Architecture and Habitability for Long-Duration Space Exploration

Executive Summary

This document synthesizes key findings on the architectural framework, habitable volume requirements, and design principles for NASA's long-duration human exploration missions, as outlined in the Moon to Mars strategy. The overarching goal is to establish a sustained human presence on the Moon and prepare for the exploration of Mars, underpinned by a systematic, collaborative, and adaptable approach.

A core principle of the architecture is to "architect from the right and execute from the left," meaning long-term Mars goals inform near-term lunar development. The architecture is structured into four campaign segments—Human Lunar Return, Foundational Exploration, Sustained Lunar Evolution, and Humans to Mars—and organized through a framework of integrated sub-architectures, including Habitation, Power, ISRU, and Robotics.

A critical finding for habitat design is the establishment of a minimum Net Habitable Volume (NHV) based on a detailed, bottom-up analysis of crew functions. This study determined a minimum requirement of approximately **28-29 m³ per crewmember**. However, a practical case study applying these requirements to a realistic habitat design indicates that the actual required volume, accounting for access ways and packaging inefficiencies, is closer to **37 m³ per crewmember**.

Extensive ground testing under the NextSTEP program has yielded crucial habitat design guidelines. A key conclusion is that **a well-designed layout is more important than total volume**. Critical design principles include the strict separation of "clean" areas (galley, science, medical) from "dirty" areas (hygiene, waste collection, exercise) to prevent cross-contamination, and the implementation of reconfigurable modules with common interfaces to ensure flexibility across evolving missions. Inflatable habitat technology, utilizing multi-layer softgoods shells made of materials like Kevlar and Vectran, presents a promising solution for reducing launch volume and mass.

The architecture for Mars presents unique and significant challenges, primarily due to the vast distances and mission durations of up to three years. Key challenges include the exponential increase in energy required for shorter transit times, the profound health and performance risks to the crew, and the operational paradigm shift necessitated by communication delays that eliminate real-time ground support and rapid abort

capabilities. A formal decision roadmap is being developed to navigate the complex trades between transportation systems, surface infrastructure, and crew health. International and commercial partnerships are not ancillary but are foundational to the entire Moon to Mars strategy, enabling the sharing of costs, risks, and capabilities to achieve common exploration goals.

The Moon to Mars Architectural Framework

NASA's Moon to Mars exploration effort is guided by a comprehensive architectural framework designed to translate broad strategic objectives into implementable programs. This framework ensures a cohesive and traceable approach to extending human presence into deep space.

Strategic Vision and Methodology

The architecture is built on two complementary principles: **"architect from the right and execute from the left."** This means that the long-term goal of sending humans to Mars (the "right" end of the timeline) is used to define the complete set of capabilities needed. These capabilities are then developed and integrated in a progressive, left-to-right sequence, beginning with near-term lunar missions.

The process for defining the architecture's features is rooted in a systematic decomposition of high-level objectives:

1. **Objectives:** Broad, implementation-agnostic goals for exploration (e.g., "Conduct science on the Moon").
2. **Characteristics and Needs:** Translation of objectives into the necessary features or products of the architecture (e.g., "Return a variety of samples from the lunar surface").
3. **Use Cases and Functions:** Specific operations and actions the architecture must perform to deliver the needed characteristics (e.g., Use Case: "Collect surface samples"; Function: "Provide tools and containers to recover and package samples").

This methodology is captured in the **Architecture Definition Document (ADD)**, which is updated annually through an Architecture Concept Review (ACR) to incorporate new technologies, partnerships, and refined concepts.

The motivation for exploration rests on three balanced pillars:

- **Science:** To understand the formation of the solar system, the history of the Sun, and human and biological responses to extreme environments.

- **National Posture:** To demonstrate U.S. leadership, strengthen alliances, and advance national interests.
- **Inspiration:** To take on audacious challenges that inspire new generations in science, technology, engineering, and mathematics.

Architectural Structure: Segments and Sub-Architectures

To manage the complexity of the endeavor, the architecture is organized into both vertical (temporal) and horizontal (functional) categories.

Campaign Segments

The overall campaign is broken down into four evolutionary segments that incrementally build capability. While they appear sequential, their operations can overlap.

1. **Human Lunar Return (HLR):** Focuses on the initial Artemis missions to re-establish human presence on and around the Moon, demonstrating core transportation and life support systems.
2. **Foundational Exploration (FE):** Builds on HLR to support increasingly complex and longer-duration missions, including excursions to diverse lunar sites and Mars-forward precursor missions that validate systems and operations.
3. **Sustained Lunar Evolution (SLE):** Represents the "open canvas" end-state of a robust lunar economy, with continuous human and robotic presence supported by U.S. industry and international partners.
4. **Humans to Mars:** Captures the capabilities, systems, and operations required for the initial human exploration of Mars, informed by the lessons and technologies developed during the lunar segments.

Sub-Architectures

The architecture is functionally partitioned into groups of tightly coupled elements and capabilities, ensuring horizontal integration across missions and segments.

Sub-Architecture	Description
Communication, PNT	Systems for data transfer, positioning, navigation, and timing.

Data Systems & Management	Capabilities to transfer, process, secure, and manage data, including cloud computing and IoT.
Habitation Systems	Provides controlled environments to ensure crew health and performance across transit and surface phases.
Human Systems	Collective capabilities of flight crew and ground teams, including training, mission design, and operations.
Infrastructure Support	Ground and surface facilities, construction equipment, and services for commodity storage and maintenance.
ISRU Systems	In-situ resource utilization for harvesting local resources to generate products like propellant, water, and construction materials.
Logistics Systems	Systems for packaging, handling, transport, and storage of supplies, consumables, and cargo, including waste disposal.
Mobility Systems	Systems enabling crew and cargo movement, including rovers, landers, ascent vehicles, and EVA suits.
Power Systems	Capabilities for power generation (solar, fission), energy storage, and power distribution.

Autonomous Systems & Robotics	Hardware and software that can assist crew or operate independently to maximize efficiency and enable uncrewed operations.
Transportation Systems	Systems for transporting crew and cargo between Earth, Moon, and Mars.
Utilization Systems	Capabilities whose primary function is to conduct science, research, technology demonstrations, and sample return.

Defining Habitable Volume for Deep Space Missions

Establishing the minimum required Net Habitable Volume (NHV) is a first-order driver for habitat design, directly influencing the habitat's mass, size, and consequently, the propulsion and propellant requirements for a mission. A comprehensive study was undertaken to define this minimum volume using a function-based methodology.

The Bottom-Up Methodology for Net Habitable Volume

Previous attempts to determine required volume relied on top-down parametric formulas derived from historical analogs, which resulted in significant uncertainty. To address this, a **bottom-up methodology** was employed, a process specifically recommended by the NASA Chief Medical Officer. This approach establishes the required habitat volume by analyzing the specific needs of the crew.

The process involved several key steps:

1. **Define Crew Functions:** A comprehensive taxonomy of all activities the crew must perform was established. These were grouped into categories such as direct operations (command and control), habitation (eating, sleeping), and health maintenance (exercise, medical care).
2. **Assign Volumetric Requirements:** A minimum operational volume was defined for each individual function. These volumes were based on key assumptions:
    - Operations occur in zero to minimal gravity.
    - Volumes are sized for the 99th percentile male/female anthropometric data.

    - The mission duration is at least 180 days.
    - Primary sources for these volumes included NASA's Human Integration Design Handbook (HIDH) and NASA-STD-3001.
3. **Identify Functional Overlaps:** The team assessed where different functions could share a common volume, provided they are separated in time and are operationally compatible. For example, some hygiene functions can occur in the same space as full-body cleaning.
4. **Define Functional Spaces:** Based on overlaps, a unique set of "Functional Spaces" was defined. The volume for each space was determined by the largest required volume of the grouped functions it accommodates.
5. **Sum Volumes:** The volumes of all unique Functional Spaces were summed to calculate the total minimum NHV. This process was completed for both 4-person and 6-person crews.

Functions related to Extravehicular Activity (EVA) that would occur in a dedicated airlock were not included in the NHV calculation.

Key Findings on Minimum Volume Requirements

The bottom-up analysis resulted in a total of 18 unique "Combined Functional Spaces" required to support all crew activities. The summation of these spaces yielded the minimum required NHV.

Crew Size	Total Minimum NHV	Minimum NHV per Crewmember
4-person	115.83 m^3	28.96 m^3
6-person	170.14 m^3	28.36 m^3

While historical parametric studies suggested a value of approximately 25 m^3 per crew, this more rigorous analysis establishes a floor value between **28 m^3 and 29 m^3 per crewmember**.

However, it is crucial to note that this represents a theoretical minimum. When these functional volumes were applied to a practical habitat case study, the actual NHV was significantly larger to account for passageways, additional access spaces, and the inherent inefficiencies of packaging functional areas into a cylindrical habitat. The case study concluded that the total NHV required to provide these minimum functions will likely be closer to **37 m^3 per crewmember**.

Habitat Design Principles and Technologies

Through the Next Space Technologies for Exploration Partnerships (NextSTEP) Phase 2 ground test program, NASA has developed a comprehensive set of design guidelines for deep space habitats based on astronaut evaluations of multiple full-scale habitat prototypes.

Foundational Design Guidelines from Ground Testing

The ground tests revealed several high-level principles that are critical for successful habitat design.

- **Layout is More Important than Volume:** A smaller, well-organized volume is generally more acceptable and efficient than a larger, poorly laid out one. Additional volume is only beneficial if it enables better separation of functions.
- **Separation of "Clean" and "Dirty" Areas:** To prevent cross-contamination and improve crew well-being, habitat layouts must separate "clean" functions (crew quarters, galley, science, medical) from "dirty" functions (waste collection, hygiene, exercise). Locating dirty areas near each other further mitigates contamination.
- **Reconfigurability and Common Interfaces:** The ability to reconfigure modules by moving pallets, payloads, and entire functional areas is essential for flexibility as missions evolve. A common secondary structure (e.g., mounting points, tracks, interfaces) throughout the habitat reduces crew overhead and the number of unique tools required.
- **Stability and Mobility Aids:** All work and habitation areas require sufficient, adjustable stability aids (handholds, foot restraints), mobility aids, and temporary stowage accommodations (Velcro, bungees, nets) to support efficient and safe operations in microgravity.

System-Specific Design Recommendations

The tests produced detailed guidelines for key habitation systems:

- **Crew Quarters:** Should provide private, rigid enclosures with doors to offer light and sound proofing for adequate rest and privacy.

- **Hygiene Station:** At least one dedicated, enclosed hygiene station is required, separate from the Waste Collection System (WCS) and crew quarters. Surfaces should be smooth, non-porous, and easy to clean.
- **Waste Collection System (WCS):** An additional WCS separate from the one in Orion is essential. It should be co-located with other "dirty" areas and have long-term waste storage vented directly to the trace contaminant control system to manage odors.
- **Galley and Table:** A galley with a potable water dispenser is needed for all missions. For missions longer than 30 days, a galley table large enough for the entire crew to eat together is desirable. The table must not interfere with access to critical workstations.
- **Workstations:** At least one **hardwired multipurpose workstation** is required for reliable critical commanding (e.g., robotics, vehicle control). Wireless tablets are acceptable only for monitoring. Critical workstations must not be blocked and should be located away from high-traffic areas.
- **Logistics Stowage:** A logical, clearly labeled location referencing system is crucial. The habitat should contain dedicated stowage for one week of consumables and critical spares, with the remainder stored in a logistics module. Cargo bags should be stored no more than one layer deep for easy access.
- **Radiation Protection:** The crew must have rapid access to a shelter for protection from Solar Particle Events (SPEs). The shelter must allow for essential functions (eating, sleeping, hygiene, critical commanding) to be performed within it or in very close proximity.

Inflatable Habitat Technology

Inflatable structures offer significant potential for reducing the launch volume and mass of large crewed habitats. Extensive development and testing have advanced this technology for space applications.

- **Design and Materials:** Inflatable habitats feature a multi-layer softgoods shell designed to provide structural integrity and environmental protection. The primary layers include:
    - **Liner:** An inner, flame-resistant layer to protect the bladder from crew activity.
    - **Bladder:** A polymeric gas barrier (often with redundant layers) that contains the internal atmosphere. It is oversized so it does not carry structural loads.
    - **Restraint Layer:** The primary structural layer, woven from high-strength webbing (e.g., **Vectran, Kevlar**) that carries the pressure loads. It is designed with a factor of safety of 4.0.

    - **MMOD Shield:** A multi-material layup of ceramic fabric and foam to protect against micrometeoroid and orbital debris impacts.
    - **Thermal Protection Layer:** Multi-Layer Insulation (MLI) to protect against the thermal extremes of space.
- **Testing and Validation:** The technology has been validated through rigorous testing, including:
    - **Hypervelocity Impact Testing:** To evaluate the MMOD shield's performance. The current pass/fail criterion is **no damage to the structural restraint layer**.
    - **Creep Testing:** Multi-year tests to characterize the long-term deformation and time-to-failure of webbing materials under constant load. This is a critical parameter for inflatable habitats.
    - **Damage Tolerance Testing:** Tests involving cutting structural webbings under pressure demonstrated that the woven design allows loads to redistribute locally without catastrophic failure.
    - **Deployment Testing:** Full-scale articles like TransHab have been successfully assembled, folded, and deployed in a vacuum chamber.
- **Potential Applications:** Beyond primary habitats, inflatable technology is being considered for airlocks, deployable tunnels connecting modules, and large in-space hangars for spacecraft assembly and maintenance.

Mars Exploration: Architecture and Unique Challenges

While lunar exploration serves as a proving ground, Mars presents a distinct and more complex set of architectural challenges that require a dedicated strategic approach.

The Mars Architecture Decision Roadmap

Given that many Mars architecture decisions have not yet been made, NASA is employing a structured process to develop a **Key Architecture Decision Roadmap**. This process is designed to trace the cascading effects of high-level decisions across the entire architecture to avoid unsustainable designs.

The process begins with the "Why?" (objectives) and flows through a series of key questions ("What," "Where," "When," "How"). A critical element is understanding the dependencies between decisions to determine the logical order of decision-making. Key decisions are those that profoundly influence the end-to-end architecture and require collaboration between multiple authorities. These decisions are modeled to understand prerequisites and flow-down impacts, ensuring that choices like propulsion technology, crew size, and return propellant strategy are made with a full understanding of their system-wide consequences.

Critical Challenges for Human Mars Missions

The human exploration of Mars is constrained by several unique factors not present in lunar or LEO missions.

- **Transportation Energy vs. Mission Duration:** The roundtrip journey is dictated by celestial mechanics. Mission profiles exist on a continuum:
  - **Conjunction-Class (Long-Stay):** Minimum-energy trajectories resulting in transit times of 180-300 days each way, but requiring a Mars stay of 300-500 days for planetary alignment. Total mission duration is around **three years**.
  - **Opposition-Class (Short-Stay):** High-energy trajectories to shorten the total mission duration to around **two years**, but at an exponential cost in propellant and propulsion system mass. This trade-off between total mission duration and required launch mass is a primary driver for transportation system design.
- **The Human System:** The health and performance of the crew over a three-year mission is a major concern. The long duration in deep space poses significant risks from radiation exposure and microgravity deconditioning. Historically, architectures prioritized minimizing launch mass (favoring long-duration conjunction missions), but a successful Mars architecture must fully integrate the human system, potentially prioritizing shorter mission durations to mitigate crew health risks.
- **Crew Safety, Autonomy, and Communication Delay:** The immense distance to Mars fundamentally changes the operational paradigm:
  - **No Rapid Abort:** Unlike LEO (hours) or lunar (days) missions, a return to Earth from Mars can take months, regardless of the emergency. This eliminates aborts as a primary safety measure.
  - **Communication Delay:** The one-way light time delay of up to 22 minutes makes real-time communication and ground support impossible.
  - **Increased Reliance on Autonomy:** These factors necessitate a greater emphasis on system reliability, redundancy, in-situ maintenance, and crew/vehicle autonomy to diagnose and resolve problems without Earth intervention.

Collaboration as a Cornerstone of Exploration

Collaboration with international and commercial partners is a recurring tenet (RT-1, RT-2) and a foundational principle of the Moon to Mars architecture. This approach distributes costs, shares risks, enhances capabilities, and fosters peaceful international cooperation.

International and Commercial Partnerships

NASA is actively pursuing partnerships across all segments of the architecture.

- **International Collaboration:** NASA has numerous agreements and ongoing discussions with international space agencies. Key examples include:
    - **Gateway:** The European Space Agency (ESA) is providing the International Habitation Module (I-Hab) and the ESPRIT Refueling Module (ERM). The Canadian Space Agency (CSA) is providing the Canadarm3 robotic system. The Japan Aerospace Exploration Agency (JAXA) is contributing to I-Hab and logistics resupply.
    - **Science Payloads:** International partners from ESA, DLR (Germany), ISA (Israel), and JAXA provided payloads for Artemis I. NASA is also contributing instruments to international missions like JAXA's LuPEX rover.
    - **Artemis Accords:** A set of principles grounded in the Outer Space Treaty that establishes a framework for responsible and peaceful cooperation in space exploration among signatory nations.
- **Industry Collaboration:** NASA is leveraging commercial innovation and services to achieve its goals.
    - **Commercial Lunar Payload Services (CLPS):** An initiative where NASA purchases payload delivery services from American companies, enabling rapid and cost-effective delivery of science and technology instruments to the lunar surface.
    - **Next Space Technologies for Exploration Partnerships (NextSTEP):** A public-private partnership program to develop deep space exploration capabilities, including the habitat prototypes that informed the design guidelines in this document.
    - **Human Landing System (HLS):** NASA is partnering with industry to develop the landers that will transport astronauts to the lunar surface.