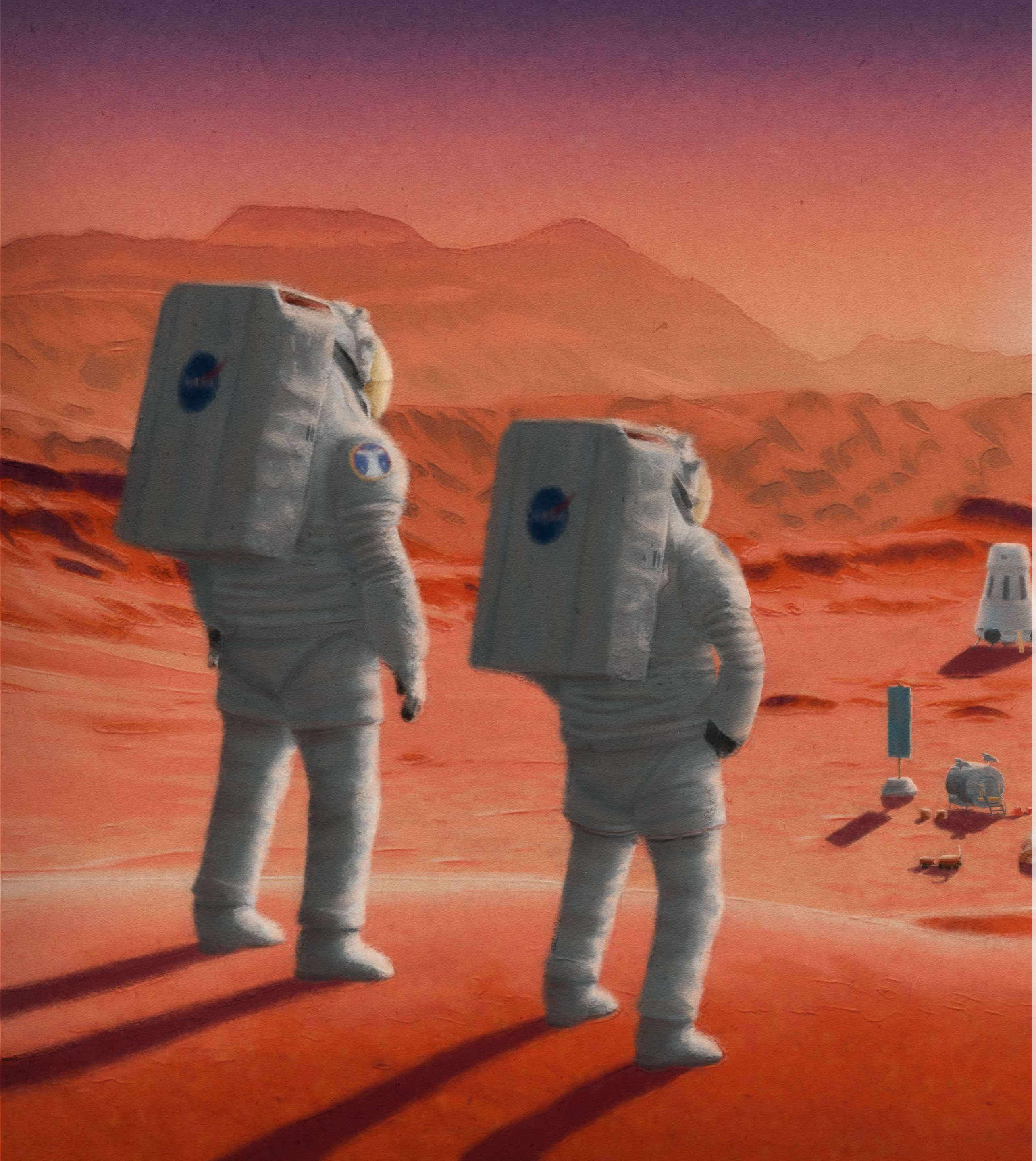


National Aeronautics and Space Administration

NASA's

Moon to Mars Architecture

CAPS and CBPSS Spring Meeting

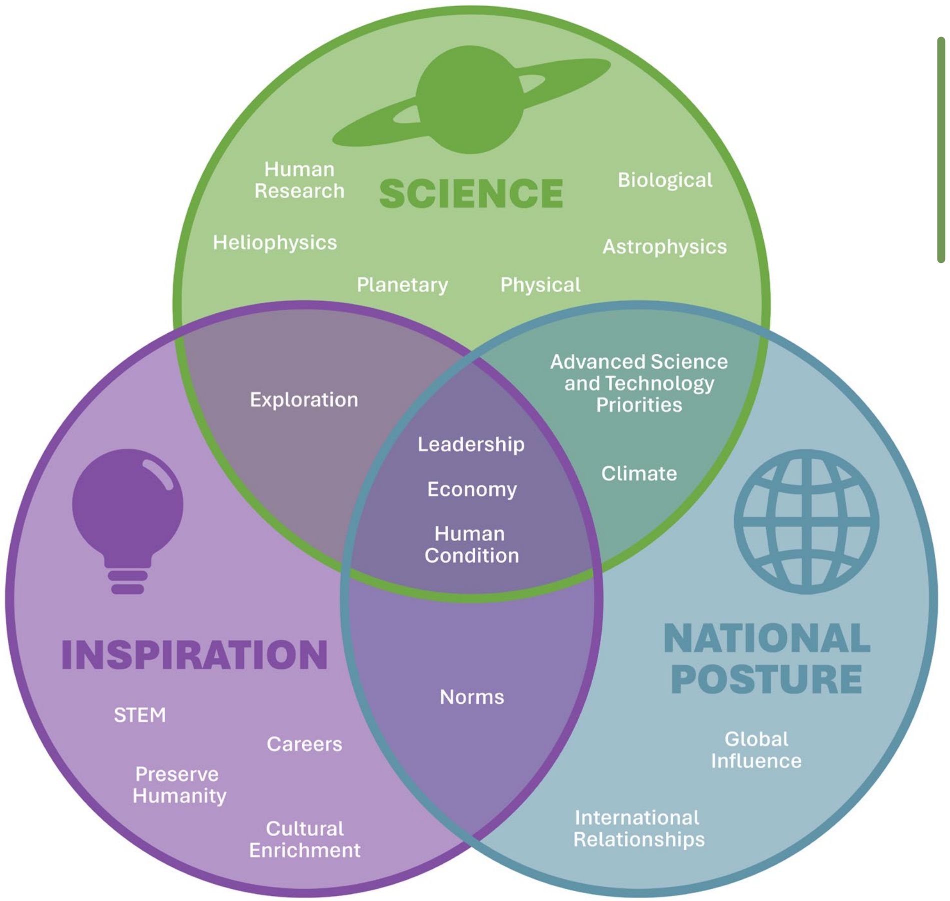
Committee on Astrobiology and Planetary Sciences (CAPS)
Committee on Biological and Physical Sciences in Space (CBPSS)
National Academies of Sciences, Engineering, and Medicine
April 2, 2025

Nujoud Merancy
Deputy Associate Administrator
Strategy and Architecture Office
Exploration Systems Development Mission Directorate

Why Moon *to* Mars?

Mars mission success will be enabled by incremental development, demonstration, and test;
Lunar exploration gives NASA the opportunity to prove the systems, capabilities, and operational paradigms needed for a successful human Mars exploration campaign.

Why We Explore...



SCIENCE

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

INSPIRATION

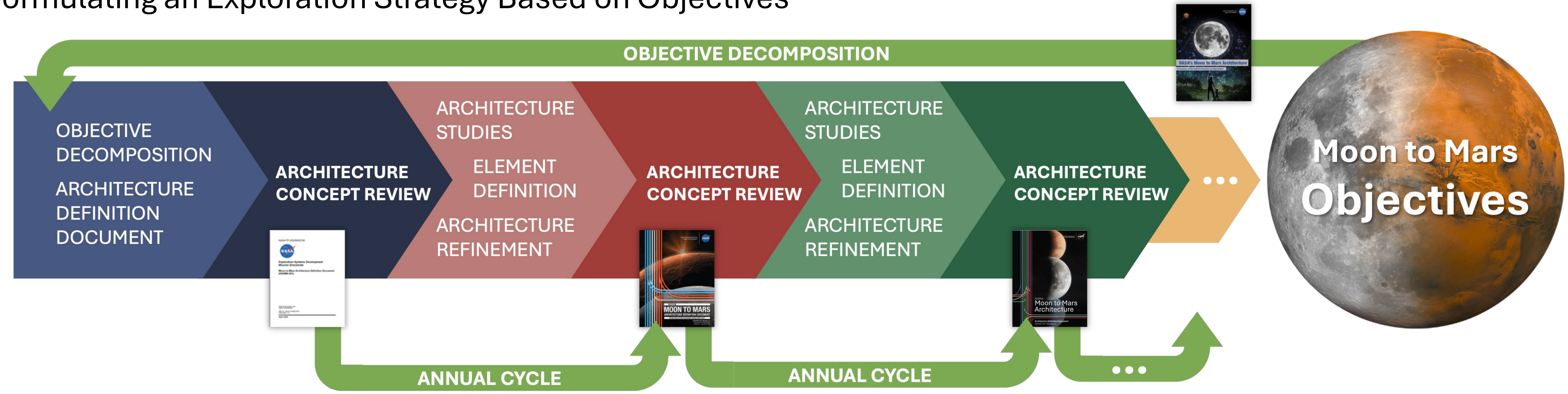
Accepting audacious challenges motivates current and future generations to contribute to our voyage deeper into space.

NATIONAL POSTURE

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

NASA's Moon to Mars Architecture

An Evolutionary Architecture Process:
Formulating an Exploration Strategy Based on Objectives



TRACEABILITY

Decomposition of Blueprint Objectives to executing Architecture elements

ARCHITECTURE FRAMEWORK

Organizational construct to ensure system/element relationships are understood and gaps can be identified

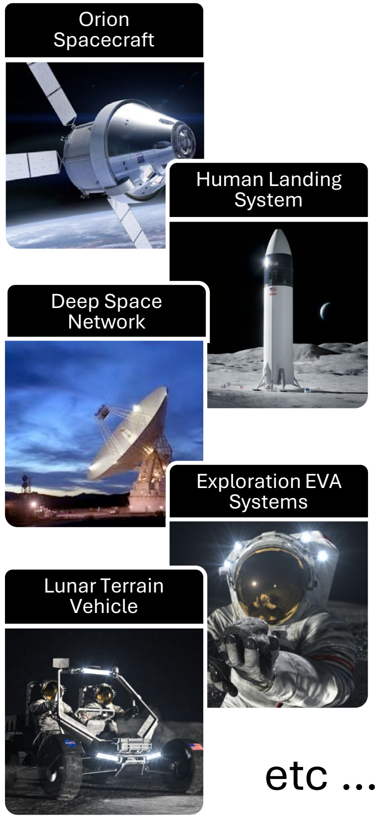
PROCESS & PRODUCTS

Clear communication and review integration paths for stakeholders

Why We Explore informed Moon to Mars objectives and definition of iterative architecture process and products to achieve horizon goals

Architecting from the Right

Programs & Projects



etc ...

Architecture

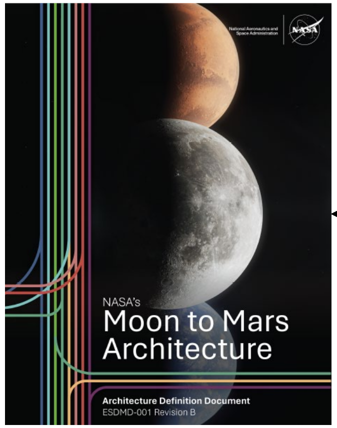
The high-level unifying structure that defines a system. It provides a set of rules, guidelines, and constraints that defines a cohesive and coherent structure consisting of constituent parts, relationships and connections that establish how those parts fit and work together.

Use Cases

Operations executed to produce desired objective needs

Functions

Actions performed to effect desired uses cases



Moon to Mars Objectives

Science | Enhance our understanding of planetary and solar, human biology, and physical sciences in unique environments of the Moon, Mars, and deep space.

Infrastructure | Develop the power, communications, navigation, resource utilization, and other capabilities necessary to support human 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.

NASA's Moon to Mars Objectives Document

https://go.nasa.gov/4eDTsk6

Rigorous systems engineering applied to identify the needs, understand relationships and identify gaps between systems to identify most effective and efficient solutions toward achieving long-term vision

Architecture Segments

FUTURE SEGMENTS
Continued development and exploration at Mars and beyond for sustained exploration of the cosmos.

HUMANS TO MARS
Initial capabilities, systems, and operations necessary to **establish human presence** and initial utilization (science, etc.) on Mars and continued exploration.

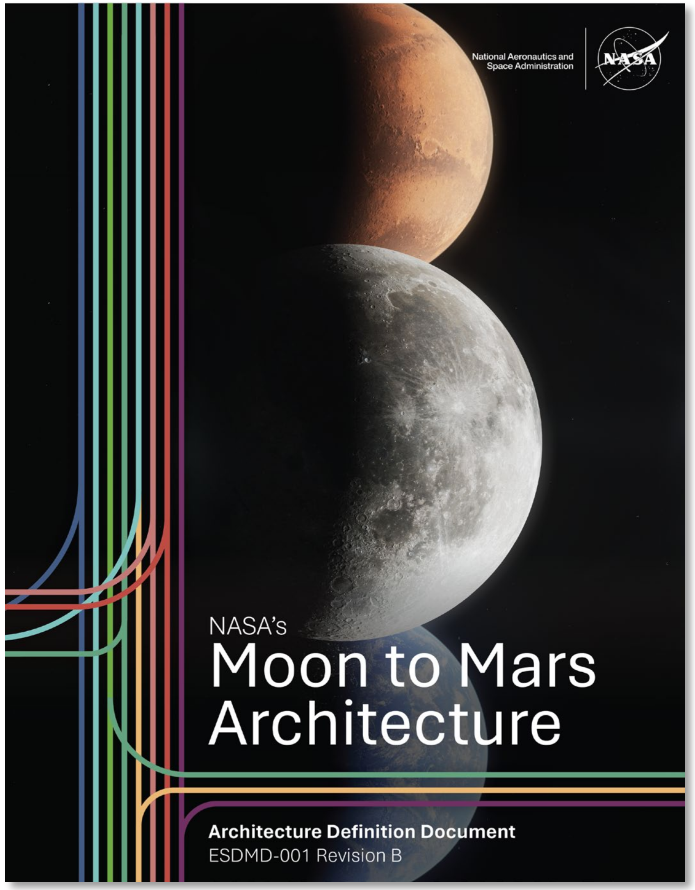
SUSTAINED LUNAR EVOLUTION
Enabling capabilities, systems, and operations to support **regional and global utilization** (science, etc.), **economic opportunity**, and a steady cadence of human presence at the Moon.

FOUNDATIONAL EXPLORATION
Expansion of lunar capabilities, systems, and operations supporting **complex orbital and surface missions** to conduct utilization (science, etc.) and **Mars forward** precursor missions.

HUMAN LUNAR RETURN
Initial capabilities, systems, and operations necessary to **re-establish human presence** and initial utilization (science, etc.) on and around the Moon.

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

2024 Architecture Updates and Products



NASA evolves its roadmap for deep space exploration through the annual Architecture Concept Review (ACR) and documents the evolution in the Architecture Definition Document (ADD) and other architecture products. 2024 architecture updates were broadly vetted through industry, academia, international partners, and throughout all agency organizations.

2024 ACR Products include:

- Revision B of NASA's Architecture Definition Document (ADD)
- Two new Moon to Mars Architecture elements
- Architecture-driven technology gaps definition and prioritization
- Initial Mars surface power technology decision
- Prioritization of 5 additional Mars architecture decisions
- 12 white papers

NASA's Moon to Mars Architecture Website

nasa.gov/architecture

ADD Rev B Updates

- **50+ pages of new content including**
  - Two new exploration elements
  - Appendix B: Key Moon to Mars Architecture Decisions
  - Appendix C: Architecture-Driven Technology Gaps
- **Objective decomposition expanded and refinements to improve clarity and feedback**
  - Addition of Humans to Mars Segment Use Cases & Functions
  - Differentiation of scale of needs (e.g. days/weeks/months)
  - Other lessons learned incorporated
- **Updated Definitions (Appendix D)**
  - Better defined the delineation between large and small cargo
  - Included call out to samples in addition to commodities and logistics items

Cargo Definitions for Objective Decomposition

Exploration Asset: All items that are in-place and being used as part of the exploration architecture.

Large Asset: For lunar, an asset that is >6 tons in mass.

Utilization Payload & Equipment: Any item that is primarily in support of and attributed to utilization activities.

Small Asset: For lunar, other non-utilization assets <6 tons in mass.

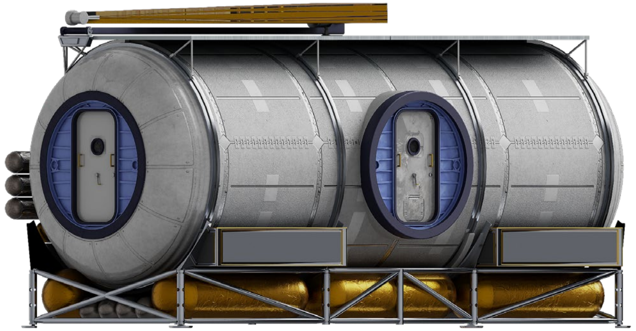
Samples/ Commodities/ Logistics Items: Samples, commodities, and supplies (not including propellant) that are needed to support mission activities.

Large Cargo: *Items greater than 6 tons that are transported from one location to another*

Small Cargo: *Items less than 6 tons that are transported from one location to another*

Utilization Payload: *Science/Research Payloads + Technology Demonstrations*

New Element: Initial Surface Habitat



Government Reference Concept
Design implementation will differ.

FN#	Primary Functions Met by Element
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 payload(s) and/or equipment for long durations (months to years+)
FN-U-201 L	Provide intravehicular activity facilities, utilization accommodation, and resources, operable during crewed and uncrewed increments on the lunar surface

+15 additional functions.

- Enables Foundational Exploration segment objectives requiring longer-duration missions, increased crew size, and enhanced surface utilization
  - Additional two crew on the surface for seven to 28 days with logistics resupply
  - Supports EVAs and science & technology utilization during crewed & uncrewed periods
  - Facilitates logistics transfer with crew portable carriers and an integrated surface docking system
  - Provides general habitation functions, such as provision of medical systems, supplying environmental control and life support system capabilities
- Extensible with augmentation to support longer-duration habitation include robust crew medical systems/health kits; enhancing surface EVAs; and providing interfaces for to become part of larger habitation system

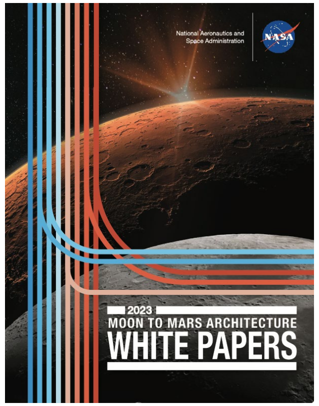
New Element: Lunar Surface Cargo Lander

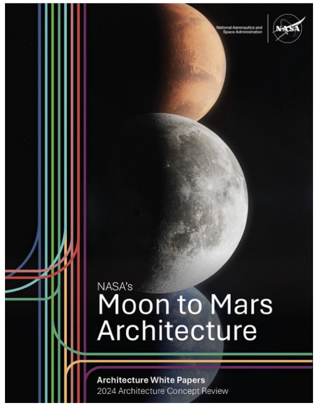
FN#	Primary Functions Met by Element
FN-T-202 L	Transport a moderate amount of cargo (1000s of kg) from Earth to south pole region sites on the lunar surface
FN-T-204 L	Transport a moderate amount of cargo (1000s of kg) from Earth to distributed sites outside of the south pole region on the lunar surface
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

- Foundational Exploration and Sustained Lunar Exploration segment goals require significant transportation of cargo to the lunar surface
- Benefit to enabling multiple cargo lander providers across both international partner and U.S. industry (e.g., through dissimilar redundancy)
  - Utilization payloads, technology demonstrations, and logistics delivery would benefit from the flexibility of a range of cargo delivery options
  - International Space Station lessons learned can be applied to a mixed cargo lander fleet approach
  - Small cargo lander capabilities can address a lower range of logistics needs and several potential utilization payloads needs

White Papers

2022 White Papers	2023 White Papers	2024 White Papers
Why NRHO: The Artemis Orbit	Lunar Communications and Navigation Architecture	Lunar Mobility Drivers and Needs
Why Artemis will Focus on the Lunar South Pole Region	Lunar Site Selection	Lunar Surface Cargo
Mars Transportation	Analytical Capabilities In-situ vs. Returned	Priority Science Enabled through Architecture
Gateway: The Cislunar Springboard	Safe and Precise Landing at Lunar Sites	Lunar Reference Frame
Systems Analysis of Architecture Drivers	Mars Communications Disruption and Delay	Mars Crew Complement Considerations
Mars-Forward Capabilities to be Tested at the Moon	Mars Mission Abort Considerations	Mars Surface Power Tech Decision
	Mars Surface Power Generation	Mars Entry, Descent, and Landing Challenges
	Key Mars Architecture Decisions	Mars Ascent Propellant Considerations
	Round-Trip Mars Mission Mass Challenges	Humans in Space to Accomplish Science Objectives
	Human Health and Performance for Mars Missions	Responsible Exploration
	Lunar Logistics Drivers and Needs	International Partnerships
	Surface Extravehicular Activity Architectural Drivers	Architecture-Driven Technology Gaps
	Exploration Lessons Learned from the Space Station	





Moon-Focused
Mars-Focused
Cross-Cutting

NASA's Moon to Mars Architecture Website
nasa.gov/architecture

White Paper | Answer questions, communicate NASA's latest thinking, and characterize architecture challenges.

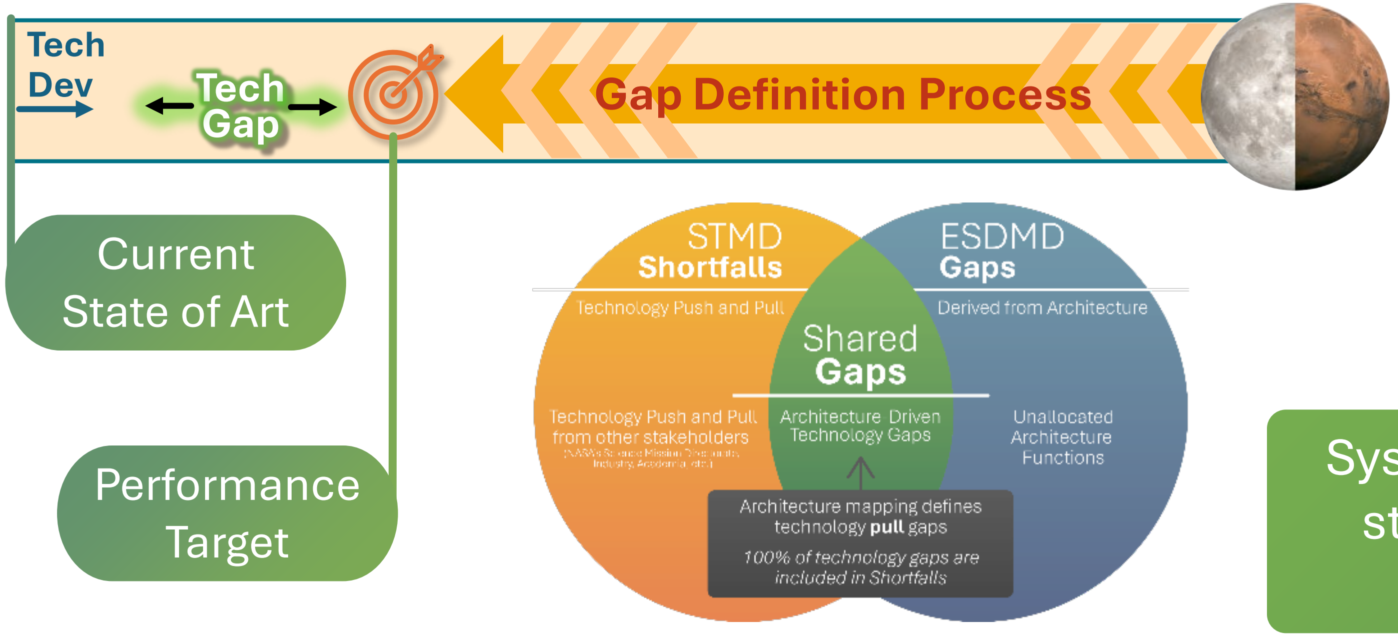
Foundational Exploration Segment Gaps

- **ACR23 ADD identified over 60 unallocated Functions for Foundational Exploration**
  - These can be grouped by similarity to identify the types of system needs (table right)
  - Highest priority needs show relative to the impact on objective satisfaction
- **Two New element additions in ACR24 addressed priority needs**
  - Surface habitation to enable 4 crew missions
  - Large cargo delivery to the surface on scales to support crew logistics and utilization
- **On-going prioritized study work to address the highest priority architectural needs**

Sub-Architecture	ACR23 Integrated Gap	ACR24 Progress
Habitation	Short Duration Crew Habitation at Lunar South Pole	Fulfilled ✓
Power	Power Sharing at Lunar South Pole	Under Study
Mobility	High-Capacity Mobility at Lunar South Pole	Under Study
Logistics	Logistics Delivery and Mgmt Systems	Under Study
Logistics	Water and Gas Transfer on Lunar Surface	Under Study
Transportation	Large Cargo Delivery to the Lunar Surface	Partial/Study ✓
Transportation	Large Cargo Return to Earth	Under Study
Habitation	Extended Crew Habitation at Lunar South Pole	
Habitation	Extended Crew Habitation in NRHO	
Utilization	Resource Identification on Lunar Surface	
Utilization	Deep Subsurface Sampling on Lunar Surface	
Utilization	Storage of Cryogenic Samples	

Architecture-Driven Technology Gaps

An **architecture-driven technology gap** is a capability that requires technology to be invented or significantly matured to enable the architecture



- ADD Appendix C: Technology gaps are **solution-agnostic**; capture a need but do not prescribe a solution
- Demand signal used globally to inform technology investments that align to NASA's Moon to Mars Architecture
- Included in STMD Shortfalls list, providing technology pull from the architecture for Moon to Mars missions
- Gaps are prioritized based on four criteria: criticality, urgency, depth, and breadth

Systems engineering process & tools governed by strict principles to enable rigorous, repeatable results

White Paper:
Architecture-Driven Technology Gaps
https://go.nasa.gov/4goQ9iq

Feedback received highlights how architecture technology gaps definition is being used across NASA, industry, and international partners to prioritize investments in research & development

Example Technology Gap

Gap Details

- Gap number, title, and description
- **Architecture impact and benefits** from architecture teams
- Current **state-of-the art** metrics sourced from technology development domain experts
- **Target performance metrics** sourced from architecture teams
- **Traceability** to sub-architectures, segments, UC/Fs and decisions
- **Priority bin** based on Gap Overall Prioritization Rating sourced from architecture teams
- Related **Child Gaps** are more specific

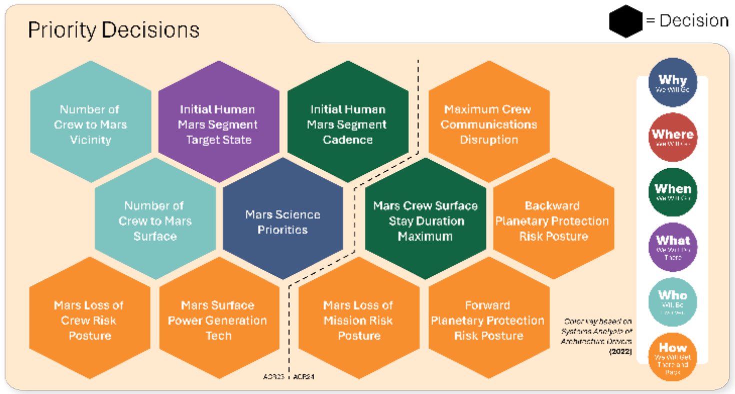
<table>
<tr><td>Gap ID
ESDMD #0301</td><td colspan="2">Gap Title
Systems to Survive and Operate through Extended Periods of Lunar Shadow</td><td rowspan="4">Priority
!
Higher Priority</td></tr>
<tr><td colspan="2">Gap Description
Assets on the surface of the Moon will be subjected to large variations in natural and induced environments. The ability to survive and operate through these extreme variations is required to enable long-duration surface operations. New or improved power, thermal management, and actuation technologies are required and will need to work together to accomplish this goal for science experiments, mobility assets, habitats, and more.</td><td>Architecture-Driven Child Gaps
• 0301-01: Freeze-tolerant thermal components
• 0301-02: Extreme temperature-tolerant mechanisms and electronics
• 0301-03: Energy storage for extreme temperatures
• 0301-04: Heat rejection systems for the lunar thermal environment</td></tr>
<tr><td colspan="2">Architecture Impact and Benefits
Without gap closure, the inability to survive extended periods of lunar shadow will impact the operating lifespan of surface assets. There may also be an inability to reuse surface assets if systems cannot survive shadowed periods.</td><td>Architecture Traceability
UC/Fs
• UC-H-105 L -- FN-H-201 L
Key Decision</td></tr>
<tr><td colspan="2">Metrics
Current State of the Art
Small spacecraft have survived extended periods of lunar shadow with damage to subsystems and degraded capability. There is currently no state of the art for any human-scale elements successfully functioning through extended lunar shadow periods.
Performance Target
Survive continuous shadow for 150 (TBR) hours or more several times a year for 10 years.</td><td>Sub-Architecture(s)
Habitation Systems
Mobility Systems
Autonomous Systems and Robotics
Campaign Segment(s)
Foundational Exploration
Sustained Lunar Evolution</td></tr>
</table>

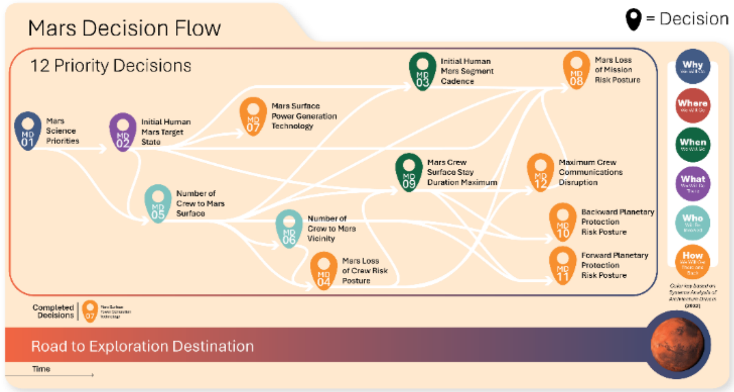
White Paper:
Architecture-Driven Technology Gaps
https://go.nasa.gov/4goQ9iq

The Architecture Definition Document includes a prioritized list of technology gaps.

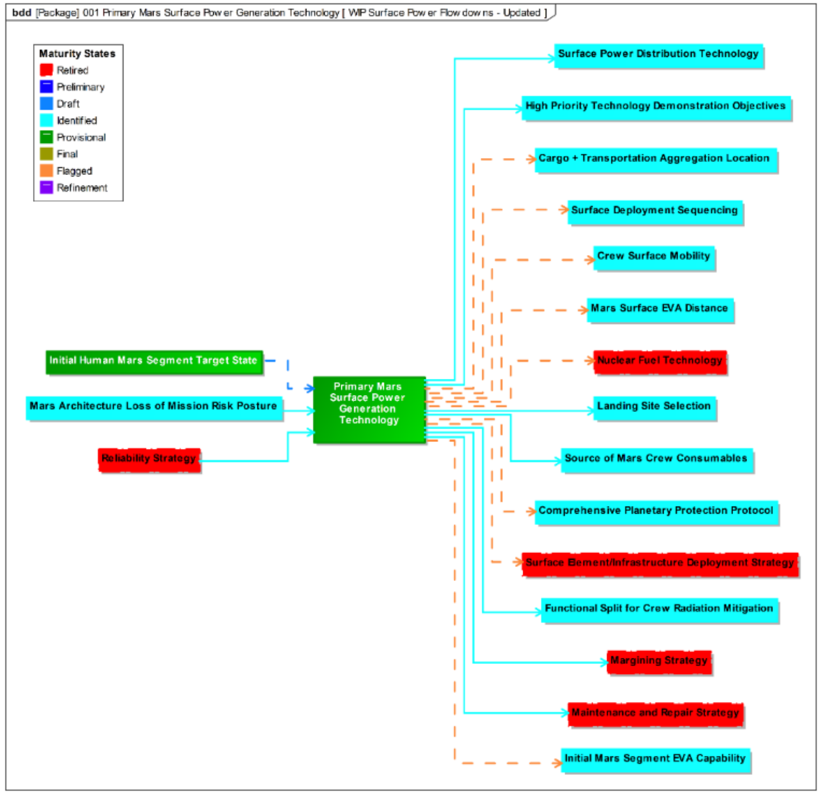
Architecture Decision Updates

- In 2023, NASA began analysis process to allow for informed decision-making by agency leadership. **This approach enables identification of needed analysis, knowledge gaps, or technologies that must be matured to achieve stakeholder objectives.**
    - Developing an exploration architecture requires innumerable decisions; every decision must be made, but not every decision must be made first.
    - The order in which decisions are made heavily influences the ultimate architecture; the flow down implications and precedence relationships of decisions must be understood.
- NASA approved **five additional priority Mars decisions** at 2024 ACR. NASA also made its first priority Mars decision, selecting the **surface power generation technology for initial human Mars missions.**
- **Complete list of key decisions**, identified through the decision process and prioritized for analysis, can be found in **Appendix B of the Architecture Definition Document.**





Mars Surface Power Decision



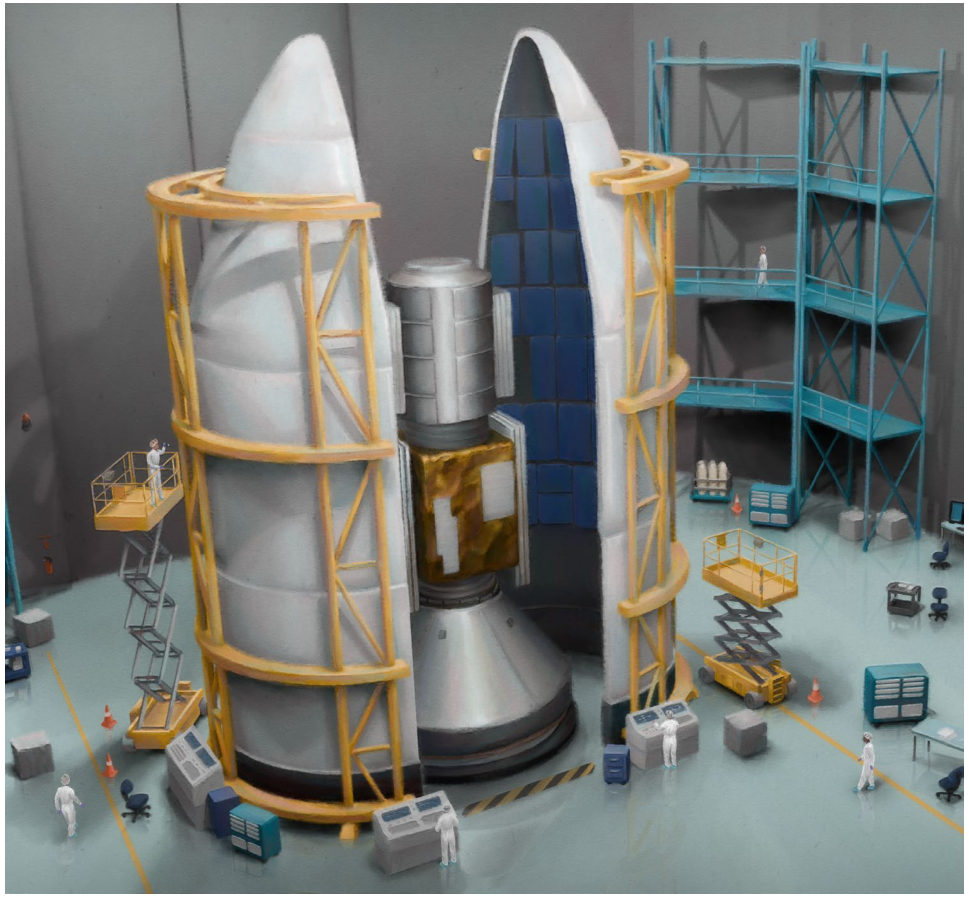
Surface power technology decision model visualization of architecture dependencies and connectivity

NASA has selected **nuclear fission power** as the optimal primary surface power generation technology for initial crewed missions to Mars

- Decision identified in ACR23 as one of highest priority due to impacts on downstream architecture
  - Decision modelling revealed decision impacts across the architecture
  - Fission power scales more easily than solar power, enabling a wider range of architectures
  - Selection of fission power also minimizes loss-of-mission risk
- Architecture analysis drew from several decades’ worth of power studies; Decision assessed with key inputs from agency experts (i.e., within STMD, OSMA, MCO); Coordinated across agency stakeholders for ACR approval

White Paper:
Mars Surface Power Technology Decision
https://go.nasa.gov/3VN2Z1r

Key Takeaways



- NASA's Moon to Mars Architecture effort applies rigorous systems engineering to develop a roadmap for achieving the Moon to Mars Objectives.
- NASA evolves that roadmap through the annual Architecture Concept Review (ACR) and documents it in the Architecture Definition Document (ADD).
- Technology and capability gaps offer opportunities to infuse innovation and global partnerships into NASA's exploration architecture.
- The architecture process and products help NASA to engage and inform potential collaborators across industry, academia, and the international community.

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https://go.nasa.gov/4206X9g

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Thank You

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