Evolution to Sustainable Lunar Habitation – Fall 2024 Project

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NASA Strategy and Architecture Office (SAO) Lunar Architecture Team (LAT)

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NASA's SAO LAT Habitation Team POCs



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National Aeronautics and Space Administration



Background

NASA’s Moon to Mars Current Habitation Efforts

Architecture Strategy

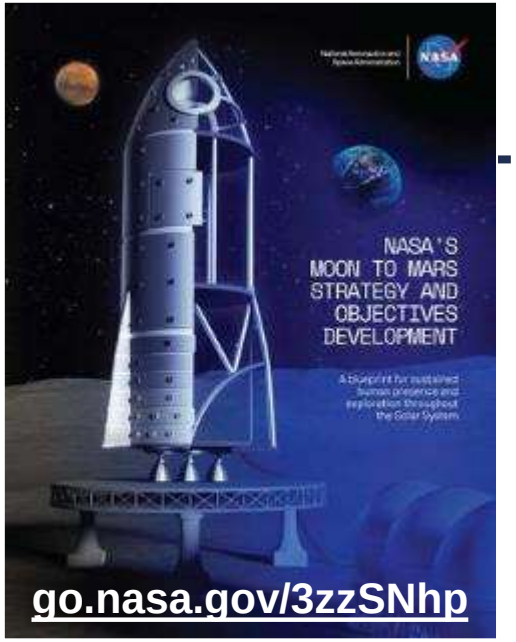
A blueprint for future human exploration, architecting from the right.

ARCHITECTURE

Iterate and evolve through annual ***Architecture Concept Reviews***

Goals and Objectives

- **SCIENCE**
- **TRANSPORTATION AND HABITATION**
- **LUNAR AND MARS INFRASTRUCTURE**
- **OPERATIONS**



go.nasa.gov/3zzSNhp

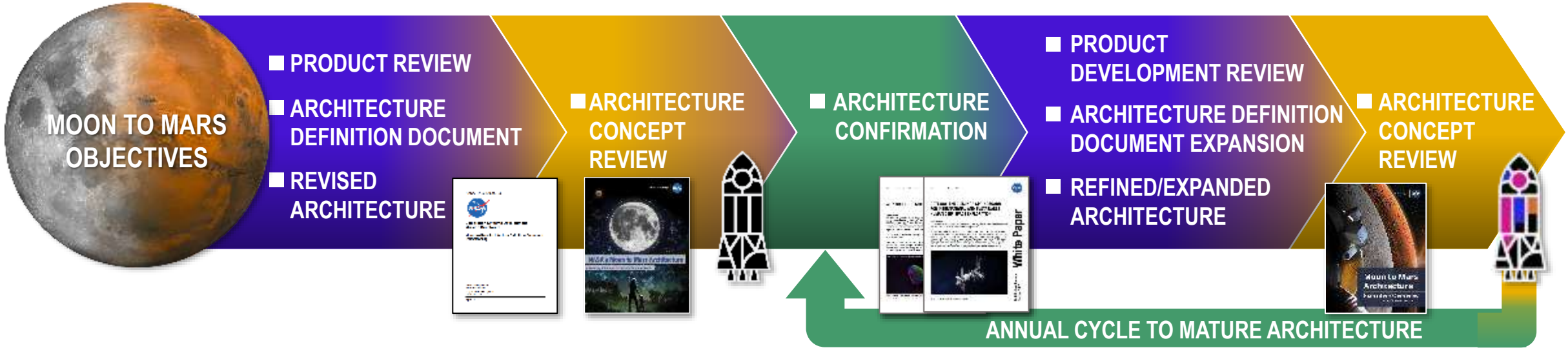
Requested feedback on these objectives in summer 2022 from the following key stakeholders:

- NASA workforce: our greatest asset
- International partners: our key current and future, anticipated collaborators
- U.S. industry, academia, DOE, NIH, NSF, etc.: our national leaders in space research and capabilities

Architecture Approach

An Evolutionary Architecture Process

Formulating an Architecture and Exploration Strategy Based on Objectives



TRACEABILITY

Decomposition of Blueprint Objectives to executing Architecture elements

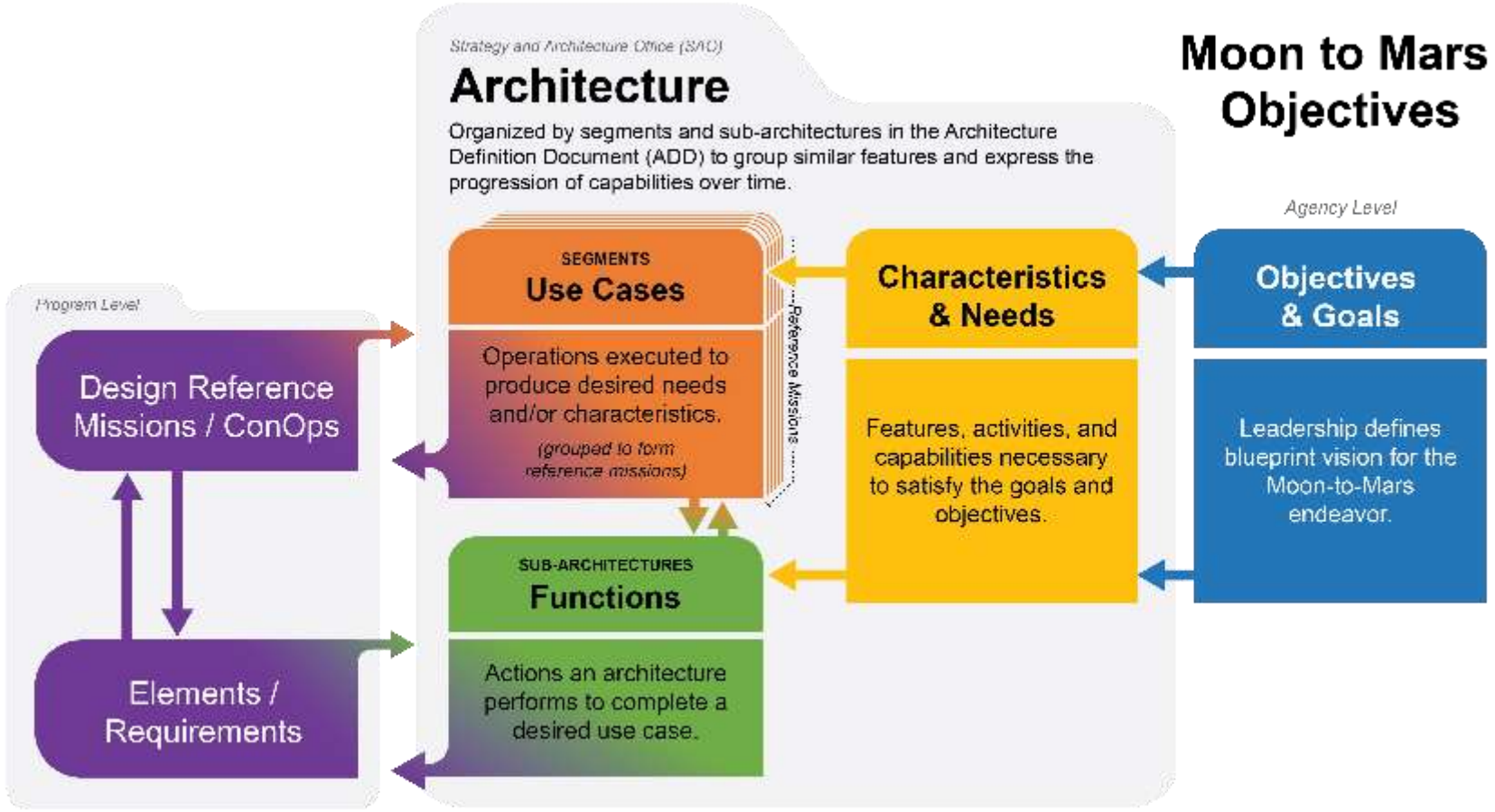
ARCHITECTURE FRAMEWORK

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

PROCESS & PRODUCTS

Clear communication and review integration paths for stakeholders

Architecting from the Right



The Architecture process requires a decomposition of Moon to Mars Objectives to element functions and mission use cases to complete the process of “architecting from the right.” This establishes the relationship of executing programs and projects to the driving goals and objectives.

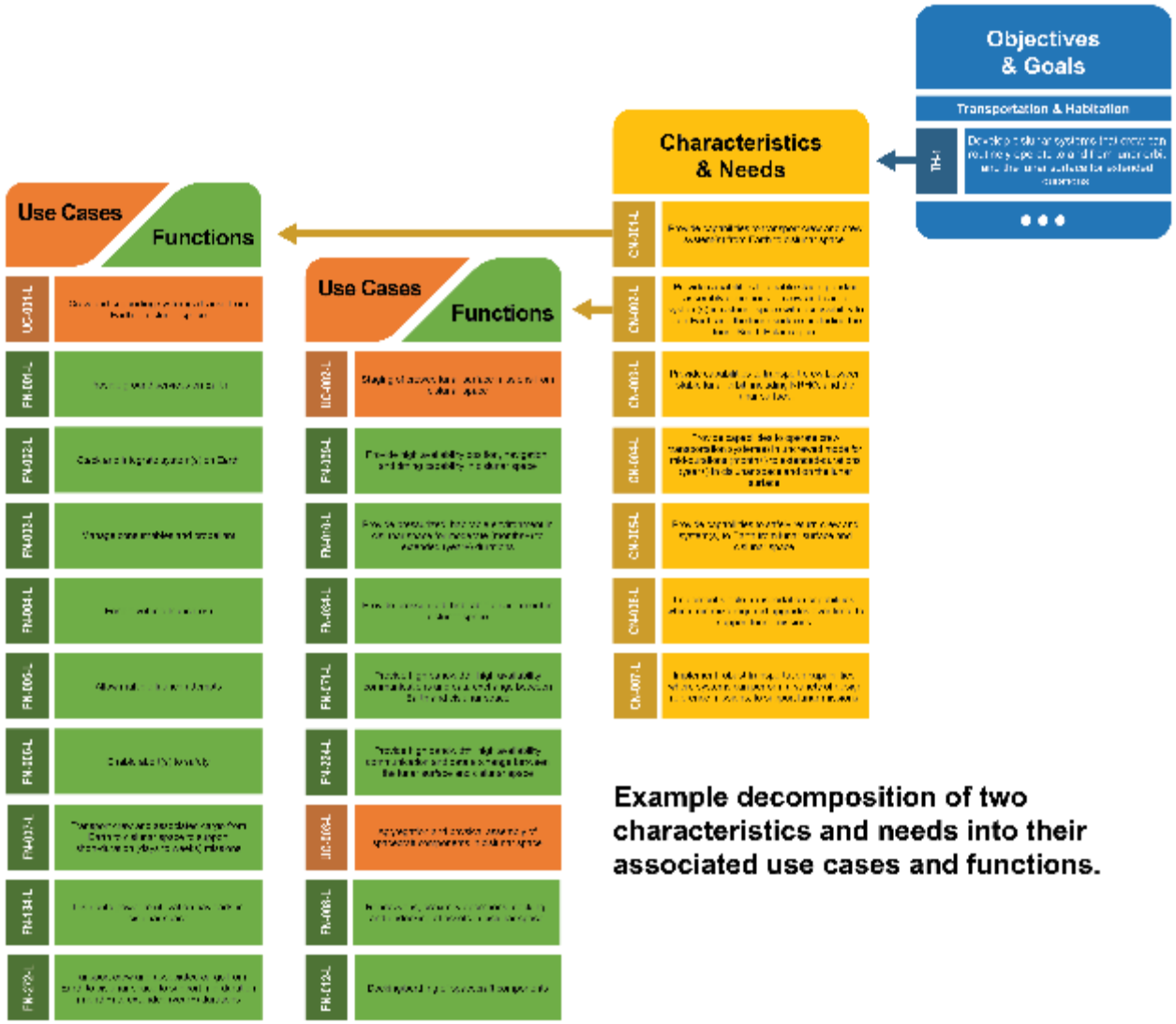
Architecting from the Right

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.

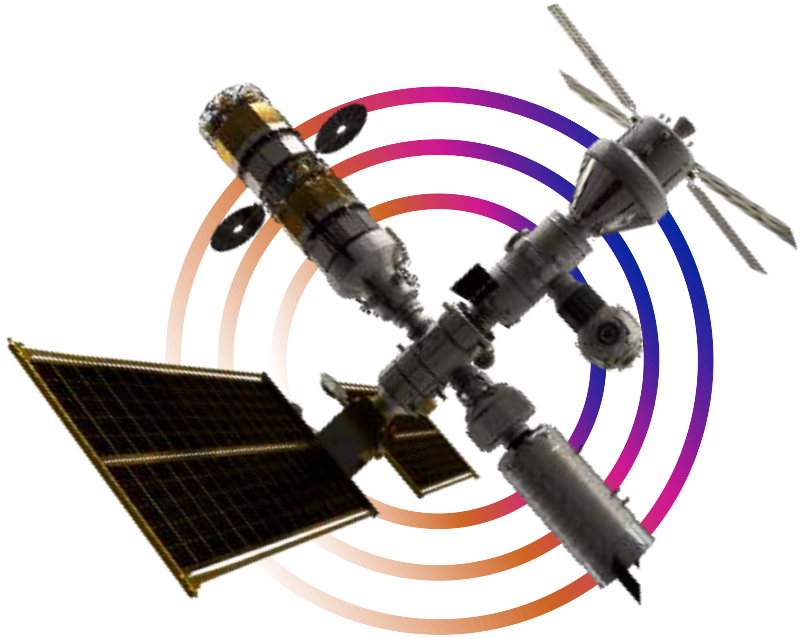
Use Case: An operation that would be executed to meet desired characteristics and needs.

Function: One of the actions necessary to satisfy a use case.

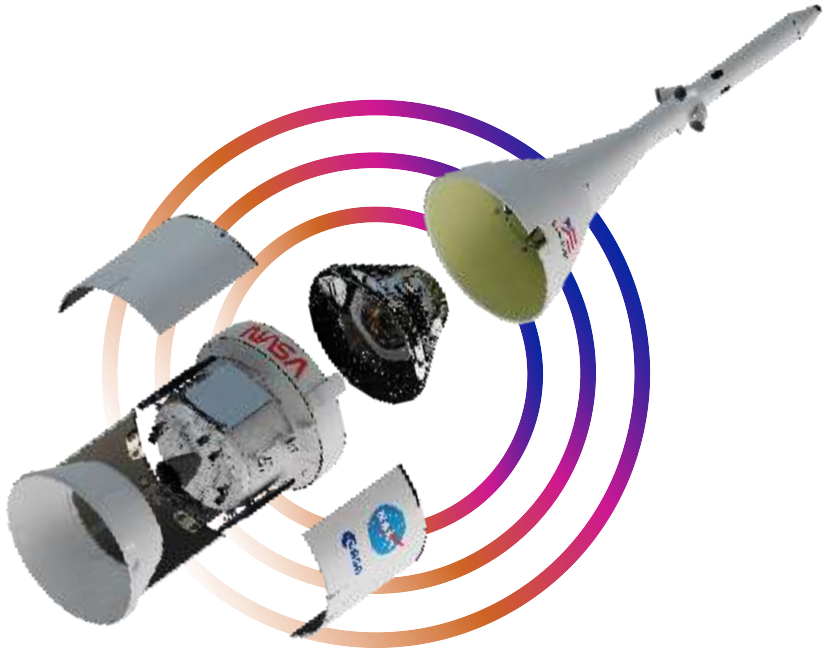


Example decomposition of two characteristics and needs into their associated use cases and functions.

Architecture Components







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

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

Elements
A notional exploration system that enables a set of functions.

Architecture Segments



Human Lunar Return

Initial capabilities, systems, and operations necessary to re-establish human presence and initial utilization on and around the Moon.



Foundational Exploration

Expansion of lunar capabilities, systems, and operations supporting complex orbital and surface missions to conduct utilization and Mars forward precursor missions.



Sustained Lunar Evolution

Enabling capabilities, systems, and operations to support regional and global utilization, economic opportunity, and a steady cadence of human presence on and around the Moon.

Future Segments



Humans to Mars

Initial capabilities, systems, and operations necessary to establish human presence and initial utilization on Mars and continued exploration.

Evolving Habitation Systems for SUSTAINABLE HUMAN EXPLORATION

Use ISS as Testbed for Evolution of ECLSS and CHPS



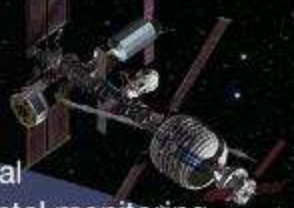
International Space Station (ISS)

Continue Testbeds on Commercial Platforms in LEO



Notional Commercial Platform in LEO

Infuse Technologies into Gateway



Orion and Gateway

- Toilet
- CO_2 removal
- Environmental monitoring
- Exercise technology
- Radiation protection and monitoring
- Medical system
- Fire suppression and cleanup

Infuse Full Long Duration Microgravity ECLSS and CHPS into Mars Transport



Mars-class Transportation

- Highly-reliable regenerative ECLSS from ISS demonstration
- Environmental monitors
- Exploration food system
- Countermeasures
- Medical system
- Radiation protection

Complementary Ground Tests and Analogs

- Food system performance and reliability testing
- CHPS integrated analogs



Human Landing System and Sustained Lunar Surface ECLSS-CHP Infusion

- Partial gravity and exploration atmosphere fire safety
- Exploration spacewalk pre-breathe and conops
- Surface habitat: regenerative ECLSS and CHPS adapted for surface
- Pressurized rover: ECLSS waste collection and transfer



Mars Surface ECLSS-CHPS

- Robust microbial and chemical monitoring
- Planetary protection compatible waste strategy



ECLSS = Environmental Control and Life Support Systems | CHPS = Crew Health and Performance Systems | LEO = Low-Earth Orbit

GRAPHICS NOT TO SCALE 20210115

Definitions: Types of Space Habitats

A class I habitat is a pre-integrated habitat, manufactured and integrated prior to launch

Example: ISS



A class II habitat is pre-fabricated prior to delivery, but deployed in space or on a planetary surface

Example: Inflatable ISS BEAM module



A class III habitat is built in situ using local resources

Example: 3D Printed Habitat on planetary surface



Image from ICON and SEArch+.

Marc Cohen and Kriss Kennedy, "*Habitats and Surface Construction Technology and Development Roadmap". Sept 4, 1997*

Surface Habitat Concept

NASA's surface habitat concept serves as a central hub for building & initial sustainment of Artemis' **Foundational Exploration** activities

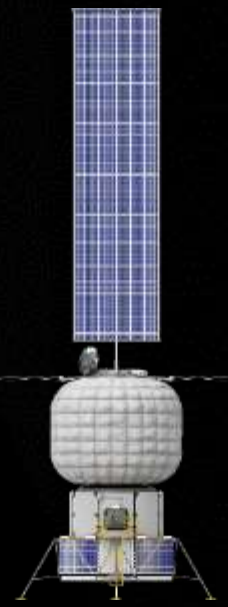
Key Surface Habitat functions:

- Power generation & energy storage (100 hrs)
- Open/Regenerative Environmental Control & Life Support (ECLS)
- Extravehicular Activity (EVA) support & suit maintenance
- Communications & data relay
- Medical support



Surface Habitat Ground Rules & Assumptions[1]

Crew Size	2 crew (nominal) – 4 crew (surge)
Mission Duration	7 days (initial) – 60 days (extended)
Lifetime	15 years
Mass Target	12 mt (goal)
Pressurized Volume	190 m^3
Operating Pressure	8.2 – 10.2 psia (70.3 – 56.5 kPa)
Oxygen Composition	26.5-34% (limits for 8.2-10.2 psia)





[1] Harris, Danny W., et al. *Moon to Mars (M2M) Habitation Considerations: A Snap Shot As of January 2022*. No. M-1538. 2022.

Transit Habitat Concept

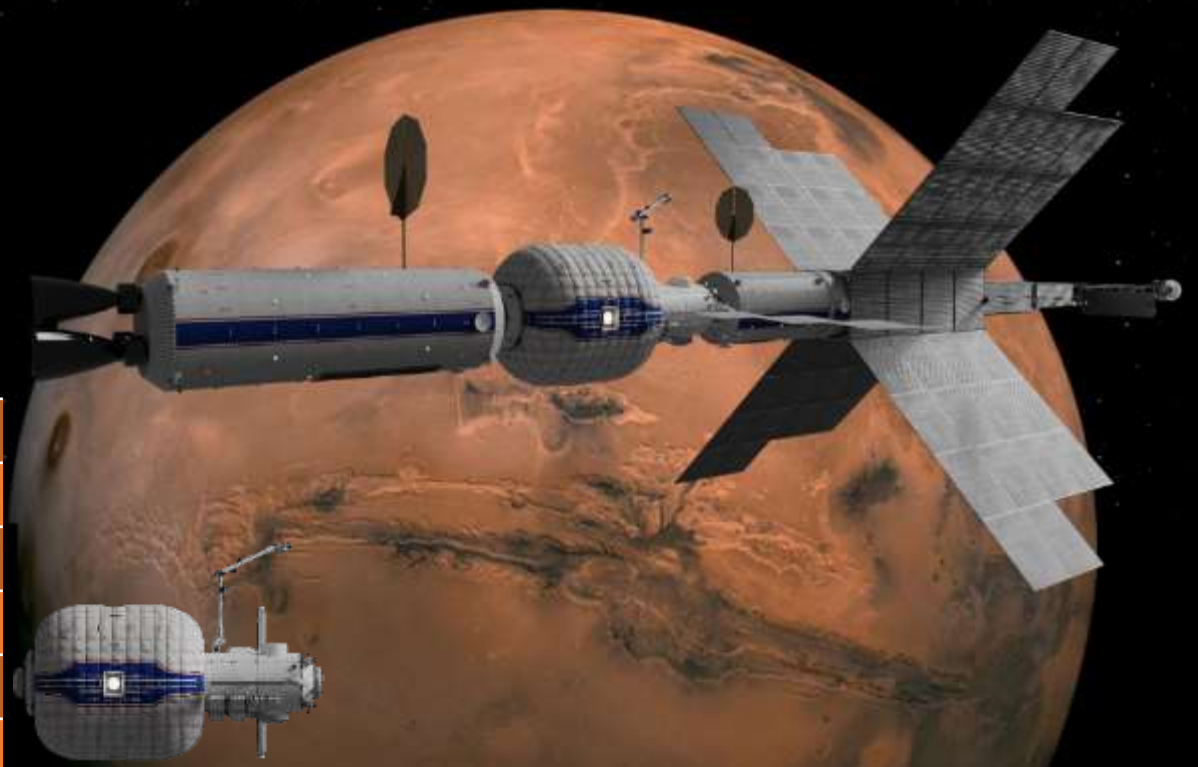
NASA's transit habitat serves as crew living quarters during Mars analog and exploration missions during Artemis' **Foundational Exploration** through **Humans to Mars** activities

Key Transit Habitat functions:

- Resource sharing and interfaces with Gateway
- Radiation and Solar Proton Event (SPE) protection
- Docking capabilities
- Regenerative ECLS
- Logistics storage



Transit Habitat Ground Rules & Assumptions[1]	
Crew Size	4 crew
Mission Duration	Up to 1,200 days
Solar Orbital Range	0.6 – 1.6 AU
Lifetime	15 years
Mass Target	26.4 mt (dry, ~50 mt departure mass)
Pressurized Volume	~400 m^3
Operating Pressure	10.2 – 14.7 psia (56.5-101.4 kPa)
Oxygen Composition	26.5-24.1% (limits for 10.2-14.7 psia)



[1] Harris, Danny W., et al. *Moon to Mars (M2M) Habitation Considerations: A Snap Shot As of January 2022*. No. M-1538. 2022.



NextSTEP Appendix A: Habitation Systems



Phase 1 – 2015-2016: Concept Designs and Operations
Phase 2 – 2016-2019: Prototype Development and Testing
Phase 3 – 2019-2023: Concept maturation and focus on long-duration, in-space and surface habitats

NextSTEP Appendix A - Habitation

Advancing near-term habitation concepts through collaborative public-private partnerships

- Current contracted partners
  - Boeing
  - Lockheed Martin
  - Sierra Space
- Softgoods (inflatable) advancement
  - Burst testing – determine ultimate burst pressure of article
  - Creep testing – determine material deformation under load
- Additional efforts:
  - Habitat concept design & maturation
  - Composite structures



NASA before/after images from test conducted at Johnson Space Center in collaboration with Sierra Space and ILC Dover





Elements

Human Lunar Return

Foundational Exploration

- Canadian Space Agency
- European Space Agency
- United Arab Emirates
- Japan Aerospace Exploration Agency



































New for ACR23

Human Landing System



SpaceX: First Crew Demonstration landing on Artemis III

Artist's illustration

Transports astronauts from lunar orbit to the lunar surface and back up to lunar orbit

- Carries two crew on early missions, growing up to four crew as capabilities grow
- On early missions, the lander itself will double as the crew's habitat
- NASA plans to procure lunar lander services from U.S. companies, much like the agency does for crew and cargo deliveries to the International Space Station
- The Gateway in lunar orbit has multiple docking ports to accommodate the lander, crew arriving in Orion, and cargo supply deliveries all at the same time.

Unpressurized Rover

Lunar Terrain Vehicle



Artist's illustration

Provides early mobility for suited Artemis astronauts to expand exploration range.

- Reusable and rechargeable for approximate 10-year service life
- Remote operation from HLS, Gateway, Earth
- Ability to traverse from one landing zone to another
- Interface with future science instruments and payloads for utilization or pre-deployment of assets
- Ability to survive eclipse periods

Pressurized Rover



Artist's illustration

Provides pressurized mobile habitation to enable long-range surface exploration in shirtsleeve environment and quick and easy access to surface.

- Habitation for 30 days for 2 crew
- Rear suitport allows astronaut egress and ingress of the vehicle via the spacesuits, leaving the suits outside the pressurized volume
- Provides volume for spares and logistics
- Power generation and energy storage for lunar environment
- Dust and radiation protection
- Reuse for multiple missions of 15-year lifetime
- Capability also identified in current concepts for first human mission to Mars

National Aeronautics and Space Administration



The Project

Architecting an evolvable lunar habitation architecture

Questions We're Trying to Answer

How do we consider "livability" in habitat design?

- What does the transition from meeting functional needs to including comfort and psychological needs look like?
- When and how do you add in social spaces?
- What are the hooks early on for making a smoother transition?

What might be the "drivers" for incrementally evolving lunar habitation?

- What are various crewed use cases?
- Will we see industrial workers, scientific crews, visiting tourists, some combinations?
- When might different user communities arrive and thereby dictate changes in habitation?

How do we best incrementally "evolve" lunar habitation?

- Would you reconfigure existing class 1 or 2 habitats?
- When does it make sense to include a class 3 habitat and at what differentiating capabilities?
- Would it be better to integrate class 3 with existing class 1/2 modules or better to fully transition to class 3 only?

What are approaches for achieving "sustainable" lunar habitation?

- How would you define sustainability in lunar habitation?
- What capabilities need to be advanced and when?

Project Vision and Goals

Vision Statement

Develop a phased habitation architecture that includes a build-up of integrated and progressively advanced habitation capabilities that lead to sustained lunar operations.

Goals

- Develop an integrated lunar habitation roadmap, that:
  - Captures common challenges and development opportunities between habitat classes
  - Defines sustainable habitation and identifies attributes that facilitate growth to a sustainable state (e.g., common interfaces, capabilities)
  - Considers scavenge and reuse of habitats and other lunar surface elements in comparison to new, independent elements
  - Include livability/psychosocial considerations in interior design and layout

Note/Guidance: Not focused on developing detailed mass properties of major elements. Keep the focus on habitation/habitation systems vice 'lunar base' planning.

Focus Areas



Habitation Class Progression

Focus on transition from Class 1 to Class 3 habitats

Identify critical architectural advancements required to transition to Class 3

Integrate all habitat classes vs. Class 3 as separate?



Earth Independent Logistics

Approaches to decrease logistical dependency on Earth resupply for habitation systems

Progression from Earth supplied to in-situ derived (as able)

Consider both delivery mass and crew time as factors



Crew Operational Roles

How will crew interact with other systems (LTV, Pressurized Rover/s) via the habitat?

Change in roles over multiple missions

Translate into functional habitation needs (e.g. volume/floor area)

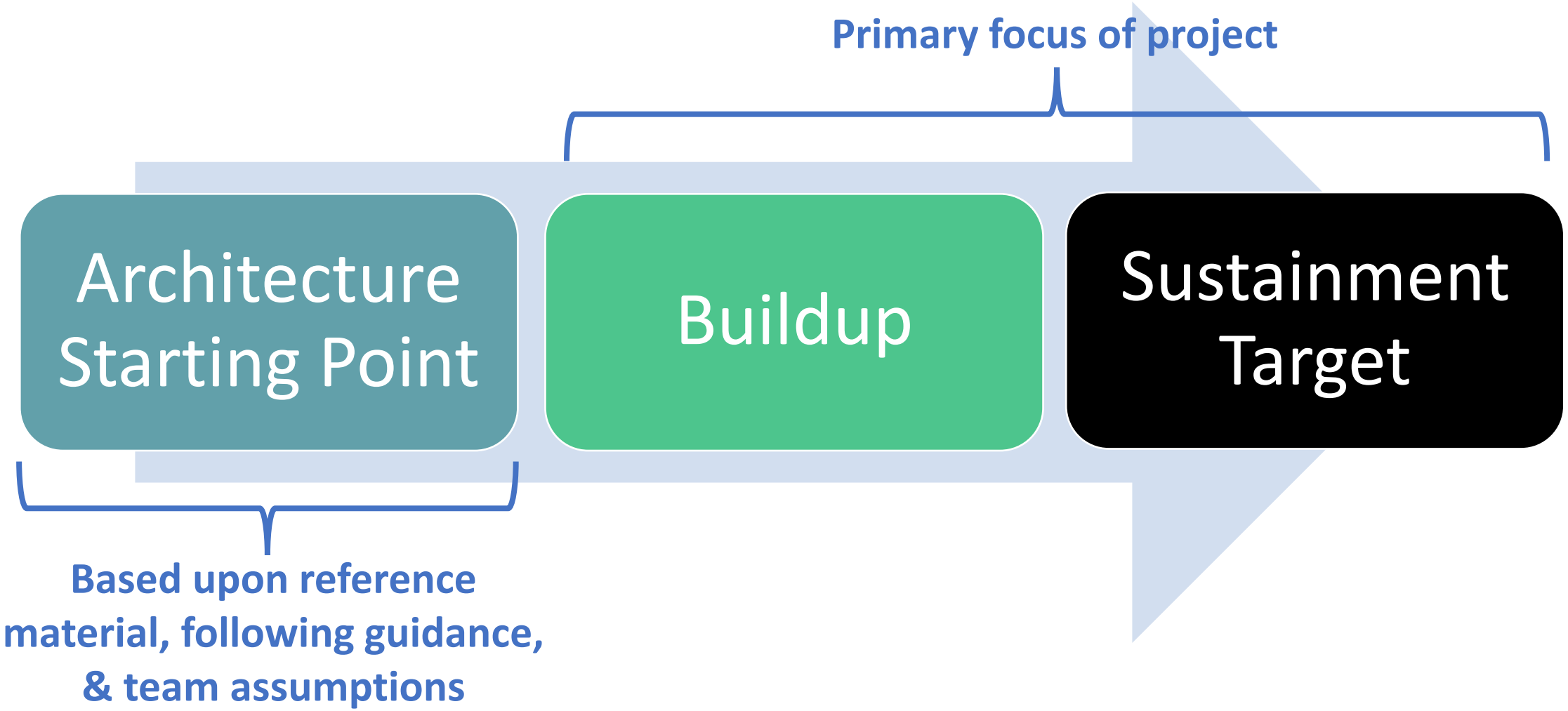
Objectives

- Develop MOEs (Measures of Effectiveness) to characterize the progression of habitation
- Demonstrate strategy for logistics mass reduction and increased sustainability over missions (see references for logistics information)
- Develop and deliver a report on the work
- Present findings to members of the Strategy and Architecture Office Lunar Architecture Team

Ground Rules

- Consider usage of various landing vehicles and associated capabilities
- Constrain to lunar south pole environment with following assumptions for architectural starting point:
  - Identifying specific site location is not a goal of this project
  - Site location between 84 degrees south to 90 degree south
  - Site slopes won’t exceed 5 degrees without improvement
- All other project assumptions will be documented

Habitation Evolution



Architecture Starting Point

Foundational Habitation Capabilities

- Open Loop ECLSS
- Class 2 Surface Habitat (see SH example) – inflatable metallic hybrid
- Class 1, small metallic habitation module (~30 – 60 cubic meter pressurized volume)
- Proposed deviations/design changes can be documented
- Cislunar Gateway

Supporting Elements

- Human Landing System
  - Transient support at beginning and end of mission
- Lunar Terrain Vehicle
  - Crewed vehicle with remote capabilities
- Pressurized Rover (Class 1)
- Fission power – 40 kW per system
- Separate solar array banks – 10 kW per array
- All other elements should be documented in assumptions

Operations

- 1 crew launch per year
- 4 crew (can be split between SH & PR)
- Up to 30-day operational duration
- 3-year max dormancy on systems
- 15-year service life of elements
- Cargo delivery assumptions to be documented (mass + cadence)
- Up to 100 hours of continuous darkness at 10 m above surface during summer months

Minimal Sustainment Target

Core Habitation

- Regenerative ECLSS (95+% water recovery from urine and condensate, high pressure oxygen generation, ISS-as-baseline)
- Surface Habitat (SH paper, Class 2) – inflatable metallic hybrid
- Additional small modular metallic habitation as needed (30 – 60 cubic meter pressurized volume copies)
- Additional habitation elements including constructed habitat(s) as envisioned by team, but at least one constructed habitat

Supporting Elements

- Pressurized Rover (Class 1) – additional as envisioned
- Human Landing System – Transient (Supports beginning and end of mission)
- Lunar Terrain Vehicle – additional as envisioned
- Fission power – 40 kW, additional as envisioned
- Separate solar array banks – 10 kW each
- Other elements as envisioned

Site Information

- No change

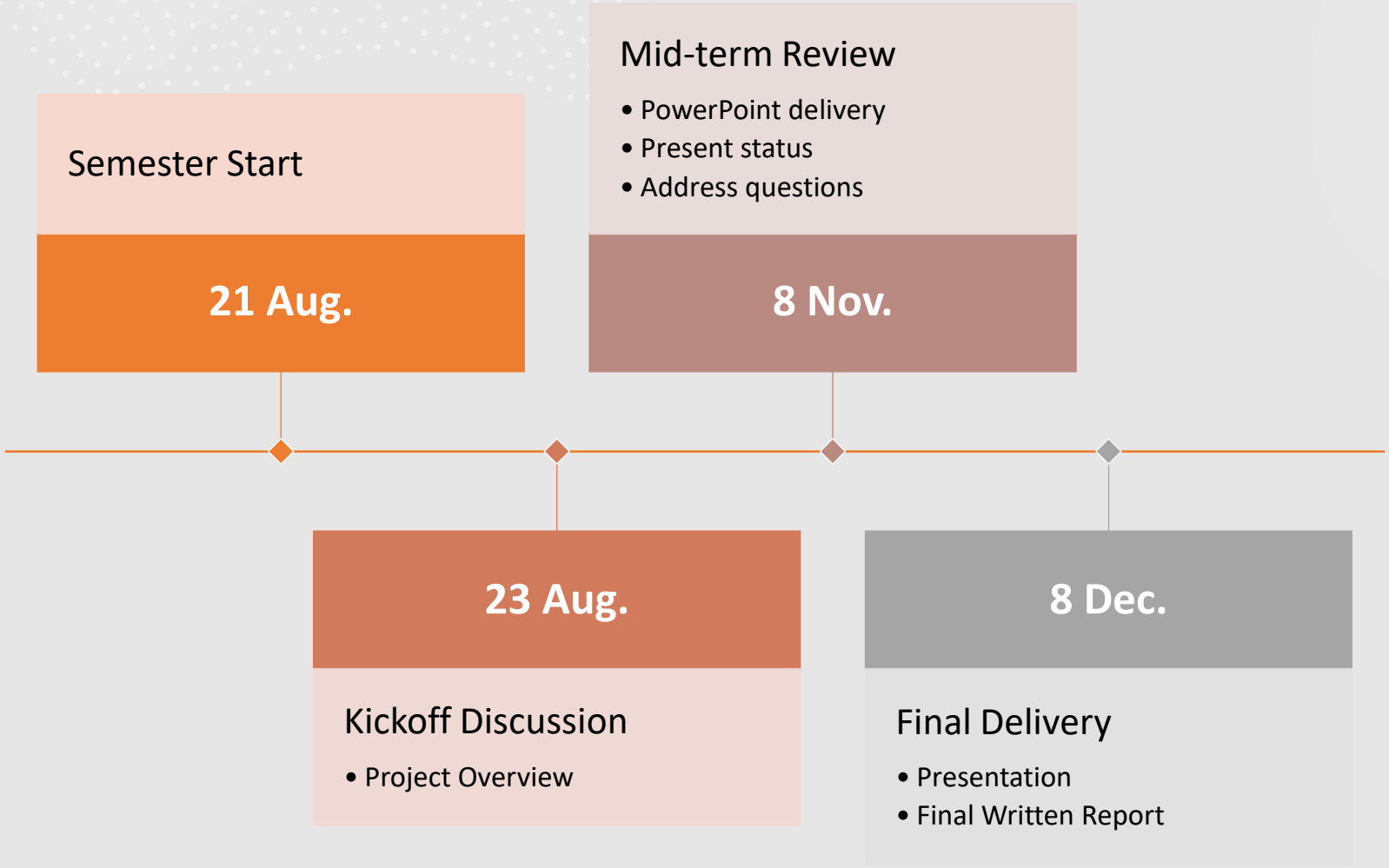
Operations

- 3 crewed launches per year
- No dormancy on systems
- 8 crew (continuous presence including darkness periods)
- Minimal Earth resupply (to be defined by team)
- 12 crew / 30-day surge capability

Other Potential Considerations

- Contingency operations – consider these scenarios and document expected response or mitigations:
  - Rapid depress
  - Fire
  - Complete loss of cooling/heating
  - Radiation/Solar Particle Event (SPE)
  - Incapacitated Crew Rescue
- Contingencies and other failure modes might best be captured as risks via matrices and high-level mitigation plans

Timeline


Semester Start
21 Aug.
Mid-term Review
• PowerPoint delivery
• Present status
• Address questions
8 Nov.
23 Aug.
Kickoff Discussion
• Project Overview
8 Dec.
Final Delivery
• Presentation
• Final Written Report

Deliverable Specifications

Summary Presentation

- Based on final report
- 20 minutes for presentation
- 8 minutes for questions

Report Format

- 25 page maximum, excluding appendices & reference list
- Single spaced, 12pt font

Report Content

- Include 1-2 page executive summary
- Constraints (hard, un-changing limitations beyond what is provided in Ground Rules)
- Assumptions (changing variables that are defined to better scope analysis)
- Depictions of interior habitat layouts/renders and external interfaces
- Measures of Effectiveness and capability needs of target state
- Timeline expected for evolution & dependencies
- Listing of challenges & opportunities
- Top 10 risks to the evolved habitation state with notional mitigation plans/actions
- Identify missing Use Cases or Functions from M2M ADD

Back-up & Reference Material

Terms and Acronyms

- **ECLSS** – Environmental Control and Life Support System
- **SH** – Surface Habitat (see references)
- **Pressurized Rover** – rover capable of transporting crew in a habitable volume
- **Lunar Terrain Vehicle** – moon rover for transporting crew in space suits
- **Human Landing System** – landing vehicle to bring crew to the surface of the moon
- **Fission Surface Power** – a nuclear power vehicle that provides power to surface systems
- **Vertical Solar Array Technology** – a solar array power grid that provides power to surface systems

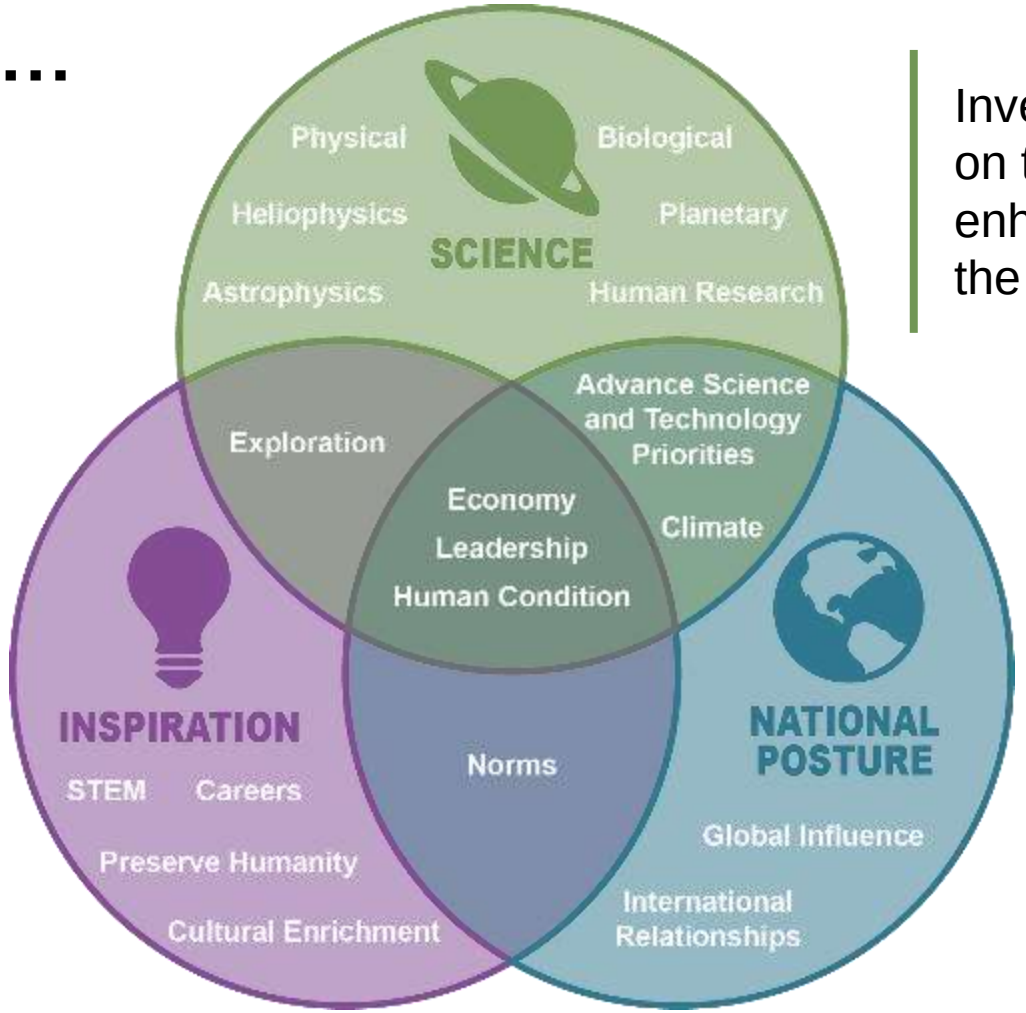
References

- NASA. (2023). Architecture Definition Document
- Howard, D., et al. "Regenerative Life Support Systems for Exploration Habitats: Unique Capabilities and Challenges to Enable Long-Duration-Mission Habitats Beyond Low Earth Orbit". ICES 2022. July 2022.
- Kessler, P., et al. "Artemis Deep Space Habitation: Enabling a Sustained Human Presence on the Moon and Beyond". IEEE Aerospace Conference. Mar 2022.
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- Anderson, Molly S., Michael K. Ewert, and John F. Keener. Life support baseline values and assumptions document. No. NASA/TP-2015-218570/REV1. 2018.
- Burke, Callie, Robert L. Howard Jr, and Paul Kessler. "Internal Layout of a Lunar Surface Habitat." 2022 ASCEND.
- Clinton Jr, R. G., et al. "Moon to Mars Planetary Autonomous Construction Technologies (MMPACT)." ASCEND, Planetary Construction technologies (2021).

The Benefits to Humanity

Why we explore…

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



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

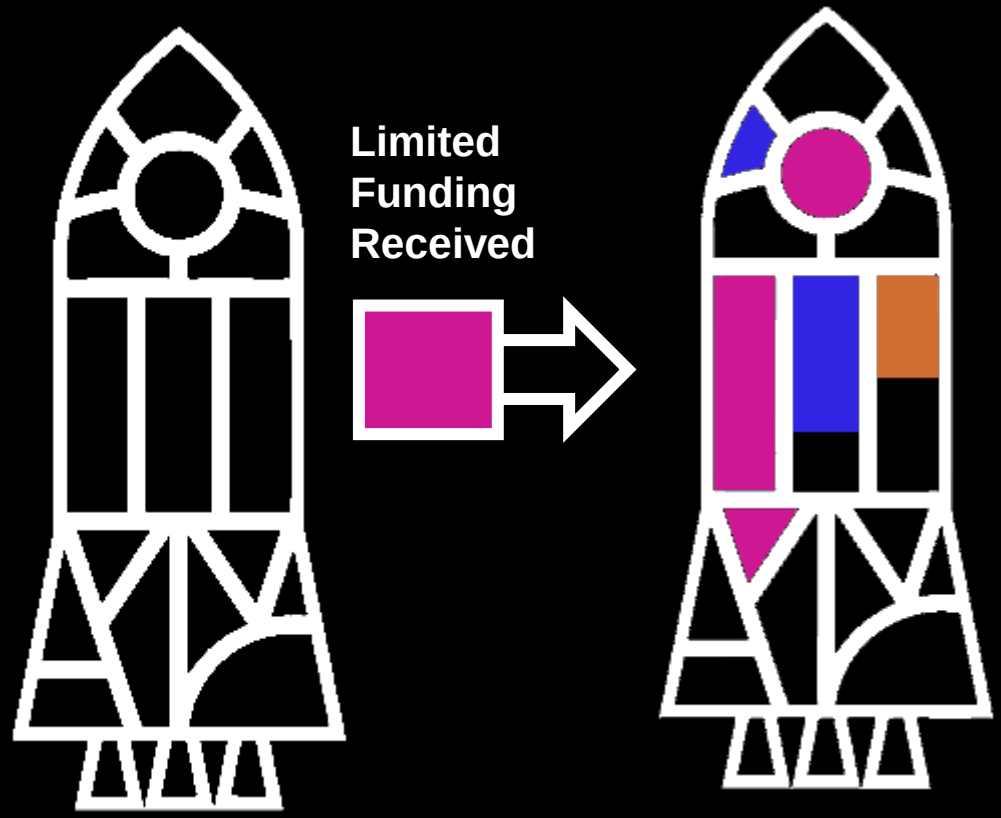
What is done, how it's accomplished, and who participates affect our world, quality of life, and humanity's future.

Historical Context: Moon to Mars Plan

We need an objective-based approach

We must think **strategically** with **resilience and flexibility** in mind and **enhance our communications** to better achieve **unity of purpose**

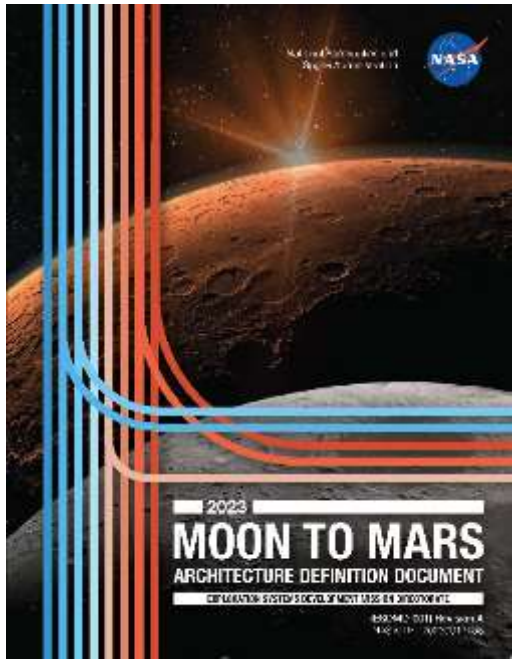
- We've been on a 30+ year roller-coaster ride for Moon to Mars development
- We've experienced widespread stress and anxiety in the wake of Constellation cancellation
- A capability-based approach does not fully support a long-term strategy to Mars



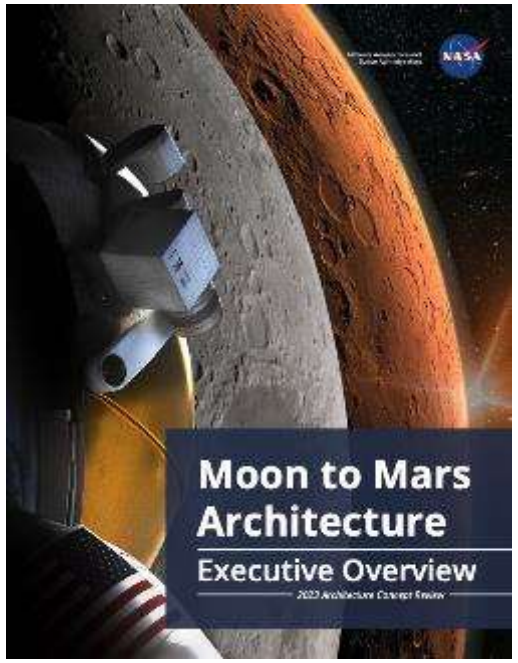
Attempts to "stick with the plan" behind the scenes

- Initially, prioritized and prepared for more fruitful days
- Led to decentralized efforts
- Over time lose clarity on overall plan

Architecture Products



Architecture Definition Document
Revision A (ADD Rev-A)



Moon to Mars Architecture
Executive Overview


National Aeronautics and Space Administration

Mars Mission
Abort Considerations

white paper

2023 Moon to Mars Architecture

Overview

Throughout the history of human spaceflight, astronauts have never been more than a few days (and rarely more than a few hours) from Earth. Aborts for missions to low-Earth orbit or the International Space Station are relatively short. Aborts for lunar missions may be longer than aborts from Earth vicinity but are still measured in days.

On the transit to Mars, mission abort is a much more complicated event because of the sheer distance between Earth and Mars. The distance and scale differences between missions to the Moon and Mars mean lessons learned from lunar mission aborts will have limited direct applicability for Mars. Depending on when an abort is initiated in a Mars mission timeline, the heliocentric nature of transit — in orbit around the Sun — may require many months to return to Earth, regardless of the transportation system selected.

For transportation architectures that refuel in Mars vicinity, mission abort during outbound transit may not even be possible. In many cases, transit abort may not be a practical response to an emergency because the time to return the crew may exceed the crew's ability to stave off the emergency.

Early human Mars missions will also have limited abort options for descent to and ascent from the surface.

- **For descent** — where abort means returning to orbit — Mars' atmosphere and gravity will make it difficult to carry sufficient on-board propellant to initiate an abort for a human-scale payload.
- **For ascent** — where abort means returning to the surface — Mars will initially lack the specialized surface infrastructure and staffing needed to aid crew after the abort. Even a successful abort to the surface may leave crew stranded, far away from assets necessary for a safe return to Mars orbit.

Both of these challenges will require an entirely new contingency operations paradigm relative to our flight experience nearer to Earth.

Transit Abort Analysis

Due to the nature of celestial mechanics, abort maneuvers are inherently more challenging than nominal mission maneuvers. To understand the fundamental nature of these abort maneuvers, NASA evaluated three propulsion concepts for a crewed Mars mission. This initial scoping assessment assumes an example trajectory with a roundtrip duration of 850 days with a short stay in Mars vicinity.

The three transportation propulsion concept scenarios analyzed were:

- A hybrid abort, where a low-thrust hybrid nuclear electric propulsion (NEP) and chemical propulsion system utilizes both stages to perform abort maneuvers.
- A NEP-only abort, where the hybrid NEP and chemical propulsion system jettisons the chemical propulsion stage and utilizes only the low-thrust electric propulsion system.
- A ballistic abort, where a high-thrust propulsion system (e.g., a nuclear thermal propulsion [NTP] or all-chemical propulsion system) performs the abort maneuvers.

In all three cases, the analyses assumed that the transportation systems depart Earth with only enough propellant for the expected round-trip mission. Scenarios in which the propulsion system carries abort-specific contingency propellant were outside the scope of this initial assessment.

2023 Moon to Mars Architecture Concept Review 1

White Papers
(13 Total)

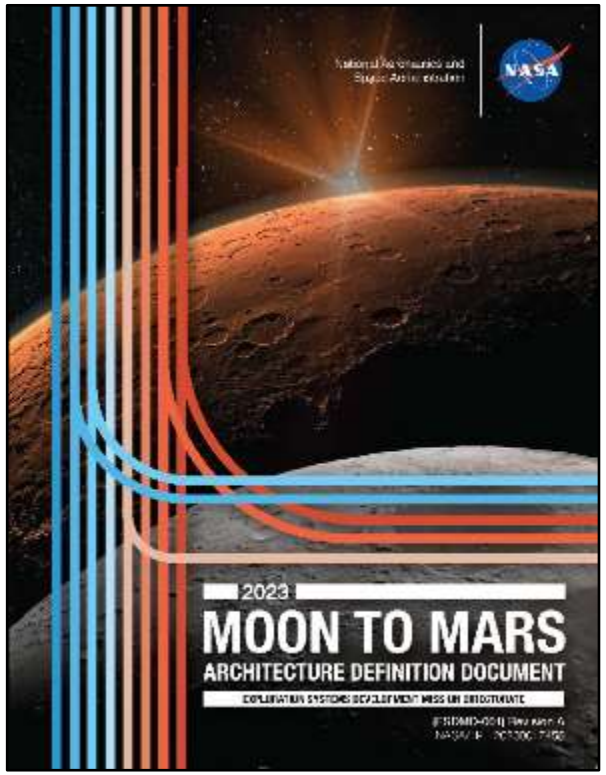
- Analytical Capabilities In-situ vs. Returned
- Safe and Precise Landing at Lunar Sites
- Lunar Site Selection
- Lunar Communications and Navigation Architecture
- Lunar Logistics Drivers and Needs
- Surface EVA Architectural Drivers
- Mars Mission Abort Considerations
- Mars Communications Disruption and Delay
- Mars Surface Power Generation
- Mars Priority Decisions
- Round Trip Mars Mission Mass Challenges
- Human Health and Performance for Mars Missions
- Exploration Lessons Learned from the Space Station

Moon to Mars Architecture Products
www.nasa.gov/architecture

Suggestion from 2023 Architecture Workshops

White paper added after ACR23 Concurrence

Enabling Informed Exploration Partnerships



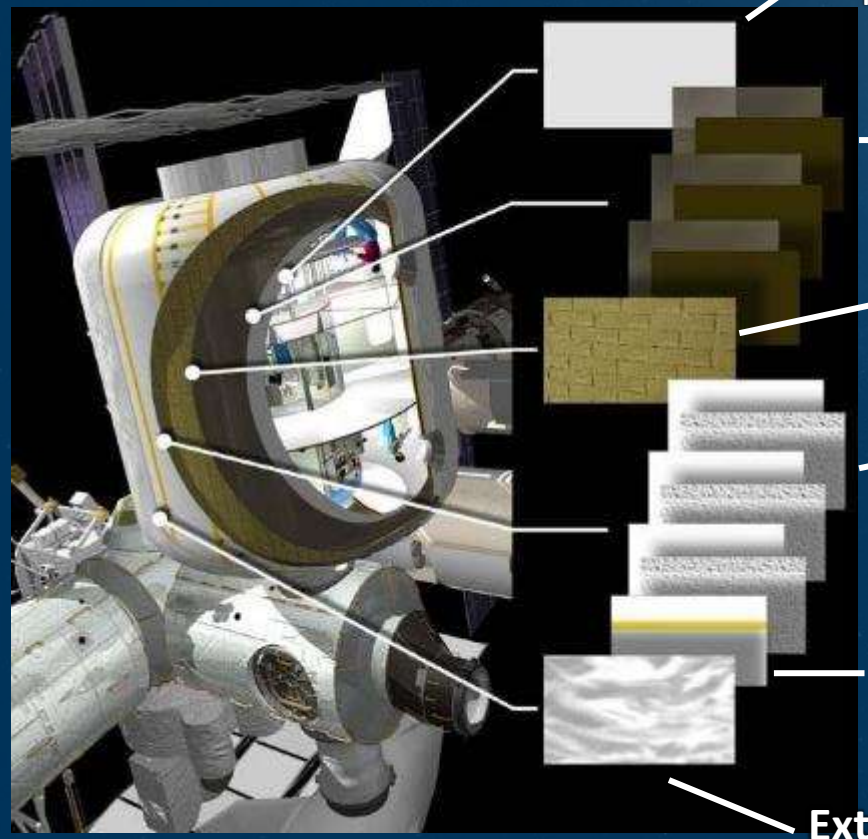
Unallocated Use Cases and Functions:
All use cases and functions *not* mapped to current systems express existing architectural needs for large systems or elements available for partnerships

Open Questions and Gaps:
Human Lunar Return and Foundational Exploration segment descriptions include lists of open questions and integrated capabilities identified by the architecture team

Utilization (Science and Technology) Opportunities:
2024 Architecture Concept Review updates will more clearly articulate areas and scenarios where smaller or emerging partners can contribute to fulfill objective needs through payloads or experiments

Moon to Mars **Architecture Definition Document (ADD)** Revision A

Moon to Mars Architecture products enable strategic conversations where NASA needs and partner strategies align.



Internal Scuff Layer: Protects against punctures and fires

Bladder: Keeps air inside the habitat from escaping

Restraint Layer: Main structure that helps hold the inflatable together

Micro-meteoroid/ Orbital Debris Shield: Multiple layers protect the structure from impacts

Thermal Blanket: Protects the crew from extreme temperatures

External Shield: Protects the habitat from erosion by molecules in space or moon dust

Inflatable Material System