MARS-FORWARD CAPABILITIES TO BE TESTED AT THE MOON

INTRODUCTION

NASA's human exploration strategy focuses on extending humanity's reach through human exploration and scientific field research at the Moon, Mars, and beyond. The agency's Moon-to-Mars Strategy and Objectives are the guideposts that frame the architecture and help prioritize development investments. As planning matures and new technologies are developed, NASA and its partners have identified a series of risk-reduction activities to practice, improve, and refine before sending an astronaut crew to Mars. These operational constructs are combined in various ways to accomplish the mission goals as we expand our reach beyond the International Space Station to the lunar vicinity and on to Mars.

Using an evolutionary approach, the Moon-to-Mars architecture enables high priority science, technology demonstrations, systems validation, and operations to live and work on a non-terrestrial planetary surface, with a safe return to Earth. Key characteristics include operating and designing the lunar systems with Mars risk reduction in mind, from a systems, operations, and human perspective. The architecture accommodates this approach in the context of available capabilities and differences in the lunar and Mars environments. Initially at the element level, then combined operations that eventually culminate in several extended-duration analogs in the lunar vicinity where the crew experiences long durations in micro-gravity coupled with rapid acclimation to partial gravity excursions using Mars-like systems and operations. While the environmental and operational strategies will differ between the Moon and Mars, if done correctly, systems deployed on the Moon may help inform design and operational strategies for future Mars missions. As an example, lunar missions begin with short-duration sortie missions leading to eventual build-up of capabilities and infrastructure to enable longer stays. Mars missions begin with the deployment of the necessary surface infrastructure prior to sending the crew. Essentially, each lunar mission can serve as an excellent down-payment to future Mars missions.

This paper highlights Mars-forward capabilities that can be demonstrated during Artemis missions on and around the Moon and cites the relevant Moon to Mars Objectives that drive NASA's architecture development. Broadly, Operational Objectives (OP) 1 and 7 apply to this topic.

- OP-1: Conduct human research and technology demonstrations on the surface of Earth, low Earth orbit platforms, cislunar platforms, and on the surface of the moon, to evaluate the effects of extended mission durations on the performance of crew and systems, reduce risk, and shorten the timeframe for system testing and readiness prior to the initial human Mars exploration campaign.
- OP-7: Validate readiness of systems and operations to support crew health and performance for the initial human Mars exploration campaign.

More specifically, the following key operational constructs, capabilities, and technologies are considered high priorities to prepare for the first human missions to Mars:

- **Human Adaptation and Accommodation in a Long-Duration Deep Space Environment (Crew Health & Performance):** Demonstrate the ability for humans to safely live and work in deep space. Conditions such as radiation, microgravity, communication disruptions and delays, isolation, independent medical care, and logistics utilization will be challenging for a crew traveling up to 1.8 billion kilometers roundtrip. Analogs aboard the International Space Station and on the ground will continue to help mitigate these risks, but operational Mars simulations at the Moon will offer higher fidelity in a true deep space environment.

  OP-6: Evaluate, understand, and mitigate the impacts on crew health and performance of a long deep space orbital mission, followed by partial gravity surface operations on the Moon.

  TH-4: Develop in-space and surface habitation system(s) for crew to live in deep space for extended durations, enabling future missions to Mars.

  TH-8: Develop systems that monitor and maintain crew health and performance throughout all mission phases, including during communication delays to Earth, and in an environment that does not allow emergency evacuation or terrestrial medical assistance

- **Deep Space Delivery and Aggregation:** Previous assessments have indicated the need to deliver elements autonomously and support incremental build-up to prepare for the eventual accumulation of systems necessary to achieve Mars capable transit systems. NASA is currently at the starting line with the operational implementation of crew transportation following the Artemis I flight test validating the Space Launch System rocket, Orion spacecraft, and Exploration Ground Systems. Contracts are in place for deep space cargo deliveries using Gateway Logistics Services and commercial launch vehicles, and for initial Gateway elements and Artemis III and IV Human Landing Systems (HLS). NASA has international partnerships with Canada, Japan and the European Space Agency to develop and operate the Gateway. All combined, NASA is ready to begin delivering crew, cargo, and spacecraft to the edge of the Earth-Moon system. Similar systems will likely also be used to ferry systems and propellant to a similar orbit to be aggregated for crewed Mars missions. The International Space Station Program also has a rich repository of lessons learned that will be applied to the next evolutionary steps in large human spacecraft. That experience will need to be extended to the edge of cislunar space and be combined with autonomous operations and propellant transfer and management. HLS and Gateway will blaze the trail for similar operations required to aggregate and supply logistics & propellant for the Mars transit vehicle.

- **Long Duration & Dormancy:** Unlike the International Space Station, lunar and Martian systems will be uncrewed for longer periods of time than they will be crewed. Crewed lunar mission durations will be on the order of weeks to months, and crewed Mars mission will be on the order of years, with system lifetimes for both of a decade or more. Reliability of systems and sparing strategies will have to be optimized for this new paradigm.

- **Autonomous Operations:** Given the long duration and dormancy nature of both the lunar and Martian systems as well as the extended duration round-trip communication delays for Mars missions, the systems will need the ability to operate themselves with little Earth intervention, predict or identify failures in a rapid manner, and adjust operations or repair themselves in the total absence of crew.

  OP-2: Optimize operations, training and interaction between the team on Earth, crew members on orbit, and a Martian surface team considering communication delays, autonomy level, and time required for an early return to the Earth

  OP-10: Demonstrate the capability to operate robotic systems that are used to support crew members on the lunar or Martian surface, autonomously or remotely from the Earth or from orbiting platforms.

- **Surface Landing & Ascent:** As mentioned previously, aggregation of infrastructure on both the lunar and Mars surface is a key component of future Mars missions. In addition, the ability to land crew and large exploration systems will be of paramount importance. Landing location accuracy will be required to place habitats, power systems and mobility systems without disturbing previously placed infrastructure or contaminating science locations. Automated landing will be required for pre-deployed cargo because crew will not be present, and due to distance induced control latencies (for the Moon and Mars). In addition, upon arrival at Mars the crew will be zero-g adapted, which will require greater automated landing capabilities to limit required crew operations during their landing phase. Reliability of systems for crew ascent and descent will be critical for mission success. Lunar demonstrations of portions of advanced technologies, such as demonstration of the production of locally produced commodities (e.g., propellants for ascent), can be an important step in future utilization of those capabilities for both the Moon and Mars.

OP-8: Demonstrate the capability to find, service, upgrade, or utilize instruments and equipment from robotic landers or previous human missions on the surface of the Moon and Mars.

Lunar Infrastructure (LI)-5: Demonstrate precision landing capabilities in support of continuous human lunar presence and a robust lunar economy.

MI-4: Demonstrate Mars ISRU capabilities to support an initial human Mars exploration campaign

- **Acclimation to Partial Gravity:** Transitioning the crew from long duration zero-gravity to partial gravity is critical from a safety and exploration value perspective. Lunar surface expeditions will eventually be about 30 days and the short-stay option for a Mars surface expedition is about 30 sols. Limiting the crew's gravity acclimation time shortens the time they must spend in the descent cabin, reducing its requirements, while also allowing them to conduct exploration and field research at the destination as soon as possible.

  OP-6: Evaluate, understand, and mitigate the impacts on crew health and performance of a long deep space orbital mission, followed by partial gravity surface operations on the Moon.

- **Crewed Surface Operations and Surface Mobility:** Extravehicular activities (EVAs) on the Moon will allow Artemis astronauts to practice the similar EVA operations that future crew will need to conduct on Mars. Similarities include crew-assisted logistics transfers, science operations, and daily crew activity cycles in combination with the mobility and habitation systems in a partial gravity, dusty environment similar to Mars. Mars will have an added complexity of forward / backward planetary protection protocols to contend with for surface operations. Mars has higher gravity and potentially contaminated dust but working out the operations on the Moon first will go a long way in reducing risk and improving efficiency. Astronauts walking on the Moon and Mars will have a limited distance that they can walk from their habitat or ascent vehicle due to limitations of the consumable supply in their suits as well as thermal constraints, walking speed, and walking terrain while maintaining a safe walk-back distance to their vehicle. Adding a single mobility system such as an unpressurized rover will drastically improve their exploration range and scientific return capabilities. Adding a pressurized rover brings even greater potential. Using these systems on the Moon over multiple missions will allow NASA and its partners to reduce risk for future Mars missions.

  OP-5: Operate surface mobility systems, e.g., extra-vehicular activity (EVA) suits, tools and vehicles.

  LI-6: Demonstrate local, regional, and global surface transportation and mobility capabilities in support of continuous human lunar presence and a robust lunar economy.

- **Nuclear Operations:** Nuclear surface power provides a robust source of continuous power that is resilient to latitude and dust storms. Nuclear systems may also be a key part of the transportation system to Mars and beyond. The Moon is the ideal location to prototype nuclear surface power because it will reduce risks associated with power plant deployment, cable deployment, long-term operation and understanding radiation safe operations in proximity to crew operations.

  OP-1: Conduct human research and technology demonstrations on the surface of Earth, low Earth orbit platforms, cislunar platforms, and on the surface of the moon, to evaluate the effects of extended mission durations on the performance of crew and systems, reduce risk, and shorten the timeframe for system testing and readiness prior to the initial human Mars exploration campaign.

  OP-7 Validate readiness of systems and operations to support crew health and performance for the initial human Mars exploration campaign.

MI-1: Develop Mars surface power sufficient for an initial human Mars exploration campaign.

- **Interoperability Standards & Capability Modularity:** Interoperability and modularity demonstrably reduce the overall system mass and offer the potential for reduced sparing and improved reliability, both at the Moon and Mars. Systems and operations need to be designed to accommodate changes in technology for increased safety, reduced cost and improved efficiency. The lunar systems will be in operation for extended durations to demonstrate reliable performance before humans venture to Mars.

  LI-Goal: Create an interoperable global lunar utilization infrastructure where U.S. industry and international partners can maintain continuous robotic and human presence on the lunar surface for a robust lunar economy without NASA as the sole user, while accomplishing science objectives and testing for Mars.

  OP-7 Validate readiness of systems and operations to support crew health and performance for the initial human Mars exploration campaign.

LUNAR MISSIONS AS PREPARATION FOR MARS

As described in the Moon-to-Mars Architecture definition Document, the Human Lunar Return segment captures the missions that will test and exercise the human lunar access system, bringing two crew to the lunar surface for 6 days in each of those years. The crew will interact with the science systems.

Mars Forward Use Cases: While many of the Human Lunar Return use cases feed forward to future human Mars missions, example Human Lunar Return key driving use cases include, but are not limited to:

- Transport crew and systems from Earth to cislunar space
- Physical assembly of integrated assets in cislunar space
- Return of crew and systems from cislunar space to Earth
- Frequent crew EVA on the surface
- Return of collected samples to Earth in sealed sample containers
- Refueling of spacecraft in space
- Vehicle rendezvous, proximity operations, docking, and undocking in cislunar space

Mars Forward Systems:

- SLS/Orion to transport crew to deep space
- HLS ascent as a demonstration for Mars ascent
- HLS autonomous terminal descent and landing including plume ejecta dynamics
- xEVAS suit is feed forward to a partial gravity Mars EVA suit
- Gateway systems such as solar electric propulsion, autonomous systems, and habitation feed forward to Mars transit and habitation
- VIPER is feed forward for Mars ice core drilling

Mars Forward Operations:

- Orion transportation and operations in NRHO as an analog to Mars elliptical orbit operations
- Crew transportation to deep space via Orion/SLS and / or other commercial launch system.
- Communication and Pointing, Navigation, and Timing
- Docking/berthing

- Habitation system performance
- Crew health maintenance
- Autonomous element control
- Logistics management and planning
- High-power solar electric propulsion
- Automated landing & hazard avoidance
- Precision landing to assist in infrastructure buildup and mitigate rocket plume interaction with previously deployed infrastructure
- Sample return back to Earth via transportation stages and Orion

The **Foundational Exploration** segment contains increasingly higher fidelity analog missions for testing the applicable Mars surface systems and similar exploration concept of operations required for the Mars surface activities. The analogs must be performed far enough in advance and with necessary fidelity / commonality of the crewed Mars mission to inform vehicle designs and operations. These analogs feature increasingly extended time in deep space coupled with missions to the lunar surface of increasing duration and mobility that are as close to the actual Mars mission profile as possible. Despite this, it should be recognized that there will be practical limitations on the fidelity of these missions, and not all relevant spaceflight hazards for Mars can be fully represented. Similarly, while mission duration is a key variable, not all human system risks are dependent on duration. These caveats aside, where mission duration is a key variable (noting that not all variables will be dependent on duration). Mars forward attributes in addition to the human lunar return segment are:

Mars Forward Use Cases:

- Delivery of large elements to and unloading of elements on the lunar surface
- Uncrewed relocation of mobility elements to landing sites around the lunar South Pole
- Robotic assistance of crew exploration, surveying sites, locating samples and resources, and retrieval of samples
- Crewed missions landing near pre-deployed assets at the lunar South Pole
- Crewed/robotic collection of samples from Permanently Shadowed Regions (PSRs)
- Crew Intra-Vehicular Activities (IVA) research on the lunar surface
- Mars analog missions with extended durations in NRHO followed by lunar surface stays
- Deployment of power generation and storage systems at multiple locations around the lunar South Pole
- Deployment of assets in lunar orbit to provide high availability position, navigation, and timing for astronauts and robotic elements at exploration locations on the lunar surface
- In-situ Resource Utilization (ISRU) demonstration

Notional Mars Forward Elements:

- Unpressurized mobility to transport cargo, elements, logistics and crew both prior to and during crew missions
- Pressurized mobility for crew exploration of the planetary surface
- Cargo transportation to deliver large elements and cargo to the surface
- Surface habitation (mobile or perhaps stationary) to support the crew while on the surface.
- Power generation, storage, and distribution on the surface
- High bandwidth communication and position, navigation and timing systems

Mars Forward Operations:

Lunar missions in the Foundational Exploration mission segment phase can serve as key operational risk reduction avenues for portions of both the Mars transit and surface operational phases. A series of Mars mission analogs where the crew spends months prior to landing on the lunar surface can provide vital human performance data simulating the Mars transit phase. Once on the surface, lunar exploration activities can also demonstrate key elements of potential Mars surface activities. Key operations or risk mitigations include:

- Gateway Logistics Services autonomously delivers logistics to Gateway as it would in preparation for a Mars mission
- Automated landing of crewed vehicle as a demonstration for Mars
- Acclimation of zero-g adapted crew (long duration but not necessarily the same full duration as a Mars transit in microgravity) to partial gravity operations
- Offloading of large elements from the cargo lander
- Exercise of autonomous vehicle operations
- Exercise of teleoperated surface assets by the orbiting crew
- Traverse of surface to simulate Mars mission profile with mobility, EVA and sample collection operations
- Dust mitigation and planetary protection approaches
- Surface logistics resupply of the crew systems with pre-deployed logistics carriers
- Interaction between surface and orbiting crew with similar mission support and communications protocols as will be used at Mars
- Demonstration of reliable lunar ISRU systems as applicable to Mars

NASA has chosen a strategy that both minimizes crew risk and required infrastructure for the Moon-to-Mars Architecture that begins as a minimally viable implementation that can be leveraged for future missions that can stay longer and explore further as systems are evolved and demonstrated by NASA and it partners. **The development and operations of the systems required for the lunar surface missions will be purposely scoped to reduce development and operations risk for the first Mars mission.**

KEY TAKE-AWAYS

While the environmental and operational strategies will differ between the Moon and Mars, if done correctly, every mission to the Moon can help inform design and operational strategies for future Mars missions by:

- Providing key information and approaches necessary to support humans at greater duration and distance in deep space;
- Demonstrating key operational capabilities and techniques;
- Evaluating advanced exploration and surface exploration techniques; and
- Reducing the risk of advanced technologies and system concepts.

This white paper was developed as part of NASA's 2022 strategic analysis cycle to address topics of frequent discussion. For the latest white papers or other architectural documents related to human missions to the Moon and Mars, please visit: **www.nasa.gov/MoonToMarsArchitecture**.