IAC-21,A3,1,12,x64322

# Long-Term Architecture Development For The Moon And Mars

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ABSTRACT:
Developing an enterprise-level architecture encompassing future human-robotic science and exploration at the Moon and Mars requires a visionary approach that ensures NASA is responsive to national priorities and global science and technology advancement objectives. While the initial capabilities needed to return humans to the Moon may be well understood, NASA is still formulating a long-term infrastructure at the Moon and working to narrow the trade space for the first human missions to Mars. This paper will focus on the formulation and current status of engineering and design applications for a long-term and robust lunar architecture that will implement the Artemis Base Camp concept, including pre-formulation activities and elements currently in formulation. Authors will demonstrate how the Moon-to-Mars campaign approach fosters commonality of requirements and standards across individual mission elements, as well as multi-destination systems and operations, to reduce risk and encourage healthy competition in the growing space market. Among the Artemis Base Camp elements discussed will be multiple surface mobility elements, a fixed, anchoring surface habitat, fission surface power, and an in-situ resource development pilot plant. The narrative will clearly illustrate the direct evolution of the base camp elements to a minimal Mars architecture concept, and also outline unique development efforts that will be required in the next decade to make it possible to send humans to the Red Planet as early as the 2030s.

**Acronyms**

| | |
|---|---|
| CLPS | Commercial Lunar Payload Services |
| CSA | Canadian Space Agency |
| ESA | European Space Agency |
| GLS | Gateway Logistics Services |
| HALO | Habitation and logistics outpost |
| HLS | Human Landing System |
| JAXA | Japan Aerospace Exploration Agency |
| LEO | Low-Earth orbit |
| LETS | Lunar Exploration Transportation Services |
| LLO | Low-lunar orbit |
| LTV | Lunar Terrain Vehicle |
| NASA | National Aeronautics and Space Administration |
| NEP | Nuclear Electric Propulsion |
| Next STEP | Next Space Technologies for Exploration Partnerships |
| NRHO | Near-rectilinear halo orbit |
| NTP | Nuclear Thermal Propulsion |
| PPE | Power and propulsion element |
| SLS | Space Launch System |
| TRL | Technology readiness level |

## 1. INTRODUCTION

In December 2017, NASA was directed to "lead an innovative and sustainable program of exploration with commercial and international partners to enable human expansion across the solar system and to bring back to Earth new knowledge and opportunities." [1] In March 2019, the National Space Council (NSpC) endorsed planning to return humans to the Moon, specifically the Lunar South Pole, by 2024. In addition, NASA was charged with establishing a sustainable, permanent presence at the Moon in support of both lunar exploration and development and future crewed missions to Mars and beyond. In response, NASA developed the Artemis architecture [2] focusing on the goal of returning humans to the lunar surface, and the Moon to Mars Campaign [3], which describes an overarching, integrated approach to long-term human exploration using all human spaceflight platforms, including Artemis, the International Space Station, and low-Earth orbit (LEO) development with a goal of enabling the first human missions to Mars.

The Biden administration, which took office in January 2021, has fully embraced the Artemis architecture and Moon to Mars Campaign [4]. NASA continues to work with the new administration to engage American industry and international partners across human spaceflight missions. This effort includes reaping the investments in the Space Launch System (SLS) and Orion, which are supported by suppliers and workers in all 50 states, and nearing their first integrated flight test. It also includes establishing new programs and partnerships with industry such as the Human Landing System (HLS), Lunar Terrain Vehicle (LTV), and the Commercial Lunar Payload Services (CLPS) initiative managed by NASA's Science Mission Directorate (SMD). All new elements of the Artemis architecture are open to companies large and small and spread throughout the nation. NASA is also strengthening and expanding America's international partnerships via the Artemis Accords and international discussions of contributions to Artemis. To date, three of the primary space station partners—the Canadian Space Agency (CSA), ESA (European Space Agency), and Japan Aerospace Exploration Agency (JAXA)—have announced planning to define participation in the Artemis architecture, and a total of 11 countries to date have joined NASA in signing the Artemis Accords,[5] which lay out a series of values, principles, and norms centered around peaceful exploration and the open advancement of scientific knowledge on the Moon.

Together, these efforts form a firm technical, diplomatic, and economic foundation that will lead to a successful and sustainable human return to the Moon and an eventual journey to Mars.

## 2. MOON TO MARS CAMPAIGN

The Moon to Mars Campaign advances common elements for both the Moon and Mars architectures and is based on evolutionary increases in capabilities, driven by national priorities and balanced with anticipated budgets to establish a steady cadence of missions and a foundation for long-term science and technology advancement in deep space. At the Moon, NASA will establish annual missions and growing infrastructure buildup in orbit and on the surface, designing hardware for dual Moon-Mars purposes as much as possible, as shown in Figure 1.

### *2.1 The Lunar Architecture*

The two anchoring locations at the Moon are the near-rectilinear halo orbit (NRHO) and the lunar surface at the South Pole. Taken in tandem, the two offer unprecedented access to the lunar environment for ground-breaking science investigations, technology demonstrations, and long-term exploration in deep space.

SLS and Orion, launched from the Kennedy Space Center launch complex, will deliver four crew to the NRHO. As the SLS evolves from Block 1 to Block 1B with the exploration upper stage, it will be capable of delivering large payloads to orbit in addition to Orion and its crew. For the first crewed demonstration landing, Orion may dock directly with the HLS, but for operational missions beyond that, Orion will deliver crew to the Gateway for transfer to the HLS and descent to the lunar surface.

Limited infrastructure on early missions will require crew to split, with two staying in orbit and two deploying to the surface. As habitation capabilities grow on Gateway and on the surface, mission durations will increase, and four crew will land on the surface. This incremental growth supports

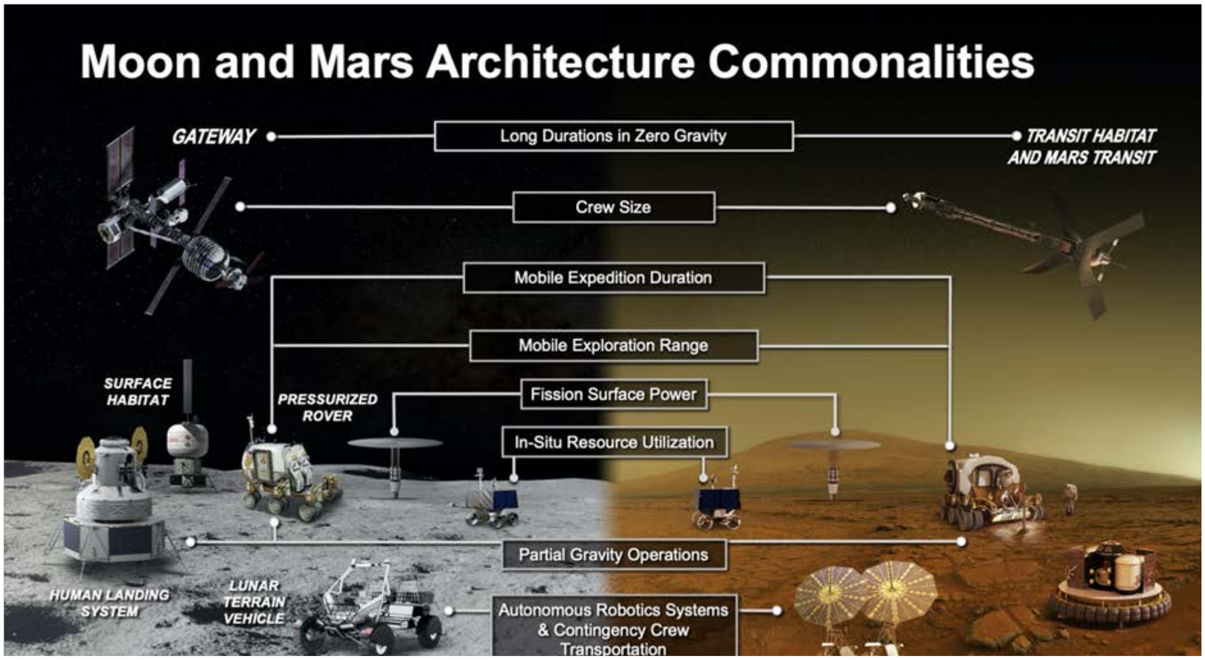



*Figure 1: The Moon to Mars Campaign includes common systems and capabilities across the Moon and Mars architectures*

increasing demand for human-led science and technology demonstrations at the Moon.

### *2.1.1 In Lunar Orbit*

Following extensive trade studies, NASA identified the NRHO as the preferred orbit in which to place the Gateway for long-term positioning around the Moon. The NRHO balances mission requirements, risk, and vehicle capabilities to ensure stable operations in orbit that can support crew expeditions and robotic missions in any location on the lunar surface.

The Gateway will be the mainstay in orbit, assembled modularly with contributions from NASA, ESA, CSA, and JAXA. The first two elements to arrive to orbit will be the Power and Propulsion Element (PPE) and the Habitation and Logistics Outpost (HALO). Launched together on a SpaceX Falcon Heavy, the PPE and HALO will serve as the foundation of the ship. PPE, built by Maxar, is a high-power, 60-kilowatt solar electric propulsion spacecraft that will provide power, high-rate communications, attitude control and orbital maintenance for the orbiting ship. The HALO, built by Northrop Grumman, will be the initial pressurized volume and first crew cabin for early astronaut expeditions aboard the Gateway. ESA will provide the International Habitat (I-Hab), including JAXA-provided environmental control and life support systems, batteries, thermal control, and imagery components. ESA also will provide the ESPRIT module for enhanced communications, refueling, and viewing through a window similar to the ESA-built Cupola aboard the International Space Station. CSA will provide advanced robotics, including Canadarm3. SpaceX will be the first Gateway Logistics Services (GLS) provider, delivering up to 5 metric tons of cargo, equipment, and consumables to the ship.

Later in the development planning, a proposed Transit Habitat is a large-volume element that would serve the dual purposes of increasing Gateway habitation volume while demonstrating the capabilities for housing the crew in deep space for the multiple years of a Mars mission transit. Even with the HALO and I-Hab, and Orion docked to augment life support systems, the Gateway will only be able to host crew for 60 days. To support longer crew stays at the Moon, and to conduct Mars mission simulations, NASA anticipates the need for a larger habitable volume at the Gateway. The proposed Transit Habitat could accommodate 1,100 day stays in deep space, with a 15-year lifetime that would allow it to be refurbished for multiple missions at the Moon or to Mars and back. Deploying it to the Gateway would allow NASA and its partners to conduct high-fidelity Mars mission analogs for up to two years at the Moon while verifying its performance in the deep space environment.

### *2.1.2 The Near-Rectilinear Halo Orbit (NRHO)*

This modular buildup of the Gateway, including cargo deliveries initially provided by SpaceX, requires a mixed fleet of rockets to assemble the ship, deliver crew to it, and keep it supplied. The human landing systems (HLS) are expected to arrive via commercial rockets as well.

Considering the three major lunar orbit types NASA studied for the Gateway—distant retrograde, low-lunar, and halo—the halo orbits, and in particular, the near-rectilinear halo orbit, traded best in terms of access (to the orbit as well as from the orbit to the surface and back), energy, environment, and communications. Those familiar with the Apollo missions that used a low-lunar orbit (LLO) often ask why NASA would make a change for Artemis. One of the key characteristics of the NRHO is that its location, situated favorably among Earth's and the Moon's gravity fields, results in a cost of long-duration orbit maintenance velocity ($\Delta v$) of less than 10 m/s per year versus in excess of 50 m/s per year in LLO. As a design trade, this is extremely attractive to support the aggregation of elements distributed across multiple launch vehicles. NRHO also provides continuous communication to Earth and near 100% solar insolation for power production purposes. In LLO, communication and solar insolation are 50% and 70% which is disadvantageous for long-duration support.[6] This approach is a key enabler of a lunar presence where each element can be used for many years by multiple crewed missions. NRHO-based operations also can support Mars mission simulations, with the orbiting Gateway serving as the Mars transit vehicle, and landers, rovers, and other surface systems serving as Mars surface systems.

### *2.1.3 On the Lunar Surface*

Astronaut expeditions to the lunar South Pole will have limited infrastructure for early Artemis missions, with crew living inside the lander cabin throughout their stay on the surface. As elements are delivered to the South Pole that support better living conditions, surface expeditions can grow in length and crew numbers. The elements on the surface will comprise NASA's proposed Artemis Base Camp, with mobility, habitation, power, and a growing number of science and technology capabilities. Other exploration technologies will be demonstrated on the lunar surface including an in-situ resource utilization pilot plant to demonstrate the ability to harvest lunar resources to support human missions.

Following the successful model of commercial delivery services to the International Space Station, NASA's goal is to establish recurring crew delivery services from the Gateway in lunar orbit to the surface and back to Gateway. Just as the agency has done with commercial crew deliveries to the space station, the first HLS to land on the Moon will be an

| | Apollo 11 | Apollo 12 | Apollo 14 | Apollo 15 | Apollo 16 | Apollo 17 | Total |
|---|---|---|---|---|---|---|---|
| **Mission Class** | G | H | H | J | J | J | --- |
| **Hours on surface** | 21.5 | 31.5 | 33.5 | 67 | 71 | 75 | 299.5 |
| **Number of EVAs** | 1 | 2 | 2 | 3 | 3 | 3 | 14 |
| **Mode of transportation** | Walking | Walking | Walking with MET | LRV | LRV | LRV | --- |
| **Approximate max distance from landing site** | 62 m | 450 m | 1.4 km | 4.7 km | 4.4 km | 7.5 km | 18.5 km |
| **Number of samples** | 58 | 69 | 227 | 370 | 731 | 741 | 2,196 |
| **Weight of samples (kg)** | 21.8 | 34.3 | 42.3 | 77.3 | 95.7 | 110.5 | 381.7 |
| **Mass of Tools & Sample Containers (kg)** | 22.85 | 29.17 | 43.07 | 50.29 | 53.03 | 45.69 | --- |

**MISSION CLASSES**
G: The initial lunar landing mission
H: Precision manned lunar landing demonstration and systematic lunar exploration.
J: Extensive scientific investigation of Moon on lunar surface and from lunar orbit.

MET: Modular Equipment Transporter
LRV: Lunar Roving Vehicle

*Figure 2: Like Artemis, Apollo missions grew in capability and duration as new supporting elements were added.*

uncrewed demonstration. The second will be a crewed demonstration, marking the 21st century return of humans to the Moon.

That first crew of two astronauts will spend approximately 6.5 days on the surface, launching back up to orbit as Orion completes one full rotation in the NRHO since the lander deployed from it. While this may seem like a short expedition, it is almost triple the time of any single Apollo surface expedition, shown in Figure 2, and increases time to accomplish the early science and utilization objectives addressed in sections 3 of this paper.

#### *2.1.4 Artemis Base Camp Buildup*

Artemis explorers need more than spacesuits and a ride to and from the Moon. NASA's goal is to establish an early lunar infrastructure that grows with each launch opportunity. The Artemis Base Camp, illustrated in Figure 3, situated near the lunar South Pole, will be a destination outfitted with rovers, a habitat, and the power systems to keep elements operational throughout uncrewed periods and extremely cold lunar nights that can last for weeks.

*Figure 3: Artist's concept of the Artemis Base Camp near the lunar South Pole*

#### *2.1.5 Human Landing System*

Human lunar landers have a long history of development in the government and private sector, with few designs making it to terrestrial flight and only one making it to the Moon.[7] When NASA was directed to return humans to the Moon under Artemis, the agency needed to find new ways to work with U.S. industry to create healthy competition in the lunar marketplace and inspire new concepts to land humans on the Moon.

To expedite the development process to achieve a crew demonstration landing as soon as possible in the mid-2020s, NASA issued the NextSTEP Appendix H solicitation in September 2019, open to all American companies interested in developing a crew lander for the Moon. NASA provided a reference lander design and concept of operations, as well as crew health and safety standards, interface requirements, and ascent and descent mass requirements, but otherwise left the door open to private-sector innovation.[8] Three companies—Blue Origin, Dynetics, and SpaceX—were selected in April 2020 to develop Artemis HLS concepts, and NASA ultimately selected and awarded SpaceX under Option A of the NextSTEP BAA contract, to continue toward flight of uncrewed and crewed demonstration landings.

As of this writing, NASA is under a voluntary "stay of performance" on the Option A award, to accommodate the litigation schedule associated with the Blue Origin-led team's bid protest filed with the Court of Federal Claims.

Following the first Artemis crew landing, NASA intends to use a services model for crew transportation between the Gateway in NRHO and the lunar surface. The agency issued NextSTEP Appendix N to help shape the strategy and requirements for the future services solicitation, called Lunar Exploration Transportation Services (LETS). On September 14, 2021, NASA announced it had selected five U.S. companies—Blue Origin, Dynetics, Lockheed Martin, Northrop Grumman, and SpaceX—to develop lander design concepts and evaluate performance, interface, safety, and mission assurance requirements, as well as crew health, medical, design, and construction standards. The companies will also mitigate lunar lander risks, for example, by conducting critical component tests or advancing the maturity of key technologies. With the NextSTEP Appendix N work under way, NASA will begin preparing the LETS solicitation, asking industry for proposals to provide recurring landing services.

#### *2.1.6 Rovers*

As we witnessed during Apollo, advanced mission classes resulted in increasingly longer stays, more moonwalks, and more samples returned, as shown in Figure 2. Apollo's J Class missions included Lunar Roving Vehicles that more than tripled the distances the astronauts were able to travel from their landers and more than doubled the weight of samples collected and returned to Earth. J Class missions also included advanced life support systems, allowing two-three full days on the surface.

NASA plans to send an unpressurized rover, called the Lunar Terrain Vehicle (LTV) to the lunar South Pole on a commercial rocket, to be available for the second Artemis crew landing. Unlike the single-use Apollo Lunar Electric Rovers, the LTV will have an expected lifetime of 10 years, spanning multiple Artemis missions, traveling up to 20 km (12.4 miles) on a single charge. It will have the ability to move between different science sites of interest. When crew are not at the Moon, NASA can teleoperate the LTV to transport cargo or collect science data and samples, a function that could be replicated to transport equipment and support crew missions on Mars. In addition to an initial request for information (RFI) issued to U.S. industry in early 2020, NASA issued a another RFI in 2021, addressing challenges associated with the LTV's lifetime, including surviving the long, cold lunar night and options to transport the vehicle to the lunar surface.

Later in the architecture, a pressurized rover will provide the first habitable element on the surface beyond the lander cabin. NASA is currently in discussions with JAXA to provide the pressurized rover, which will enable long-range surface exploration for two crew traveling in plain clothing as their spacesuits are docked to suitports at the rear hatch of the vehicle.[9] By entering and exiting through their spacesuits, astronauts will greatly reduce the chances of tracking harmful lunar dust inside the vehicle. The pressurized rover will be designed for reuse over a 15-year lifetime, providing storage volume for spares and logistics, dust and radiation protection, and habitation for 30 days for two crew, who can travel 40-60 km (25-37 miles) per charge. In NASA's current concept for a first human mission to Mars, a close duplicate of this rover could serve as the crew's surface habitation throughout their approximate 30 days on the surface.

### *2.1.7 Surface Habitat*

A fixed surface habitat will serve as the anchoring element of the Artemis Base Camp near the lunar South Pole. Accommodating up to four crew, it will be designed to last at least 15 years, spanning multiple crew surface expeditions for up to 60 days each. The surface habitat will have a medical bay, exercise facilities, a galley, crew sleeping quarters, and stowage volume. Its EVA airlock will have room and tools for spacesuit maintenance. The habitat will have power generation and communications capabilities, serving as a recharge station and communications hub for other surface assets. Through NextSTEP Appendix A, NASA is working with U.S. companies who are refining deep space habitation concepts, helping NASA to refine requirements for both the surface habitat and the proposed Transit Habitat.

### *2.1.8 Surface Power*

As crew numbers and expeditions grow on the surface, a dedicated power source will be required to support Artemis Base Camp assets throughout eclipse and lunar night periods when base camp assets need an additional source of power. A 10 kW fission surface power technology demonstrator at the Artemis Base Camp would provide continuous and ample power for human landers, habitats, rovers, and ISRU systems. Proving the operational capability in deep space for multiple years will be an important step in extending it as the primary power capability for human missions on Mars. As human presence and the supporting systems on the Moon evolve, there may be additional utilities needed, including additional power beyond 10 kW larger scale in-situ resource utilization, for example, may need higher power.

### *2.1.9 In-situ Resource Utilization Pilot Plant*

Among the high-priority technology demonstrations at the Artemis Base Camp is an In-situ resource utilization (ISRU) pilot plant. Extracting resources from the lunar regolith could have several ground-breaking impacts on lunar exploration and commercial applications. This ISRU plant could extract water from volatiles or extract and produce oxygen from lunar regolith for up to five years with little human involvement and maintenance. Mission implications for this early capability could include production of water or oxygen for astronaut consumables or oxygen for human lander ascent propulsion.

The Future of Lunar Operations

Artemis enables contributions from multiple nations and the private sector, and requires a mixed fleet of launch vehicles to deliver crew and hardware to orbit and the surface. The modular architecture, with internationally agreed-to interoperability standards,[10] provides opportunity for more contributors to bring their capabilities to market through Artemis.

The Artemis Base Camp represents the foundational, U.S. government-funded capabilities on the current budget horizon. NASA recognizes that the demand for access to the Moon will increase over the coming decades, spurring competition for new commerce across the entire lunar surface. Buildup of the Artemis Base Camp provides a foundational infrastructure and first-to-market capabilities that the private sector, academia, and other governments can leverage to pursue interests across the entire lunar surface.

*2.2 The Mars Architecture*

NASA's overall goal for the initial human mission to Mars is to land astronauts on the surface and return them safely to Earth while conducting research to search for signs of past and extant life. Landing site selection for this first mission will be driven by crew safety, available capabilities, and recommendations derived from the results of ongoing missions and the 2023 Planetary Science Decadal Survey from the National Academies of Science Engineering and Medicine. Once the crew lands and validates habitation/exploration/ascent capabilities, they will perform high priority science objectives, which will be finalized by NASA's Science Mission Directorate closer to the development of the mission.

*2.2.1 Challenges Influencing Human Mars Mission Architectures*

As compared to Artemis lunar missions, Mars offers three unique challenges for human exploration. The first challenge is the sheer distance. Minimum distance between the two planets varies over a 15-16-year synodic cycle, with optimum alignments occurring about every 26 months. In general, the distance traveled to Mars will be different than the return distance back to Earth. A typical round trip from Earth to Mars is 1.8 to 2 billion kilometers (1.2 billion miles), compared to less than a million kilometers round-trip from Earth to the Moon. The trajectory, date of departure, propulsion system, and time spend at Mars all set overall mission duration; Round-trip Mars missions are expected to be two to three years long.

A second challenge is that we have no human performance data for such long periods away from Earth. Research to meet this challenge uses Earth-based analogs[11] and the International Space Station (ISS) to study the effects of closed environments, isolation, and confinement, and of course we use the ISS to study the effects of reduced gravity.[12] Artemis lunar missions will also give us an opportunity to study human re-adaptation to partial gravity, deep space radiation, and living and working for extended periods in hostile, reduced gravity environments.

A third challenge is landing—and ascending—from Mars. Our robotic Mars exploration missions have thus far been entirely one-way affairs. Mars has less gravity and atmosphere than Earth, but much more than the Moon. To return home, we'll need to climb out of the Mars "gravity well" [Figure 4] and that translates to tons of ascent propellant. There are two ways to acquire our ascent propellant: either import it to Mars, or use technology called In Situ Resource Utilization (ISRU)—plus significant power mass—to manufacture ascent propellant at industrial scale on Mars. Either method will require us to meet the challenge of substantial landed mass, estimated to be at least 20 times larger than our largest robotic landers to date. Past robotic missions, such as Curiosity and Perseverance, have advanced our landing technologies at smaller scales, and we'll learn more about ascent with the upcoming Mars sample return mission. Artemis will also advance our landing and ascent skills, particularly in the areas of precision landing.

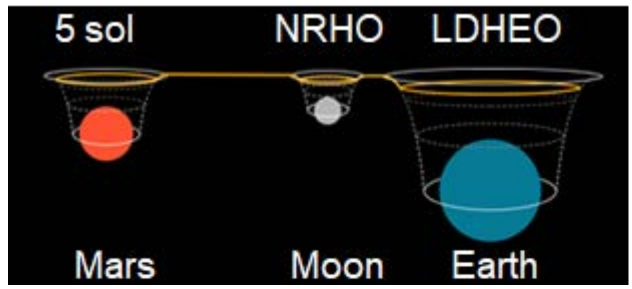



*Figure 4: Gravity Wells: Relative energy states for 5-sol Mars orbit, Near Rectilinear Halo Orbit (NRHO) at the Moon, and Lunar Distant High Earth Orbit (LDHEO) Earth.*

*2.2.2 Human Mars Mission Trade Space*

NASA's last published human Mars reference architecture focused on what is known as a conjunction class or long-stay mission, characterized by relatively fast transit to Mars when the planets' relative positions allow a minimum energy transit, followed by a very long loiter period at Mars waiting for an optimum trajectory that enables a fast return transit. Design Reference Architecture 5.0 [13] opted to spend the 500+ day loiter period on the surface of Mars, which offered substantial exploration time, but at the expense of substantial surface infrastructure. Surface systems included a large habitat, 40 kiloWatts of electric power (kWe), ISRU, and multiple surface mobility systems. The overall mission duration required a trip of more than three Earth years and at least 80 metric tons (t) of landed mass at Mars.

More recently, NASA was challenged to explore a different corner of the trade space, focusing instead on minimizing crew time away from Earth and emphasizing a lighter surface exploration footprint. Using what is known as an opposition class or short-stay mission mode, crew would minimize loiter time at Mars before their return departure window closes. At least one leg of the journey (either in- or out-bound) requires significantly more energy than a comparable conjunction class mission. As shown in Figure 5, the impulsive roundtrip change in velocity (meters per second) required for transit to Mars from a Lunar Distant High Earth Orbit (LDHEO) and return, for an opposition class mission in the 2039 example, is more than twice that of the conjunction class mission. In practical terms, this can equate to hundreds of tons more propellant mass, though in some cases the gravity assist offered by a Venus flyby can aid in reducing propellant mass. Why would we attempt such a difficult mission? The advantage of these opposition class missions is that they can shave a year or more from the duration that crew are away from Earth, relative to conjunction class missions.

reaction to propel hydrogen; and Nuclear Electric Propulsion (NEP) which generates electricity from the fission reaction to drive electric thrusters. Both of these technologies aligned with renewed national interest in space nuclear power and propulsion.[15]

For analysis purposes, NASA developed two nuclear-enabled, opposition class Mars transportation concepts, one featuring an NTP system, the other a hybrid transport,[16,17] that paired a high-efficiency NEP module with a chemical stage for high thrust maneuvers. Both profiles assumed a 2039 Earth departure to assess one of the more challenging opposition class opportunities, and both assumed a 50-day loiter period in Mars orbit to enable a 30-sol surface exploration period. Both transportation systems also assumed the payload was a 47.5 t, 4-crew Mars transit habitat.

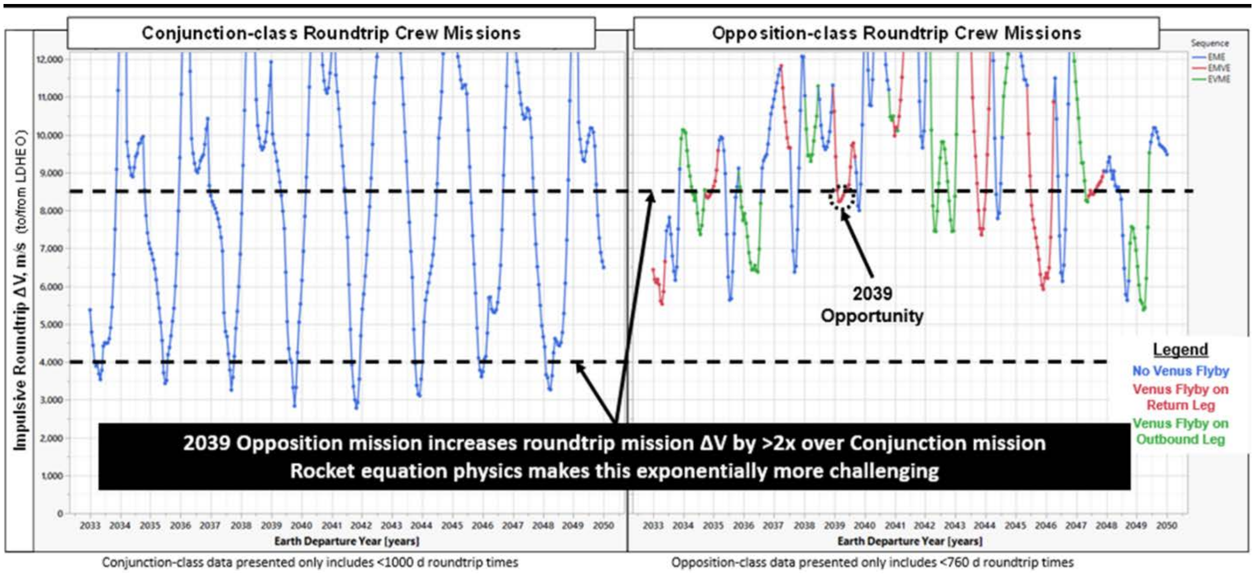



*Figure 5: Roundtrip Mars mission energy requirements, full synodic cycle 2033-2050*

Several factors prompted NASA's interest in evaluating such a challenging approach, including recent analysis indicating that shorter roundtrip mission durations could significantly reduce the risk of loss of health, loss of crew,- or loss of mission,[14] the emergence of robust commercial capabilities lowering launch costs from Earth, and a desire to leverage Artemis-derived lunar surface systems as much as possible for Mars, rather than place untested surface technologies into the first human mission's critical path. To achieve the higher energy transits required for an opposition class mission, NASA evaluated two different nuclear propulsion options: Nuclear Thermal Propulsion (NTP), which uses heat generated from a fission

Figure 6 shows a high-level comparison of the two nuclear-enabled crew transportation systems in an "all up" configuration, meaning they would depart Earth carrying all the propellant needed to get to Mars orbit and back again. As noted above, holding crew time in deep space to less than about two years in the opposition class mode requires significant energy. For the 2039 opportunity, both nuclear-enabled transportation systems are estimated at about 600 t stack mass in High Earth Orbit (HEO). To put this into perspective, ISS is about 400 t, but in Low Earth Orbit (LEO). As expected, relaxing mission duration to about 850 days (~2.3 years) in deep space can cut stack masses by half, which translates to fewer Earth-launched vehicle fueling flights.

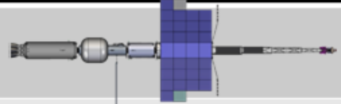
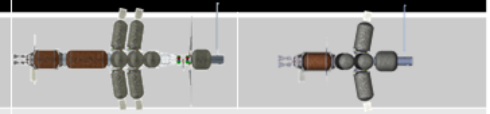
| 2039 Mission Opportunity Shown | Nuclear Electric Propulsion (NEP)/Chem Hybrid | | Nuclear Thermal Propulsion (NTP) | |
|---|---|---|---|---|
| Vehicle Concept (not to scale) |  | |  | |
| Primary Technologies | ➢ Deployable modular radiators<br>➢ 100kWe Class Hall Thrusters<br>➢ Liquid Oxygen (LOX)/Liquid Methane ($LCH_4$) Chemical Propulsion<br>➢ Zero Boiloff LOX/$LCH_4$ Storage | | ➢ Nuclear Thermal Rockets 900s Isp, 25k $lb_f$ thrust<br>➢ Zero Boiloff Liquid Hydrogen ($LH_2$) Storage | |
| **Mission Characteristics** | Variant 1 | Variant 2 | Variant 1 | Variant 2 |
| Total Time Away from Earth | 870 days | 960 days | 800 days | 960 days |
| Time in Deep Space | 730 days | 850 days | 690 days | 850 days |
| Time in Mars Vicinity | 50 days | 50 days | 50 days | 50 days |
| "All-Up" Crew Stack Mass Aggregated in High Earth Orbit | ~600 t | ~300t | ~600t | ~285t |

*Figure 6: Comparison of Mars nuclear-enabled, opposition class transportation options*

### *2.2.3 Short Stay Human Mars Architecture Concept*

For the purpose of analyzing short stay mission concepts with a light exploration footprint, NASA developed a mission concept around the relaxed duration NEP/Chemical hybrid transportation system (Variant 2 in Figure 6 above), paired with a long duration Mars transit habitat sized for four crew. Two of the four crew would descend to the surface, living and working out of a pressurized rover for the 30-sol exploration period before ascending back to the 5-sol orbit in a pre-deployed Mars Ascent Vehicle (MAV) and rejoining their crewmates. A 5-sol Mars parking orbit best balanced the propellant mass needed for the large transportation system to climb out of the Mars gravity well with the landed ascent propellant mass needed for the MAV. For this analysis, NASA assumed a 25 t payload envelope per lander, comfortably within the bounds of key entry, descent, and landing technologies such as the Hypersonic Inflatable Aerodynamic Decelerator [18] (HIAD) and supersonic retro propulsion. This payload envelope means that each major Mars cargo item must either be less than 25 t, or be divisible into smaller pieces, delivered on separate landers and reassembled on the surface of Mars. For an initial exploration mission limited to just 30 sols on the surface, two crew could comfortably live in a pressurized rover, eliminating the need for a large, long-duration habitat (and substantial surface power for long-duration close-loop life support). Other crew support systems, such as a 10 kWe Fission Surface Power (FSP)[19] or crew logistics also fit within the 25 t envelope. Without ISRU in the short stay scheme, landing a fully fueled MAV, capable of lifting two crew and return cargo to 5 sol orbit, is challenging to package within the 25 t envelope; however, some ascent propellant could be delivered on a separate lander and robotically transferred to the MAV. Many of the human Mars mission concepts previously studied planned cargo delivery years in advance of crew to allow sufficient time for surface infrastructure deployment and subsequent MAV fueling via ISRU (which is a lengthy process). Without ISRU MAV fueling, critical cargo could theoretically be delivered shortly before crew, with just enough lead time for robotic MAV surface propellant transfer. However, two reasons to consider delivering cargo well in advance of crew are 1) to gain 25 t payload entry, descent, and landing experience in a timeframe that enables crew lander modifications based on cargo lander lessons learned; and 2) to take advantage of lower-energy conjunction class opportunities for more efficient cargo delivery.

To best balance these competing constraints and challenges, the resulting multi-phase scheme, depicted in Figure 7, would consist of three 25 t landers. The first lander, shown left in the image, would deliver the MAV propellant, FSP, and a robotic surface mobility system. The second lander, shown center, would deliver a partially fueled MAV, which would be robotically topped-off with propellant before the crew arrives on the third lander, shown on the right. Crew would live in and work from a pressurized rover, also delivered on the third lander, as they explore the Martian surface, returning to orbit aboard the MAV for rendezvous with the Mars transportation system. For the sake of depicting the entire complement of landers, Figure 7 shows them fairly close together, but to prevent subsequent landers from inadvertently damaging pre-deployed systems, landers would actually be spaced about a kilometer apart.

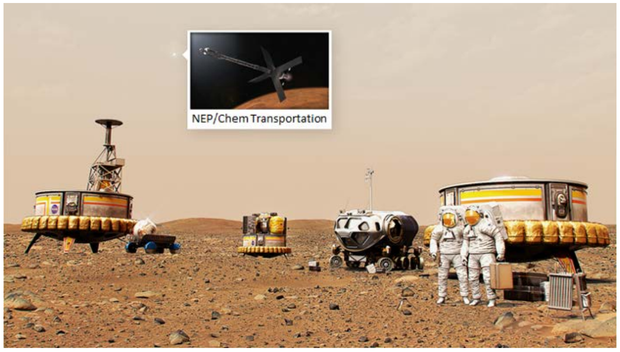



*Figure 3: Artist's concept of the short stay human Mars mission architecture*

### *2.3 Short Stay Human Mars Mission Concept of Operations*

For this concept, a human Mars architecture might begin with the launch of a Mars Transit Habitat designed to house crew for the long transit to and from Mars (as previously discussed in the lunar architecture). After assembly and outfitting at Gateway, the fully assembled habitat would spend several years in cis-lunar space, undergoing crewed test and evaluation and serving as a Mars mission analog to validate the long habitation duration operations needed for the Mars mission. If deployed at Gateway, the highly capable Mars transit habitat could also enhance Artemis operations. Up to four years before the first human Mars mission, the hybrid NEP/Chemical crew transportation stage would launch to cis-lunar space where the hybrid system is fueled in space via a series of commercially launched tankers. The hybrid NEP-Chemical system would then mate with the transit habitat and begin a series of "sea trials" to validate integrated vehicle performance. Meanwhile, the three Mars landers and their cargo would be pre-deployed to Mars orbit. Two of the three landers—one carrying the MAV and the other carrying MAV propellant, FSP, and a robotic mobility system—would descend and land within one kilometer of each other and the planned crew landing site. After autonomously activating the FSP, MAV propellant would be robotically transferred from the first lander to fill the partially empty MAV tanks on the second lander; without ISRU, this minimizes lander payload mass by distributing the MAV's wet mass across two smaller landers, mitigating the entry, descent, and landing risk of larger landers.

Crew transit from Earth to Mars will depend on the particular departure opportunity and trajectory selected, but for the relatively challenging 2039 opportunity a transit time for this particular architecture is estimated to be a little less than 10 months. During the outbound transit, nominal crew operations would include routine vehicle system health monitoring, maintenance, and repair, and vehicle course monitoring and corrections. Housekeeping activities would include habitation maintenance and repair. In deep space, crew will have opportunities for solar system astronomical observations, to conduct research on the effects of the deep space environment on humans and vehicle systems, and to conduct other planned science research. To maintain fitness for landing, crew would exercise daily, undergo health and performance monitoring and testing, and utilize on-board training systems to maintain proficiency for critical entry, descent, and landing operations. The landing crew would use on-board training systems to virtually practice surface mission transits and science operations.

Upon arrival at Mars, the transportation system would enter a 5-sol Mars orbit for a 50-Earth day loiter, which allows a 30-Mars sol surface stay period plus margin for vehicle staging and phasing. Two of the four crew members would transfer to a lander-mounted Pressurized Rover for descent to the Martian surface. Prior to initiation of the surface mission, controllers will have verified that all MAV propellant has been robotically transferred. In this concept, two crew would remain aboard the orbiting transportation system, providing critical support to the surface crew by handling remote tasks, such as telerobotic operation or monitoring of surface assets, or data analysis to support next-day planning and coordination with subject matter experts on Earth. During surface EVA operations, orbital crew serve much the same function as mission control's EVA console position does for ISS, providing oversight and immediate support faster than Earth-based ground personnel could, due to the communications lag back to Earth. The orbital crew may also use their vantage point for Mars surface or Phobos/Deimos observations.

### *2.4 Human Mars Architecture Risks and Forward Work*

NASA assessed the short stay human Mars architecture concept using a structured process to identify top risks and development challenges. Key mission risks identified include: transit propulsion system failures; transit habitat mass growth and integration with the transit propulsion element; loss of primary habitable environment on the Mars surface; MAV refueling on the Martian surface; advanced EVA architecture uncertainty; entry, descent and landing criticality; and long-duration spaceflight crew health concerns. Programmatic risks include nuclear transportation system technology development; entry, descent, and landing, and cryogenic propellant zero boil-off technology maturation; and multiple, parallel design, development, and test activities. Several additional aspects of the Mars mission were identified for study during the next analysis cycle. These include: assessment of logistics and fueling launch rates; lander delivery timing; reuse implications of first mission elements for subsequent missions; and planetary protection considerations.

A key take-away is that round trip Mars missions as fast as two years total duration are certainly possible from a performance standpoint, though challenging, with flow-down implications to capabilities and cadences needed to launch, assemble, and fuel the vehicle in space. That, in turn, has implications to overall mission complexity, risk, and cost: given the very short departure and return windows for opposition class missions, there may be little margin for a single launch delay that might domino across an integrated architecture schedule.
In the next analysis cycle, the short stay, hybrid NEP/chemical transportation architecture will be used as a measuring stick against which three alternative mission architectures will be compared. Continuing research into NTP propulsion technologies[20] will aid NASA in refining NTP-based transportation architectures. Solar Electric Propulsion (SEP), used on Gateway,[21] paired with a chemical stage similar to the NEP/Chemical hybrid configuration, is an attractive non-nuclear transportation option. Previous studies[22] have shown that SEP/Chemical systems optimized for propellant mass efficiency are better suited to the longer duration conjunction class missions, but NASA will evaluate potential component commonality and extensibility from SEP/Chemical to NEP/Chemical architectures, and options for accelerated SEP/Chemical mission durations.

Finally, the emergence of reusable, commercial chemical transportation systems offers intriguing possibilities to enhance the human Mars architecture. A series of trade studies and analyses will evaluate various emerging launch capabilities, and potential extensibility of integrated lunar capabilities to Mars operations.

## 3. UTILIZATION

As architecture systems and capabilities are formulated and developed for human missions, it is important to understand the full spectrum of demand and all potential users and use cases across a variety of mission scenarios. NASA's Utilization Plan ensures that Artemis missions will support the maximum possible goals and objectives for science, technology, and exploration research and development. Utilization in this case refers to the use of platforms and missions to conduct science, research, development, test and evaluation, public outreach, education, and commercialization. This is distinct from the carriers designed to sustain the mission and health of the crew (which include launch vehicles, transportation vehicles, orbital modules, and space suits).

The utilization goals and objectives are defined by NASA's Science Mission Directorate (SMD), Space Technology Mission Directorate (STMD) and Human Exploration and Operations Mission Directorate (HEOMD). The overarching goals and objectives will be used to identify how human missions will support the science and technology communities to conduct fundamental research about our universe and solve the scientific and technological challenges for sustaining and expanding human exploration throughout deep space.

### *3.1 Scope*

The scope of the Utilization Plan is applicable to Artemis lunar exploration missions, but it defines a set of evolving capabilities for low-Earth orbit (LEO) and human exploration of the Moon, Mars and beyond. The utilization goals and objectives are implemented through science and technology activities across the International Space Station Program, Commercial LEO utilization, the Artemis architecture to cislunar space and the lunar surface, and the architecture for the first human missions to Mars. It will be revised and updated to align with mission directorate strategic goals and objectives as the Moon to Mars campaign evolves. Future revisions of the Utilization Plan will capture strategic objective updates from the mission directorates and additional details as the human spaceflight platforms and campaigns evolve.

### *3.2 The Utilization Goals*

The Utilization Goals that are described in Table 1 below are supported by the overarching Human Exploration Goals and objectives. The goals and individual objectives (not listed) come directly from the respective mission directorates.

*Table 1: Summary of Human Exploration Utilization Goals by Mission Directorate*

| Mission Directorate | Goal Number | Utilization Goals |
|---|---|---|
| SMD | SMD Utilization Goal 1 | Enable scientific investigations from the lunar surface, including field relationships, in situ observations, and sample return, to address multidisciplinary objectives of the Science Mission Directorate |
| | SMD Utilization Goal 2 | Enable scientific investigations from human spaceflight platforms to address the multidisciplinary objectives of the Science Mission Directorate |
| | SMD Utilization Goal 3 | Enable science investigations on the surface of mars, in Mars orbit, and in Mars transit. |
| STMD | STMD Utilization Goal 1 | Enable sustainable living and working farther from Earth (“Live”) |
| | STMD Utilization Goal 2 | Enable transformative missions and discoveries (“Explore”) |
| HEOMD | HEOMD Utilization Goal 1 | Advance knowledge to support safe, productive human space travel, and perform systems testing to reduce risks for future human exploration |
| | HEOMD Utilization Goal 2 | Advance the operational capabilities required for sustainable lunar operations and the first human missions to Mars, including demonstrating approaches to planetary protection |
| NASA Multi-Directorate | Multi-Directorate Utilization Goal 1 | Enable commercial, interagency, and international partnerships to make space exploration more affordable and sustainable, grow new markets, and increase capabilities |

### *3.3 Cornerstone Utilization Capabilities*

The Utilization Plan identifies a set of cornerstone utilization capabilities that are needed to achieve the utilization goals outlined above. In addition to enabling the stated utilization goals, they must meet the integrated needs across multiple organizations and mission directorates. Each cornerstone capability is tied to the multi-directorate goals and objectives. Table 2 below lists the eight use cases that were used to define the most complex capabilities needed for utilization.

### *3.4 Mission Specific Plan for the First Artemis Crewed Landing*

The utilization goals and cornerstone capabilities provide a guiding blueprint for long-term science and technology at the Moon. For the first crewed landing, the Utilization Plan also identifies high level strategic utilization requirements, and future mission-specific requirements will be added for future missions. These requirements uphold agreements between mission directorates and will inform implementation plans, but will not require formal engineering verification since they require the operations of many systems together.

As a first step for Artemis missions the Science Mission Directorate issued the Artemis III Science Definition Team Report,[23] which serves as a reference for helping define requirements for human exploration systems and across the Artemis architecture, and specifically for the first crewed mission to the lunar South Pole. Priorities for the overarching strategy outlined in the Artemis III Science Definition Team Report are based on a variety of sources, including Decadal Survey objectives as outlined in the 2013-2023 Planetary Decadal survey (NRC, 2011), the 2007 National Research Council Report on the Scientific Context for the Exploration of the Moon (NRC, 2007), the United States Lunar Exploration Roadmap maintained by the NASA Lunar Exploration Analysis Group (LEAG, 2016), and the 2018 LEAG Advancing Science of the Moon Report (LEAG, 2018). These reports all demonstrate that the Moon offers rich opportunities for exploration,

*Table 2: Cornerstone Utilization Capabilities*

| |
|---|
| **1.1 Model Traverse Approaches**: Access to and operations in new terrain, including traverse use cases to inform crew and rover mobility, and communications needs |
| **1.2 End-to-End Sampling Strategy**: End-to-end sampling, curation, analysis and transport strategy, including collection of rocks, regolith, cores, biological samples/human research, physical sciences and ISRU samples; include cold-conditioned sample stowage |
| **1.3 Integrated Planetary Protection Strategy**: Integrated planetary protection strategy and microbial monitoring across the Artemis program and elements |
| **1.4 Extended Missions**: Extended duration orbit/surface missions for experiments and technology development (applies to both ISS and Artemis) |
| **1.5 Integrated Crew Research**: Integrating/coordinating access to human test subjects from pre- to post-flight |
| **1.6 Robotic Utilization for HEO Assets**: Uncrewed/robotic operations for utilization of HEO assets to support science and technology objectives |
| **1.7 Integrated Instrumentation Strategy**: In-situ instrumentation, deployed experiments, and measurements, including external instruments, IVA science and real time EVA measurements |
| **1.8 Complex Operations in Cold/Shadowed Regions and Volatile-bearing Terrain**: Conducting science investigations and resource utilization in partly or permanently shadowed regions (PSRs) |

with numerous opportunities to impact our understanding of the Solar System, the Universe around us, and our place within it.
Artemis science goals will be implemented through competitive opportunities that will be released in the future, and uphold all NASA research standards, open data policies, and competitive research through lunar investigation opportunities.,

The first crewed landing utilization requirements are:

- The mission shall return lunar samples of diverse types.
- The mission shall include deployment of instrumentation packages by the crew on the lunar surface.
- The mission shall perform human research
- Data available from on-board instrumentation to be used for performance and model validation by NASA.

### *3.5 Utilization enabled by future capabilities*

In addition to the landing requirements, the Gateway’s PPE and HALO will launch with three science investigation suites to study the NRHO’s radiation environment. When the crew spends time at gateway, the missions will perform human research, space biology research, and study the space environment. The scope of utilization activities will increase as more logistics to cislunar orbit become available and more long-term orbital investigations can be delivered.

The development of surface mobility and systems to enable lunar nighttime survival will expand and enhance scientific investigations, which will harness not only NASA contributions, but also those of international partners who may send instruments or rovers to the Moon.

## 4. TECHNICAL INTEGRATION

To coordinate this large effort across the Moon to Mars Campaign, strong technical integration is required to achieve a cohesive technical baseline and to ensure that NASA policies and goals are met throughout the Moon and Mars exploration architectures. This integration is aimed at translating top-level agency goals, objectives, and architectural concepts, many of which are described in this paper, into objective measures for the successful execution of flight hardware programs and projects.

Technical Integration establishes and maintains top-level requirements documentation and allocates those requirements to campaign elements and initiatives. These requirements include the overall capability of the architecture to achieve NASA goals, human rating requirements to ensure that crew safety is paramount in the design, and mission requirements to communicate mission-to-mission objectives.

In addition to requirements, Technical Integration maintains top-level campaign and mission objectives. The campaign objectives provide context to the hardware developers to ensure that designs will meet their intended uses. The mission objectives break that context down further into goals and requirements targeted at one specific mission. When taken altogether, the human rating requirements, capability and functional requirements, campaign objectives, and mission objectives form the technical baseline on which hardware development and mission integration is built.

coordinated across the architecture. Formal technical evaluation and performance measures occur through participation in hardware lifecycle reviews. These interactions help identify gaps and risks, and they inform the final assessments of system performance. This process closes the loop of requirements verification, stakeholder commitments, and overall risk posture.

## 5. IDENTIFYING AND PRIORITIZING CAPABILITY GAPS

Another key area of coordination across the Moon to Mars Campaign is understanding where capability needs for lunar missions can also address Mars mission needs for a more efficient and sustainable plan toward human exploration of Mars.[24] NASA's human exploration campaign documents capability needs to achieve the phased exploration approach to support all campaign segments, illustrated in Figure 8.

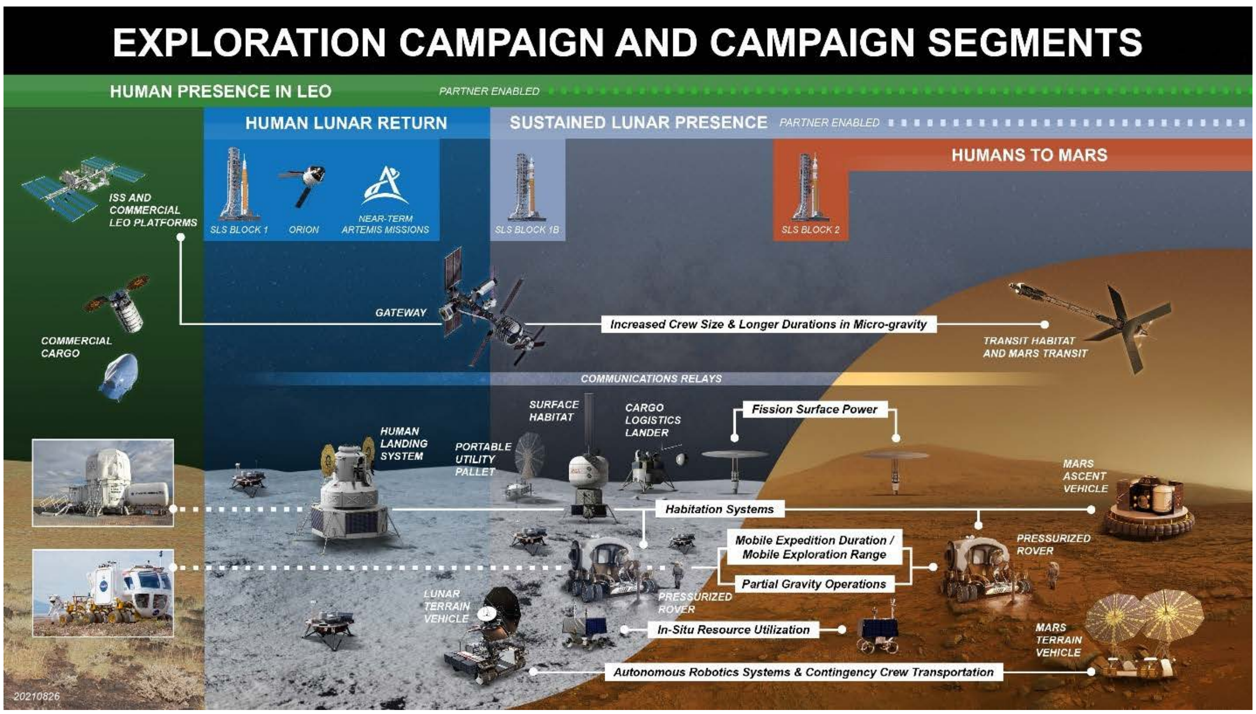



*Figure 8: Exploration Campaign and Campaign Segments*

The hardware development organizations are responsible for leading the design and mission certification. Technical Integration ensures that flow down and implementation, in both element and interface design, continue to meet the intent of the overall architecture and reflect stakeholder agreements. This occurs through support of various working groups, panels, and boards and is

When all architecture options were considered this year, 472 capability gaps were identified. The largest portion of these were classified as "Development Gaps," representing items that were simply a matter of engineering development. These items often described challenges with integrating components in a new or different way or they required existing technologies to undergo flight demonstration to establish gap closure. These mainly represent challenges that can be solved through formulation and implementation phases of spaceflight program development.

The Human Health, Life Support and Habitation Systems Capability area had the largest number of gaps. A closer review revealed that approximately 20% of these gaps are items that called for increased reliability over the current state of the art to reduce sparing requirements. If successful in closing these gaps, the capabilities could enhance the missions by reducing logistics and associated mass and other costs.

Most Communications, Navigation, and Orbital Debris Tracking and Characterization gaps were classified as development gaps. Of these, approximately 35% described enhancements that could improve interoperability with international and commercial partners or provide for high-quality video to enable the public to witness the return of humans to the Moon. It is also worth noting that 43% of these gaps can be closed on the ground and 30% of these gaps must be demonstrated on ISS or other potential LEO platforms. 79% of the technology and development gaps identified through this process relate to capabilities that ultimately enable human Mars surface missions.

Figure 9 further examines technology gaps and the platforms enabled by closure of those gaps. Similarly, Figure 10 further examines gaps and the platforms enabled by closure of those gaps. As we proceed from Gateway to the Lunar Surface to Mars, gaps are progressively closed at each platform, building up the needed capabilities and reducing the risk for human Mars surface missions.

It can be observed in Figures 9 and 10 that the number of technology gaps for each platform are lower than the number of development gaps, due to the continued technology development efforts by NASA and other partners. Figure 8 demonstrates that 90% of Technology gaps for Human Mars Surface and 60% for Sustained Human Lunar are closed by activities completed on other platforms. Similarly, Figure 10 demonstrates that 97% of Development gaps for Human Mars Surface and 67% for Sustained Human Lunar. The "closed previously in the architecture" items for each platform assume a serial order of platforms to enable future platforms. If the architecture order is changed or platforms are added/removed, the gaps would need to be reassigned to new or existing platforms. The number of identified gaps is greatest for the sustained Lunar surface phase and the Human Mars surface phase. Each of these phases require the closure of a significant number of gaps. When comparing the Sustained Human Lunar Surface and the Human Mars Surface, the number of gaps is similar. This is

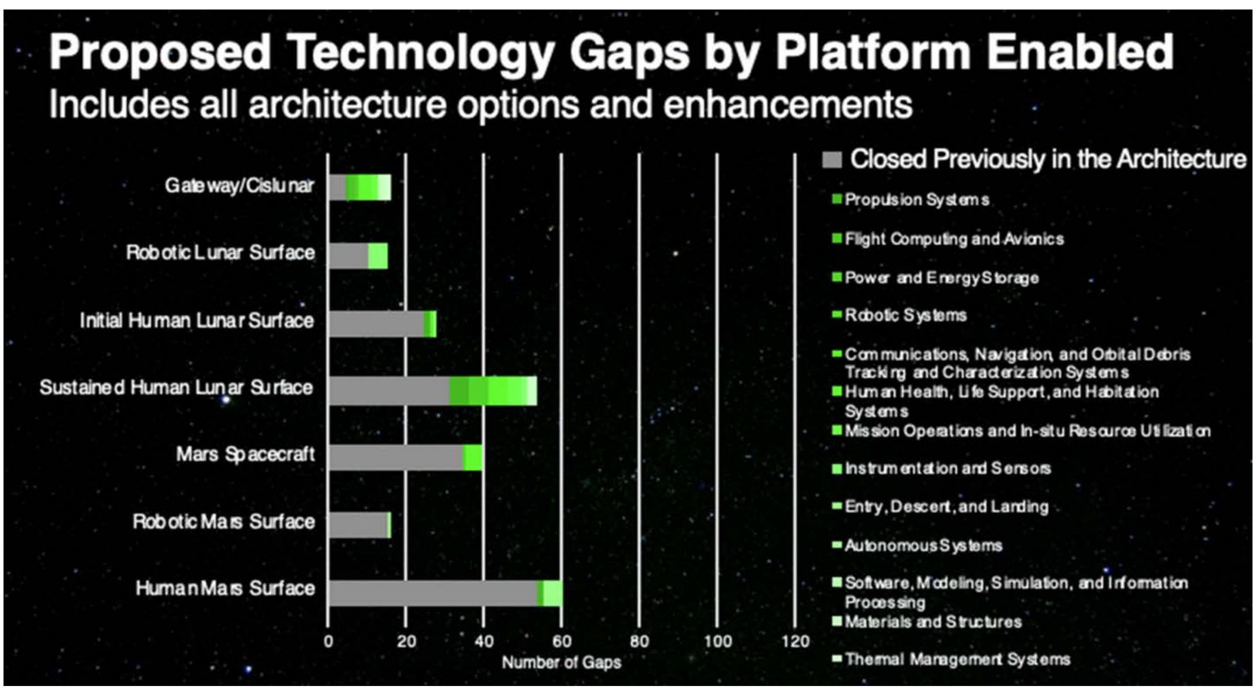


*Figure 9: Proposed Technology Gaps by Platform Enabled*

partially due the differences application of in-situ resource utilization gaps on the lunar surface and on the Mars surface.

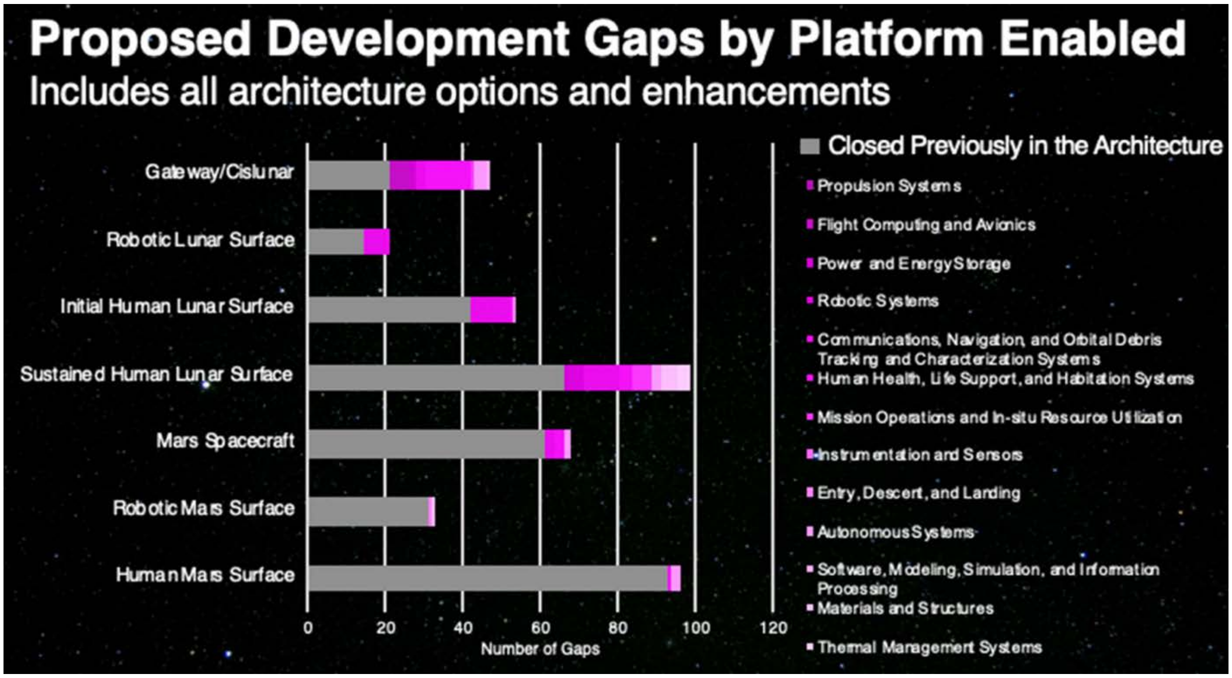



*Figure 10: Proposed Development Gaps by Platform Enabled*

The tracking of gaps is in the process of being combined across the three mission directorates. This will enable NASA to be more strategic in the investment strategy and plans for demonstration platforms through to the first enabled platform and then on to further enabled platforms demonstrates the progression of capability development and gap filling between phases. It also demonstrates the benefit of leveraging existing and nearer term platforms to enable future exploration missions. For instance, most of the gap closing activities identified in this effort can be closed via ground testing and/or on an ISS/LEO platform. Finally, the trace from ground-based activities through ISS/LEO, cislunar, and lunar demonstrates the necessity of progressive investments in technology and risk reduction to enable Mars missions. Trying to fill all the identified Mars gaps at once would be untenable. Alternatively, in the plan identified here, those capabilities are developed and tested over multiple phases, resulting in a sustainable, affordable exploration plan.

## 6. SUMMARY

It took millennia for humanity to develop the capability to achieve powered flight, and from there it took just six decades to fully break free of Earth's clutches to set foot on the Moon. Those ambitions of the 20th century found far-reaching applications that the original innovators couldn't possibly have imagined. These life-changing societal impacts and applications of aeronautics and spaceflight transformed human existence in less than a century.

And then we took a very long break from the Moon, hitting pause on the dream of science fiction ideals to establish long-term human presence at our nearest celestial neighbor. What we learned during those six Apollo landings was that our knowledge of the Moon, and our ability to keep humans healthy and productive there was not well enough understood to justify more, and longer lunar missions. We had a lot of work to do to understand the human health and performance implications for deep space exploration. And since the final Apollo mission in 1972, that's what we've done—NASA has used more affordable platforms closer to home to better understand how to keep humans safe, comfortable, and productive in the harsh space environment. Free from the mid-20th century geopolitical objectives, we were able to find common ground with international partners and begin working with the private sector to develop advanced capabilities that dramatically improved our collective abilities in space, and we saw the emergence of new markets off Earth.

With these expanded capabilities and better knowledge of human health and performance, we now have the confidence to go back to the Moon for longer stays, establishing a steady cadence of missions to evolve our understanding of humanity's place in the solar system—not just what it is, but what it safely could be. We will use what we learn at the Moon to take that next leap: sending humans to Mars. At the Moon, we will be perfecting our systems and operations, and further expanding our deep space capabilities. Yes, we *could* go to Mars today—but we might get there and (just like during Apollo) realize we aren't quite ready to stay.

The Moon to Mars Campaign establishes that the two destinations are not mutually exclusive, but to achieve human missions to Mars, we must pursue progressively challenging missions in deep space. We will establish foundational deep space capabilities at the Moon while we can operate in the relative safety of Earth's neighborhood—where we will have the benefit of growing commercial rocket capabilities, regular resupply missions, and time to operate systems and optimize protocols—before embarking on the much more arduous first human mission to Mars.

## ACKNOWLEDGEMENTS

The authors wish to thank Patrick Chai, Andrew McCrea, Katie McBrayer, Emily Judd, Laura Burke, Stephen Edwards, Bret Drake, and the NASA Marshall Spaceflight Center's ACO Team, and Steve Oleson and the NASA Glenn Research Center's COMPASS Team for Mars transportation system analysis; Steve Hoffman and Alida Andrews for Mars surface systems analysis; Bette Siegel for support of activities in Utilization; and Kandyce Goodliff for lunar architecture systems analysis.

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