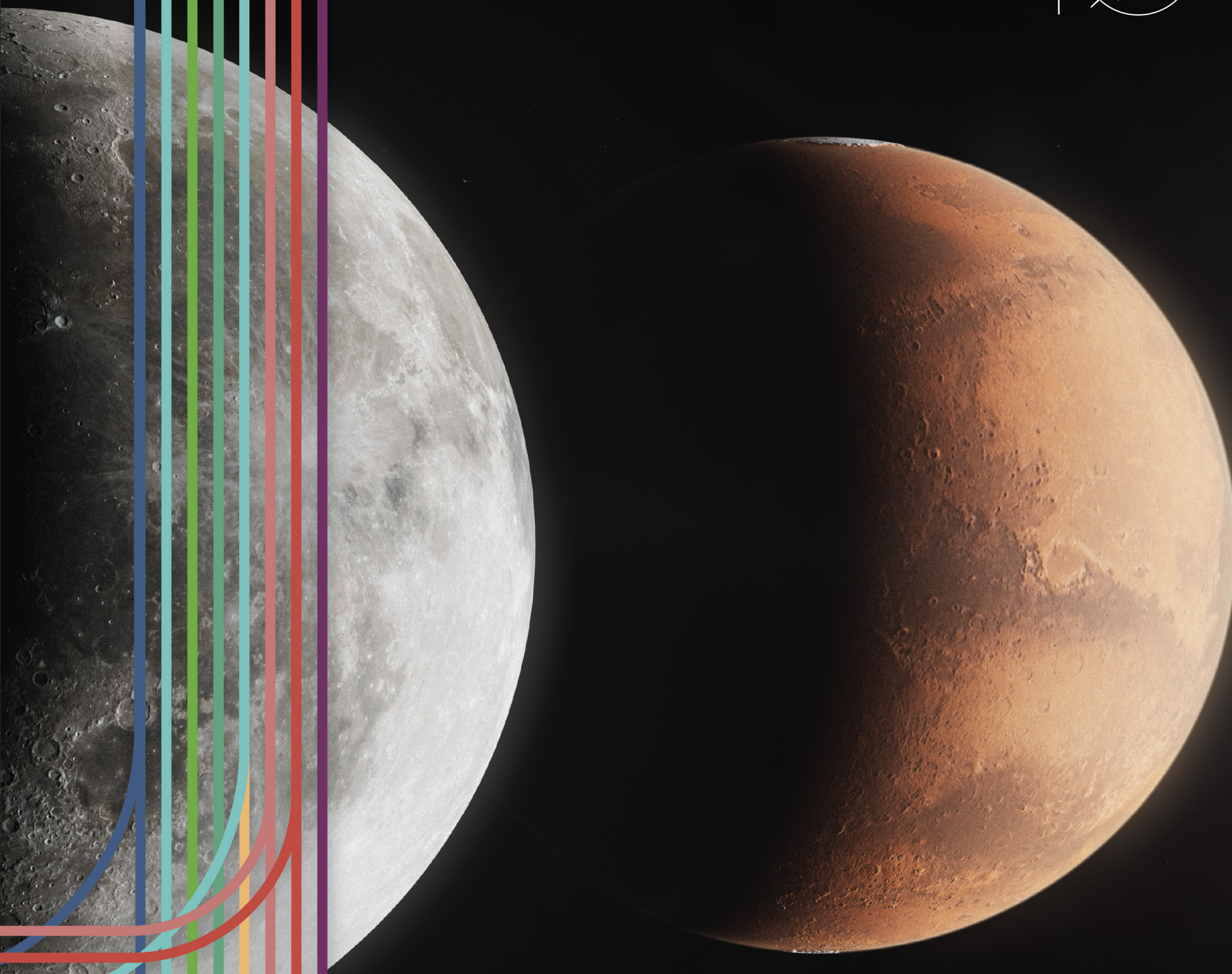
National Aeronautics and
Space Administration



NASA's
Moon to Mars Architecture

Executive Overview

2024 Architecture Concept Review

TABLE of CONTENTS

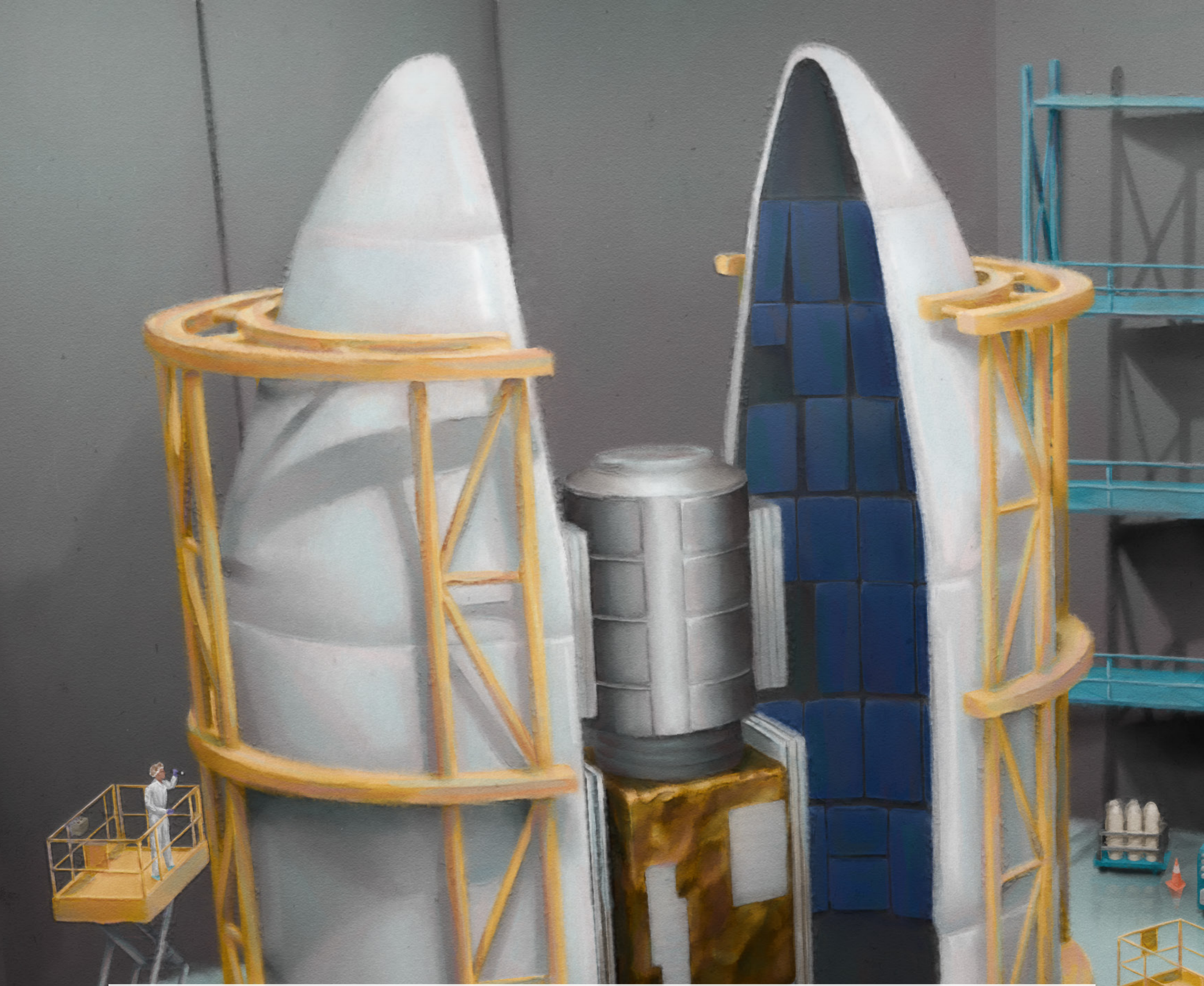
2024 FEATURES

ABOUT the ARCHITECTURE

Moon to Mars Architecture Executive Overview
2024 Architecture Concept Review

Exploration Systems Development Mission Directorate
National Aeronautics and Space Administration

www.nasa.gov/architecture



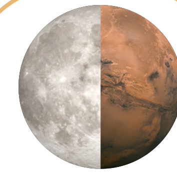
2024 ACCOMPLISHMENTS

In 2024, NASA's Moon to Mars architecture effort focused on solidifying the process developed in 2023 through improved traceability of needs and the application to new element pre-formulation. Several key accomplishments in support of architecture maturation included:

- Published Revision B of the Architecture Definition Document, a detailed snapshot of NASA's Moon to Mars Architecture. This edition adds two new exploration elements, an updated objective decomposition, new key driving architecture decisions, and new architecture-driven technology gaps.
- Solicited U.S. industry proposals for innovative architecture solutions that could help the agency land and move cargo on the lunar surface.
- Selected nuclear fission power as the primary surface power generation technology for the initial human missions to Mars.
- Signed an agreement with the Japan Aerospace Exploration Agency, in collaboration with the Japanese automotive industry, formalizing partnership on the Pressurized Rover.

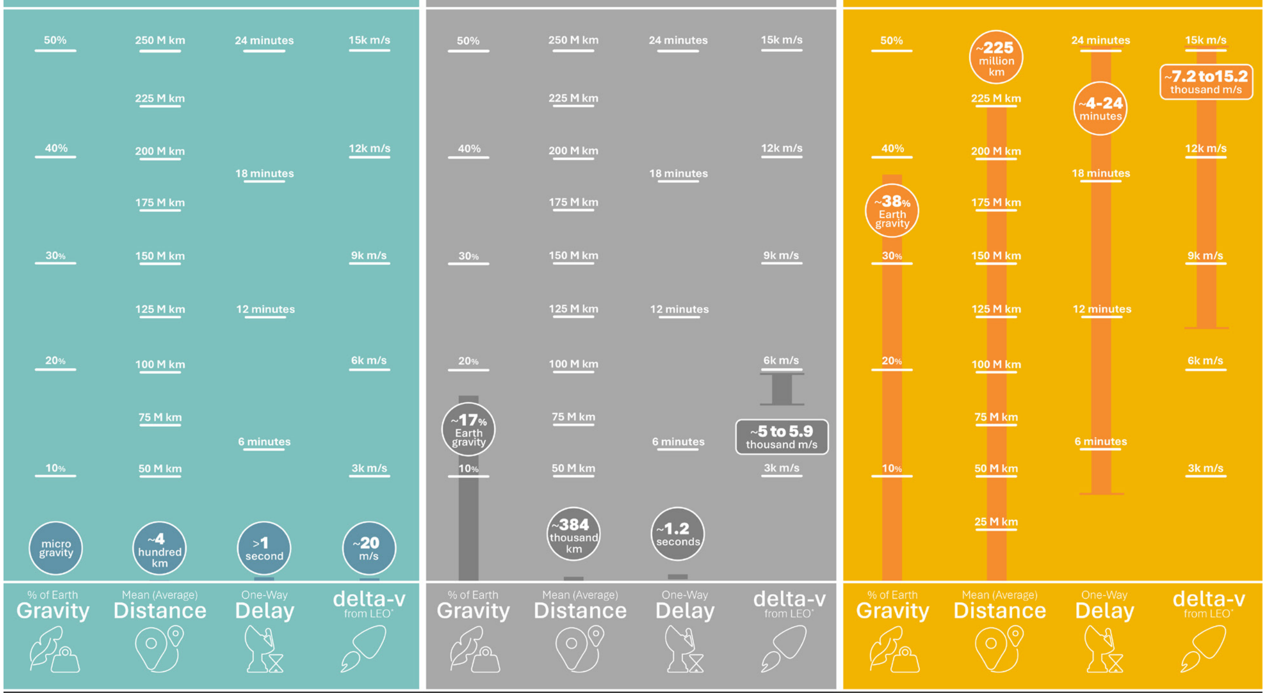
This document provides updates related to 2024 architecture analysis and tasks followed by a general overview of NASA's Moon to Mars Architecture.

Why Moon *to* Mars?



Exploration **Challenges** by Crew Destination

Orbital Missions	**Moon Missions**	**Mars Missions**
Crew in Low Earth Orbit (LEO)	Crewed Lunar Exploration	Crewed Mars Exploration



Exploration **Experience** by Crew Destination

*round trip delta-V from LEO to destination orbit and Earth entry/deorbit

Orbital Missions

7 Crewed Mercury Flights
10 Crewed Gemini Flights
135 Crewed Space Shuttle Flights
20+ Years on the Space Station
270+ Visitors to the Station

60+ Years of Crew Experience
(1962-present)

Moon Missions

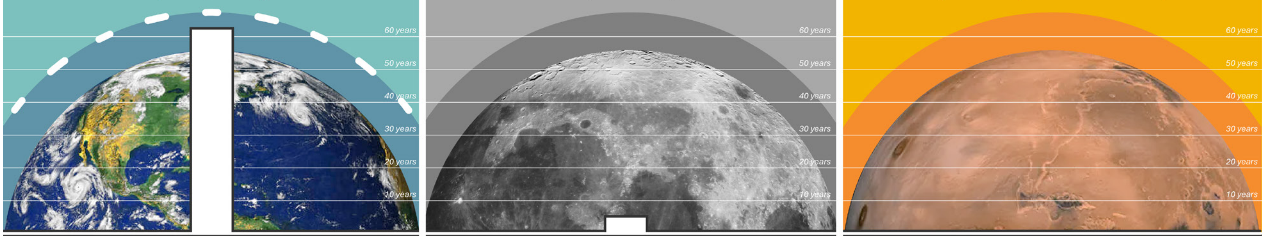
9 Crewed Apollo Missions
1 Integrated Artemis Flight Test
12 Explorers on the Surface
5% Lunar Surface Explored

5 Years of Crew Experience
(1968-1972)

Mars Missions

12 Successful *Robotic* Landings
1% Mars Surface Explored

Zero Years of Crew Experience
(Exclusively Robotic Missions)



Extensive Crew Experience	**Minimal** Crew Experience	**Zero** Crew Experience

Why Moon *to* Mars?

INTRODUCTION

Over 50 years ago, NASA led an effort to send astronauts to explore the surface of the Moon and safely return them to Earth. The extraordinary triumph of the Apollo program has left a lasting impression that lunar exploration is relatively easy and of limited value today. Why then should humanity return to the Moon before sending crews to explore of Mars and beyond?

To address this question, the agency has applied rigorous systems engineering to its exploration goals, developing NASA's **Moon to Mars Architecture**. The architecture establishes a roadmap for iterative development that achieves progressively more complex exploration objectives.

The architecture illustrates how returning to the Moon enables the journey to Mars through its segments. After the initial Artemis missions of the **Human Lunar Return** segment, activities in the lunar **Foundational Exploration** segment will prove the technologies, capabilities, and systems needed for the **Humans to Mars** segment. The **Sustained Lunar Evolution** segment will see increased scientific and commercial utilization of the Moon while government-led development continues toward the next horizon.

EXPLORATION DESTINATIONS

NASA has over 60 years of experience traveling to and from low Earth orbit, beginning with John Glenn's historic flight in 1962. Crewed lunar exploration spans 9 Apollo missions on and around the Moon over the course of 5 years; only 12 humans that have walked on the lunar surface. To date, only robotic missions have explored Mars. Each destination presents unique challenges and requires architectures of different scope and scale.

The most apparent difference between destinations is their distances from Earth. The varying distances of these exploration destinations result in proportional impacts to communications delays, trip durations, abort considerations, and practically every aspect of mission design.

The infographic on the left highlights how challenges grow with each progressive destination. It also shows differences is gravity and operational experience that will inform architecture-level design considerations, technology readiness, and mission risk.

KEY CONSIDERATIONS

Four key facets of the underlying rationale for using crewed lunar missions to prepare for the journey to Mars are national posture, engineering design, mission operations, and human systems.

National posture considerations include:

- **Space leadership:** How do we maintain U.S. influence in and set norms for the peaceful exploration of space?
- **Partnerships:** What industry and international partnerships can fill technology and capability gaps?
- **Technology readiness:** What technology demonstration do we need to ensure the reliability and readiness of Mars-forward capabilities?
- **Economic development:** How do we foster a robust U.S. commercial sector and industrial base to support a crewed Mars exploration campaign?

Engineering design considerations include:

- **Vehicle design:** What type of propulsion is most safe and efficient? How do we slow down and safely land on the surface of our destination?
- **Supplies and logistics:** How do we keep our astronauts fed, hydrated, and equipped with everything they need at increasingly distant destinations from Earth?
- **Maintainability and reliability:** How do we ensure safety through the repairability, redundancy, and longevity of systems?

Mission operations considerations include:

- **Autonomy and Earth-independence:** What is our concept of operations for missions so far from Earth that relying solely on terrestrial controllers becomes impractical?
- **Coordination and aggregation:** How do we stage systems where and when we need them given increasing architectural complexity?
- **Risk and contingency planning:** How can we buy down risk for Mars missions? How do we plan for contingencies when mission abort could take months or years?

Human systems considerations include:

- **Health hazards:** How do we overcome the human health and performance hazards of long-duration deep space missions?
- **Lessons learned:** How can we leverage human experience at the space station and on the Moon for longer and more distant flights?

KEY TAKEAWAYS

Exploration of the cosmos remains a great calling for humanity. Each progressive step from our home planet represents orders-of-magnitude increases in opportunity, challenge, and risk. A sustained exploration campaign that uses the Moon as a proving ground for Mars will allow NASA and its partners to gain and apply the knowledge and experience necessary to take the next giant leap.

Choosing to return to the Moon is not in opposition to humanity's journey to Mars. Lunar exploration will put Mars within our reach.

Initial Surface Habitat Element

The **initial surface habitat element** will house astronauts, empowering them to live on the lunar surface. It will increase the crew size, range, and duration of exploration missions and enable science and technology utilization during both crewed and uncrewed periods.

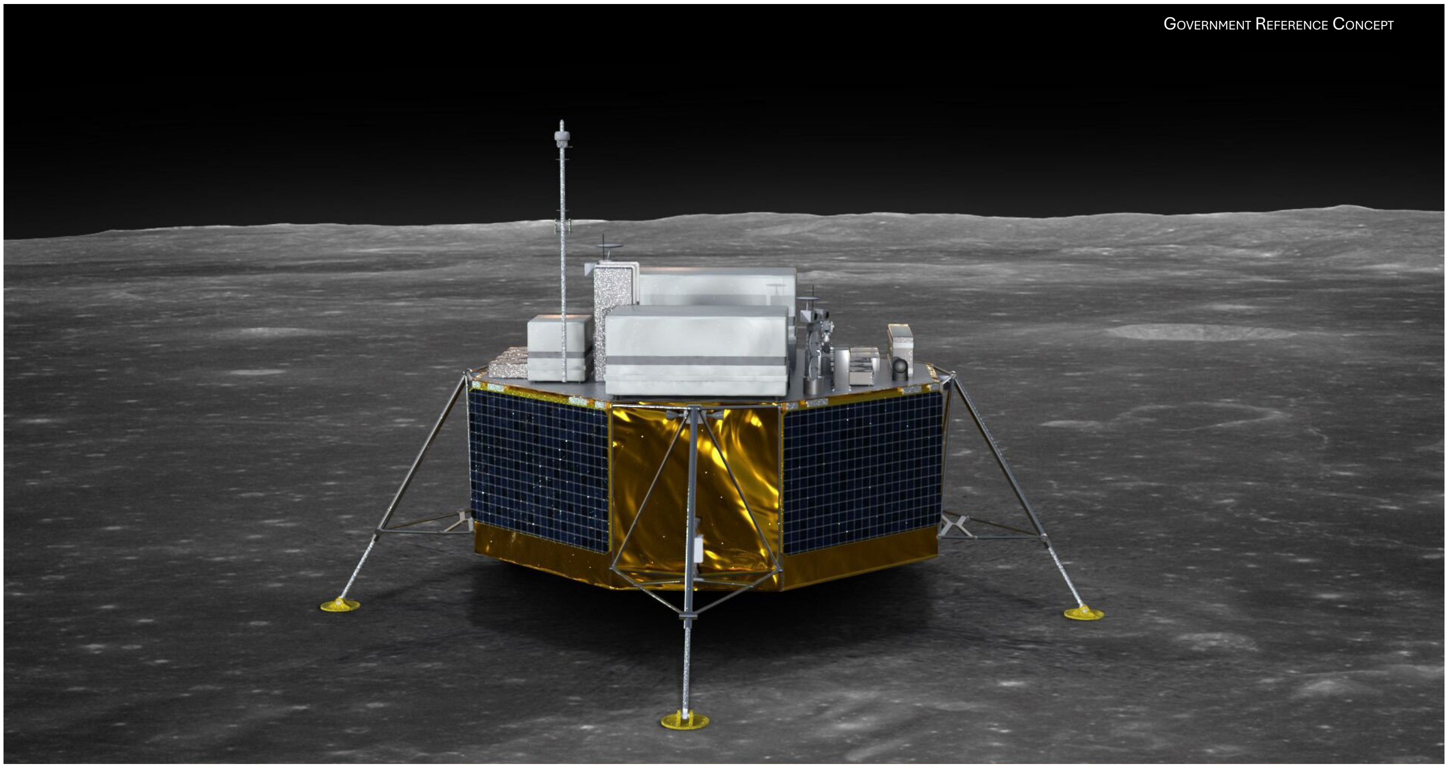
Functions Fulfilled by the Initial Surface Habitat Element During the Foundational Exploration Segment

FN-H-101 L	Enable a pressurized, habitable environment on the lunar surface for short durations (days to weeks)
FN-H-201 L	Operate habitation system(s) in uncrewed mode between crewed missions on the lunar surface
FN-P-402 L	Provide power for deployed external surface utilization payloads(s) and/or equipment for long durations (months to years+)
FN-U-204 L	Provide intravehicular activity facilities, utilization accommodation, and resources, operable during crewed and uncrewed increments, on the lunar surface

+15 additional functions.

Lunar Surface Cargo Lander Element

The **lunar surface cargo lander element** will deliver cargo to the lunar surface, with a payload capacity between that of Commercial Lunar Payload Services landers and Human-Class Delivery Landers. Small cargo landers could transport logistics, utilization payloads, power systems, communications systems, and more.



Functions Fulfilled by the Lunar Surface Cargo Lander During the Foundational Exploration Segment

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

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.

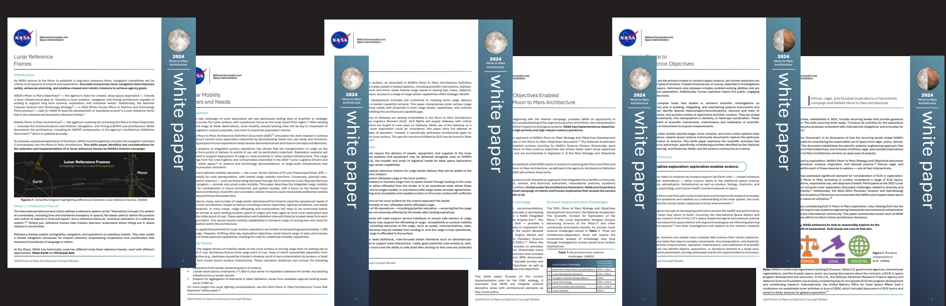
PRIORITY SCIENCE ENABLED THROUGH ARCHITECTURE
Surveys landmark studies that inform NASA's science goals and how the Artemis campaign is realizing those goals.

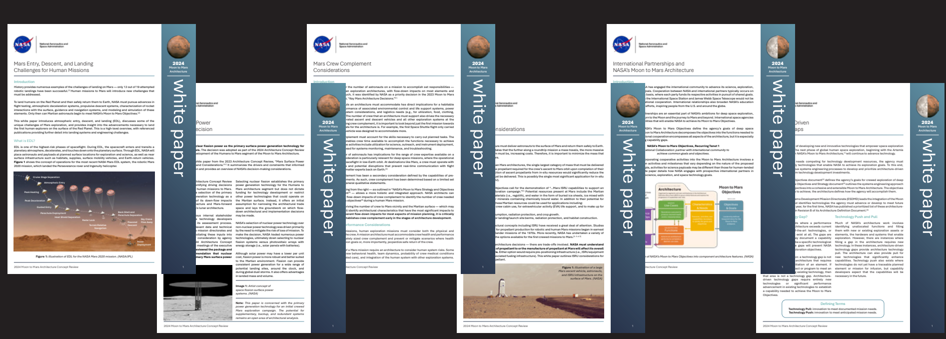
LUNAR REFERENCE FRAMES
Offers considerations for developing an architecture that supports multiple reference frames to meet diverse positioning, navigation, and timing needs.

MOON-FOCUSED 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.

Read the white papers:
nasa.gov/architecture





White Papers

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. *(See associated feature on page 10)*

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.

MARS-FOCUSED WHITE PAPERS

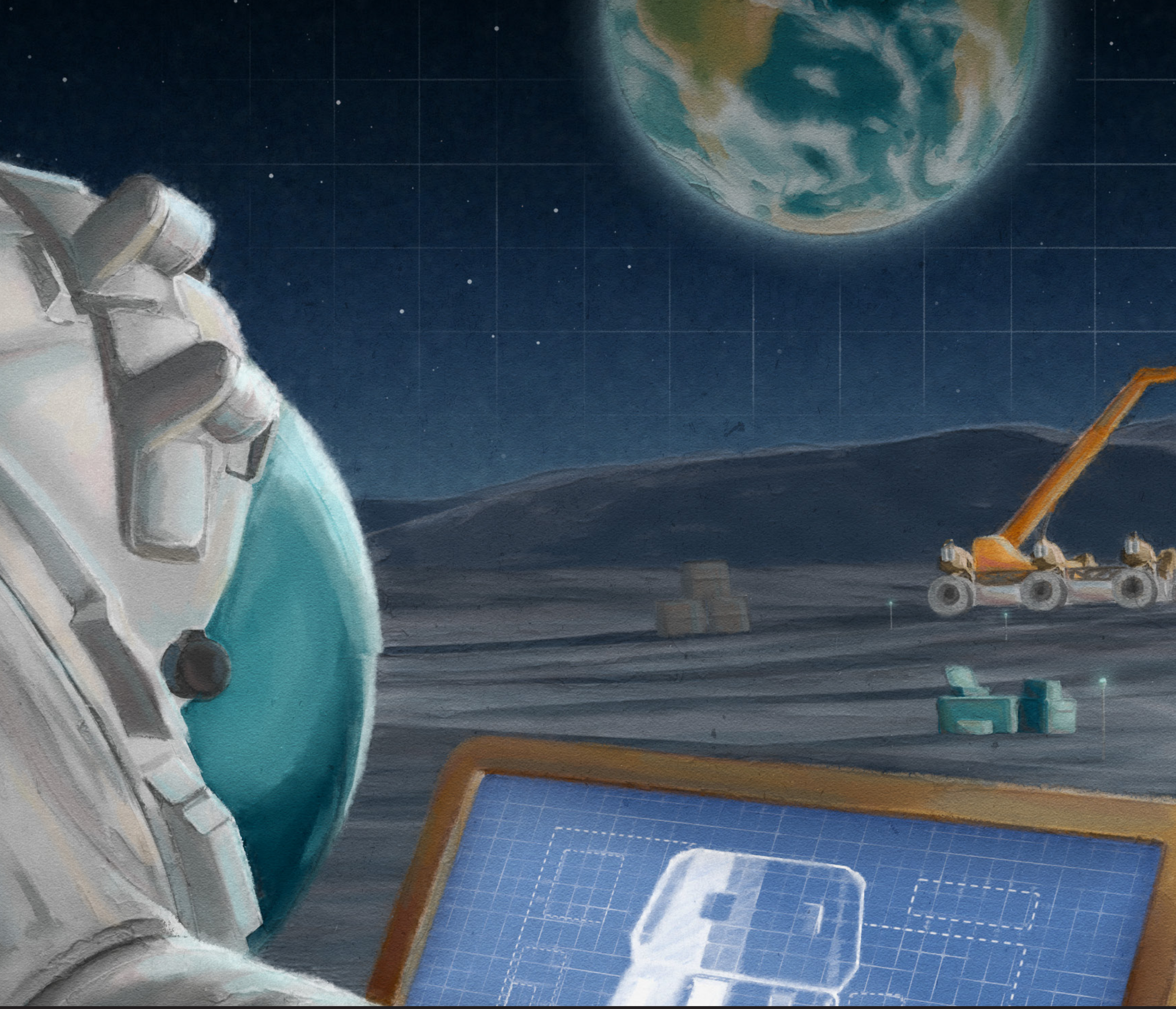
CROSS-CUTTING WHITE PAPERS

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.

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

INTERNATIONAL PARTNERSHIPS
Policies, Opportunities, and Engagement: Elaborates on how NASA engages and collaborates with space agencies from around the world. *(See associated feature on page 8)*

ARCHITECTURE-DRIVEN TECHNOLOGY GAPS
Explains how NASA identifies technology gaps for needed architecture capabilities and encourages innovation to close them. *(See associated feature on page 10)*



2024 FEATURE

Partner Pre-Formulation

For more detail on pre-formulation for international partners, see the associated 2024 white paper, “International Partnerships and NASA’s Moon to Mars Architecture.”

Well before they launch, NASA missions and systems are brought to life in pre-formulation. The pre-formulation process helps NASA define viable and affordable concepts for new NASA programs and projects via concept studies.

For systems supporting NASA's Moon to Mars Architecture, pre-formulation helps NASA identify approaches can that best fill architecture gaps and achieve the Moon to Mars Objectives. This process also offers opportunities to engage with partners in U.S. industry or the international space community who want to participate in the architecture by providing particular capabilities, instruments, technologies, or exploration elements.

To illustrate the partner pre-formulation process, consider a totally fictional Moon to Mars Objective, one that requires NASA to make coffee beverages for astronauts on the Moon. First, the agency would decompose that objective through its characteristics and needs into the use cases and functions that would fulfill them.

Upon finding gaps for a lunar coffee maker element, NASA would begin the pre-formulation process, which includes a series of key reviews. As we continue through this process, the concept matures from a general notion to a specific element that can be built or procured and the "trade space" (the range of theoretical options) narrows.

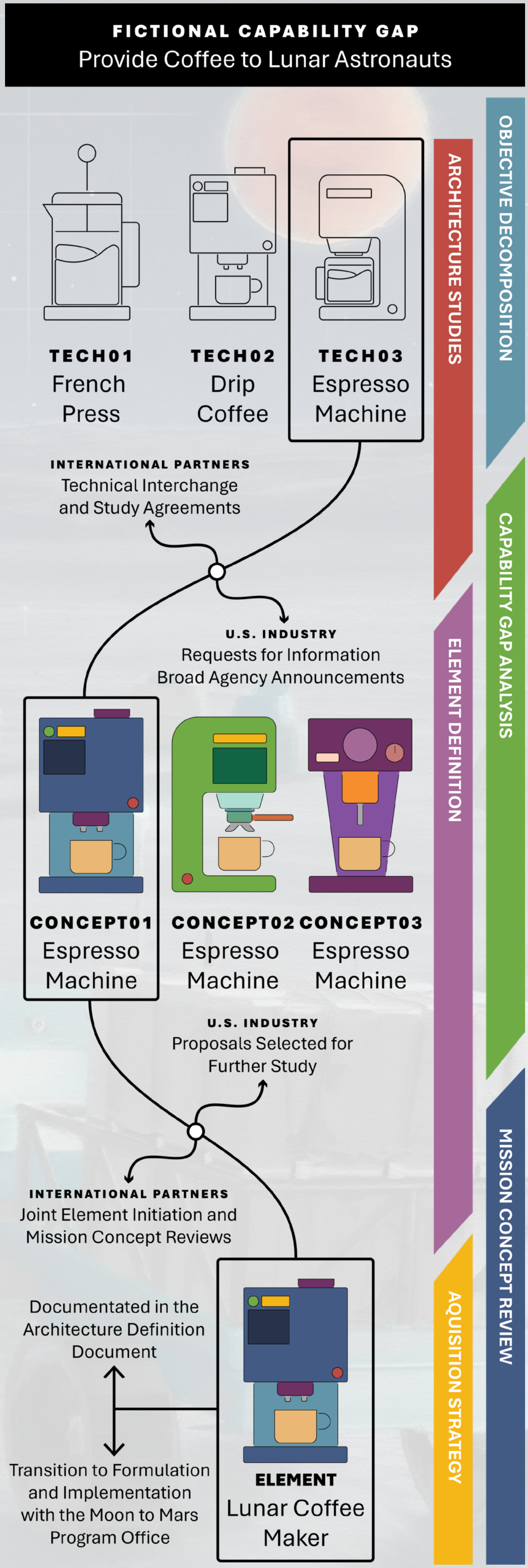
Initial studies consider a host of options that trade against one another for considerations like cost, technical maturity, and objective satisfaction. In our hypothetical example, this might mean comparing and contrasting a drip coffee maker, an espresso machine, and a French press — all of which make coffee, but with different pros and cons.

This analysis feeds into the first major review: element initiation. During element initiation, NASA assesses whether a preliminary capability meets the architecture's needs. In our hypothetical example, this might mean confirming that an espresso maker is the right approach to fill the need for a lunar coffee maker.

Next, NASA begins to produce a preliminary concept for the element that will be assessed at mission concept review. In our hypothetical example, this might mean a more detailed preliminary espresso maker concept that fits within the existing constraints of the architecture (e.g., variations in mass, volume, or coffee output). After a successful mission concept review, the concept is added in as an element in the Architecture Definition Document.

At an acquisition strategy meeting, where the element moves ahead for implementation, NASA decides whether the new element should be built by NASA, an industry partner, or an international partner. The illustration to the right shows the path of our hypothetical example, with partner integration points.

This fictional, simplified example demonstrates how NASA uses the pre-formulation process to identify needs and develop concepts into exploration elements ready to explore the Moon, Mars, and beyond.



2024 **FEATURE**

Architecture-Driven Technology Gaps

For more detail on architecture-driven technology gaps, see the associated 2024 white paper and Architecture Definition Document appendix.

As part of the architecture definition effort, NASA has identified technologies that the agency must mature or develop to achieve the Moon to Mars Objectives. The latest revision of the Architecture Definition Document captures those areas of needed innovation in the form of architecture-driven technology gaps. These gaps outline capabilities that the architecture cannot accomplish with existing technology.

NASA defines these architecture-driven technology gaps in solution-agnostic terms. The agency recognizes that it needs to mature a capability, but does not prescribe or prejudice an approach or technology that could supply that capability.

Public documentation of the technology gaps allows NASA to communicate desired capabilities to industry and international partners. Each gap represents fruitful areas for research, development, and innovation that can help NASA and its partners invest technology development resources wisely.

The Architecture Definition Document appendix for technology gaps includes a full list of the technology gaps, including key aspects of each technology gap, segment and sub-architecture mappings, subsidiary "child gaps," and a brief summary.

The gaps are listed in a priority ranking based on four weighted metrics: criticality (the degree to which closing the gap would enable the architecture), urgency (how soon investment in the gap is needed), breadth (how common the gap is across sub-architectures), and depth (the degree to which the gap depends on future architecture decisions). NASA assigns every gap a score for each metric; the resulting normalized scores create the priority list.

The architecture-driven technology gaps are a dynamic effort. The list will evolve over time as technologies mature and fill the gaps, the prioritization of gaps changes in response to architectural decisions, and new gaps are identified.

NASA identifies a wide range of technologies that can enable future spaceflight. The architecture-driven technology gap effort was coordinated with the recent Civil Space Shortfalls effort led by NASA's Space Technology Mission Directorate. All of the architecture-driven technology gaps appear in that list of shortfalls, alongside a wide variety of other technology needs.

NASA has a long history of developing new and innovative technologies to advance spaceflight, benefiting humanity in the process. The Moon to Mars Architecture effort continues that legacy by stoking the creation of new technologies through gap definition.

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

Five high-priority technology gaps identified in 2024. The initial list included 56 total gaps, but NASA will revise as developments and analysis occur. For the most up-to-date version of the gaps, see the current revision of the Architecture Definition Document.

Example Tech Gap

Gap ID	Gap Title	Priority
ESDMD #0101	Lunar Surface Positioning, Navigation, and Timing Systems for Extreme Temperature, Radiation, and Dust	! Higher Priority

Gap Description

Current positioning, navigation, and timing (PNT) systems for exploration assets and crew provide relative position but lack the ability to determine their absolute location. Long traverses across the lunar surface will require absolute localization to facilitate path planning and execution. There is a need for improvements to current absolute and relative PNT systems and technologies to accurately track crew and mobile surface assets. Additionally, PNT systems should be operable for expected durations and protected from lunar debris, dust, temperature variations, and exposure to radiation or any other space weather/lunar phenomena.

Architecture-Driven Child Gaps

- 0101-01: Positioning and navigation systems for lunar surface applications
- 0101-02: Accurate and stable timing systems for surface exploration assets on the lunar surface
- 0101-03: Robust positioning, navigation, and timing systems for the extreme lunar surface environment

Architecture Impact and Benefits

Without gap closure, the impacts may include reduced positioning, navigation, and timing systems accuracy. Additionally, due to the environment, there is a risk of PNT systems being compromised and unable to operate and perform at expected levels.

Architecture Traceability

UC/Fs

- UC-M-601 L -- FN-C-201 L
- UC-C-202 L -- FN-C-201 L
- UC-C-203 L -- FN-C-201 L

Key Decision

Metrics

Current State of the Art

There are no current NASA or ESA rovers on the moon. Current Mars rovers possess state-of-the-art PNT capabilities for mobile assets on another planetary surface.

Performance Target

Achieve absolute localization of crew, mobile, and in-place assets on the order of TBD meters.

Sub-Architecture(s)

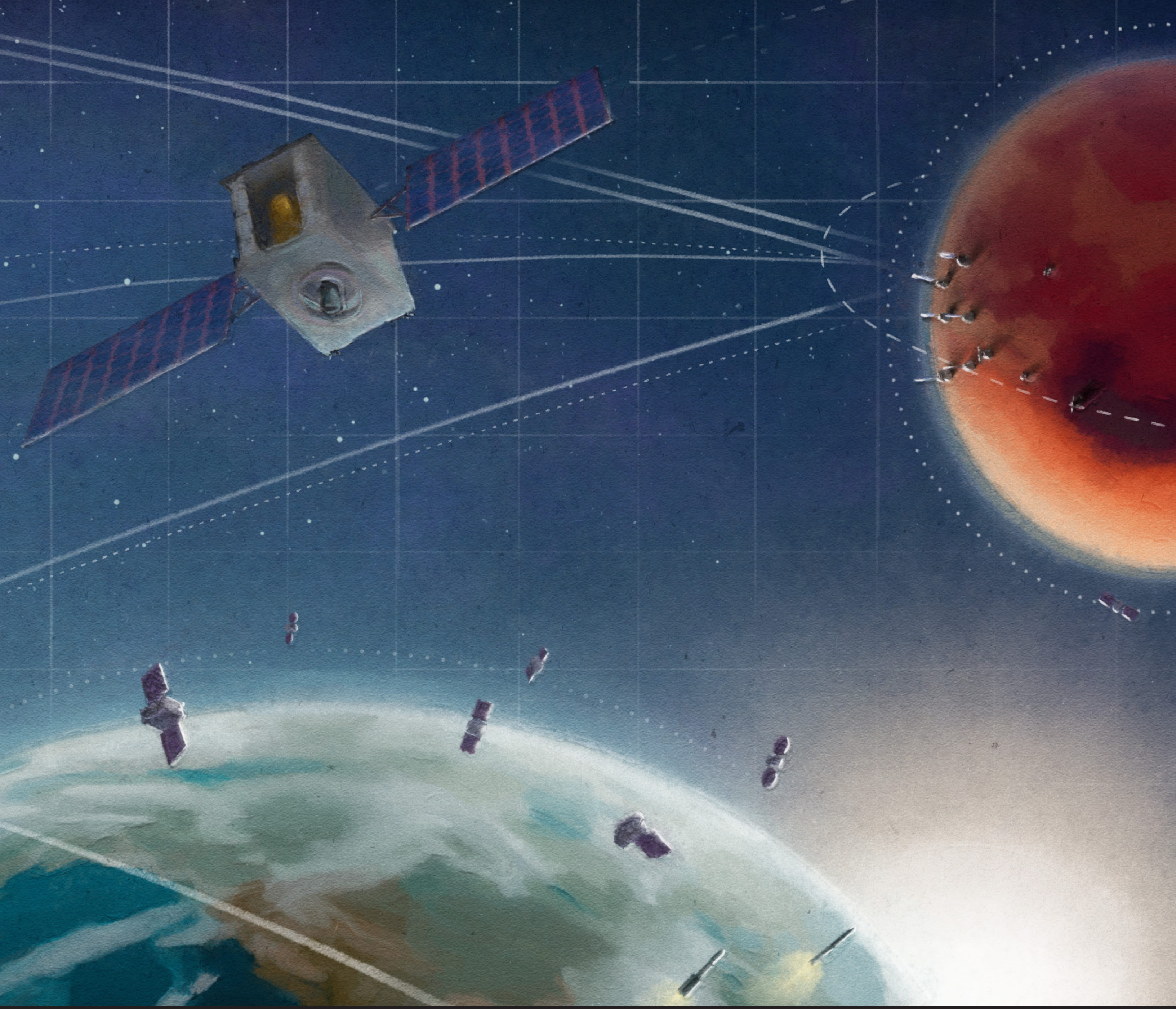
Communications and Positioning, Navigation, and Timing Systems

Campaign Segment(s)

Foundational Exploration

Sustained Lunar Evolution

Consult the Architecture Definition Document Appendix



2024 **FEATURE**

Architecture Decision Roadmapping

For more detail on architecture decision roadmapping, see the associated 2023 white paper, "Key Mars Architecture Decisions," and Architecture Definition Document appendix.

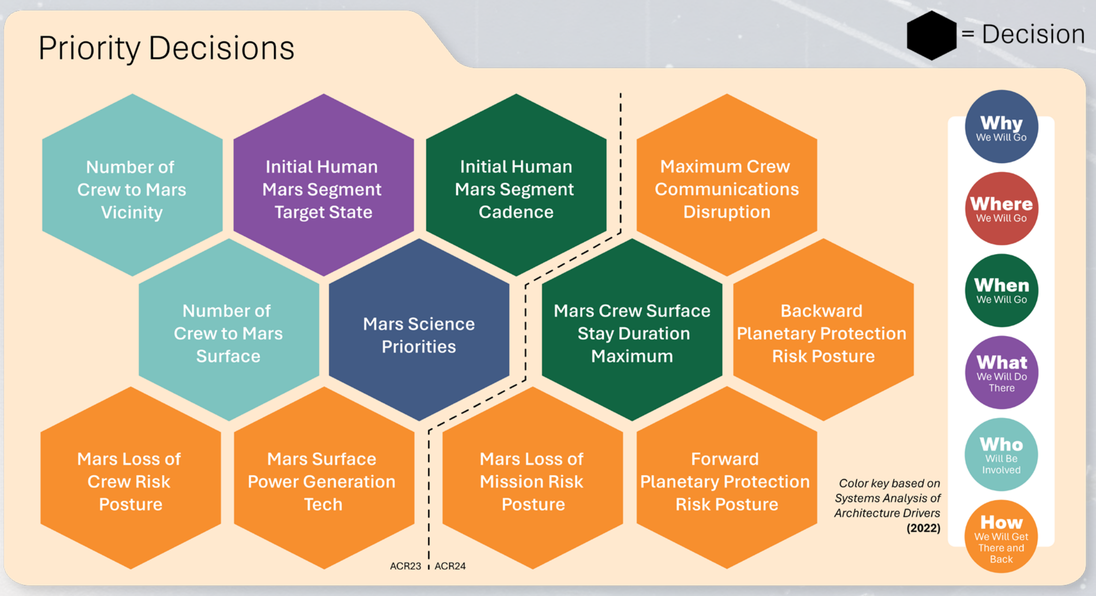
Developing an exploration architecture requires an incredible number of decisions across NASA. Each of these decisions has precedent or flow-down impacts on the architecture.

While every decision is important, some will have major flow-down impacts on other subsequent decisions. Mapping out these driving decisions and making them at the appropriate time is key to the success of an evolutionary architecture development effort. For example, when developing a Mars architecture, the decision to use a certain power technology, to send a certain number of astronauts to the surface, or to use a particular fuel for ascent will affect a huge number of later decisions.

As part of NASA's Moon to Mars Architecture development, NASA has undertaken a decision roadmapping effort to identify driving decisions and better understand their impacts on the architecture. The agency developed a new decision methodology and built cutting-edge digital engineering tools to track the entire decision space (i.e., the network of decisions and the relationships between them). The latest revision of the Architecture Definition Document includes a new appendix documenting this effort.

NASA provides a concise decision statement (e.g., how many crew to the Mars surface per mission?), expands on the context (e.g., how different numbers of crew to the surface changes the end-to-end architecture), and traces the flow-down relationships between this and other decisions. These are architecture decisions, not implementation decisions; they set a target while allowing for flexibility in mission planning.

As part of the annual Architecture Concept Review cycle, NASA's architecture teams develop "decision packages" that agency leaders can use to make those decision. As key driving decisions are made and documented in the Architecture Definition Document, NASA will add and track new or flow-down decisions.



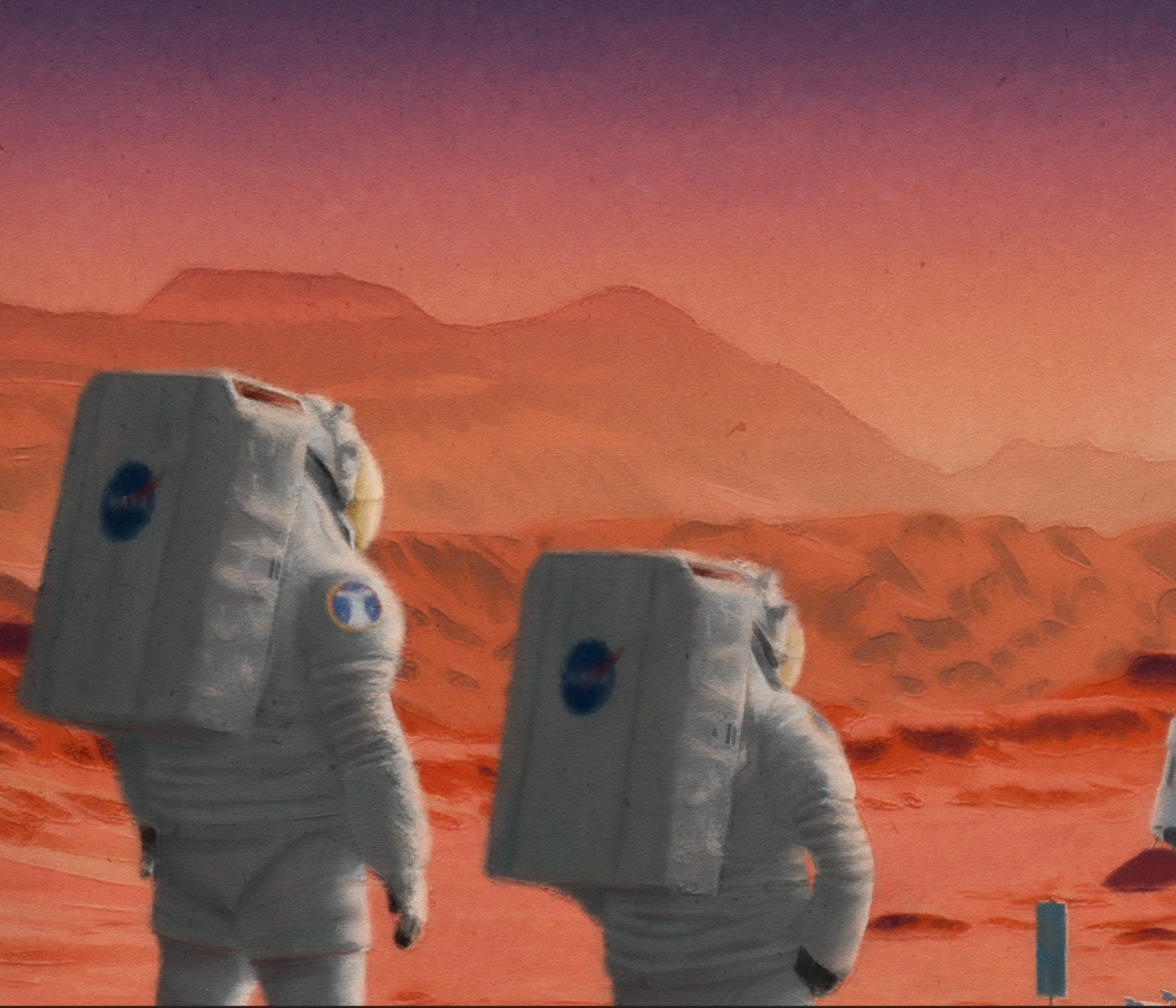
Consult the Architecture Definition Document

Appendix

Example Decision

MD-01 INITIAL HUMAN MARS SEGMENT SCIENCE OBJECTIVE PRIORITIES

The agency's Moon to Mars strategy identifies science as one of three pillars on which the blueprint for sustained human presence and exploration throughout the solar system is built. The needed decision outcome is a formulation of more specific science objectives — traceable to NASA's high-level "blueprint" science objectives — for missions carried out during the initial human Mars segment and prioritization of these objectives. Decision prerequisites will include inputs from and coordination between affected science communities and organizations such as academia, National Academies, affected NASA science advisory committees, and the Human Research Program. Priority science objectives have substantial flow-down impacts to most architecture and operations decisions. Therefore, the Mars science priorities key decision must be placed earlier in the Mars decision roadmapping process.



2024 FEATURE

Mars Surface Power Decision

For more detail on NASA's decision regarding surface power for initial human Mars missions, see the associated 2024 white paper, "Key Mars Architecture Decisions," and Architecture Definition Document appendix.

At the 2024 Architecture Concept Review, NASA selected nuclear fission power as the primary surface power generation technology for initial human Mars missions. This was the first driving architecture decision made under the decision roadmapping process.

The Martian surface poses many unique environmental challenges for power generation. Any power generation source must be resilient to global dust storms, strong winds, and gravity that is about double that of the Moon. If a mission relies on in-situ resource utilization, power generation technology must also be deployed autonomously, before human explorers arrive. Even with humans present to tend to the equipment, Mars's sheer distance from Earth means that opportunities for major repairs or spare parts will be in short supply.

Additionally, a Mars power generation technology must scale to accommodate a variety of potential architectures. NASA engineers conducted in-depth studies of a variety of options, including solar power, nuclear power, fuel cells, geothermal energy, wind power, and biogeneration, coordinating with subject matter experts across NASA.

Trade space studies ultimately recommended that nuclear fission power offers the ideal combination of energy output, environmental resiliency, cost, and overall reduction of risk. The Artemis campaign offers the opportunity to test this technology on the Moon, reducing risk for later Mars missions. NASA debuted these findings and the associated decision at the 2024 Architecture Concept Review.

White Paper Excerpt

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 stood out as offering the most value: nuclear power and solar power.

Solar power could be feasible as a primary power source for initial human Mars missions if designed to address the challenges of dust accumulation and the day/night cycle. To clear accumulated dust from solar panels, NASA could augment panels with robotic dust wipers, pressurized gases, mechanical array tilting, or other manners of dust removal. However, these 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.

High energy density **nuclear power** — either 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 suitable to applications with smaller power loads. For higher power needs (e.g., support or in-situ resource utilization), fission surface power is readily scalable to the needs of diverse Mars architectures.

While **geothermal energy** could be used for eventual Martian settlements, NASA has limited data on local geothermal availability and has not matured geothermal technologies for Mars.

Mars has insufficient sustained winds for reliable power using **wind turbines**. Wind is a key design consideration for Mars surface power, but would not suffice as the primary source of power.

Fuel cells, which generate electricity through chemical reactions, do not trade well because they require large amounts of landed reactant or large amounts of energy to make reactants in situ.

Biogeneration uses microorganisms to convert organic feedstock into heat or a commodity that can be used to generate power. This technology would greatly complicate planetary protection.

Note: Content has been abbreviated for this executive overview. Consult the white paper for more detail.

Architecture Strategy

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 development effort for the agency's exploration architecture, focusing on work performed during the 2024 Architecture Concept Review cycle. It begins with an overview of the architecture process and then highlights NASA's key architecture activities over the past year.

HISTORICAL CONTEXT

Since the conclusion of the Apollo program, which saw humanity's first steps on the Moon in the 1960s and 70s, the quest to return human explorers to the lunar surface and journey on to Mars has been a topic of continuous discussion, development, and analysis. Over the last 50 years, the agency has considered many different architectures that would resume crewed missions to the Moon or send them on to the Red Planet.

Each approach reflected the goals or focus of the environment or technologies available at that time. However, that interest and desire has not translated into flight missions until NASA's Artemis campaign.

To ensure the long-term utilization of the Moon for science, discovery, and economic benefit, and to set the stage for Mars exploration, the agency adopted and published **NASA's Moon to Mars Objectives**. Then, the agency initiated an annual process to establish and evolve **NASA's Moon to Mars Architecture**, the framework to achieve those objectives.

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 and to improve life on Earth.

STRATEGY AND OBJECTIVES

NASA's Moon to Mars Strategy applies a rigorous and thoughtful systems engineering approach to crewed deep space exploration. Systems engineering distills NASA's grand vision for science and exploration into attainable goals. This process involves establishing objectives, evaluating needs, appreciating risks, and understanding the broader context.

The strategy is not static; it is evolutionary. Annual analysis — in the form of the **Architecture Concept Review** cycle — realizes change in response to new technologies, discoveries, and priorities.

NASA's Moon to Mars Objectives are the cornerstone of the agency's strategy for crewed exploration of deep space. They establish and document an objectives-based — as opposed to a capabilities-based — approach to human exploration. They focus on the big picture, the "what" and "why" of what NASA should be doing, before prescribing the "how" (e.g., a specific launch vehicle, technology, or acquisition approach).

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

Applied Science | Carry out science utilizing integrated human and robotic techniques to inform the design of exploration systems.

Lunar Infrastructure | Enable 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.

Read the Objectives

Architecture Process

OVERVIEW

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

NASA's architecture approach distills agency-developed objectives into operational capabilities 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 agency mission directorates — Space Operations, Science, Space Technology, and Aeronautics — as well as commercial, academic, and international partners, NASA's Exploration Systems Development Mission Directorate leads crewed deep space exploration for the agency. The directorate develops and implements the systems necessary to achieve its exploration goals through the Moon to Mars Architecture.

Within the directorate, NASA's Strategy and Architecture Office leads the definition, documentation, and disposition of the architecture with buy-in from all stakeholders. They do so through the annual Architecture Concept Review process.

ARCHITECTURE CONCEPT REVIEW

The Architecture Concept Review cycle culminates in a meeting where leaders from across NASA's mission directorates, centers, and technical authorities to consider updates to the architecture. The architecture team polls attendees, seeking concurrence on the architecture to ensure a united vision for crewed exploration in deep space.

After completing the Architecture Concept Review, the agency releases a new revision of the Architecture Definition Document and white papers on specific technical topics. These products share updates, foster collaboration, and build excitement for humanity's future among the stars.

STRATEGIC ANALYSIS CYCLE

The Architecture Concept Review cycle begins with the kickoff of that year's strategic analysis cycle. Strategic analysis cycle tasks and trade studies help NASA to better understand the architectural needs, capability gaps, and opportunities to enhance the architecture through the addition of new elements.

ARCHITECTURE WORKSHOPS

Each year, shortly after the release of the latest architecture products, NASA hosts workshops to gather feedback from industry, academic, and international partners. There, attendees dive into the latest updates to the architecture and discuss how partnerships can help NASA achieve its Moon to Mars Objectives.

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 and 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 | An action 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.

ARCHITECTING FROM THE RIGHT

To develop NASA's Moon to Mars Architecture, NASA begins from its broadest goals — the farthest in the future on the timeline — in a process called "architecting from the right." This process distills NASA's Moon to Mars Objectives into the capabilities NASA needs to achieve those objectives and then maps them to the specific elements, systems, and hardware that will take us back to the Moon and beyond.

Architecting from the right helps NASA ensure that it's making the right investments now to build the capabilities it will need in the future. The Moon to Mars Architecture is evolvable, with capabilities building on one another to enable increasingly ambitious missions. The lessons we learn by exploring the Moon will help us decide how to venture on to Mars and beyond.

DECOMPOSITION FEATURES

This process of architecting from the right translates desired outcomes (the objectives) into the features of an architecture needed to produce them, or characteristics and needs. These characteristics and needs are further distilled into actionable functions and use cases that must be employed to produce them. From there, engineers group functions and use cases into exploration elements or reference missions that could effectively provide that subset of capabilities.

Objective decomposition is part of the agency's annual Architecture Concept Review process. NASA documents the decomposition in a model-based systems engineering environment, where use cases and functions can be further mapped to individual requirements owned by elements' implementing programs.

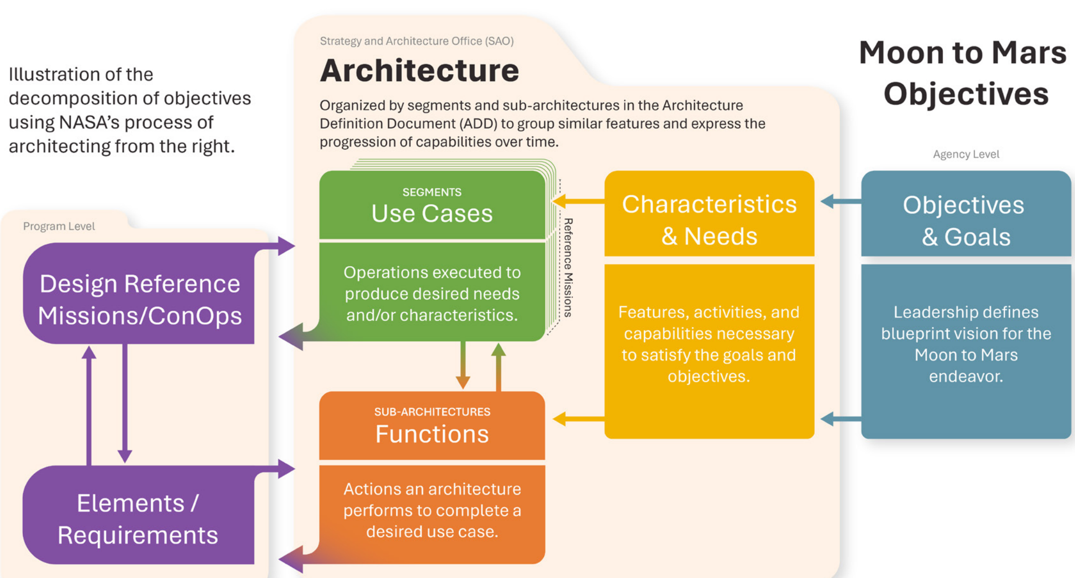
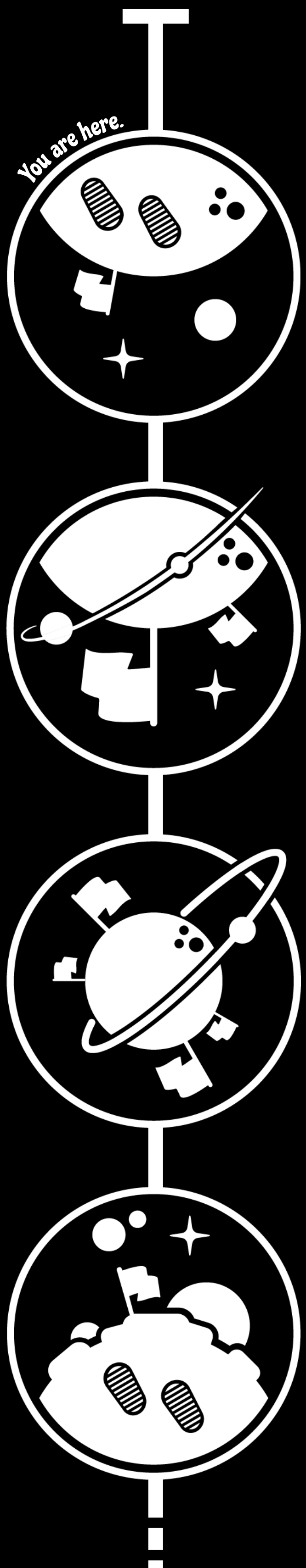


Illustration of the decomposition of objectives using NASA's process of architecting from the right.

Architecture Segments

NASA's Moon to Mars Architecture currently comprises four segments: Human Lunar Return, Foundational Exploration, Sustained Lunar Evolution, and Humans to Mars. These segments capture the evolutionary nature of NASA's Moon to Mars exploration strategy, growing in complexity over time to meet more of the agency's Moon to Mars Objectives.



HUMAN LUNAR RETURN

Includes the inaugural Artemis missions that 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, first person of color, and first international partner astronaut on the lunar surface. Missions pursued in this segment will lay the groundwork to achieve the Moon to Mars Objectives.

FOUNDATIONAL EXPLORATION

Will expand 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 stimulate future economic investment and foster participation in lunar science and exploration. The segment will increase our science capabilities, mission duration, and 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 human 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 our 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 in future segments beyond Humans to Mars.

Sub-Architectures

Each of the 12 sub-architectures represents a task, technology, or process that NASA must master to achieve the Moon to Mars Objectives.

AUTONOMOUS SYSTEMS AND ROBOTICS
Employ software and hardware to assist the crew and operate during uncrewed periods.

C&PNT
COMMUNICATIONS AND POSITIONING, NAVIGATION, AND TIMING SYSTEMS
Enable transmission and reception of data, determination of location and orientation, and acquisition of precise time.

DATA SYSTEMS AND MANAGEMENT
Transfer, distribute, receive, validate, secure, decode, format, compile, and process data and commands.

HABITATION SYSTEMS
Ensure the health and performance of astronauts in controlled environments.

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

ISRU SYSTEMS
IN-SITU RESOURCE UTILIZATION SYSTEMS
Extract resources in space or on the Moon or Mars to generate products.

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

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

MOBILITY SYSTEMS
Move crew and cargo around the lunar and Martian surfaces.

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

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

UTILIZATION SYSTEMS
Enable science and technology demonstrations.

Architecture Elements

Individual elements in the architecture are the systems and hardware that enable exploration. NASA maps elements to one or more sub-architectures, and they may be used across multiple campaign segments.

Some elements predate the architecture development effort (e.g., the Space Launch System rocket and Orion spacecraft) and were mapped to the use cases and functions they already fulfill when this effort began. Other elements have arisen from capability gaps that were not fulfilled by existing elements.

As the Moon to Mars Architecture progresses through the segments, NASA will instantiate more elements to increase the number of Moon to Mars Objectives that missions may accomplish.

SPACE LAUNCH SYSTEM

NASA's Moon Rocket

ORION SPACECRAFT

Our Ride to the Moon

EXPLORATION GROUND SYSTEMS

Assembly, Launch, Recovery

EXPLORATION EVA SYSTEMS

Spacesuits for Moonwalks

LUNAR TERRAIN VEHICLE

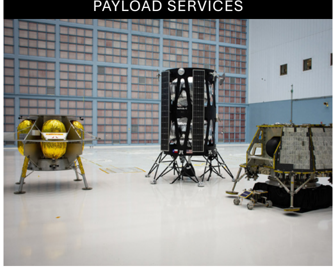
The Artemis Moon Buggy

PRESSURIZED ROVER

Mobile Lunar Lab

CLPS

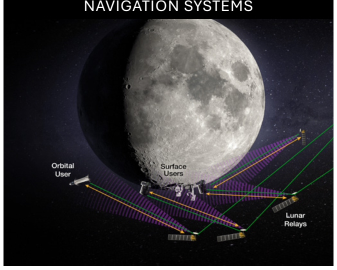
COMMERCIAL LUNAR PAYLOAD SERVICES



Science and Tech Deliveries

LCRNS

LUNAR COMMUNICATIONS RELAY AND NAVIGATION SYSTEMS

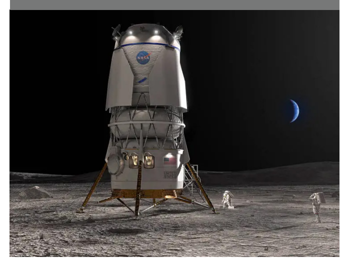


The Moon's Mobile Network

HUMAN LANDING SYSTEM

SPACE X STARSHIP

BLUE ORIGIN BLUE MOON

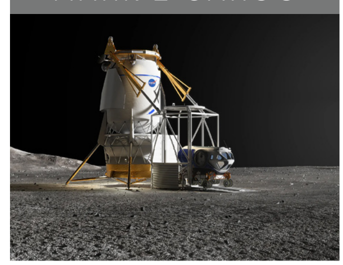


Artemis Astronauts' Lunar Landers

HUMAN-CLASS DELIVERY LANDER

SPACE X STARSHIP

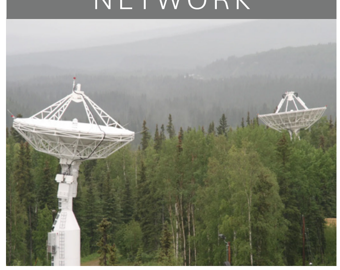
BLUE ORIGIN MARK 2 CARGO



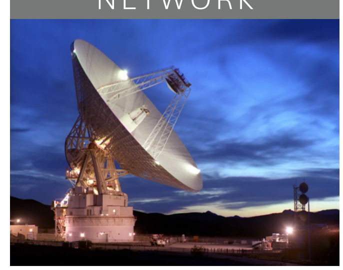
Lunar Freight Deliveries

NASA COMMUNICATIONS NETWORKS

NEAR EARTH NETWORK



DEEP SPACE NETWORK

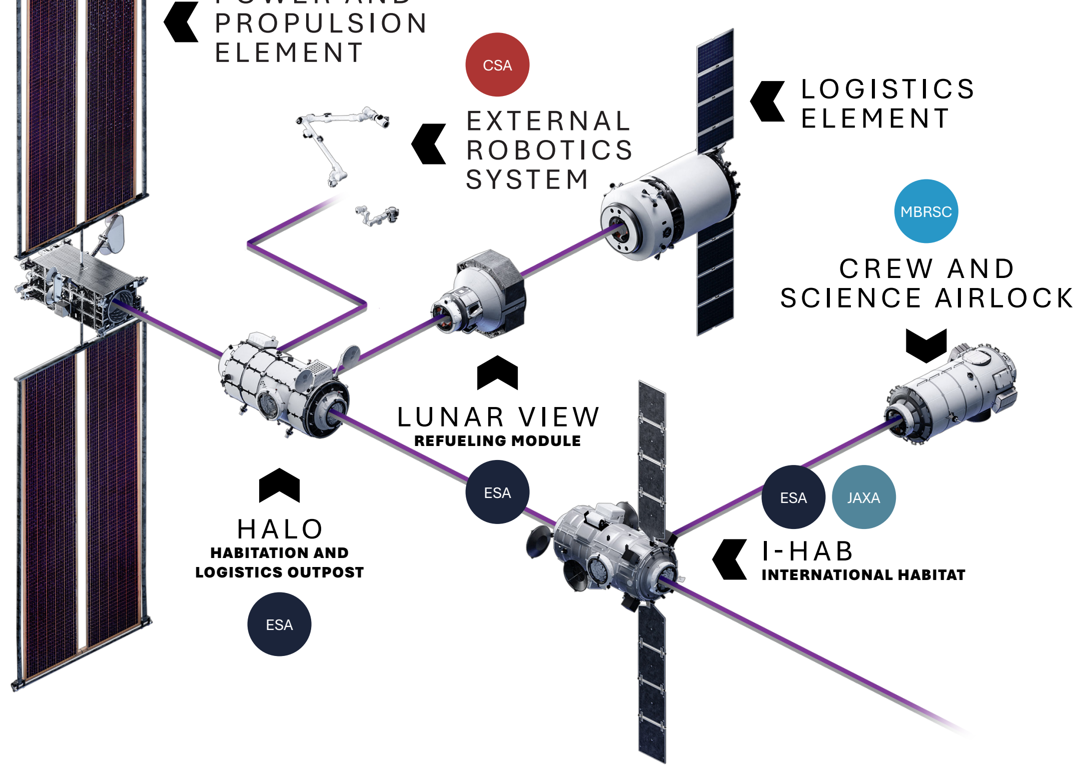


Call Home from Space

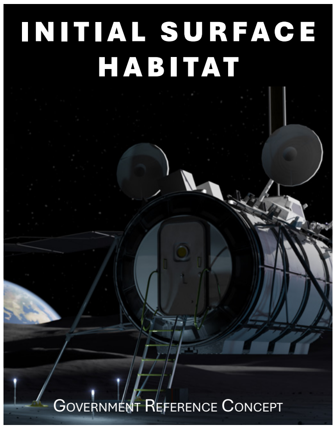
Architecture Elements

GATEWAY

Our Home in Lunar Orbit



Logistics, Delivered



Home on the Lunar Surface

INTERNATIONAL PARTNERS

- CSA — Canadian Space Agency
- ESA — European Space Agency
- JAXA — Japan Aerospace Exploration Agency
- MBRSC — Mohammad Bin Rashid Space Centre

NASA encourages countries and international space agencies to engage in the agency's Moon to Mars Architecture. International cooperation will be key to establishing a long-term presence on the lunar surface and setting humanity on a path to the Red Planet.

Countries or international space agencies seeking to contribute to or engage should reach out to NASA's Office of International and Interagency Relationships: **HQ-M2Marchitecture-International@mail.nasa.gov**

Selecting the Right Tools

Architecting from the right means developing capabilities and technologies needed to achieve specific long-term goals, not 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.

2025 **LOOK-AHEAD**

In 2025, NASA will continue to refine the architecture by maturing the objective decomposition for the Moon and Mars, updating the architecture-driven technology gaps, and making progress on driving architecture decisions. NASA will also engage with industry and international partners to identify innovative solutions to architecture challenges and coordinate with the science community to ensure the architecture can meet science goals.

nasa.gov/architecture

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