

National Aeronautics and
Space Administration



— 2023 Architecture Concept Review —

Moon to Mars Architecture

Executive Overview

JANUARY 2024



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Introduction

NASA is leading a campaign of human exploration, science, and discovery that begins in lunar space and journeys on to Mars. This document summarizes the agency's recent body of planning, focusing on work performed during the 2023 Architecture Concept Review cycle.

NASA established its Moon to Mars Objectives in 2022 with input from U.S. industry, academia, international space agencies, and its workforce to guide deep space exploration. NASA's Moon to Mars Architecture serves as a roadmap to accomplish those objectives, identifying the technologies and capabilities needed to return to the lunar surface and venture on to the Red Planet. Every year, NASA updates its Architecture Definition Document to reflect the latest architectural development work.

Why Explore?

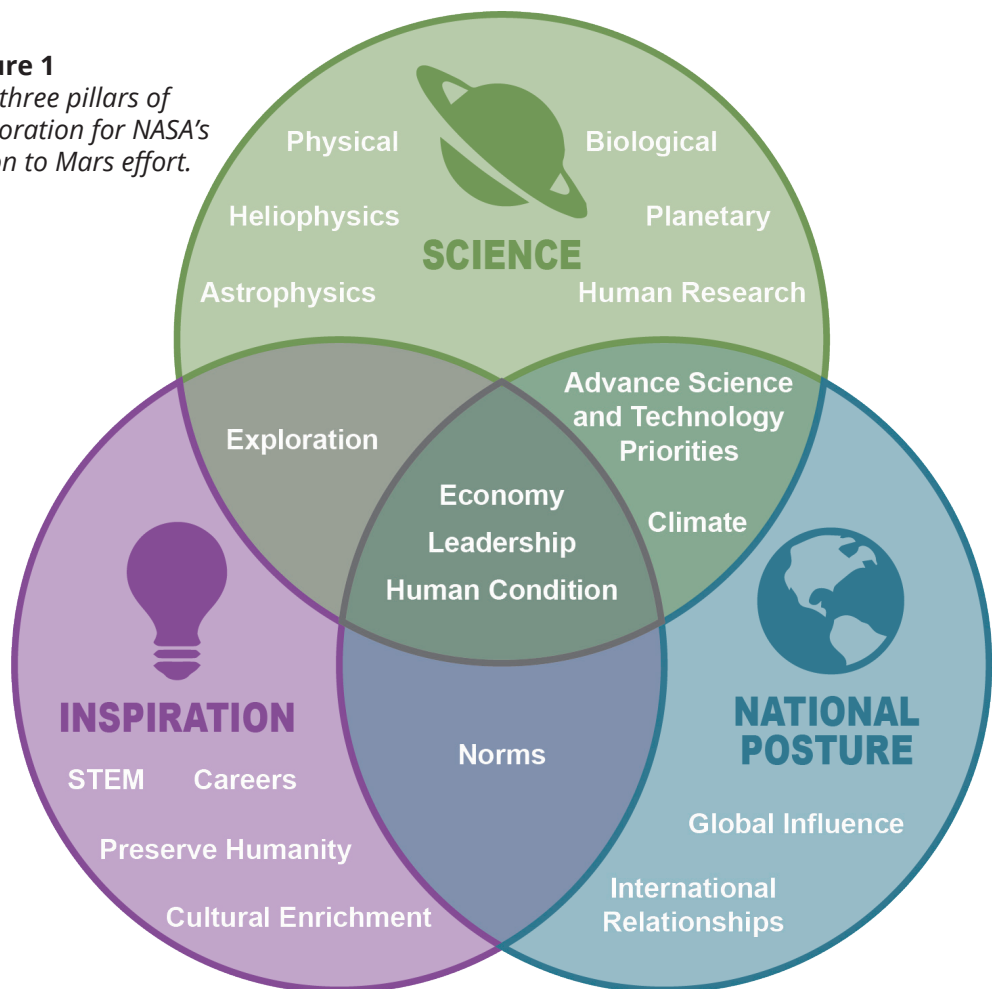
NASA anchors its vision for exploration in the value it provides humanity. Three pillars form the foundation: science, national posture, and inspiration.

Science: Investigations in deep space, on the Moon, and on Mars will enhance our understanding of the universe and our place in it.

National Posture: What is done, how it's accomplished, and who participates affect our world, quality of life, and humanity's future.

Inspiration: Accepting audacious challenges motivates current and future generations to contribute to our voyage deeper into space.

Figure 1
The three pillars of exploration for NASA's Moon to Mars effort.



Crewed exploration of the Moon and Mars will strengthen these three pillars, leading to a new era of science and discovery. **The Moon to Mars Objectives define NASA's ambitions; the Moon to Mars Architecture shows how to realize them.**

The Architecture Process

When most think of architecture, they envision skyscrapers, cantilevered homes, or marbled museums. In this case, architecture is not limited to the built environment. It isn't a mission, a manifest, or a set of requirements. Instead, NASA's Moon to Mars Architecture defines the systems needed for long-term, human-led scientific discovery in deep space and the relationships between them.

NASA's architecture approach distills agency-developed objectives into operational systems and elements that support science and exploration goals. Working with experts across the agency, industry, academia, and the international community, NASA continuously evolves that blueprint for crewed exploration, setting humanity on a path to the Moon, Mars, and beyond.

In collaboration with other NASA mission directorates — Space Operations, Science, Space Technology, and Aeronautics Research—NASA's Exploration Systems Development Mission Directorate establishes systems for Moon to Mars exploration. Within the mission directorate, NASA's Strategy and Architecture Office leads definition, documentation, and disposition of the overarching Moon to Mars architecture in consultation with stakeholders.

NASA begins with the broadest goals — far in the future on the timeline. From there, each objective is traced to relevant architectural needs and systems. This methodology — called "architecting from the right" — identifies technology and capability gaps that NASA must address to achieve the Moon to Mars Objectives. This process empowers decision-makers to select the right tools for the job.

NASA develops and invests in solutions that fulfill Moon to Mars Objectives based on their decomposition into needed use cases and functions. The agency catalogs these solutions in the Architecture Definition Document, a living record of NASA's overarching plan for crewed deep space exploration.

Each year, NASA conducts a strategic analysis cycle that culminates in the Architectural Concept Review and the releases of an updated Architecture Definition Document. Additional Architecture Concept Review cycle activities and products include workshops, webinars, white papers, and other resources that explain or expand upon concepts.



key terms

Architecture

The unified structure that defines a system, providing rules, guidelines, and constraints for constituent parts and establishing how they fit and work together.

Characteristics & Needs

Features, activities, and capabilities necessary to satisfy goals and objectives.

Use Case

An operation that would be executed to meet desired characteristics and needs.

Function

One of the actions necessary to satisfy a use case.

Element

A notional exploration system that enables a set of functions.

Sub-architecture

A group of tightly coupled elements, functions, and capabilities that work together to accomplish one or more objectives.

Segment

A portion of the architecture that integrates sub-architectures and progressively increases in complexity and objective satisfaction.



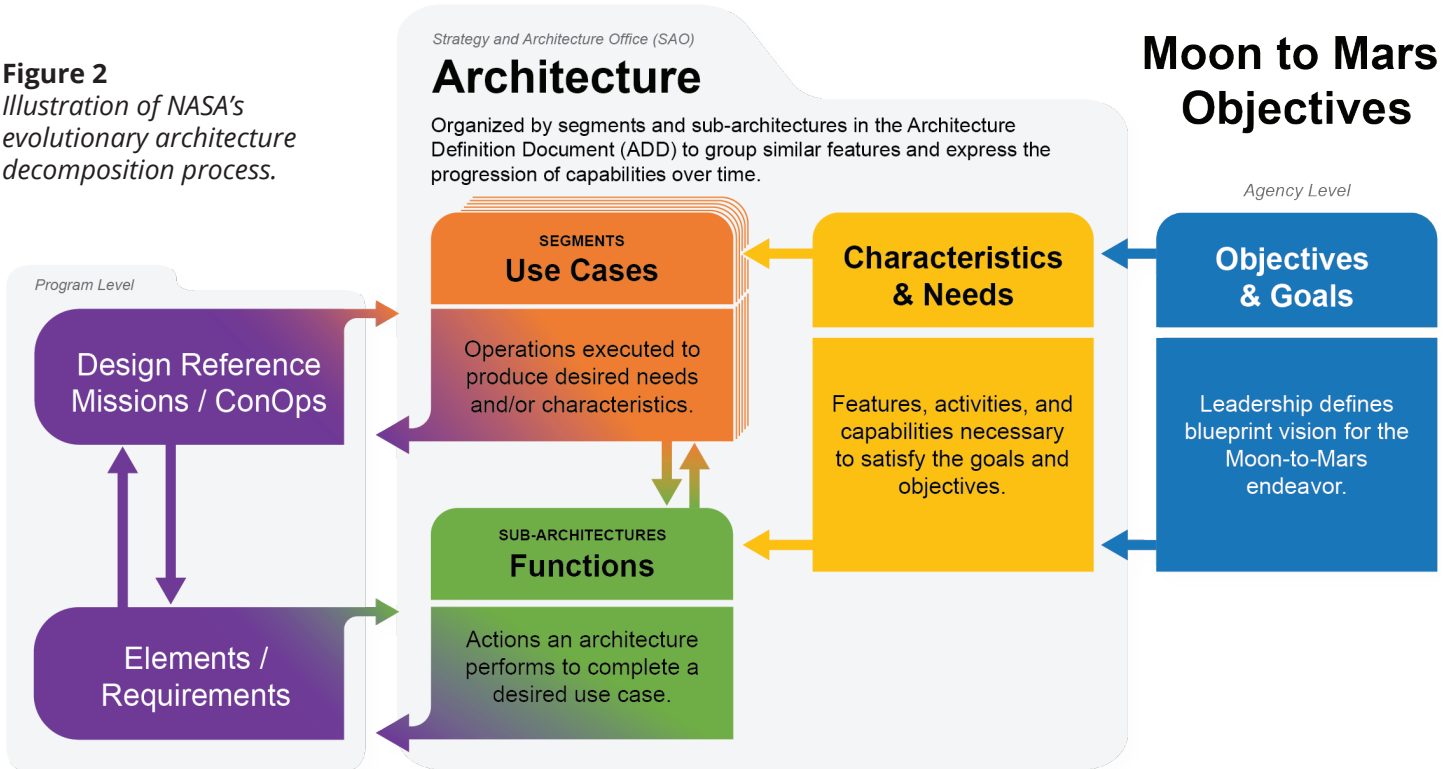
Architecture Concept Review attendees listen to welcome remarks from NASA leadership on Nov. 14, 2023, at NASA's Kennedy Space Center in Florida. Attendees included representatives from all of NASA's centers, leaders from all of NASA's mission directorates, various technical authorities, and other stakeholders across the agency. (Credit: NASA/Kim Shifflet)



Detailed explanations of the architecture effort and concepts simplified for this overview can be found on our website:

<https://www.nasa.gov/architecture>

Figure 2
Illustration of NASA's evolutionary architecture decomposition process.



selecting the right tools

Architecting from the right means developing the capabilities and technologies needed to achieve specific long-term goals, not just making decisions arbitrarily or out of short-term convenience.

For example, if one needs to write something down, the instinct might be to choose a yellow #2 pencil, but what is the essential function needed? Writing is the use case, being erasable is an operational constraint, and being yellow is a design feature. The #2 pencil meets the need, but a pen, marker, or paint might be just as well suited to the task. Ensuring a full understanding of the needs, constraints, and long-term applications is essential to the decision.

In the same way, NASA must consider its objectives and then build the systems to accomplish them, not simply select tools that may already exist. The architecture process enables methodical deliberation to avoid bias, and instead favors the most effective tools.



Moon to Mars Objectives

NASA's Moon to Mars Objectives seek to expand humanity's frontiers in space science and exploration. The objectives fall into the overarching goals below:

Lunar and Planetary Science

Answer questions about the formation of our solar system, the geology and chemistry of planetary bodies, and the origins of life.

Heliophysics

Advance our study of the Sun and our ability to observe, model, and predict space weather.

Human and Biological Science

Grow our understanding of how the lunar, Martian, and deep space environments affect living things.

Physics and Physical Sciences

Investigate space, time, and matter in the unique environments of the Moon, Mars, and deep space.

Science Enabling

Develop integrated human and robotic techniques that address high-priority scientific questions around and on the Moon and Mars.

Applied Science

Conduct science utilizing integrated human and robotic techniques to inform the design of exploration systems.

Lunar Infrastructure

Create an framework for government, industry, academia, and international partners to participate in a robust lunar economy and facilitate science.

Mars Infrastructure

Develop the power, communications, navigation, and resource utilization capabilities to support initial human Mars exploration.

Transportation and Habitation

Create the systems necessary for humans to travel to the Moon and Mars, live and work there, and return to Earth safely.

Operations

Conduct crewed missions to gradually build technologies and capabilities to live and work on planetary surfaces other than Earth.

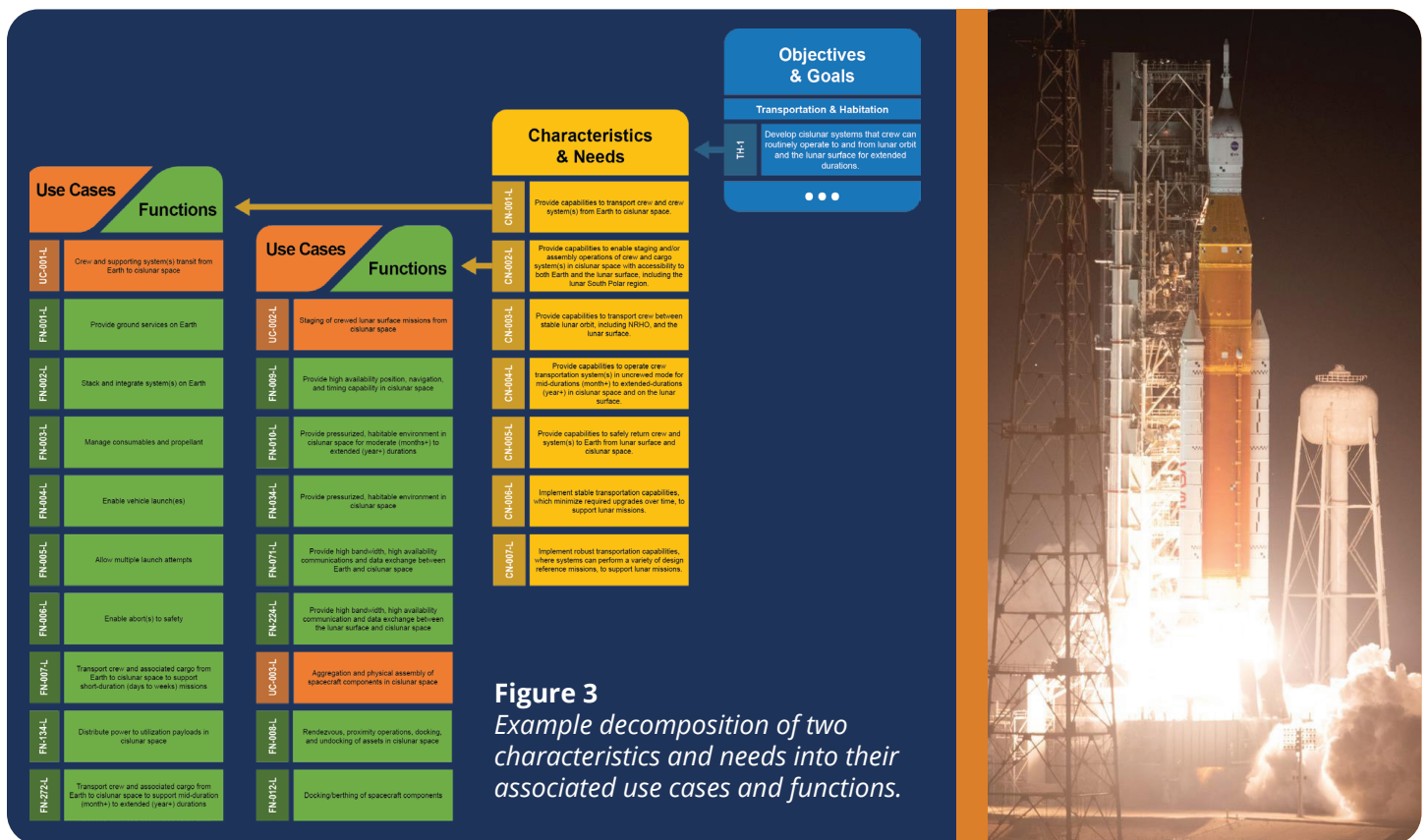
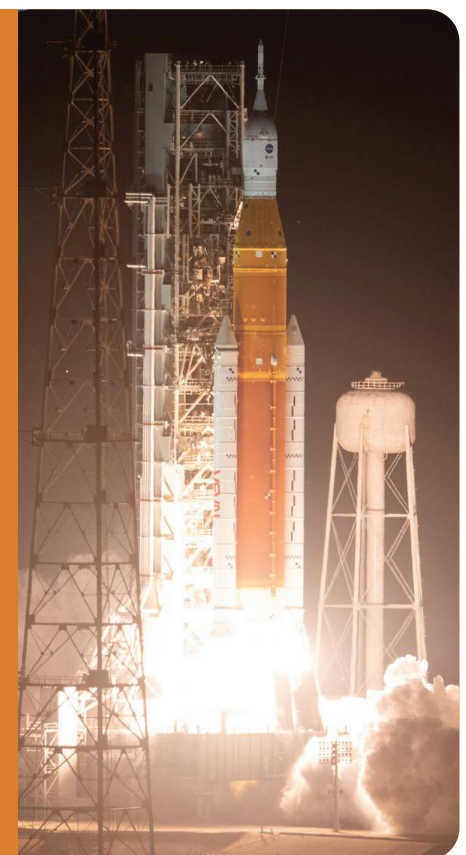
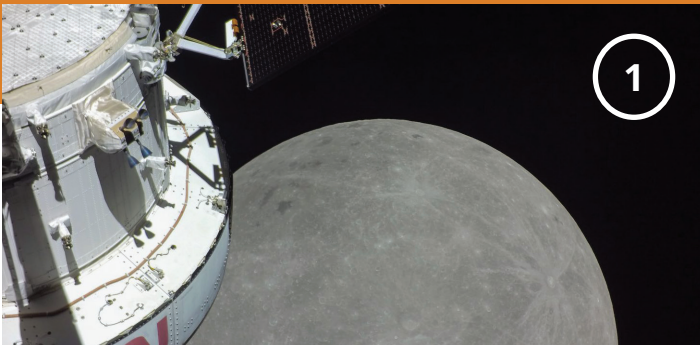


Figure 3
Example decomposition of two characteristics and needs into their associated use cases and functions.



Architecture Segments

The architecture segments below capture the evolutionary nature of NASA's Moon to Mars exploration strategy, growing in complexity over time to meet more of NASA's Moon to Mars Objectives.



Human Lunar Return

Includes the inaugural Artemis missions which will return humanity to the Moon for the first time since the Apollo missions of the 1960s and 70s. This segment will demonstrate and validate core systems and capabilities for the Moon to Mars effort.

This segment will test crew and cargo transportation systems, deploy lunar communications relays, demonstrate technologies, and land the first woman and first person of color on the lunar surface. Missions pursued in this segment will lay the groundwork to achieve the Moon to Mars Objectives.



Foundational Exploration

Will prepare for future segments by expanding operations, capabilities, and systems supporting crewed missions to lunar orbit and the Moon's surface. It will build on initial Human Lunar Return capabilities and validate exploration systems for future Mars missions.

Surface missions in this segment will feature increased duration, expanded mobility, and regional exploration of the lunar South Pole. Orbital operations will also increase in duration. The needs of future missions will influence this segment's activities, which may include reconnaissance, Mars risk reduction, and initial infrastructure for long-term lunar evolution.



Sustained Lunar Evolution

Will aim to build future economic opportunity and greater participation in lunar science and exploration. The segment will increase our science capability, mission duration, and the production of goods and services derived from lunar resources.

This segment is an "open canvas," embracing new ideas, systems, and partners to realize a long-term presence on the Moon and grow the lunar economy. This sustained architecture could achieve existing science objectives and address new science objectives identified through discoveries in previous segments.



Humans to Mars

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

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

Sub-Architectures

Each sub-architecture represents a task, technology, or process that NASA must master to achieve the Moon to Mars objectives. The first eight of the sub-architectures listed below were included in the first edition of the Architecture Definition Document, with the last four added as part of the 2023 Architecture Concept Review process.



Communications, Navigation, Positioning, and Timing Systems

Enable transmission and reception of data, determination of location and orientation, and acquisition of precise time.



Human Systems

Execute human and robotic missions; this includes crew, ground personnel, and supporting systems.



Mobility Systems

Move crew and cargo around the lunar and Martian surfaces.



Transportation Systems

Convey crew and cargo to and from Earth to the Moon and Mars.



Data Systems and Management

Transfer, distribute, receive, validate, secure, decode, format, compile, and process data and commands.



Infrastructure Support

Includes facilities, systems, operations planning and control, equipment, and services needed on Earth, in space, and on planetary surfaces.



Habitation Systems

Ensure the health and performance of astronauts in controlled environments.



Logistics Systems

Package, handle, transport, stage, store, track, and transfer items and cargo.



Power Systems

Generate, store, condition, and distribute electricity for architectural elements.



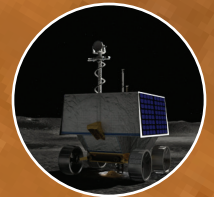
Utilization Systems

Enable science and technology demonstrations.



In-situ Resource Utilization (ISRU) Systems

Extract resources in space or on the Moon or Mars to generate products.



Autonomous Systems and Robotics

Employ software and hardware to assist the crew and operate during uncrewed periods.

New for 2023

New for 2023

2023 *White Papers*

Surface Extravehicular Activity Architectural Drivers

When humans return to the Moon, they won't simply land — they'll explore the lunar surface during extravehicular activities, or spacewalks. NASA and its partners will need to address the unique challenges of walking on the Moon. The lessons learned on the lunar surface will directly influence plans for crewed Mars missions.

Lunar Communications and Navigation Architecture

NASA's return to the Moon will require reliable communications services and accurate navigation data. A network of ground stations, space relay satellites, and surface-to-surface communications equipment provided by NASA, industry, and international partners will keep Artemis astronauts connected with Earth.

Lunar Logistics Drivers and Needs

To support crewed missions, the missions need numerous logistics items — the equipment and supplies necessary to sustain life, maintain systems, and conduct science — supplied to the lunar surface. The composition and amount of these items vary significantly based on mission requirements.



White Papers written in response to suggestions at 2023 Moon to Mars Architecture workshops.

Lunar Site Selection

Exactly where Artemis missions land when humans return to the Moon will depend on a wide variety of factors. Surface conditions, science objectives, the lighting environment, communications availability, system capabilities, and more can affect landing site selection.

Safe and Precise Landing at Lunar Sites



Precision lunar landings will become increasingly important as space agencies and private companies explore more of the Moon. More precise landings enhance crew safety, minimize site contamination risks, and enable missions to reach specific, scientifically significant sites.

Analytical Capabilities In-situ vs. Returned



Samples collected on the lunar surface may be analyzed by science instruments launched to the Moon or at laboratories on Earth. In-situ analysis is limited by the capabilities of instruments that can be launched to the Moon, whereas samples returned to Earth can benefit from more refined analyses. However, returning pristine samples — those kept in the environment in which they were collected — to Earth presents technological challenges.

In January 2024, alongside the release of an update to the Architecture Definition Document, NASA published 13 new white papers on select Moon to Mars Architecture topics as part of the annual Architecture Concept Review cycle. Experts from across the agency authored the papers; some topics arose from suggestions at workshops for industry, academia, and international space agencies. The white papers explore the challenges of crewed missions to deep space and raise questions that need to be answered to build a future among the stars.

Mars Mission Abort Considerations

Crewed Mars missions have more challenging abort factors than lunar missions due to the sheer distance from Earth. An abort in transit to Mars will take months, not days. Early Mars missions will have limited abort options from the surface. This paradigm shift will require fundamental changes in mission planning.

Mars Communications Disruption and Delay

Communications blackouts and delays are unavoidable for crewed Mars missions, though blackouts can be mitigated through thoughtful design. Crewed Mars exploration must respond to the unique constraints of the Red Planet; to account for disruption and delays, system and crew autonomy must be a significant focus in mission planning.

Mars Surface Power Generation

The first human explorers on Mars will need energy to power the systems they use to live and work on the surface and ascend back to orbit. The Martian environment poses unique challenges for generating power and power requirements will vary significantly based on mission profile.

Key Mars Architecture Decisions

NASA has developed analysis tools to better understand the relationships between the many decisions it will need to make to begin planning initial crewed missions to Mars. Using these tools, seven key Mars architecture decisions have been identified. They are not the only questions to answer, but their answers will affect the many decisions that follow.

Human Health and Performance For Mars Missions

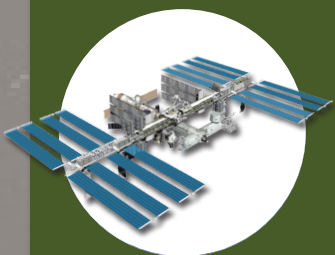
Astronauts on missions to Mars will face a series of interrelated risks to their health and performance, including radiation exposure, changing gravity, isolation, distance from Earth, and environmental factors on the surface. Mission architecture and equipment design should consider these risks and minimize them wherever possible.

Round Trip Mars Mission Mass Challenges

Round-trip Mars missions are much more difficult than one-way trips. Mars "gear ratios" are multipliers of the mass required to launch any given payload from Earth's gravity well to Mars' and then return it home. The mass requirements for each leg of a round-trip mission will affect mission cost, schedule, and complexity.

Exploration Lessons Learned from the Space Station

The International Space Station is humanity's testbed in low-Earth orbit. The orbiting laboratory is advancing capabilities in life support, navigation, extravehicular activities, and human health. Lessons learned on the space station are enabling deep space exploration.



Read the white papers here:
<https://go.nasa.gov/3TM8c9y>

New Architecture Elements *for 2023*

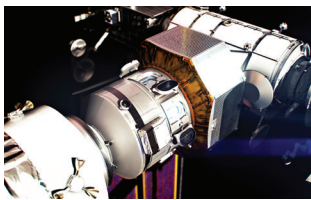
Elements include hardware that has already launched, like the Orion spacecraft and the Space Launch System rocket, but also include in-development systems, like the Human Landing System, the Gateway lunar space station, and the spacesuits astronauts will wear on the lunar and Martian surfaces.

In the first edition of the Architecture Definition Document, NASA established nine elements for the Human Lunar Return segment. In 2023, NASA added six new elements to the segment:

Gateway Extravehicular Robotic System

Canadian Space Agency

The next-generation Canadarm3 will install science experiments on the outside of Gateway, assist astronauts in spacewalks, and perform external surveys.



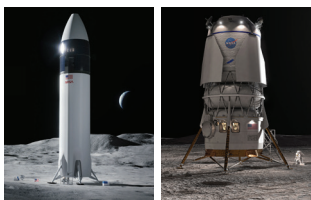
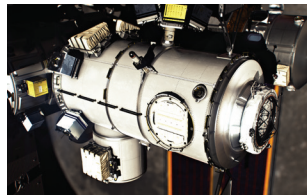
Gateway ESPIRIT Refueling Module

European Space Agency

This habitable module will contain refueling tanks, cargo space, and large windows to allow astronauts aboard Gateway to view outside the station.

Gateway Airlock Module

The airlock is the access point between Gateway's pressurized cabin and the vacuum of space. It will enable astronauts aboard Gateway to conduct spacewalks and can also be used as an additional docking port.



Human-class Delivery Lander

This lander will transport cargo for human lunar missions. Crew members will arrive aboard the Human Landing System, and additional cargo will arrive aboard the Human-class Delivery Lander.

Pressurized Rover

This rover will allow astronauts to live and work at a variety of locations on the lunar surface. It will carry scientific equipment and function as a mobile laboratory and can be remotely repositioned between missions.



Lunar Terrain Vehicle

This unpressurized vehicle will transport crew and equipment across the lunar surface. It can also be operated remotely.

element initiation

In 2023, NASA's Exploration Systems Development Mission Directorate introduced a new integration milestone for formulating Moon to Mars architecture elements: element initiation.

During element initiation, the directorate reviews whether a potential concept provides a solution to needs or gaps identified in the Moon to Mars Architecture. The element initiation process will ensure that NASA invests in the most effective technologies and capabilities to meet the Moon to Mars objectives, and that those technologies and capabilities demonstrate sufficient maturity and contribute to the needs of the architecture.

NASA initiated two new elements through the element initiation process in 2023: a lunar surface habitation element, which may provide an initial home for astronauts on the Moon, and a lunar surface cargo lander element, which may deliver supplies and equipment to the Moon.



Forward Work

As NASA prepares for the Artemis II mission, which will return humans to cislunar space for the first time since the Apollo missions of the 1960s and 70s, the agency continues to refine its Moon to Mars Architecture. Preparations are underway for the 2024 strategic analysis cycle. NASA will hold workshops for industry, academia, and international partners in February 2024, prompting discussions about how to help achieve the Moon to Mars Objectives.



Figure 4
Illustration of the annual cadence of the Architecture Concept Review process.

During the 2024 strategic analysis cycle, NASA will begin to:

- Address gaps in the Human Lunar Return and Foundational Exploration segments, introducing elements that provide key capabilities such as returning cargo to Earth, offloading and relocating assets on the surface of the Moon, and other important lunar logistics functions.
- Perform strategic analysis for sub-architectures, developing strategies for services like surface communications, mobility, power, and in-situ resource utilization, which would allow missions to harness local resources at mission destinations.
- Conduct studies and begin to develop recommendations for the priority decisions identified for an initial campaign of crewed Mars exploration. These decisions will allow NASA to take an informed and tactical approach to mission development, optimize lunar demonstrations and analogs to prepare for Mars, and set humanity on a course for the Red Planet.

The results of these efforts will be reviewed at the next Architecture Concept Review in the fall of 2024. NASA will release revision B of the Architecture Definition Document shortly thereafter, plus a new suite of white papers on relevant topics and other architecture tools, products, and documents.

This will be the first full-year cadence of the Architecture Concept Review cycle, normalizing the processes outlined in this document. As this process becomes routine, shared language and expectations across the agency will empower all of NASA's mission directorates to actively contribute to our bold ambitions in deep space.

Our voyage to the Moon, Mars, and beyond has only just begun.



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