primary* and not *supplementary* power generation technologies specifically for *initial* crewed missions to Mars.

The Moon as a Testbed for Mars

The Moon's proximity to Earth offers opportunities to demonstrate candidate Mars surface power generation technologies with reduced consequences of failure. To ensure extensibility to Mars, lunar surface power systems would need to account for the environmental differences, including Mars' atmosphere, increased gravity, shorter day/night cycle, wind loads, dust storms, communications delay, etc. While implementing Mars-forward technologies at the Moon could add cost or complexity, surface power technology demonstrations during the Artemis campaign would significantly reduce risk for initial crewed missions to Mars, serve as pathfinders for power system operations, and ultimately reduce the cost of implementing systems for Mars.

Summary

NASA examined the factors detailed above in developing the decision package for the primary Mars surface power generation technology. The team evaluated different power generation options across a variety of attributes, including:

- reliability and availability (i.e., their resilience to the environmental factors described above),
- ability to meet the power needs of a range of potential missions,
- extensibility to future segments,
- and key drivers of affordability.

The team consulted with stakeholders from across NASA's mission directorates and technical authorities, ultimately offering a recommendation that was approved by agency leadership.

Because of the advantages it offers in power availability and reliability, NASA will baseline nuclear fission power as the primary surface power generation technology for initial crewed Mars missions. This decision represents a significant step in defining the first human missions to the Red Planet and enables Mars-forward power considerations during lunar missions.

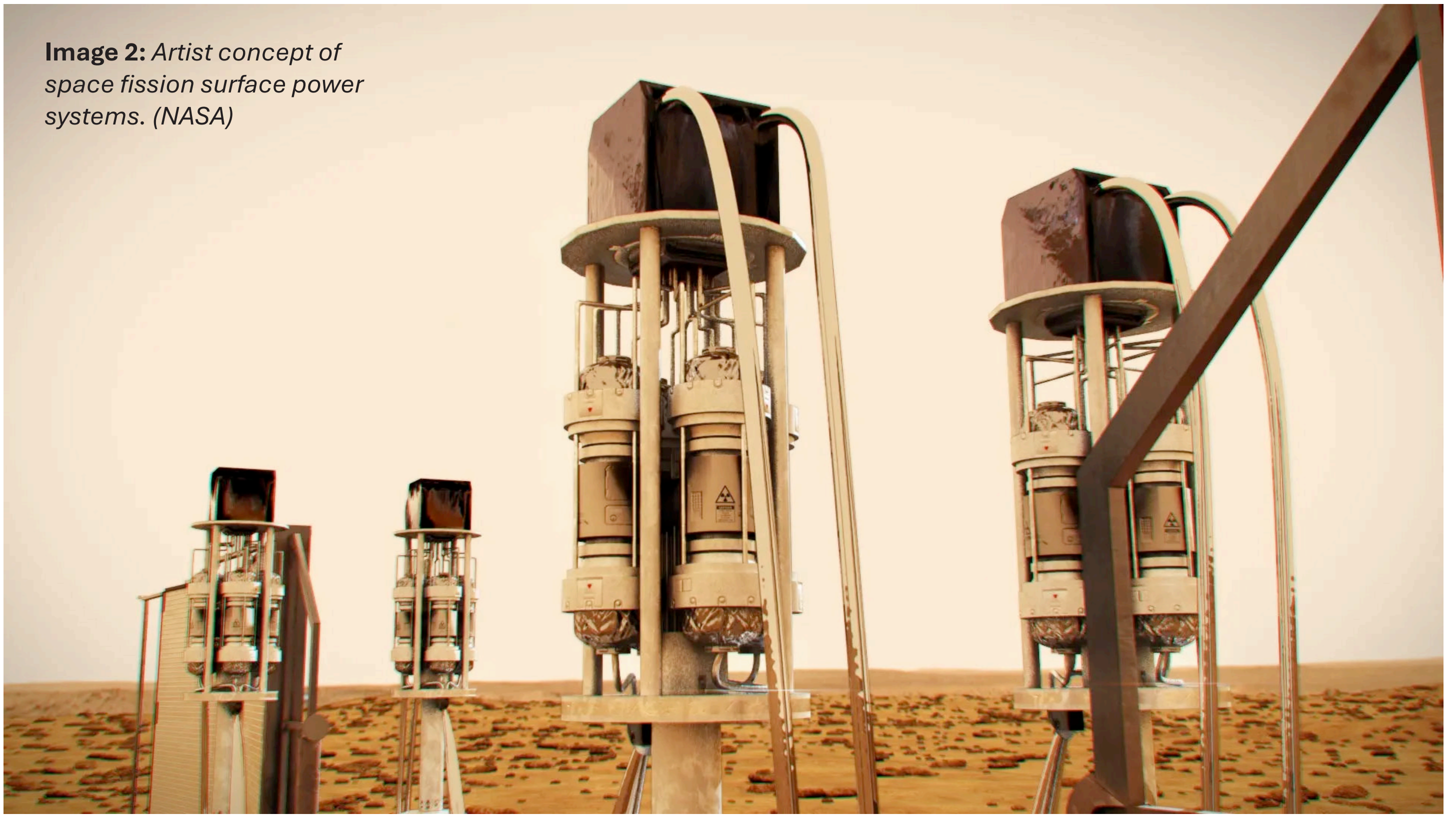


Image 2: *Artist concept of space fission surface power systems. (NASA)*

Key Takeaways

The minimum power required for a modest, short duration, human Mars surface mission with a limited crew complement is about 10 kW. More complex architectures leveraging significant in-situ resource utilization could require MW-class power systems.

The Mars surface power generation technology selected for the initial crewed missions to Mars must accommodate anticipated operational needs and the unique challenges of the Mars environment, with limited repair or replacement options.

The Artemis campaign offers an opportunity to test safety-critical Mars surface power generation technologies and operations on the Moon to reduce risk for later Mars missions.

Architecture Decision

NASA has baselined fission power as the primary surface power generation technology for initial crewed missions to Mars due to its robustness to surface environmental and atmospheric conditions as well as mass and volume advantages considering the power levels needed for human Mars exploration.

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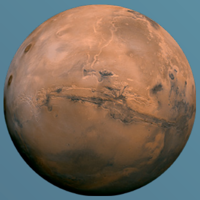

Mars Crew Complement Considerations

Introduction

Crew complement — or the number of astronauts on a mission to accomplish set responsibilities — is a key driver for human exploration architectures, with flow-down impacts on most elements and sub-architectures. As such, it was identified by NASA as a priority decision in the 2023 Moon to Mars Architecture white paper, “Key Mars Architecture Decisions.”[1]

The number of astronauts an architecture must accommodate has direct implications for a habitable element’s volume, performance of associated environmental control and life support systems, power needs, crew support system considerations, and logistics needs (e.g., for utilization, food, clothing, medical supplies, etc.). The number of crew that an architecture must support also drives the necessary capabilities for human-rated ascent and descent vehicles and all other exploration systems at the destination. In determining crew complement, it is important to look beyond just the first mission towards what the desired end state for the architecture is. For example, the first Space Shuttle flight only carried two astronauts, but the vehicle was designed to accommodate more.

Operationally, crew complement must account for the skills necessary to carry out planned tasks. The number of astronauts enables crew time available to accomplish the functions necessary to achieve mission objectives. These activities include utilization for science, outreach, and instrument deployment, as well as mission overhead for systems monitoring, maintenance, and troubleshooting.

Additionally, the number of astronauts has implications for the range of crew expertise available on a given mission. This consideration is particularly relevant for deep space missions, where the operational paradigm differs from spaceflight in low-Earth orbit. At destinations like Mars, a crew must operate with communications delays and potential disruptions that prevent real-time communication with flight controllers and subject matter experts back on Earth.[2]

Historically, crew complement has been a secondary consideration defined by the capabilities of pre-selected exploration elements. As such, crew complement has been determined based on a limited set of capabilities or more general qualitative statements.

The process of architecting from the right — as outlined in “NASA’s Moon to Mars Strategy and Objectives Development” document[3] — allows a more holistic and integrated approach. NASA architects can evaluate the drivers and flow-down impacts of crew complement to identify the number of crew needed to achieve Moon to Mars objectives[4] during a human Mars mission.

This methodology for deriving the number of crew to Mars vicinity and the Martian surface — which may be different values — will identify architectural characteristics that have the most significant impacts to the decision. **Due to inherent flow-down impacts for most aspects of mission planning, it is critically important that NASA establishes crew complement early in the stages of architecture development.**

Crew Health and Performance Considerations

Unlike purely robotic missions, human exploration missions must consider both the physical and psychological health of the crew. A mission architecture must accommodate crew health and performance needs with an appropriately sized crew complement and prevent or mitigate scenarios where health issues could affect mission goals or, more importantly, jeopardize safe return of the crew.

The unique challenges of a Mars mission require an architecture to consider human system risks. Some of these risks include crew behavioral health, team dynamics, probability of crew medical conditions (and duration of associated care), and integration of the human system with other exploration systems.

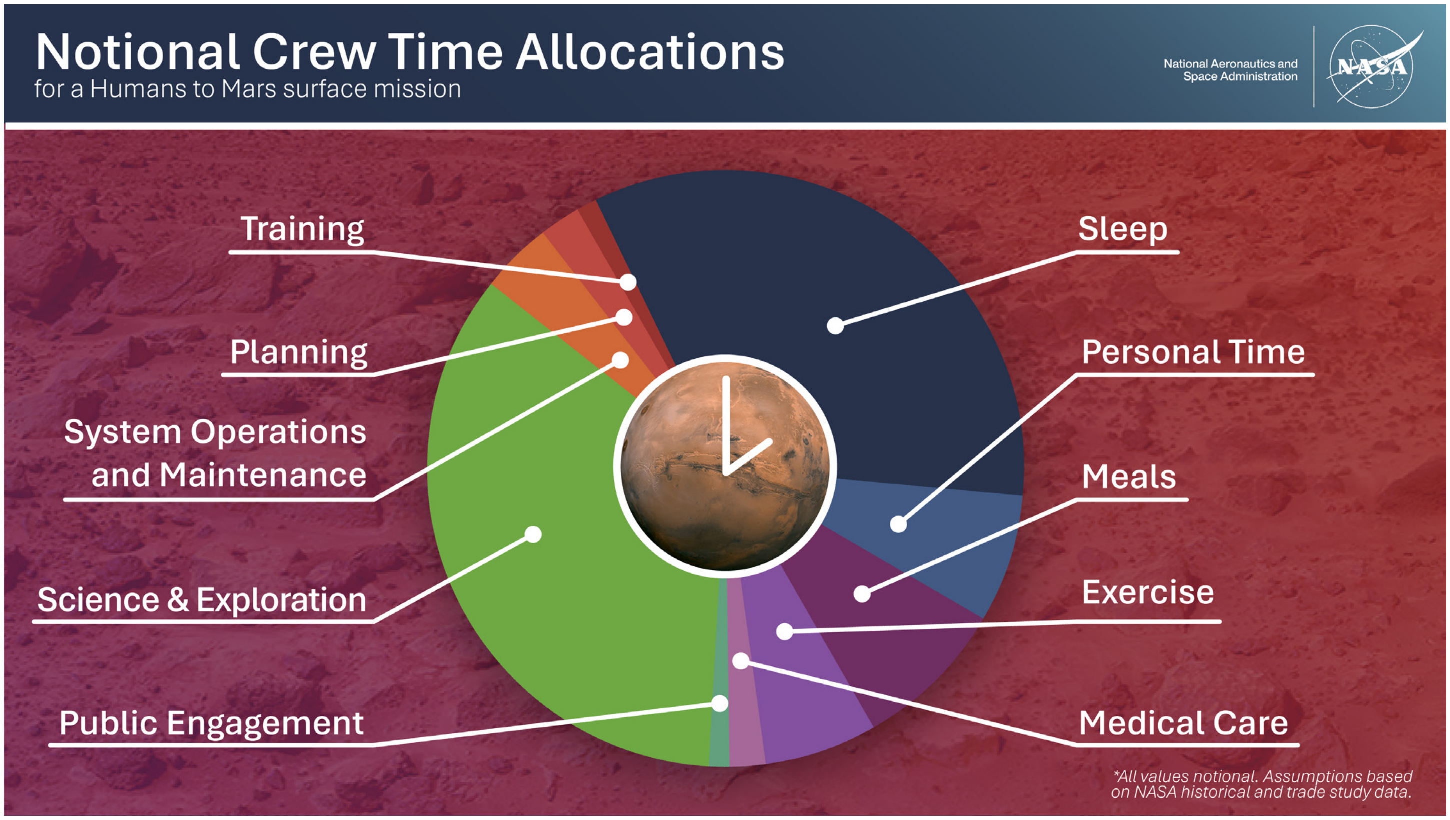

Figure 1: *Notional crew time allocations for a Humans to Mars segment surface mission. (NASA)*

Human systems integration is perhaps the most complex of these risks. These risks are intrinsically linked with crew task load, system design, and human interactions with exploration systems.

Additionally, the demands on astronauts may change throughout the mission. Deviations in environmental, communication, or mission phase–related stressors can have deleterious effects on crew physical and psychological health.

For more details, read the 2023 Moon to Mars Architecture white paper, "Human Health and Performance: Keeping Astronauts Safe & Productive On a Mission to Mars."[5]

Crew Responsibility Considerations

Each crew member will have defined responsibilities and proficiency levels to support a Mars mission. Specific expertise may be leveraged across an entire mission (e.g., for vehicle monitoring and maintenance, medical care, etc.) or called upon during specific mission-critical phases (e.g., for launch or landing preparation, in-space docking, surface exploration, etc.).

There are practical limitations on how many in-mission responsibilities a single crew member can support. Extended periods where a mission requires intense mental strain or burden on crew ability — whether during nominal operations or critical events — can result in burnout and significantly degrade health and performance. The more crew on a mission; the more that duties may be shared and stressors may be minimized.

Due to the distances and communications delays associated with a Mars mission;[2] the crew must also have the capability to operate independently, particularly during mission critical events. Crew members will need to accomplish many responsibilities traditionally performed by terrestrial mission control during low-Earth orbit or lunar missions.

In establishing a crew complement, NASA must consider the complement of astronauts needed to ensure needed skills and expertise to accomplish nominal tasks, time-critical contingency operations, and mission utilization objectives.

Crew Workload Considerations

Understanding a crew's day-to-day workload and ensuring a healthy work-life balance are key aspects of selecting the number of crew. Daily, the crew must maintain mission systems; conduct science, technology utilization, and public engagement activities; plan for upcoming mission milestones; and keep up with necessary training — all while meeting the physical and cognitive requirements of specific tasks.

Each day must also include sufficient time for meals, exercise, hygiene, sleep, relaxation, and other crew health and performance activities. Successful mission design for crew workload will fall within reasonable human limitations. An excessive workload can increase the rate of human error during task execution, result in a failure to complete tasks, and degrade response time during critical or contingency operations.

Many tasks performed on the International Space Station (e.g., during extravehicular activity (EVA)) rely on significant coordination and support from Earth-based personnel. During a Mars mission, much of that real-time support will need to be provided by members of the crew instead because of communications delays, disruptions, and limitations.

Autonomous technologies and systems could reduce crew burden and, ergo, the minimum crew complement needed to support exploration systems and functions. However, an architecture must identify opportunities for the implementation of automation and autonomy early enough in the mission design process to allow for the design, integration, and testing of new systems.

Mission Concept of Operations Considerations

Crew allocation decisions result in differing concepts of operations, with flow-down impacts on exploration systems design and many other aspects of an architecture. Mission objectives or constraints may lead to splitting a crew between different locations. Some crew members may remain aboard a spacecraft in the vicinity of Mars while the rest descend to the surface. If the entire crew lands on the surface, any vehicles remaining in space would need to remain uncrewed and may increase vehicle autonomy needs in the design.

In the event of a divided crew, each group must be appropriately sized to safely complete their respective responsibilities and mission objectives. Mars mission architects must consider operational needs for tasks and activities specific to both the vicinity and the surface of the Red Planet. For example, surface EVAs have significant safety and operational support requirements. Sending a crew member on an EVA alone or leaving a crew member alone in a habitation element while others are on EVA may result in unacceptable risks.

Mission Complexity and Value Considerations

Crew complement can affect the overall complexity of a mission. The scale and complexity of vehicles and systems may vary based on crew complement, although increasing crew complement may also provide opportunities for economy of scale.

The number of crew an architecture must support can also drive the development of new technologies and systems. This is particularly true for Earth-independent systems needed to overcome the constraints of a more limited crew complement. A decision about crew complement may reveal a need for precursor missions to demonstrate certain integrated systems that enable a specific crew complement to achieve mission science and exploration objectives.

To support a larger number of crew, NASA may need to modify or expand crew training and Earth reconditioning facilities. Finally, programmatic, administrative, budgetary, and schedule constraints can also influence crew complement for a human mission to Mars.

Summary and Forward Work

NASA's Moon to Mars architecture allows for the opportunity for a holistic analysis on crew complement. NASA architects must carefully balance crew workload, skills, health, and safety with their need to achieve NASA's Moon to Mars Objectives. They must also consider the current state of the art, prioritizing the development of the autonomous systems needed to empower a given crew complement. Further, they must weigh the costs associated with a given crew complement against budgetary constraints.

Decisions about crew complement are enormously important and must be made early in the process of architecture development. The many flow-down impacts of the number of astronauts included on a Mars mission can shape all aspects of mission planning.

In the coming years, NASA will continue to analyze the Mars crew complement trade space, considering data and insights from its mission directorates, centers, technical authorities, and stakeholders. Ultimately, NASA will develop an integrated decision package that includes analyses and recommendations for review and approval by agency leadership as part of the annual Architecture Concept Review process.

For an example of a key driving decision made using this process, see the 2024 Mars Initial Surface Power Decision white paper published concurrently to this paper.

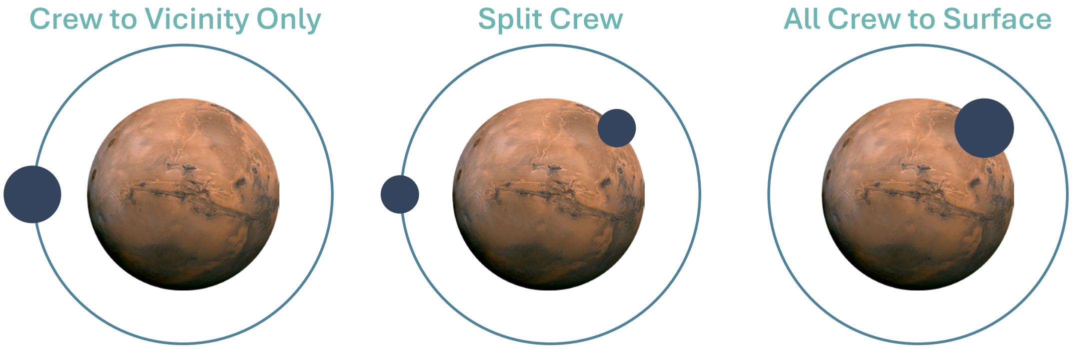

Figure 2: *Three crew concepts of operations for a Humans to Mars segment mission. (NASA)*

Key Takeaways

The number of crew an architecture must support has flow-down impacts on most sub-architectures and elements, with profound implications for key exploration systems, including launch vehicles, transit systems, ascent vehicles, communications infrastructure, and power generation.

Splitting a crew between locations (e.g., in space, inside habitat, on EVA, etc.) significantly impacts the architecture necessary to support them.

Key considerations for establishing the number of crew to the vicinity and the surface of Mars include balancing crew health, performance, operations, safety, utilization, technology integration, and exploration objectives.

Due to these flow-down impacts, it is critically important that NASA makes a decision regarding crew complement early in the stages of architecture development.

NASA will continue to analyze the trade space in support of a decision on crew complement, developing a decision package for review by agency leadership.

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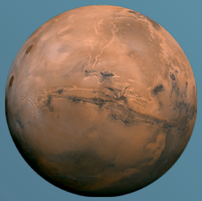


2024
Moon to Mars
Architecture

white paper

Mars Entry, Descent, and Landing Challenges for Human Missions

Introduction

History provides numerous examples of the challenges of landing on Mars — only 12 out of 19 attempted robotic landings have been successful.[1] Human missions to Mars will introduce new challenges that must be addressed.

To land humans on the Red Planet and then safely return them to Earth, NASA must pursue advances in flight testing, atmospheric deceleration systems, propulsive descent systems, characterization of rocket interactions with the surface, guidance and navigation systems, and modeling and simulation of these elements. Only then can Martian astronauts begin to meet NASA's Moon to Mars Objectives.[2]

This white paper introduces atmospheric entry, descent, and landing (EDL), discusses some of the unique challenges of Mars exploration, and provides insight into the advancements necessary to land the first human explorers on the surface of the Red Planet. This is a high-level overview, with referenced publications providing further detail into landing systems and engineering challenges.

What is EDL?

EDL is one of the highest-risk phases of spaceflight. During EDL, the spacecraft enters and transits a planetary atmosphere, decelerates, and touches down onto the planetary surface. Through EDL, NASA will place astronauts and payloads at planned surface locations for exploration and science, as well as near surface infrastructure such as habitats, supplies, surface mobility vehicles, and Earth-return vehicles. **Figure 1** shows the concept of operations for the most recent NASA Mars EDL system, the robotic Mars 2020 mission, which landed the Perseverance rover and Ingenuity helicopter.

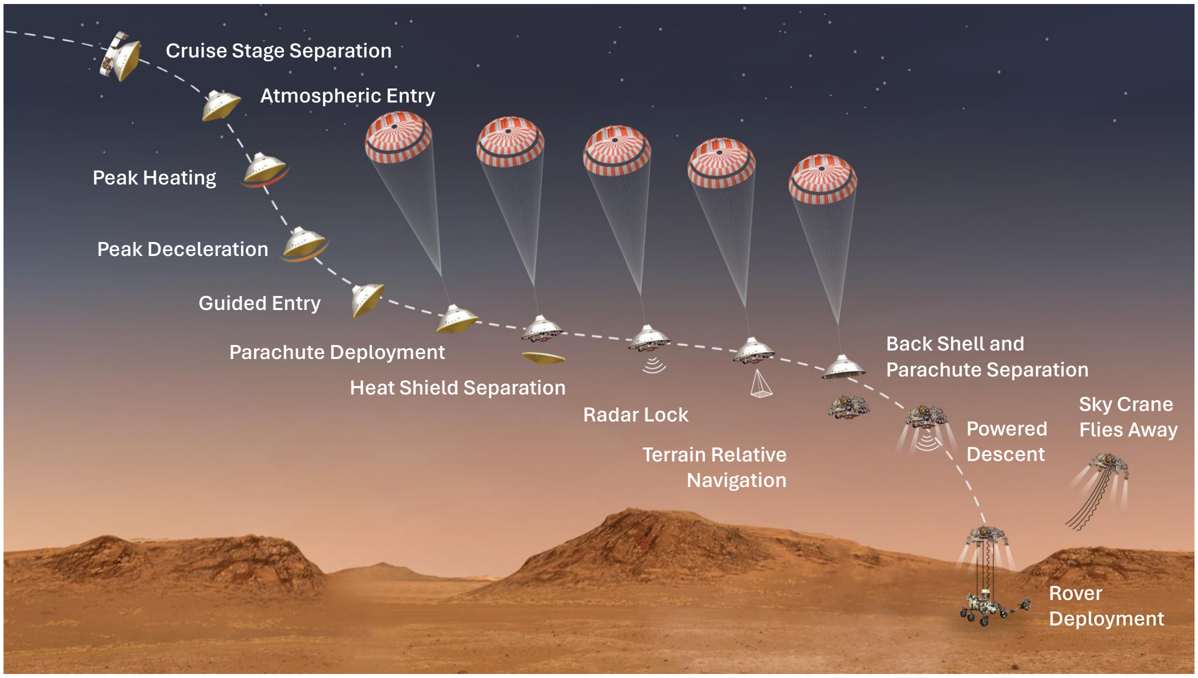


Figure 1: *Illustration of EDL for the NASA Mars 2020 mission. (NASA/JPL)*

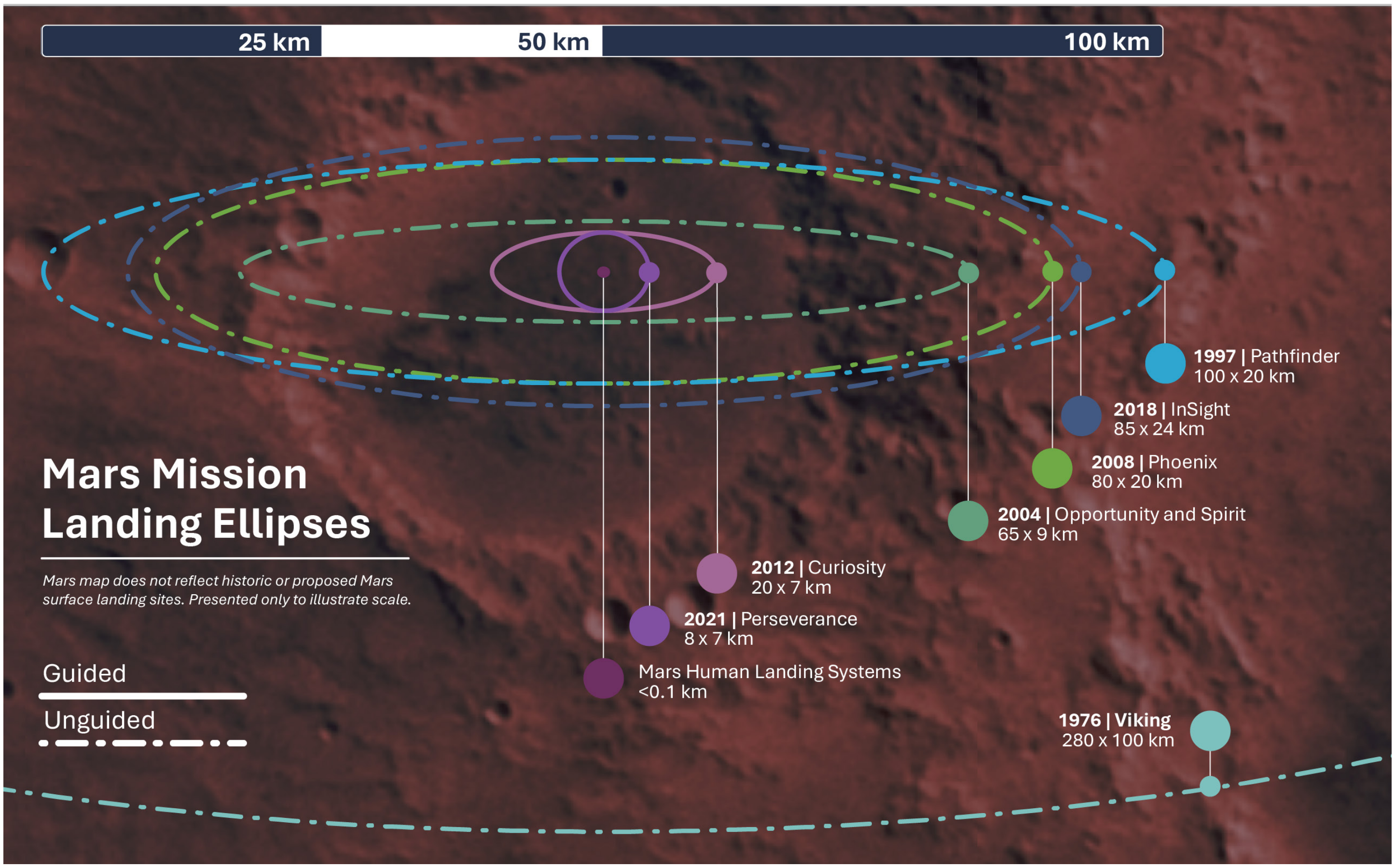


Figure 2: *Overlay of NASA Mars operational landing ellipses, shown at Gale Crater. Landing ellipses for human missions to Mars will be smaller than any previous robotic missions. (NASA)*

Entry

The entry phase begins at atmospheric entry interface, when vehicle aerodynamic forces and aerothermal heating induced by the atmosphere become non-negligible. During this phase, a spacecraft must manage aerodynamic forces and thermal loads to successfully decelerate the vehicle from hypersonic velocities.

Large variabilities in the atmospheric entry point, atmospheric density, and vehicle aerodynamic predictions contribute to large landing errors, as shown in **Figure 2**. Implementing active guidance and reaction control systems aboard recent Mars EDL systems has helped to achieve much smaller landing ellipses than prior missions.

Descent

The descent phase begins with deployment of a dedicated deceleration system. The transition from entry to descent depends on the specific mission and vehicle, but typically occurs during supersonic flight.

Heritage Mars descent approaches include parachutes and retropropulsion systems, thrusters that fire against the direction of travel.

- Heritage parachute systems are inherently un-steerable, and wind drift can add a kilometer or more of landing error.
- Retropropulsive system maneuvers can help avoid hazards and reduce touchdown distance from the intended landing site, relying on vehicle navigation sensors to refine onboard knowledge of surface-relative position and velocity during deceleration.

Landing

The landing phase takes place after the vehicle slows to touchdown velocity, chosen for soft and safe landing near the identified destination. Vehicle designs must handle the touchdown loads, velocity, and final orientation to ensure surface operations can proceed after landing.

Previous Mars missions have leveraged either retropropulsion or airbag systems for touchdown. Retropropulsive landing system engines induce plume-surface interaction (PSI) with the ground. PSI can lead to surface erosion below the lander and ejected debris, which pose a risk to the landing vehicle and nearby surface assets.

Historic Challenge of Mars EDL

NASA has performed successful EDL at planets and moons throughout the solar system.[3] EDL systems for Earth benefit from a well-characterized atmosphere for deceleration, well-known terrain for landing, and Earth-based navigational capabilities like GPS for guidance.

On airless bodies such as the Moon, the atmospheric entry phase does not exist. Ergo, landers do not need heat shields or aerodynamics-based deceleration systems. Instead, onboard retropropulsion fully decelerates and lands spacecraft. Landings on the Moon provide valuable insight for Mars EDL, although Mars possesses several unique characteristics that create new EDL challenges.

Atmosphere

The Martian atmosphere is thin but provides enough aerodynamic drag to decelerate an entry vehicle while still inducing non-negligible aerothermal heating. An entry vehicle must mitigate this overheating, which is substantial enough to result in loss of mission.[4]

The atmospheric density at the Martian surface is comparable to Earth's atmospheric density at approximately 30 kilometers in altitude. Atmospheric density and wind variability for any Mars EDL produce large uncertainty in predicted touchdown location. The resulting variability in descent timelines limits reachable surface site altitudes.

Figure 2 shows how landing accuracy at Mars has improved over time and highlights the kilometers of improvement still needed for human missions. Several improvements have reduced the ellipse sizes: improved interplanetary navigation that better target the initial entry point, the use of capsule aerodynamics during entry to steer toward the target, and enhanced transition-to-descent parachute trigger methods.

The remaining challenges in landing accuracy for heritage systems stem from:

1. errors in onboard navigation accuracy during the entry phase, which limits steering accuracy,
2. parachute sensitivity to wind variability, which occurs after the entry steering is complete, and
3. aeroheating, as necessary heatshields complicate the use of navigation sensors during entry to improve onboard navigation.

Surface Hazards

Many Martian surface regions of scientific interest have terrain features that pose risks to safe lander touchdown. Landing site selection includes surface hazard risk assessments based on orbital imagery and planetary geology models.

The best images from the Mars Reconnaissance Orbiter provide 25 cm resolution. At that resolution, mission planners can identify rocks and features as small as 1 meter in size. Even when select landing ellipses that minimize hazards, some Mars landers have touched down near large rocks that would have caused a landing failure if struck. For example, **Figure 3** shows a 1-meter-tall boulder within 8 meters of Viking 1's landing location.

NASA must address landing system surface hazard tolerance either via pre-flight analysis — based on knowledge of the planned touchdown area — or sensors to detect and avoid hazards during descent and landing. Landers with retropropulsive rockets further complicate surface hazard considerations, as PSI erosion of surface regolith (**Figure 4**) could produce unstable or unacceptably sloped landing surfaces and eject debris, dust, and regolith at and away from the lander. Additionally, both PSI and naturally occurring Mars atmospheric dust affect EDL sensor measurements and, in turn, EDL navigation.

System Validation

Validation of Mars EDL systems presents significant challenges. There are no Earth-analog test conditions that completely mimic Mars EDL. The Martian EDL environment comprises different atmospheric pressures, temperatures, chemistry, wind, dust, humidity, gravity, and surface composition. Hence, a "test as you fly" approach is simply not possible to validate Mars EDL systems prior to a mission.

Past missions to the Red Planet have approached validation by combining high-fidelity, system-level modeling and simulation in parallel with terrestrial component-level tests in Mars-representative conditions. NASA uses facilities and testbeds including wind tunnels, vacuum chambers, arc jets, suborbital rockets, and aircraft to validate models and build confidence in EDL components and systems.[4] This testing, combined with the data collected from past robotic Mars missions, will help NASA develop subsequent Mars missions.

Figure 3:
Lander-size 'Big Joe' boulder 8 meters away from Viking 1. (NASA/JPL)

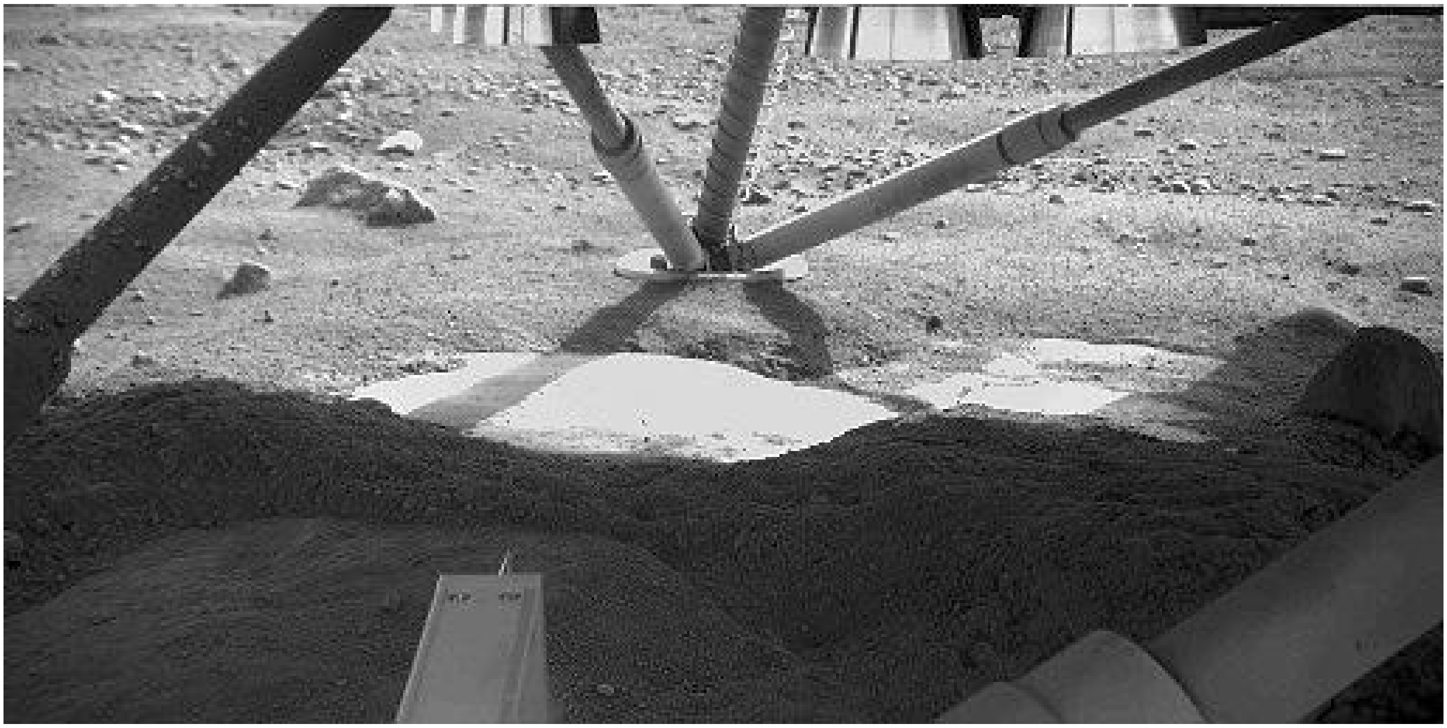


Figure 4: *Subsurface ice exposed by 2008 Phoenix landing engines. (NASA/JPL)*

System Scalability

Since the 1970s, NASA Mars EDL systems have leveraged scaled variations of the original Viking entry capsule and parachute designs. Component testing has been necessary to qualify heavier and higher-velocity Mars EDL systems, but, because of cost, there has not been an extensive redesign.

Recent Mars missions have approached the payload mass limit of the Viking design, and future missions will exceed it. **Figure 5** highlights the evolution of NASA Mars EDL systems since Viking. All flown EDL systems to date have had landed masses between 0.3 and 1 metric tons. The projected jump for human-class Mars EDL requires an increase to landed masses in excess of 20 times greater, or over 20 metric tons.[4] This is well beyond what a scaled-up Viking design could achieve.

Transition to Human-Class Mars EDL

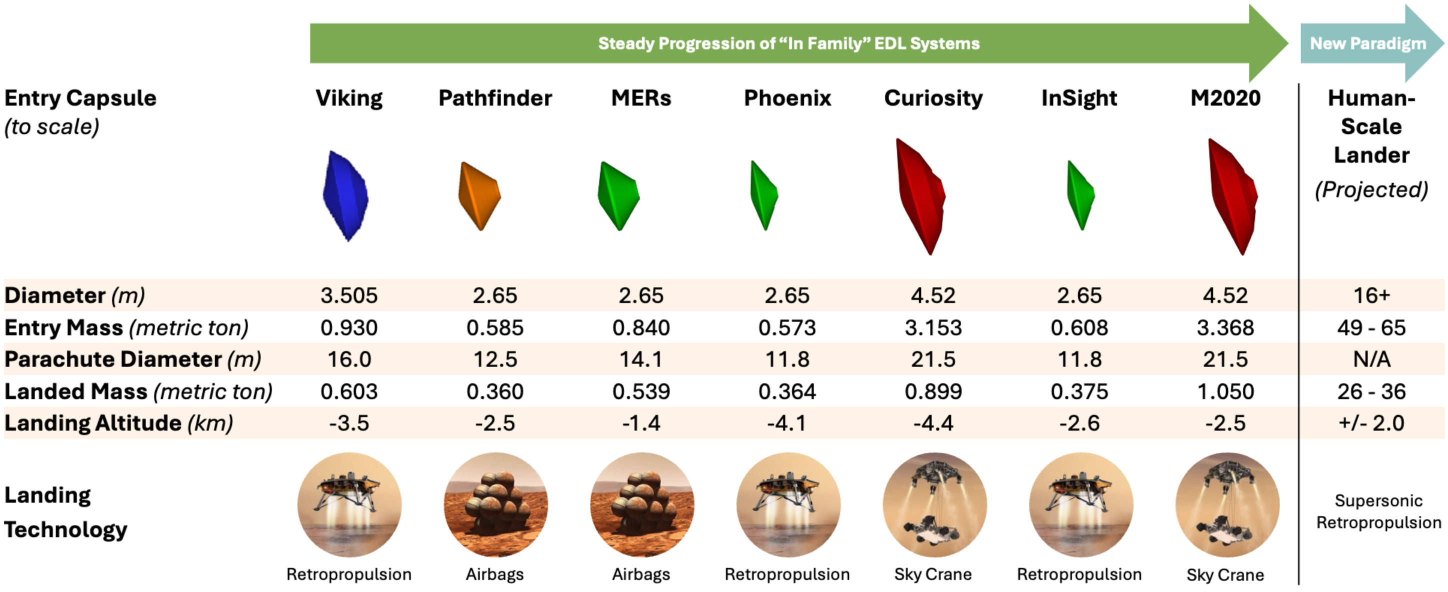
The Mars 2020 EDL in **Figure 1** represents the current state of the art for Mars EDL systems. Each successive Mars robotic EDL has drawn from the knowledge and experience of past missions. Those lessons learned are informing ongoing studies to meet the requirements of human-class Mars landers. Areas of ongoing research include entry modeling and instrumentation, new deceleration systems, guidance and navigation, and new landing systems.

The projected mass of human-class landers (**Figure 5**) requires advancements in entry systems design and modeling. Numerous NASA design studies[4, 5, 6, 7] are using high-fidelity simulations to investigate concepts for large, inflatable aerodynamic decelerators and higher-lift aerodynamic bodies to inform and gain insight into industry development efforts (**Figure 6**). EDL simulations are using the latest data on the Martian atmosphere and vehicle technologies to assess the viability of designs for human-class systems.

Deceleration systems cannot be validated with test articles at Mars, but subscale development and high-altitude flight testing on Earth can produce valuable data for developing human-class systems. Larger entry vehicles will need to manage significant aerothermal heating, transition from hypersonic to subsonic flight, and decelerate for a soft touchdown, all of which may require new technologies and concepts of operation (**Figure 7**). Terrestrial testing can validate these new systems to ensure they are ready for crewed missions.

Robotic Mars missions have continuously advanced state-of-the-art guidance and navigation capabilities, contributing to the landing error reductions shown in **Figure 2**. However, the need for more precise accuracy for human-class landers will require further advancements in guidance and navigation sensors and algorithms, alongside supersonic retropropulsion and aerodynamic performance.[7] New sensors and systems can enable advanced terrain relative navigation, allowing spacecraft to use visual reference data to establish their location and navigate to avoid landing hazards in a variety of conditions (**Figure 8**).

Landing systems will also need to evolve beyond robotic Mars and human lunar systems to account for the constraints of human Mars missions (**Figure 9**). Higher-thrust engines on human-scale landers will likely create significant PSI ejecta and obscure landing sites. Understanding and modeling PSI-induced changes to the surface will inform mitigations to protect landers and other assets close to the landing site. While lunar PSI data can be valuable, the Martian regolith behaves differently than the lunar regolith, requiring Mars-specific modeling and ground testing.



Entry Capsule *(to scale)*	**Viking**	**Pathfinder**	**MERs**	**Phoenix**	**Curiosity**	**InSight**	**M2020**	**Human-Scale Lander** *(Projected)*
Diameter *(m)*	3.505	2.65	2.65	2.65	4.52	2.65	4.52	16+
Entry Mass *(metric ton)*	0.930	0.585	0.840	0.573	3.153	0.608	3.368	49 - 65
Parachute Diameter *(m)*	16.0	12.5	14.1	11.8	21.5	11.8	21.5	N/A
Landed Mass *(metric ton)*	0.603	0.360	0.539	0.364	0.899	0.375	1.050	26 - 36
Landing Altitude *(km)*	-3.5	-2.5	-1.4	-4.1	-4.4	-2.6	-2.5	+/- 2.0
Landing Technology	Retropropulsion	Airbags	Airbags	Retropropulsion	Sky Crane	Retropropulsion	Sky Crane	Supersonic Retropropulsion

Figure 5: *Evolution of Mars EDL systems. (NASA)*

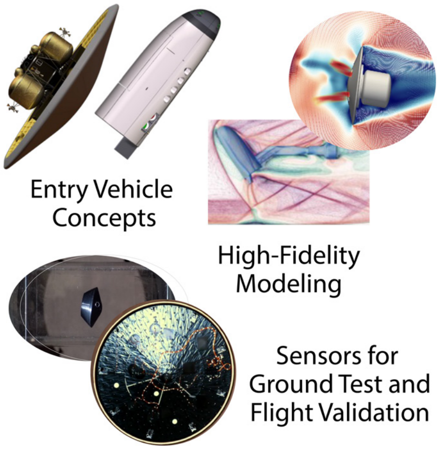


Figure 6: *Entry modeling and simulation. (NASA)*

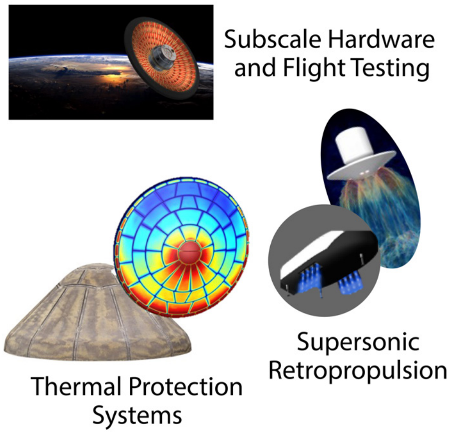


Figure 7: *New deceleration systems must be developed. (NASA)*

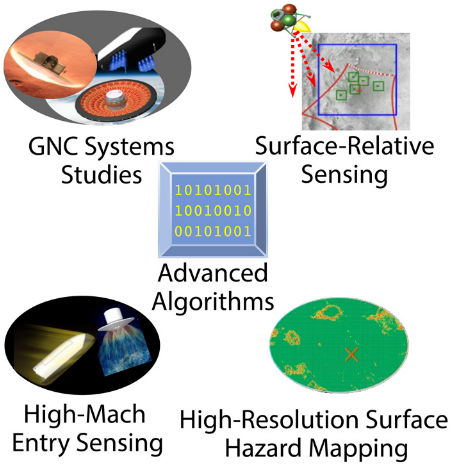


Figure 8: *Development areas for guidance and navigation systems. (NASA)*

Figure 9: *Capability needs for landing systems and environments. (NASA)*

Key Takeaways

While lunar landings help prepare NASA for the journey to the Red Planet, Mars landers encounter a variety of unique challenges not present on the Moon that must be understood and addressed. This includes the Martian atmosphere, surface hazards, plume-surface interaction, and terrestrial validation of systems intended for Mars.

Robotic Mars landers have used variations on heritage designs that do not scale to the mass requirements of human-class Mars landers. To land larger vehicles on the Martian surface, NASA and its partners must develop and validate new technologies, including entry instrumentation, deceleration techniques, and navigation systems.

Advances and testing by NASA and its partners will enable the agency to overcome the challenges of Mars EDL and successfully land humans on the Red Planet.

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2024
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Mars Ascent Propellant Considerations

Introduction

A human Mars architecture must deliver astronauts to the surface of Mars and return them safely to Earth. The rocket equation dictates that the further along a roundtrip mission a mass travels, the more massive its transportation system must be, increasing costs. Therefore, it is important to minimize the mass that must be delivered to Mars.

For most proposed human Mars architectures, the single largest category of mass that must be delivered to the Mars surface is the propellant required for the crew's ascent to Mars orbit upon completion of their surface mission. Production of ascent propellants from in-situ resources would significantly reduce the propellant mass that must be delivered. This is possibly the single most significant application for in-situ resource utilization (ISRU).

NASA's Moon to Mars Objectives call for the demonstration of "…Mars ISRU capabilities to support an initial human Mars exploration campaign."[1] Potential resources present at Mars include the Martian atmosphere, surface materials (i.e., regolith), and water in the form of buried ice sheets, ice mixed with near-surface regolith, or minerals containing chemically bound water. In addition to their potential for propellant production, these Martian resources could be used for applications including:

- breathing gases for crew cabin use, for extravehicular activity (EVA) life support, and to make up for airlock losses.
- water for crew consumption, radiation protection, and crop growth.
- building materials for landing/launch site berms, radiation protection, and habitat construction.

Not surprisingly, architectural concepts including ISRU have received a great deal of attention. Studies examining Martian ISRU for propellant production for robotic and human Mars missions began in earnest shortly after the Viking lander missions of the 1970s. More recently, NASA has undertaken a variety of studies to characterize the options available for the first crewed missions to Mars.[2, 3, 4, 5]

However — as with all architecture decisions — there are trade-offs involved. **NASA must understand how the transportation of propellant to or the manufacture of propellant at Mars will affect its overall exploration architecture.** Either option would require pre-positioning infrastructure (i.e., ISRU equipment or propellant and its associated fueling infrastructure). This white paper outlines ISRU considerations for Mars ascent vehicle propellant.

Figure 1: *Illustration of a large Mars ascent vehicle, astronauts, and ISRU infrastructure on the surface of Mars. (NASA)*

Literature Survey

NASA has performed numerous trade and architecture studies considering ISRU and non-ISRU Mars ascent propellant approaches. As an introduction to this research, this white paper summarizes three of those studies, which include a range of proposed landed infrastructure:

2009

Mars Reference Mission Architecture

This study[4] examined a campaign of three missions, with six crew each, to three different locations. It considered four scenarios for ascent propellant: no ISRU, two options that use a combination of the Martian atmosphere and Earth-origin resources, and an option that uses Martian atmosphere and water extracted from regolith. Overall, the study found that using Martian oxygen for ascent offered the best balance between mass savings, total volume required, and power generation needs and that ISRU generally lowered the overall mass that must be delivered while improving overall mission flexibility.

Note: This study predated the 2018 Mars global dust storms and their effects on power systems, which promoted lessons learned for subsequent architecture studies.

2021

Human Mars Architecture Study

This study[6] from the 2021 strategic analysis cycle considered a basic mission that does not manufacture propellant from Martian resources. However, it incorporates several important operational functions necessary for the previously described ISRU cases — specifically, transporting propellant across the surface and loading that propellant into an ascent vehicle. The study showed that architectures without ISRU are feasible, but have their own associated challenges. It also reveals that non-ISRU architectures can share important characteristics with ISRU architectures and could demonstrate capabilities that reduce associated risks.

2024

Strategic Analysis Cycle

This study[7, 8, 9] examined a single mission of four crew, two of whom would descend to the Martian surface. It considered three options for ascent propellant using pre-deployed infrastructure: using water from Earth, acquiring water from buried ice sheets, and acquiring water from the Martian regolith. While the ISRU options explored in this architecture offer significant mass savings and flexibility for mission planning, they also require significant energy, time commitments, and unique assets.

Mars Ascent Propellant Trade Space

These studies identified several options for Mars ascent propellant, including several different types of ISRU. Each option has its own specific requirements and trade-offs to consider when examining the trade space as a whole.

No ISRU

Architectures that Rely Exclusively on Earth-Origin Ascent Propellant

First is the option to use no ISRU at all. A non-ISRU architecture will land fuel needed for ascent before the arrival of the crew for safety reasons, as the crew should not arrive on the Martian surface until their means to return are in place.

This means that non-ISRU missions share some features with missions that use ISRU. This includes pre-placement of equipment, supplies, and power systems and — in cases where the ascent vehicle is not landed fully fueled — autonomous fueling operations.

Limited ISRU

Architectures Incorporating ISRU and Raw Material from Earth for Ascent Propellant

There are a range of ISRU options in which some supplies for propellant production are sent to Mars from Earth. Examples include using a combination of the Martian atmosphere and Earth-origin methane or the Martian atmosphere and Earth-origin hydrogen.

The 2024 study mentioned above examined sending water from Earth to make propellant on Mars. While this approach does not use Martian resources, the manufacturing and conditioning of the propellant takes place on the Red Planet, using many of the same processes and technologies as ISRU-intensive architectures (e.g., autonomous manufacturing, conditioning, and transportation of propellant).

Comprehensive ISRU

Architectures Where ISRU Generates Most or All Ascent Propellant

Finally, NASA has examined scenarios in which all components of Mars ascent propellant are sourced from Mars. Two options considered in the studies listed above use a combination of the Martian atmosphere and water extracted from water-bearing regolith or extracting water from buried ice sheets.

These options maximize the use of Martian resources, but also require the most support equipment. Harvesting resources and using them to manufacture propellant would also represent a significant time commitment. If initial human Mars missions maintain the requirement to have ascent propellant in place before the crew arrives, mission planning will need to account for this timeline.

Key Findings

The variety of ISRU (and non-ISRU) options that NASA has examined reveals a complex trade space with opportunities and challenges presented by all proposed architectures. Mission planning must account for a wide variety of needs, forcing architects to balance cost, risk, mass, power generation, crew safety, mission flexibility, site selection, mission timelines, and more when selecting an ascent propellant strategy.

Studies conducted thus far offer some important key considerations, with three of the most driving factors considered below: mass, site selection, and production rate.

Mass Considerations

The largest driver of cost for space exploration missions is mass. Any resources that do not need to be launched from Earth to Mars represent a potential cost savings. This makes the opportunity to manufacture propellant using resources partially or entirely sourced from the destination incredibly attractive from a propellant cost perspective.

However, ISRU does not always represent a total mass cost savings from a mission architecture perspective. Local ISRU requires extensive infrastructure to extract resources and manufacture, condition, and transport propellant. The cost of developing these systems and transport them to Mars can exceed the cost of sending propellant (especially if those systems cannot be used across multiple missions).

That said, these mass constraints are not exclusive to ISRU architectures; any mission that does not land a fully fueled ascent vehicle would need to devote some mass to systems for autonomous transportation and loading of propellant.

Site Selection Considerations

Choosing ISRU to manufacture ascent propellant naturally constrains site selection. The landing site must offer the resources necessary for the chosen ISRU strategy, constraining the mission to one site or type of sites, versus multiple diverse regions.

The investment in landed ISRU infrastructure could enjoy cost savings if multiple missions land at the same location to re-use emplaced infrastructure. However, this architectural limitation would reduce the diversity of regions available for study and which hinder NASA's ability to accomplish science and exploration objectives.

Site selection decisions might also have flow-down impacts on decisions about using ISRU. A mission that intends to primarily explore a single site might benefit from ISRU infrastructure, while a mission that explores multiple sites might benefit from landing of propellant.

Production Rate Considerations

ISRU options that rely more heavily on Martian resources usually require a significant time investment. The 2024 strategic analysis cycle study found that the most ISRU-intensive architectures could require NASA to emplace and operate infrastructure years before a crewed mission.

While some options do not require as much lead time, mission planning must account for the time required for ascent propellant to be ready before the crew arrives. The time between Mars mission availability windows (roughly 26 months) further complicates this consideration given the number of assets needed for comprehensive ISRU.

Summary

ISRU offers the opportunity to overcome one of the biggest challenges of a human Mars mission: the mass of ascent propellant. Recent studies have examined a range of options that use resources from the Red Planet to manufacture some or all of the needed ascent propellant from in-situ resources.

However, ISRU is not without trade-offs. Mission planners must carefully assess the potential mass savings against the necessary specialized infrastructure, constraints on site selection, and additional time that come with using ISRU. While ISRU capabilities have garnered interest from the spaceflight community, further study will be critical as NASA develops an architecture that will support the first crewed missions to the Red Planet.

Key Takeaways

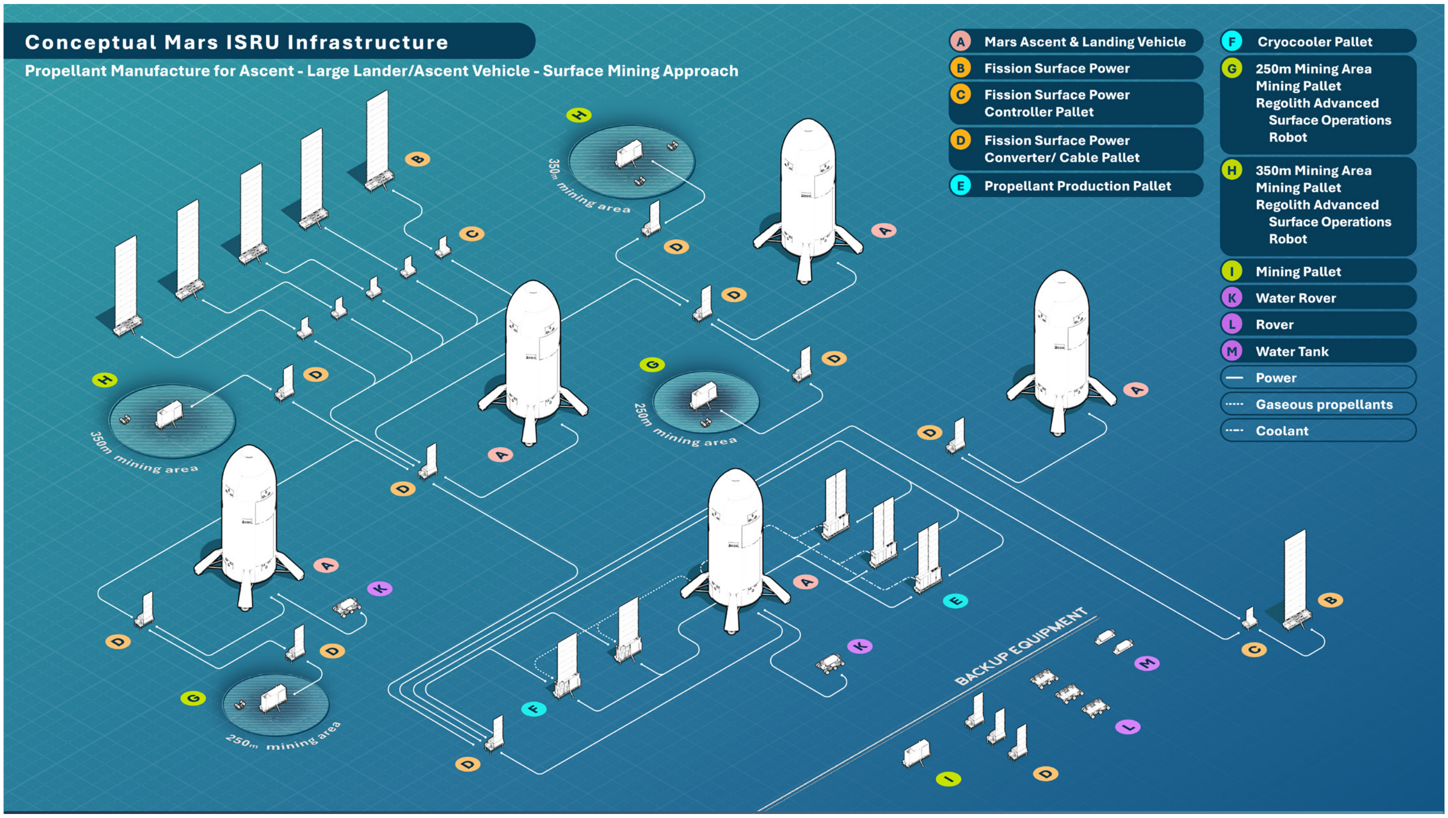
For most proposed Mars architectures, ascent propellant represents the single largest category of landed mass.

Production of ascent propellants from in-situ resources could significantly reduce the propellant mass that must be delivered, but ISRU has significant impacts on the overall exploration architecture.

Various ISRU options offer a wide range of trade-offs, including considerations of overall mass, site selection, and production rate.

NASA must thoroughly consider the ascent propellant trade space before selecting an approach to create an architecture that is achievable, objective-oriented, and extensible to future exploration.

Figure 2: *Illustration of a notional regolith-based ISRU surface infrastructure developed during the 2024 strategic analysis cycle ISRU study. (NASA)*



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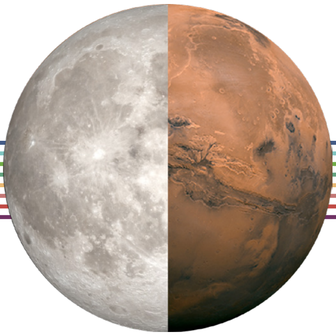

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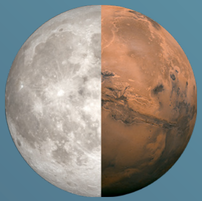


Architecture-Driven Technology Gaps

Introduction

NASA has a long history of developing new and innovative technologies that empower space exploration and benefit humanity. The next phase of global human space exploration, beginning with the Artemis campaign and defined in NASA's Moon to Mars Architecture,[1] will continue to advance technology.

With a broad array of needs competing for technology development resources, the agency must judiciously target priority technologies that enable NASA to achieve its exploration goals. To this end, NASA has applied rigorous systems engineering processes to develop and prioritize architecture-driven technology gaps to inform technology development investments.

NASA's Moon to Mars Objectives document[2] defines the agency's goals for crewed exploration of deep space. The Moon to Mars Objectives and Strategy document[3] outlines the systems engineering approach that decomposes the objectives into a cohesive and extensible Moon to Mars Architecture. The objectives define *what* NASA wants to achieve; the architecture defines *how* the agency will accomplish them.

NASA's Exploration Systems Development Mission Directorate (ESDMD) leads the integration of the Moon to Mars Architecture and identifies technologies the agency must advance or develop to meet future architecture needs. This year, for the first time, NASA has published a prioritized list of these architecture-driven technology gaps in Revision B of its Architecture Definition Document.[4]

What is a Technology Gap?

A technology gap exists where a performance target defined in the architecture exceeds current capabilities of state-of-the-art technologies, or the capability does not exist at all. The gaps are solution-agnostic — they document a capability need, but do not prescribe a specific technological solution. Left open, the gaps will prevent NASA from achieving all its exploration objectives.

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 Push and Pull

Much of NASA's architecture work involves identifying unallocated functions and filling them with new or existing exploration assets or elements, the hardware and systems that enable exploration. However, there are instances where filling a gap in the architecture requires new technology. In these instances, architecture-driven technology gaps provide architecture technology pull. The architecture can also provide pull for new technologies that significantly enhance capabilities. Technology push also exists where technologies do not yet have a traceable planned element or mission for infusion, but capability developers expect that the capabilities will be necessary in the future.

Defining Terms

Technology Pull: innovation to meet documented mission needs.
Technology Push: innovation to meet anticipated mission needs.

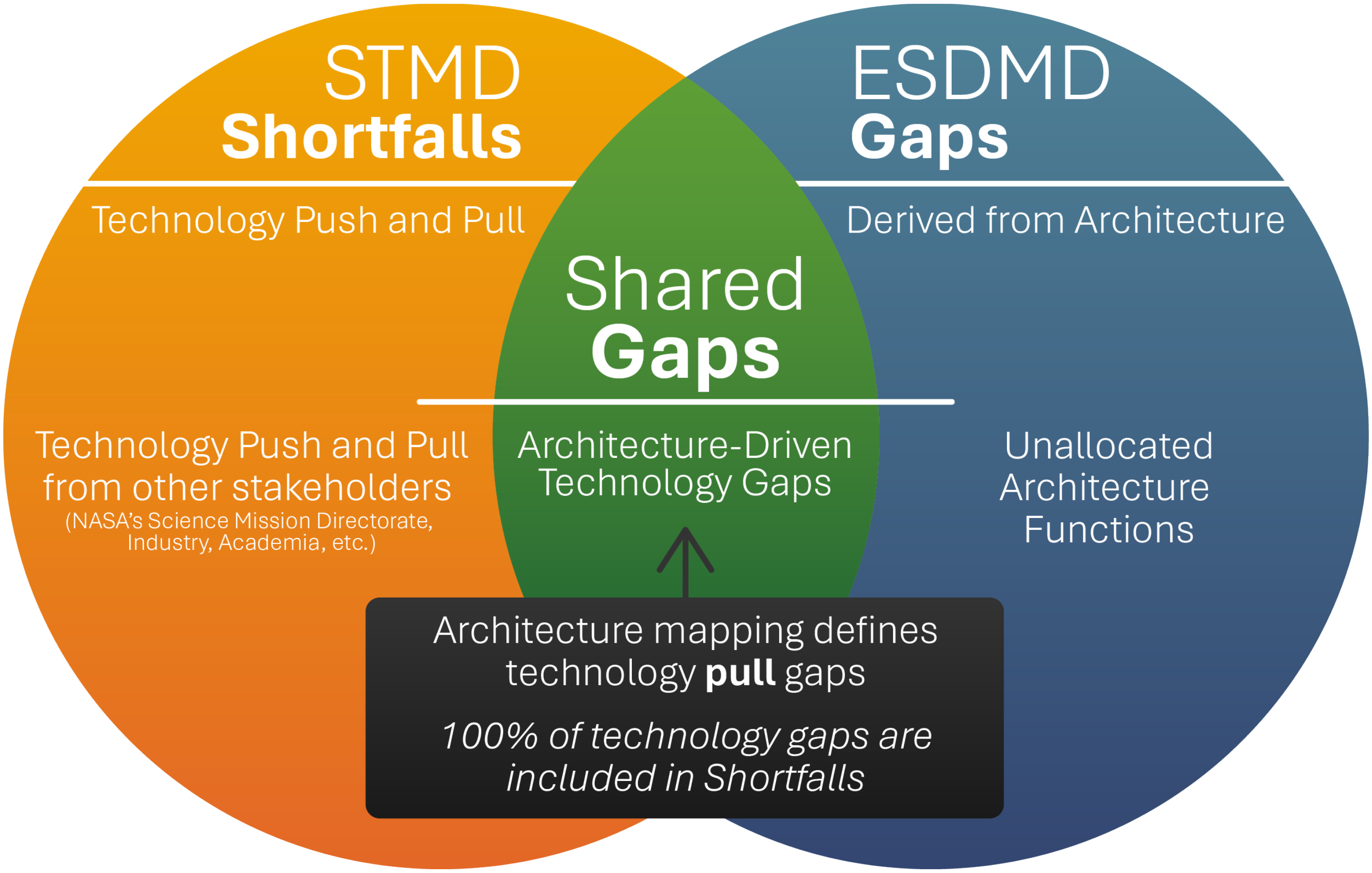


Figure 1: *Complementary and overlapping gap definition efforts by STMD and ESDMD. (NASA)*

Architecture-Driven Technology Gaps and Civil Space Shortfalls

NASA's Space Technology Mission Directorate (STMD) has long considered these complementary concepts in their development portfolio. Their Civil Space Shortfall Ranking[5] published in 2024 reflects some push and a mixture of technology pull from all stakeholders.

A shortfall is a technology area requiring further development to meet future exploration, science, and other mission needs. The term "gap" is widely used across NASA and the aerospace industry and implies both ends of the problem – the current state of the art and the technology performance target needed – are known. In the case of shortfalls, we may only know where we are today.

ESDMD provided STMD with its architecture-driven technology gaps during development of these shortfalls. As such, the Civil Space Shortfalls document includes all the architecture-driven technology gaps, plus ESDMD's ranking of shortfalls for applicability to future human exploration missions. The Civil Space Shortfalls also capture technology needs from across NASA's mission directorates and other sources.

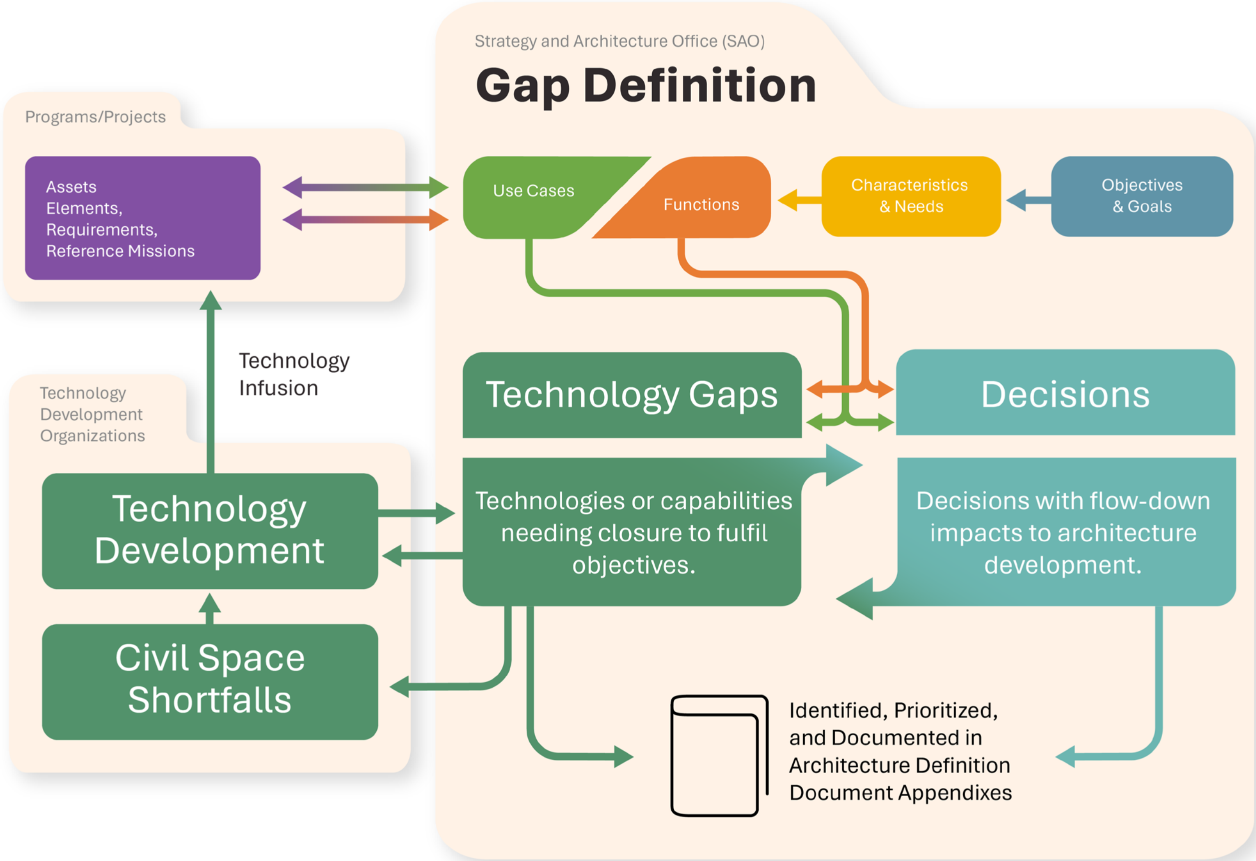
Figure 1 shows the relationship between Moon to Mars architecture gaps — including the architecture-driven technology gaps — and the Civil Space Shortfalls compiled by STMD.

Gap Definition and Traceability

Architecture-driven technology gaps are traceable back to the Moon to Mars Objectives through the gap definition process shown in **Figure 2**. Revision B of the Architecture Definition Document, released alongside this white paper in December 2024, includes a new appendix for architecture-driven technology gaps.

That appendix features a detailed, prioritized list of gaps mapped to their associated use cases, functions, decisions, campaign segments, and sub-architectures. Each documented gap includes a description, architecture impacts and benefits, target performance metrics, current state-of-the-art metrics, and subsidiary "child" gaps.

Specific technology maturation needs derived from the architecture signal a future need or demand; NASA publishes technology gaps to inform industry, academia, and our international partners about the technology development required for future human exploration missions.



NASA identifies technology and capability gaps in the Moon to Mars Architecture through the objective decomposition process. NASA then prioritizes and documents gaps in the Architecture Definition Document and relies on technology development organizations to close them.

Figure 2: *Technology Gap Traceability through the architecture to Moon to Mars Objectives. (NASA)*

Prioritizing Technology Gaps

Prioritizing technology gaps helps NASA optimize limited funding and guides smart investments by external partners toward the agency's most important needs. NASA technology development organizations are already utilizing the architecture-driven technology gaps to drive internal investment strategies.

NASA follows rigorous systems engineering processes and governing principles to define and execute its prioritization process. NASA prioritized the architecture-driven technology gaps using the process shown in **Figure 3**. The agency defined four priority metrics — gap attributes that measure an aspect of architecture preference and can be evaluated for every gap: criticality, urgency, breadth, and depth.

- **Criticality** measures the degree to which closing a technology gap would enable or enhance the Moon to Mars Architecture.
- **Urgency** measures how soon investment in a technology gap is needed to ensure a capability is available for future missions.
- **Breadth** measures the prevalence of a technology gap across sub-architectures.
- **Depth** measures the degree to which closing the gap is dependent on future architecture decisions. (See the Architecture Definition Document appendix on architecture decision roadmapping for more details.)[4]

Each priority metric has a relative weighting (W_x%) defined by the architecture teams to establish its relative importance to the architecture in the overall priority ranking. Applying the prioritization process detailed in Figure 3 results in the priority ranking of the architecture-driven technology gaps published in Revision B of the Architecture Definition Document.[4]

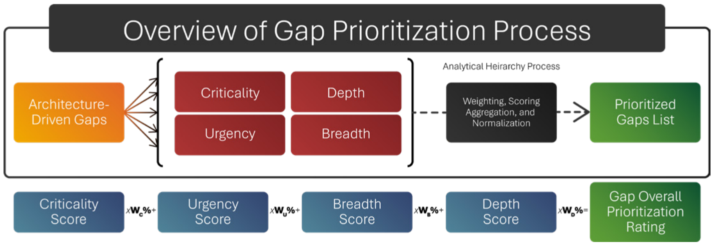


Figure 3: *Architecture-driven technology gap prioritization process flow diagram and weighted gap scoring formula. (NASA)*

Technology Gap Evolution

The current list of architecture-driven technology gaps (and their priority order) will be revised annually. **Table 1** features the five highest priority gaps identified in Revision B of the Architecture Definition Document, published in 2024.[4]

The gaps will evolve as NASA refines the architecture during the annual strategic analysis cycle. NASA will validate, update, add, or close gaps as technologies develop or new needs arise. The priority ranking will also change as NASA makes driving architecture decisions. Updated lists will be published in subsequent revisions of the Architecture Definition Document.[4]

EXAMPLE TECHNOLOGY GAPS (2024)
Lunar Dust Tolerant Systems and Dust Mitigation
Systems to Survive and Operate through Extended Periods of Lunar Shadow
High-bandwidth, High-reliability Surface-to-Surface Communications
Mars Transportation Propulsion
Extreme Environment Avionics

Table 1: *Five high priority technology gaps identified in 2024. The initial list included 56 total gaps, but the gaps will change each year. For the most up-to-date version of the gaps, see the current revision of the Architecture Definition Document. (NASA)*

Key Takeaways

Technology gaps exist when a capability that NASA needs exceeds the current technology state of the art.

Strategic technology investments to close technology gaps enable future Artemis missions.

Architecture-driven technology gaps map to specific architecture segments and sub-architectures and trace to NASA's Moon to Mars Objectives through the Moon to Mars Architecture's use cases, functions, and driving decisions.

Architecture-driven technology gaps are defined and prioritized using rigorous systems engineering processes and principles.

All architecture-driven technology gaps are included in the list of Civil Space Shortfalls developed by NASA's Space Technology Mission Directorate.

Architecture-driven technology gaps and their prioritization will be updated as the architecture evolves and as technology matures.

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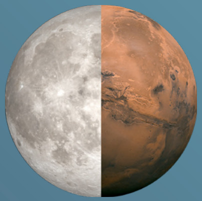


2024
Moon to Mars
Architecture

white paper

Humans in Space to Accomplish Science Objectives

Introduction

Teleoperated robotic probes are the primary means to conduct space science, but human explorers can enable or enhance particular types of science. Crewed missions are, of course, essential to investigations of the human body itself in space. Astronauts also possess complex problem-solving abilities and are adaptable to changing mission parameters. Additionally, human explorers inspire the public, engaging them in space science and discovery.

Astronauts can perform complex tasks that enable or enhance scientific investigations as researchers and operators, but also in building, integrating, and maintaining science instruments and experiments.[1] Astronauts can identify desired objects/specimens/situations, discover and react to unforeseen situations and events, and provide context of specimens and their curation. They are suited to tasks requiring complex movements, fine manipulation or dexterity, or hand-eye coordination. These include precision emplacement of scientific instruments, maintenance and calibration of scientific instruments, and operations of instruments to acquire measurements.

Sending human explorers to other worlds requires larger, more complex, and more costly systems than purely robotic missions. However, several space science community documents capture the particular advantages of crewed exploration to science. This white paper examines the scientific activities that may be enabled or enhanced by astronauts, specifically considering priorities identified by the National Academies of Science, Engineering, and Medicine; NASA; and the science community as a whole.

The Benefits of Crewed Science

Science enables exploration; exploration enables science.

In this white paper, *exploration* refers to missions by humans beyond low Earth orbit — crewed missions to the Moon, Mars, and other destinations — while *science* refers to the traditional space science disciplines (planetary science, astrophysics, heliophysics) as well as physics, biology, chemistry, and studies of human physiology, psychology, and human health countermeasures in space.

Astronauts on and around the Moon and Mars will conduct field work and fundamental research to answer longstanding planetary science questions and redefine our understanding of the solar system, the lunar and Martian environments, and the human body's response to those environments.[2]

NASA's Human Research Program focuses on developing methods to protect the health and performance of astronauts in space, and when they return to Earth. Currently, the International Space Station and Earth-based ground analogues conduct most of the U.S.'s space-based biological and physical science research.[3] The lessons learned aboard the space station and at ground analogues are informing planning for the Artemis campaign and beyond,[4] and their investigations will expand as the Artemis missions progress.

For space science disciplines, humans can enable more complex field science than robotic explorers. Humans demonstrably improve tasks that require complex movements, fine manipulation, and dexterity. Astronauts can empower precision emplacement, operation, maintenance, and calibration of scientific instruments in situ. Astronauts can identify objects, specimens, or situations relevant to a study area. They can react to evolving mission parameters, turning unforeseen events into opportunities for discovery.

Benefits to Planetary Science

For planetary science, crewed missions offer particular advantages over robotic missions. Human explorers can understand the context and setting of a geologic sample, thinking independently to make sampling stops and adjusting traverse plans to take advantage of serendipitous sampling opportunities. They can collect the most valuable samples, which is essential given sample return mass constraints. NASA can build an optimal scientific sample return program by relying on the observations of well-trained astronauts aided by modern tools and real-time communication with scientists on Earth.

Experiments with complex deployments benefit from a human touch. Deployed experiments consist of autonomous instrument packages installed on the lunar surface, either robotically or by astronauts. These “suitcase science” packages enable a variety of geophysical and environmental investigations. They can also improve astronauts’ awareness of the survey area in real time, enabling them to collect more valuable samples.

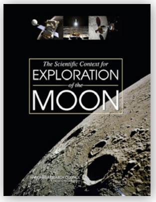
Geophysical and geochemical instruments can benefit from more interaction, such as precise siting, alignment, and strong coupling with the surface or subsurface. Humans can carry out this work and troubleshoot issues more effectively than robots, especially for sensitive instruments that require precise placement.[2]

Science Community Documents

Many documents produced by the science community outline the benefits of crew involvement in particular priority science campaigns. The following reports from the National Academies and other NASA science community study or analysis groups (e.g., Mars Exploration Program Analysis Group (MEPAG)) demonstrate how effective, efficient science can greatly benefit from crewed exploration.

Science Community Report: National Research Council [2007]

The Scientific Context for Exploration of the Moon



“Guidelines on how the lunar science concepts might be addressed with different possible elements of the VSE (Vision for Space Exploration) are provided in Table 4.1... column (e) provides examples of human fieldwork to be undertaken for each science concept. These are activities that specifically benefit from the abilities of humans present to carry out integrated or challenging tasks. Well-designed human-robotic partnership will be central to the success of the activities.”

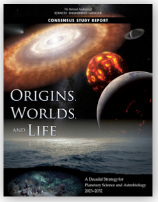
The Scientific Context for Exploration of the Moon[5] bases its guidelines for setting science priorities on those outlined in the National Research Council’s decadal survey, *New Frontiers in the Solar System: An Integrated Exploration Strategy*.[6] Those are, in order of importance:

1. Scientific Merit
2. Opportunity and Realism for Achieving a Goal
3. Technological Readiness

Using these criteria, the report ranks science goals across a range of topics. These include the early Earth-Moon system, terrestrial planet differentiation and evolution, solar system impact record, and lunar environment. It also notes the associated human fieldwork needed to accomplish these objectives. The report calls for a well-designed complement of human and robotic capabilities to conduct diverse scientific investigations on the lunar surface.

Science Community Report: National Academies [2022]

Origins, Worlds, and Life



“The retrieval and return to Earth of a substantial suite of samples collected from diverse locations across [the South Pole-Aitken basin] represents an ideal synergy between NASA’s human and robotic exploration of the Moon. It would produce flagship-level science at the cost of a medium-class mission...Planetary Science and Astrobiology field studies benefit from an astronaut’s ability to observe sites in striking detail, recognize unexpected observations, analyze critically in real-time to create and refine conceptual models, and react to changing conditions, hypotheses, and interpretations while in the field.”

The National Academies of Science, Engineering and Medicine produce decadal surveys that recommend science and missions in each Science Mission Directorate science discipline over the next 10 years. *Origins, Worlds, and Life: A Decadal Strategy for Planetary Science and Astrobiology 2023–2032*[1] notes that astronauts’ ability to make sharp observations of geologic context and respond to unexpected real-time scientific sampling opportunities can enable the Artemis campaign to conduct breakthrough science.

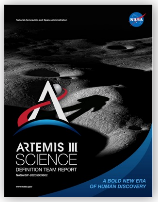
The report prioritizes three overarching science themes:

1. Solar System History
2. Geologic Processes
3. Water and Volatiles

NASA adopted these themes as the basis for the first three Lunar and Planetary Science Objectives documented in NASA's Moon to Mars Objectives.[7] The report details how a combination of human and robotic missions can accomplish new science associated with these themes.

NASA Document [2015]

Artemis III Science Definition Report



National Aeronautics and Space Administration

ARTEMIS III
SCIENCE
DEFINITION TEAM REPORT
NASA/SP-20205009602

www.nasa.gov

A BOLD NEW ERA
OF HUMAN DISCOVERY

> *"With this notional program, mission planners can weigh operational constraints to develop a science implementation plan for the mission, including the collection of samples, deployment of instruments, and key in situ observations by the crew. Procedures and operations techniques, particularly for sample acquisition and curation, developed for the Artemis III mission will influence future Artemis missions...and future expeditions to Mars."*

NASA's Science Mission Directorate provided planning input for Artemis III through the science definition team. Their report[2] builds on the seven overarching Artemis III science objectives by adding proposed goals and investigations. It also details how human explorers can enable field geology, sample collection and return, in situ and field science, and deployed experiments. The report offers recommendations for specific training, investigations, mass requirements, and data collection to maximize the science that Artemis III and follow-on missions can accomplish.

Science Community Report: Mars Exploration Program Analysis Group (MEPAG) [2023]

Report of MEPAG Tiger Team on Mars Human-Mission Science Objectives

Report Of MEPAG Tiger Team On Mars
Human-Mission Science Objectives

Bruce Jakosky, Univ. of Colorado, Chair
(bruce.jakosky@lasp.colorado.edu)
Original submission, 28 September 2023
Rev. 1, 24 October 2023
Final, 24 October 2023 (no changes from Rev. 1)

> *"Vital science can be accomplished by humans on Mars that would be much harder or impossible to do with robotic spacecraft; the capabilities of human missions have the potential to change both the objectives and the priorities — and can definitely accelerate the pace — for Mars scientific exploration."*

NASA's Science Mission Directorate tasked MEPAG with identifying science objectives for the Moon to Mars Architecture's Humans to Mars segment. Their *Report of [the] MEPAG Tiger Team on Mars Human-Mission Science Objectives*[8] includes a discussion of the wide range of benefits that human explorers offer for observation and analysis on the Martian surface. These advantages are not limited to human missions to Mars — MEPAG's findings on the advantages of human explorers are easily applied to the Moon or other potential human destinations.

Summary

While teleoperated robotic probes play the major role in space science missions, human explorers can offer significant advantages to the exploration architecture. Astronauts' complex problem-solving abilities, adaptability, and creativity can help NASA to address high-priority science goals. Many of the documents and organizations that establish NASA's scientific objectives highlight the benefits of crewed exploration.

Key Takeaways

Crewed exploration offers particular advantages for accomplishing space science objectives.

NASA’s scientific objectives are informed by a variety of sources, many of which highlight the need for human explorers to achieve priority investigations and conduct groundbreaking science.

Reports from the space science community and NASA documents have consistently called for well-designed partnerships between astronauts and robotic explorers.

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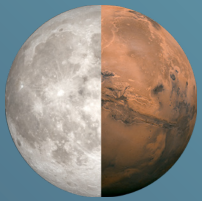

2024
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Responsible Exploration

Ethical, Legal, and Societal Implications of the Artemis campaign and NASA's Moon to Mars Architecture

Introduction

NASA's Moon to Mars Objectives, established in 2022, include recurring tenets that provide guidance for how NASA should explore. The sixth recurring tenet reads, "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."

NASA's Architecture Definition Document, in its discussion of how the recurring tenets shape NASA's Moon to Mars Architecture, calls for considering the responsible use of space from legal, policy, ethical, and societal perspectives.[1] The document establishes the specific systems engineering approach that NASA uses to achieve its Moon to Mars Objectives, but inclusion of ethical, legal, and societal implications (ELSI) into the agency's Moon to Mars Architecture remains an open area of analysis.

NASA considers ELSI important to exploration. NASA's Moon to Mars Strategy and Objectives document outlines three pillars of exploration: science, inspiration, and national posture.[2] Ethical, legal, and societal factors are present within each of these reasons to explore — and at their intersections.

The aerospace community has expressed significant demand for consideration of ELSI in exploration. Participants at NASA's 2022 Moon to Mars workshop in London considered a range of ELSI topics, including public communications, responsible use, and disposal of waste. Participants at the 2022 Lunar Surface Science Workshop on inclusive lunar exploration discussed challenges related to diversity and inclusion in the lunar community.[3] Additionally, the 2023–2032 Planetary Science and Astrobiology Decadal Survey by the National Academy of Sciences recommended that NASA solicit expert views about the ethics of planetary in-situ resource utilization.[4]

While NASA has already begun considering ELSI in Moon to Mars exploration, fully infusing ELSI into the Moon to Mars Architecture will require new systems engineering frameworks and enhanced collaboration with industry, academia, and the international community. This paper summarizes recent work at NASA related to ELSI of Moon to Mars efforts to inform future architecture decisions.

Ultimately, NASA embraces its duty to responsibly explore for the benefit of humankind. ELSI issues are core to that aim.

Figure 1: *The three components of ELSI. (NASA)*

Note: *NASA is not the only organization tackling ELSI issues. Other U.S. government agencies, international organizations, and the broader space sector are having discussions about the inclusion of ELSI in space program development and execution. In the U.S., the Defense Advanced Research Projects Agency and National Science Foundation are actively considering how to incorporate ELSI into program development and contributing research. Internationally, the United Nations Office for Outer Space Affairs held a conference on sustainable lunar activities in June of 2024, which included discussion of ELSI topics and aimed to foster avenues for global cooperation.*[5]

ELSI Efforts at NASA

NASA has recently undertaken several efforts to identify ELSI for its Moon to Mars exploration campaign. This section surveys a selection of these activities, highlighting ELSI considerations and lessons learned.

Artemis, Ethics, and Society Workshop

In 2023, NASA hosted a workshop seeking input on the incorporation of ELSI into the Artemis campaign and Moon to Mars exploration.[6] This two-and-a-half-day workshop gathered 55 participants from various fields in both technical and non-technical disciplines. This included historians, philosophers, sociologists, lawyers, and engineers, among others. The goal was to gain a breadth of perspectives on ELSI; identify ELSI considerations and implications; and source potential ideas to address them.

NASA synthesized these discussions into five key ELSI themes:
1. Sharing the benefits of space exploration
2. Reflecting on core values for exploration
3. Defining sustainability for lunar exploration
4. Balancing shared access to the lunar surface
5. Addressing cultural sensitivities around lunar activities

From participant input, NASA observed that key ELSI related to Moon to Mars exploration involved sharing its benefits, reflecting on core values for exploration, (e.g., sustainability, balancing shared access), and addressing cultural sensitivities around lunar payloads and activities.

In addition to identifying these ELSI, the workshop also explored ways to address ELSI at NASA and the challenges that might arise when doing so. Participants discussed policy options, management processes, educational resources, formalizing research capabilities to guide decision-making, and continuing to engage stakeholders and ELSI experts.

NASA is still formulating approaches it can implement to address ELSI. Workshop participants noted that the agency could face workforce culture challenges, resource limitations, political pressures, and other practical obstacles of unanticipated ELSI issues. Regardless of the path forward, participants expressed interest in continued ELSI dialogue between NASA and the space community.

Additional Studies

Recently, NASA has released publications considering ELSI for Moon to Mars exploration.

- A 2022 NASA paper highlighted policy considerations for landing and operating on the lunar surface; this analysis included ELSI-related topics such as protection of humanity's lunar exploration heritage and non-interference across lunar activities.[7]
- Following this analysis, another NASA report identified 12 policy questions that can guide future deep space exploration efforts.[8] That study included cultural and ethical considerations as a policy question, specifically asking how NASA should ensure its activities are consistent with values of the global community. Further, it notes that ELSI policy questions often emerge early in mission and program lifecycles.
- A 2023 paper explored what it means to responsibly mine off-world. It looked to terrestrial mining for lessons learned on minimizing environmental impacts of lunar in-situ resource utilization.[9]

Space Sustainability

NASA has recently initiated other ELSI activities, which will help inform Moon to Mars Architecture decisions. In 2023, NASA's deputy administrator charged a cross-directorate team under the Space Environment Sustainability Advisory Board to create an agency space sustainability strategy.

In 2024, NASA released volume one of this strategy, which focuses on Earth orbit.[10] That document defines space sustainability as, "the ability to maintain the conduct of space activities indefinitely into the future in a manner that is safe, peaceful, and responsible to meet the needs of the present generations while preserving the outer space environment for future activities and limiting harm to terrestrial life."

Specifically, the strategy concerns itself with the issues of orbital debris, space situational awareness, and space traffic coordination. These ELSI challenges can have profound implications on future spaceflight capabilities, especially for emerging space actors not responsible for the accumulation of space debris. As part of this strategy, NASA appointed a lead for space sustainability to enhance organizational support of these issues.

A future volume of the space sustainability strategy will address similar considerations for cislunar space. Goals set forth in that document will inform the evolution of NASA's Moon to Mars Architecture and enhance its consideration of ELSI.

Soliciting Community Feedback

In 2024, NASA released a call for proposals through the Research Opportunities in Space and Earth Sciences (ROSES) solicitation on Economic, Social, and Policy Analyses of Lunar Surface Sustainability.[11] This opportunity seeks new ideas from non-governmental organizations that will yield insights, including proposed frameworks, for evaluating sustainability that can be factored into mission planning, policy, and strategy. NASA made two awards in July 2024, with plans to recieve briefings on research results in 2025.

NASA also welcomes feedback on how to best approach ELSI considerations as part of Architecture Concept Review workshops and associated stakeholder meetings.

The Artemis Accords

In 2020, the United States—led by NASA and the U.S. Department of State — and seven other initial signatory nations established the Artemis Accords, identifying an early set of principles promoting the beneficial use of space for humanity. The Artemis Accords provide a common set of principles to enhance the governance of the civil exploration and use of outer space. The Artemis Accords reinforce the commitment by signatory nations to the Outer Space Treaty, the Registration Convention, the Rescue and Return Agreement, as well as best practices and norms of responsible behavior for civil space exploration and use.[12]

The principles of the Artemis Accords are: peaceful exploration, transparency, interoperability, emergency assistance, registration of space objects, release of scientific data, preserving heritage, space resources [utilization], deconfliction of activities, and orbital debris [mitigation]. The Artemis Accords foster an environment of trust and cooperation where all nations can contribute to the safe and sustainable exploration of space. [13]

Forward Work

Considering ELSI in Moon to Mars exploration requires expanded dialogue. Seeking feedback from diverse stakeholder communities — including international space agencies, academia, non-profits, and especially under-represented communities — is core to ELSI.

Conversations with a wide range of stakeholders empower NASA to uphold its commitment to explore for the benefit of humankind. Continuing to leverage expertise in disciplines not traditionally associated with spaceflight (e.g., ethics or humanities) will better position the agency to answer questions about responsible exploration in the interest of the global community.

Considering the responsible use of space and seeking input from a broad range of perspectives and disciplines can lead to more well-rounded conversations and decisions about humanity's future at the Moon and Mars.

Summary

NASA engages with a variety of institutions and partners and will continue to pursue dialog with people and organizations representing a range of societal perspectives. NASA remains open for input on ELSI considerations via broader policy mechanisms and through its Moon to Mars Architecture process. NASA is supporting directed research on economic, policy, and social aspects of lunar surface sustainability.

NASA must champion responsible exploration when developing a Moon and Mars exploration ecosystem. This requires the agency to move beyond considering what we could do and ask what we should do. It requires a comprehensive understanding of how our exploration activities may affect others' beliefs and exploration efforts. It serves as a guide that will shape humanity's future.

Key Takeaways

Responsible use is a recurring tenet in NASA's Moon to Mars Objectives. Recurring tenets are broadly applicable across objectives and serve as practical guidance for *how* objectives should be carried out.

Incorporating the concept of responsible use into the Moon to Mars Architecture requires an understanding of the ethical, legal, and societal implications of space exploration. This means reflecting on the underlying values of exploration, responsible use of in-situ resources, cultural sensitivities of exploration efforts, and many other considerations.

NASA is pursuing research and dialogues to better understand how the agency might embrace and encourage responsible behavior in and use of space.

To ensure the Moon to Mars Architecture reflects diverse perspectives, NASA must continue to engage with academia, industry, and international partners to empower the responsible use of space.

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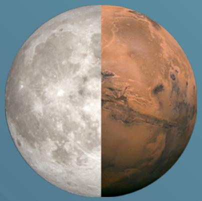

International Partnerships and NASA's Moon to Mars Architecture

Introduction

Since its inception, NASA has engaged the international community to advance its science, exploration, and space technology goals. Cooperation between NASA and international partners typically occurs on a no-exchange-of-funds basis, where each party funds its respective activities in pursuit of shared goals. Incredible programs like the International Space Station and James Webb Space Telescope would not be possible without international cooperation. International relationships also broaden NASA's education and public engagement efforts, inspiring people from the U.S. and around the globe.

Today, international partnerships are an essential part of NASA's ambitions for deep space exploration, enabling humanity's return to the Moon and the journey to Mars and beyond. International space agencies provide essential capabilities that will enable NASA to achieve its Moon to Mars Objectives.

Published in 2022, NASA's Moon to Mars Objectives define the agency's goals of deep space exploration.[1] NASA's Moon to Mars Architecture decomposes the objectives into the functions needed to achieve them.[2] International cooperation encompasses all aspects of the architecture, but it is especially important for addressing capability gaps.

NASA's Moon to Mars Objectives, Recurring Tenet 1
International Collaboration: partner with international community to achieve common goals and objectives.

NASA's process for incorporating cooperative activities into the Moon to Mars Architecture involves a series of pre-formulation activities and milestones that vary depending on the nature of the proposed cooperation — for example, activities for science payloads may be different than those for human-tended infrastructure. This white paper details how NASA engages with prospective international partners in support of the agency's science, exploration, and space technology goals.

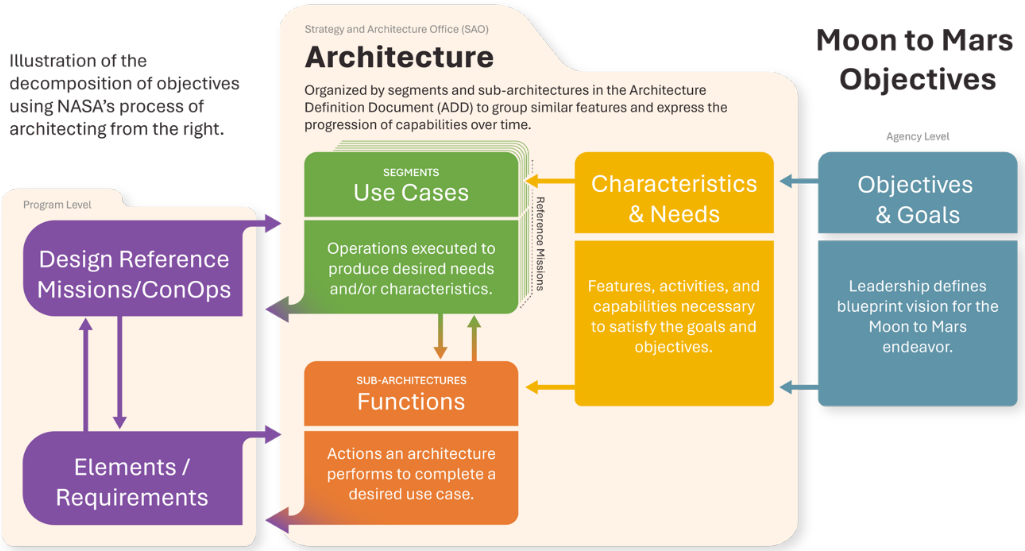
Illustration of the decomposition of objectives using NASA's process of architecting from the right.

Figure 1: *Decomposition of NASA's Moon to Mars Objectives into component architecture features. (NASA)*

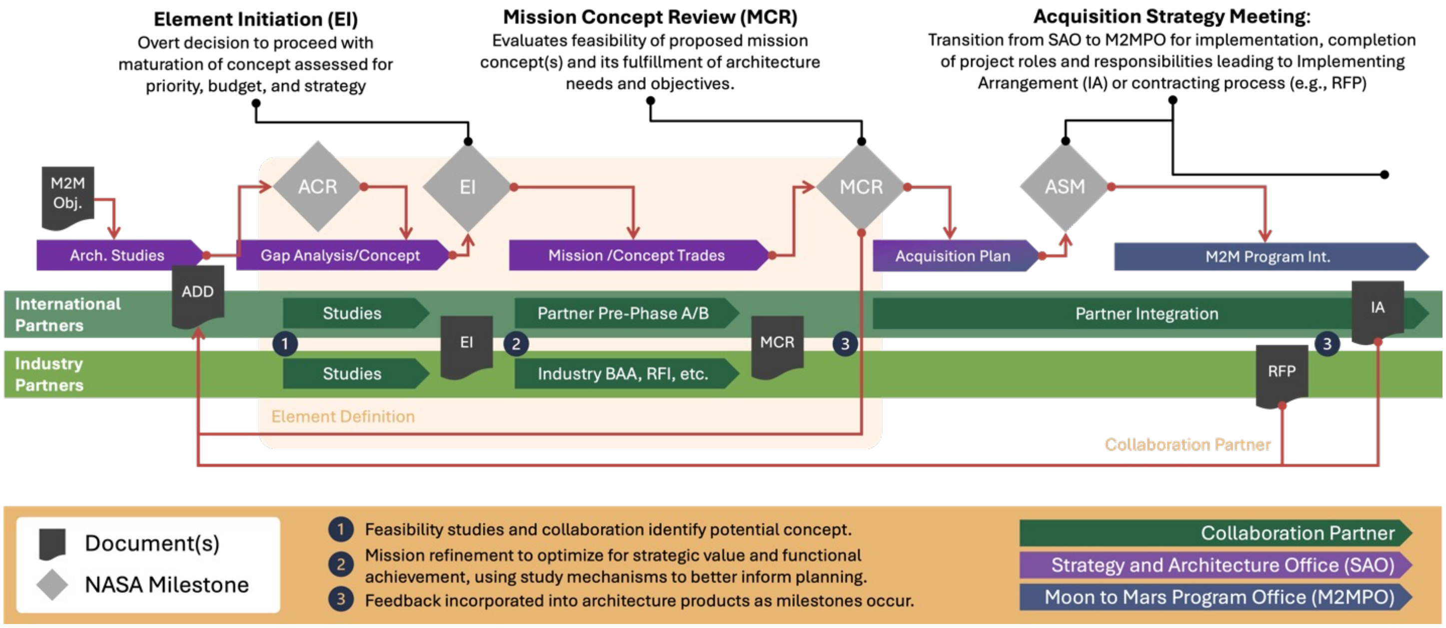

Figure 2: *ESDMD pre-formulation process, including partner roles. (NASA)*

Getting Started

Each year, NASA publishes a suite of documents updating the Moon to Mars Architecture. This includes white papers[3] that dive into specific technical topics and the Architecture Definition Document (ADD),[4] which captures the current state of the architecture. NASA houses these resources on a dedicated website[2] alongside other supporting materials and links to related resources. These documents serve as the basis for NASA's collaboration with industry, academia, and the international community.

The ADD decomposes the Moon to Mars Objectives into the characteristics and needs of an architecture that could satisfy them. This process of architecting from the right is outlined on NASA's architecture website,[5] in NASA's Moon to Mars Strategy and Objectives Development document,[6] and in Figure 1.

Architecture gaps (i.e., use cases and functions that do not currently trace to an element) are areas ripe for collaboration and serve as excellent starting points for initial discussions on partnerships. NASA is open for international partners to provide exploration assets — ranging from scientific instruments to entire elements — that map to unallocated use cases and functions and fill architecture gaps.

Establishing a study agreement between NASA and an international partner can be an effective first step to identifying shared interests. These agreements enable technical interchange and more detailed conversations between the agencies about needs and capabilities.

Pre-Formulation Milestones

Once NASA and a partner have identified one or more viable areas for potential cooperation, they engage in studies and technical discussions. These engagements refine element concepts* and define the use cases and functions they would perform to advance the Moon to Mars Architecture.

> ***Note:** *This section focuses on elements, which are substantial, architecture-level contributions. This paper addresses avenues for collaboration on smaller payloads or scientific instruments in later sections.*

As Moon to Mars Architecture element concepts mature through NASA's pre-formulation process, the first major milestone is element initiation. During the element initiation milestone, NASA assesses whether an element concept meets priority architectural needs and whether prospective technologies and capabilities are likely to demonstrate sufficient maturity. After a successful element initiation, element concepts are further refined through trade studies and technical interchanges. This overarching element definition process culminates in the mission concept review, which evaluates the proposed concept's feasibility, ability to fulfil its objectives, and maturity to begin formulation.

Following mission concept review, NASA undertakes an acquisition planning process that culminates in an acquisition strategy meeting to determine whether to make, buy, or partner on a particular element. If NASA decides to proceed with a partnership approach, NASA would then engage its potential international partner to establish an agreement that formalizes respective roles and responsibilities for formulation and implementation. Only once that international agreement is completed will NASA document elements as partner-provided in the next revision of the ADD.

Science Cooperation

Science is one of the three pillars of NASA's Moon to Mars Strategy,[6] alongside national posture and inspiration. Because scientific experiments and instruments carry less of a financial burden than elements, science is an excellent way for international partners to collaborate with NASA.

Moon to Mars exploration seeks to address the important science-based questions that will help inform our understanding of Earth, the Moon, Mars, and the universe. NASA welcomes collaboration to achieve the high-priority science goals outlined in the Moon to Mars Objectives and decadal surveys produced by the National Academies of Sciences, Engineering, and Medicine.[7]

International space agencies seeking to partner on science experiments may join U.S.-led proposals to Payload and Research Investigation from the Surface of the Moon (PRISM) and Artemis Deployed Instruments Program solicitations. These solicitations can be found through the online NASA Solicitation and Proposal Integrated Review and Evaluation System (NSPIRES) system.[8] NASA selects scientific investigations from these solicitations for delivery as payloads on human or robotic missions to the lunar surface.

NASA may also provide opportunities for international partners to submit proposals directly, without a U.S.-led partner. The 2023 Artemis III Deployed Instruments Program solicitation offered this opportunity, and NASA expects to continue international-led science proposals for future Artemis Deployed Instrument Program solicitations. The cost of developing these proposals and the instruments themselves must be covered by the sponsoring international agency or institution.

If NASA selects an international proposal, the U.S. and the international partner may establish a formal cooperation agreement. NASA has also contributed scientific instruments to international-led missions and plans to continue to do so on a cooperative basis. The assessment of Recurring Tenet 1: International Collaboration in the ADD contains more detail about NASA's current international science cooperation efforts.[4]

Opportunities for Continued Engagement

As NASA refines its Moon to Mars Architecture and incorporates feedback from the international community, new avenues for international cooperation may emerge, enabling NASA to engage new partners and leverage existing partners in new ways. The agency is actively seeking international collaboration to expand humanity's reach throughout the solar system.

NASA's Office of International and Interagency Relations (OIIR) manages the agency's international engagements, facilitating dialogue, and establishing cooperation. OIIR can help international space agencies hold preliminary discussions to understand the intent, purpose, and scope of proposed cooperation.

International agencies with cooperative proposals that fill identified gaps in the Moon to Mars Architecture should reach out to the appropriate OIIR point of contact, as listed on the Moon to Mars Architecture website.[9] NASA also encourages prospective international partners to attend its Moon to Mars workshops, held annually following the release of the latest architecture products. For the latest, navigate to the architecture website and subscribe to updates.[2]

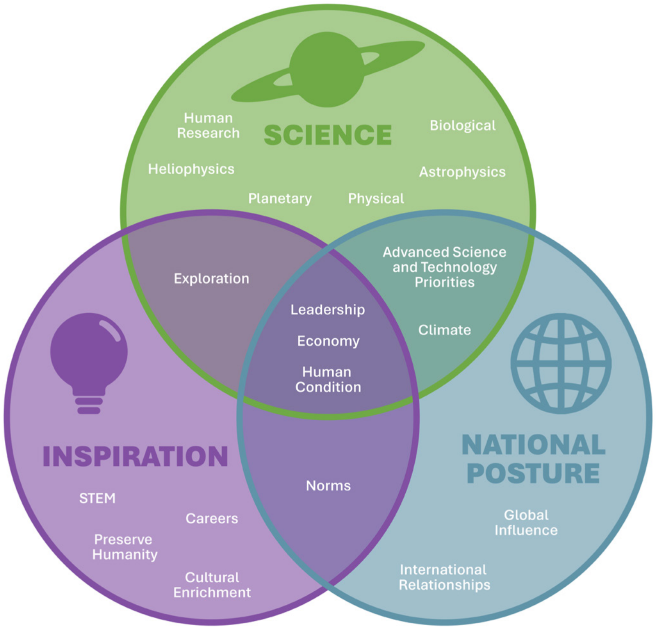

Figure 3: *Three pillars of exploration. (NASA)*

Key Takeaways

NASA considers international cooperation foundational for deep space exploration and a key part of its Moon to Mars strategy.

International partners can cooperate with NASA in a variety of ways, from participating in scientific investigations to providing exploration assets or elements that fill gaps in the architecture.

For exploration elements — substantial, architecture-level contributions — NASA has defined a clear pre-formulation process that incorporates partners at every step.

NASA encourages new and existing partners to engage its Office of International and Interagency Relations with questions or to begin partnership discussions.

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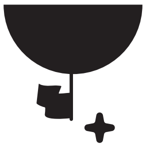

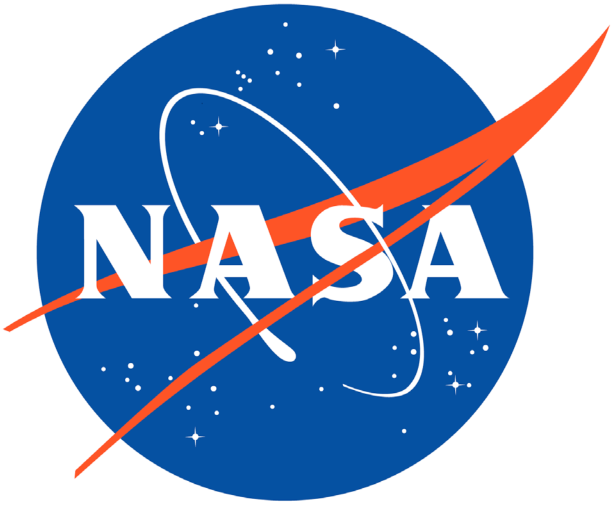
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