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Capabilities Development: From International Space Station and the Moon to Mars

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Abstract—**The President of the United States, in signing Space Policy Directive-1, directed the NASA Administrator "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. Beginning with missions beyond low-Earth orbit (LEO), the United States will lead the return of humans to the Moon for long-term exploration and utilization, followed by human missions to Mars and other destinations." NASA is charged to land American astronauts on the lunar South Pole in 2024 and to continue a campaign of sustainable lunar surface exploration in order to develop necessary technologies and capabilities to enable initial human missions to Mars.**

NASA's lunar surface exploration plans are part of a continuum of activities utilizing platforms in low Earth orbit (LEO), cislunar space, and the lunar surface to demonstrate advanced technologies, advance operations concepts, and develop countermeasures to lessen the impacts of the space environment and long duration exposure on the crew working in space. NASA is using a capability-driven approach to identify critical gaps to be addressed as part of a focused program to reduce risk for future deep space exploration missions building to eventual human missions to the surface of Mars. Teams of discipline experts from across NASA identify capability gaps between the current state of the art and the needs of proposed exploration missions and develop integrated strategies and roadmaps for filling those gaps. These inputs include assessment of platform needs for demonstration and testing of new capabilities. Generally, the International Space Station (ISS) and Gateway are needed for demonstration of capabilities for Mars transit, while Lunar surface activities focus on development of capabilities and operational protocols for Mars surface.

This paper discusses the activities required to advance critical exploration capabilities, focusing on selection of demonstration and test location based upon the unique environments and characteristics of the ISS, Gateway, and potential lunar surface assets. The optimal strategy will be a combination of ISS/LEO, Gateway, and lunar surface testing; however, not all capabilities require all these steps on their path to deep space exploration missions.

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1. INTRODUCTION

As NASA and the international spaceflight community develop plans to return to the Moon, it is valuable to develop those plans with the needs of future human Mars missions in mind. Understanding where capability needs for lunar missions can also address Mars mission needs enables a more efficient and sustainable build towards the ultimate goal of human exploration of Mars.

This paper describes an overview of NASA's human exploration campaign through a description of a phased exploration approach with capabilities to support those phases. A framework is presented that was used to develop the capability gaps. Architecture assumptions are presented that were used to derive the capability gaps. Results and conclusions are then provided to describe the demonstration and enabled platforms for the capability gaps.

2. BACKGROUND

In keeping with Space Policy Directive-1, NASA is charged with landing American astronauts at the South Pole of the Moon by 2024, followed by a long-term presence on and around the Moon, leading toward human missions to Mars [1]. This requires a new strategic approach by NASA, which is divided into distinct phases: Phase 1: 'Initial Human Lunar Landing'; Phase 2: 'Long-term Presence on the Lunar Surface'; and Exploration Architectures beyond Phase 2. For the purposes of this paper, the Exploration Architectures beyond Phase 2 are further differentiated into Phase 3: 'Lunar Sustainability', Phase 4: 'Shakedown & Mars Orbital', and Phase 5: 'Mars Surface'.

Phase 1: Initial Human Lunar Landing

Phase 1 primarily focuses on the systems required to achieve the 2024 human landing. These systems are comprised of the Gateway, an Integrated Lander, an Extra-vehicular activity (EVA) suit, and the Exploration Systems Development

(ESD) Enterprise's Space Launch System (SLS), Orion crew vehicle, and ground systems. The objective of Phase 1 is to send four crew to Gateway and land at least two crew at the South Pole of the Moon by 2024. This phase requires NASA and commercial partners to move forward in parallel to complete the human lunar architecture and deliver crewmembers to the lunar surface. Initially, Gateway will consist of a minimum configuration comprised of a Power and Propulsion Element (PPE), Habitation and Logistics Outpost (HALO), and Logistics Module (LM).

Phase 2: Long-term Presence on the Lunar Surface

Phase 2 primarily focuses on evolving Phase 1 systems for sustainability and long-term presence on the lunar surface after 2024. Expanding habitation on and around the Moon and deployment of surface systems will be a primary focus during this phase. The key functional capability in Phase 2 is extending the duration of total lunar vicinity missions beyond the Phase 1 goal of 30 days mission duration and 6.5 days on the lunar surface.

Deployment of surface assets during this phase will support crew on the surface, potentially allowing for longer surface durations, including the ability to survive through eclipse periods at the South Pole. Staging surface missions from pre-placed surface assets and pre-deploying consumables and other supplies will remove mass and other burdens on the descent element, allowing at least four crew to be delivered and supported on the surface. Surface habitation is expected to consist of mobile and/or stationary assets that provide improved capability including increased exploration range using unpressurized and pressurized roving vehicles. Two options are presented to include fixed habitation and mobile habitation.

This period will also see augmentation of the Gateway to support lunar missions beyond 30 days total duration and future extended duration missions in cislunar space. This may include: addition of habitation element(s), utilization module(s), logistics element(s), extra-vehicular robotics, and an airlock element. These expansions will also enable testing of systems needed for long-duration Earth-independent operations, including multi-year missions to Mars.

Exploration Beyond Phase 2

Exploration architectures beyond Phase 2 primarily focuses on evolving Phase 2 systems, sustained presence in cislunar space and on the lunar surface, and assessing human exploration systems required for missions beyond the Earth-Moon system, as well as missions to Mars. These phases will continue to identify technology development needs for enabling sustainable missions to Mars. Integrated prototype systems for Mars exploration will be tested first on and around the Moon to reduce future mission risk. For additional granularity, this phase has been divided into additional phases, Phase 3: Lunar Sustainability, Phase 4: Shakedown and Mars Orbital, and Phase 5: Mars Surface.

Phase 3: Lunar Sustainability—Phase 3 focuses on additional capabilities beyond Phase 2 to support sustainable lunar exploration. The options presented trend toward past studies such as NASA's Constellation Program Lunar Surface System approach [2] and International Space Exploration Coordination Group (ISECG) Reference Architecture for Human Lunar Exploration [3], enabling longer durations and/or longer range mobility beyond Phase 2. Similar to phase 2, the capabilities assume either a fixed or mobile habitation approach. In addition, other capabilities may include in-situ resource utilization and additional surface power generation.

Phase 4: Shakedown and Mars Orbital—The Mars operations concept includes a shakedown, or testing of the integrated Mars Spacecraft, in cislunar space prior to departure for Mars. The shakedown mission would be staged from Gateway to accomplish critical test objectives, such as gaining in-space flight time on exploration systems. It would also serve to reduce system risk by demonstrating the currently assumed Mars mission-class hybrid solar electric propulsion (SEP)-chemical propulsion and verifying the Mars Spacecraft system re-start after long periods of dormancy. The mission would provide further data on humans in a deep space environment by exposing them to long communication delays and 'black out zones' as well as regions that offer limited mission abort capabilities. The same Mars Spacecraft would be used for potential Mars orbital missions and future Mars surface missions.

Phase 5: Mars Surface—In this phase, the goal is to place humans on the surface of Mars, leveraging all the previous testing and demonstration of capabilities. The same Mars Spacecraft used for the Shakedown and potential Mars orbital missions would be used to transport the crew to the Martian vicinity prior to landing. Additional capabilities needed include entry, descent, landing, and ascent systems along with surface infrastructure. Many of these capabilities will have been proven out prior to the crew landing on the surface of Mars.

3. CAPABILITIES DEVELOPMENT FRAMEWORK

Definitions

The following definitions are used within the context of the framework and this activity.

Capability: The ability to complete a task or meet an exploration objective through Architecture, Engineering, Technology, or Operations for a given set of constraints and level of risk.

Capability Area: A group of functions that performs a similar task (i.e. propulsion, robotic systems, power and energy storage). The NASA Office of Chief Technologist (OCT) 2020 NASA Technology Taxonomy was used for the capability areas [4].

Capability Gap: The inability to complete a task or meet an exploration objective. The gap may be the result of no existing capability, lack of proficiency or sufficiency in an existing capability solution, or the need to replace an existing capability solution to prevent a future gap.

Technology: A solution that arises from applying the disciplines of science to synthesize a device, process, or subsystem, to enable a specific capability (definition from the NASA strategic technology investment plan).

Mission: A major activity required to accomplish an Agency goal or to effectively pursue a scientific, technological, or engineering opportunity directly related to an Agency goal. Mission needs are independent of any particular system or technological solution. (definition from NASA Procedural Requirement 7120.5 [5]).

Architecture: A set of functional capabilities, their translation into elements, their interrelations and operations. The architecture enables the implementation of various mission scenarios that achieve a set of given goals and objectives.

Framework

NASA is using a capability-driven approach to identify critical items to be addressed as part of a focused program to reduce risk for future deep space exploration missions building to eventual human missions to the surface of Mars. The process employed aims to ensure that the capabilities required to execute NASA's human exploration plans are identified, along with strategies for filling those gaps. As illustrated in Figure 1, this involves two steps: i) defining the capability gaps, and ii) understanding the range of activities and closure pathways that are needed.

Capability gaps are defined simply as the difference between the capabilities of current missions or platforms and the needs of planned future missions. High-level mission requirements are defined by the human spaceflight architecture which takes into account national space policy, stakeholder considerations and NASA strategic guidance. Teams of discipline experts from across NASA review these mission requirements and identify capability needs within their capability area. They then articulate the gaps between the current state of the art and the capability needs of the proposed exploration missions.

Once the capability gaps have been determined, the discipline experts further characterize by type, indicating possible closure via new technology development, engineering development, acquisition of new knowledge/science, or architectural trade studies. An additional possible closure route is development of operational procedures that mitigate a potential gap identified through this process. Completion of architectural trade studies or new scientific results feed back into the capability needs and gaps articulation process and can eventually lead to determination that there are additional capability gaps. As gap closure routes are considered, testing needs to facilitate gap closure are also considered including selection of ideal test platform to demonstrate and validate new capabilities. Test platform requirements vary from standard engineering qualification testing conducted on the ground to flight tests conducted at ISS or on or around the Moon.

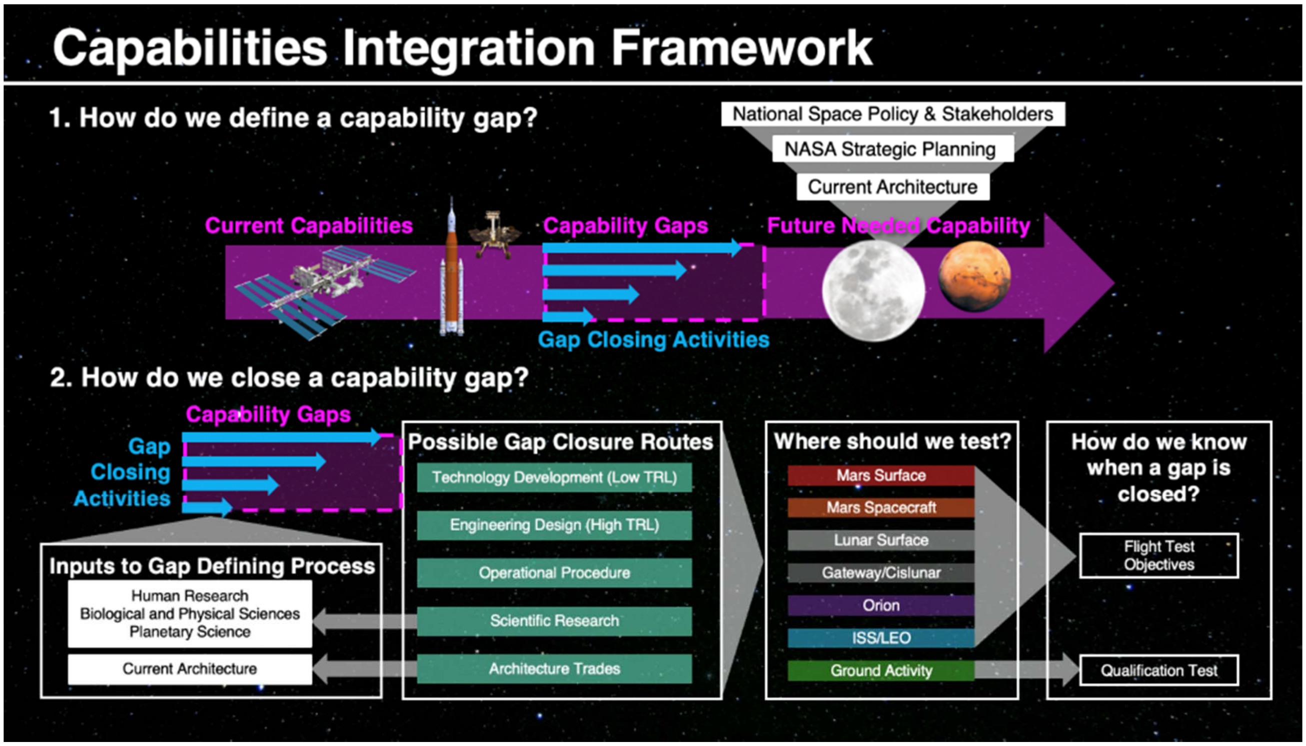


Figure 1. Capabilities Integration Framework

4. ARCHITECTURE ASSUMPTIONS

Architecture assumptions were provided for each of the phases described in Section 2 and for some of the phases, 2-3 options were presented. In addition, continuous human presence in low Earth orbit was assumed, providing research and development opportunities via the ISS and/or commercial platforms throughout the timeframe. The commercial platform(s) were assumed to have capabilities similar to ISS today for the purpose of continued testing and demonstration.

Table 1. Phase 1 Architecture Assumptions

Gateway	Crew duration of up to 30 days per year, augment Orion capability
	Support HLS - provide docking interfaces, logistics delivery and stowage
	Communications relay
	Utilization (science and technology demonstration)
HLS	2 crew for up to 6.5 days on the surface
	South Pole destination, crew operations during the daylight
	Crew live and operate out of the lander
	Mobility range of 10 km radius, based on 1 unpressurized rover

Assumptions for Phase 1: Initial Human Lunar Landing

Architecture assumptions for phase 1 focus on returning humans to the Moon. These architecture assumptions are shown in Table 1 for Gateway and HLS. In addition to these assumptions, Commercial Lunar Payload Services (CLPS) [6] may be leveraged to provide payloads to support the crew lunar mission and advance science and exploration objectives. Figure 2 shows an artist's concept for the initial Gateway and docked HLS.

Assumptions for Phase 2: Long-term Presence on the Lunar Surface

Phase 2 will include an increase in Gateway capabilities, possibly including additional habitation elements, an airlock, and an external robotic arm. Timing of these elements will depend on budget availability and international partner desire to support Gateway activities. For lunar surface, two options were considered, light mobility and light habitation. The primary difference is whether the initial lunar surface habitation capability is mobile or not. Table 2 displays the architecture assumptions for the lunar surface for each option. Figure 3 displays notional elements for the phase 2 options.

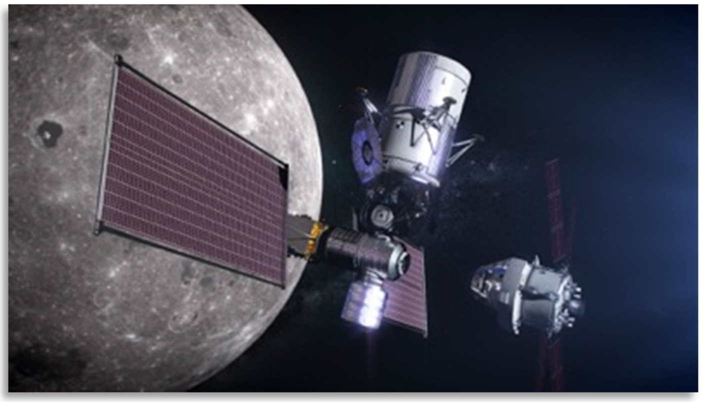


Figure 2. Phase 1 Gateway and Human Landing System (Artist Concept)

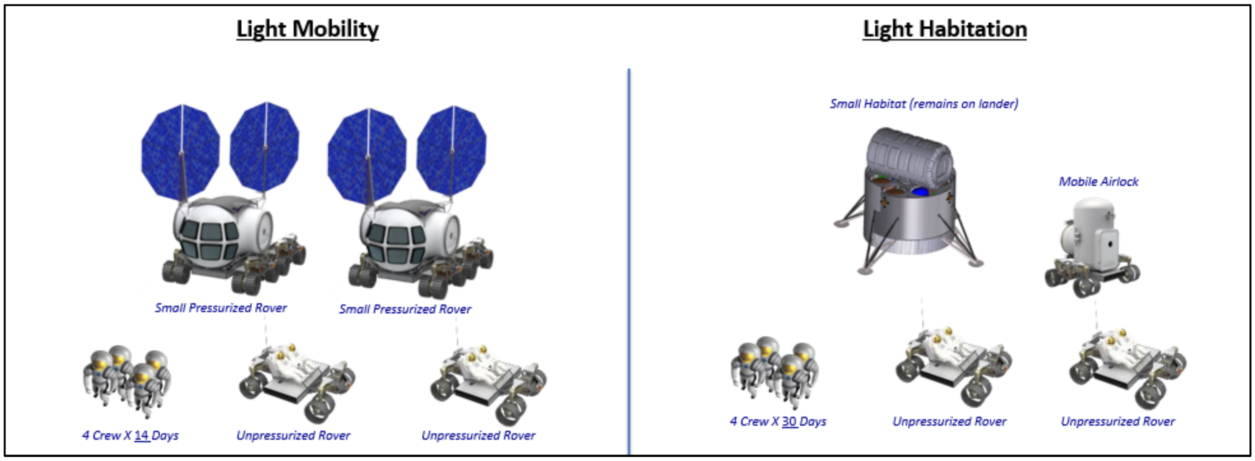


Figure 3. Phase 2 Options – Light Mobility and Light Habitation (notional elements)

Table 2. Phase 2 Architecture Assumptions

Light Mobility	4 crew for up to 14 days on the surface per mission
	Crew live and operation out of 2 small pressurized rovers (SPRs)
	Multiple landing sites (assets relocate between crew missions)
	Crew translate from lander to the SPRs through a tunnel
	Mobility range of up to 250 km radius from crew lander
Light Habitation	4 crew for up to 30 days on the surface per mission
	Crew live and operate out of small habitat (remains on lander)
	Fixed landing site
	Mobile airlock to mate with habitat to allow crew access to surface, requires tunnel for transfer from lander
	Mobility range of 20 km radius, based on 2 unpressurized rovers

Assumptions for Phase 3: Lunar Sustainability

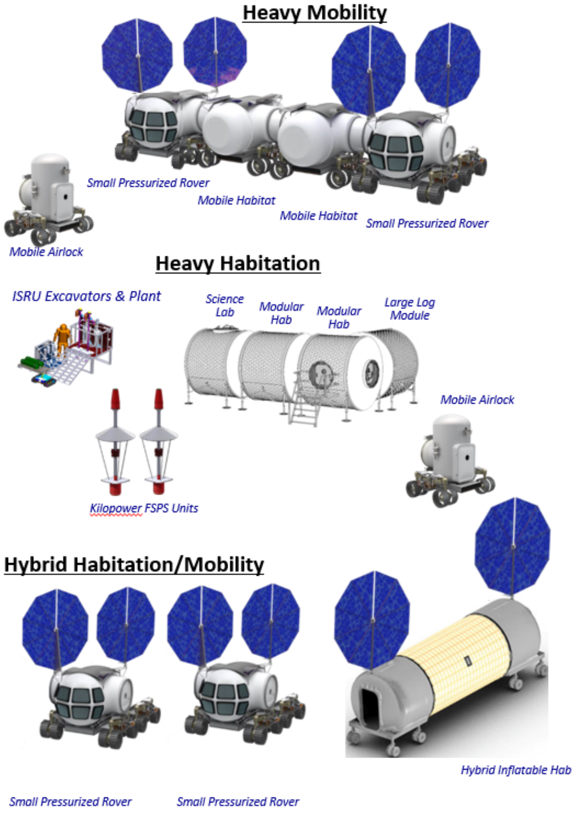


Figure 4. Phase 3 Options – Heavy Mobility, Heavy Habitation, Hybrid Habitation/Mobility (notional elements)

Phase 3 assumes no change in Gateway capabilities. For lunar surface, three options were considered, heavy mobility, heavy habitation, and hybrid habitation/mobility. The surface infrastructure builds upon what was assumed in phase 2 with additional elements to enable longer durations. Table 3 displays the architecture assumptions for the lunar surface for each option. Figure 4 shows conceptual elements for the phase 3 options.

Table 3. Phase 3 Architecture Assumptions

Heavy Mobility	4 crew for up to 60 days on the surface per mission
	Crew live and operation out of 2 small pressurized rovers (SPRs) and 2 mobile habitats
	Multiple landing sites (assets relocate between crew missions)
	Crew translate from lander to the SPRs through a tunnel
	Mobility range of 500+ km radius from crew lander
Heavy Habitation	4 crew for up to 90 days on the surface per mission
	Crew live and operate out of modular habitat
	Fixed landing site
	Mobile airlock to mate with habitat to allow crew access to surface, requires tunnel for transfer from lander
	Mobility range of 20 km radius, based on 2 unpressurized rovers
	In-situ resource utilization for oxygen production
Hybrid Habitation/Mobility	4 crew for up to 30 days on the surface per mission
	Crew live and operation out of 2 SPRs and 1 habitat
	Fixed landing site
	Crew translate from lander to the SPRs through a tunnel
	Mobility range of up to 250 km radius from crew lander

Assumptions for Phase 4: Shakedown and Mars Orbital

Phase 4 leverages as much as possible from the previous phases in the design and operations of the Mars Spacecraft. It is assumed that an integrated system test is completed prior to the first departure of Mars. This demonstration and testing of the Mars Spacecraft in the cislunar environment, called the Mars Spacecraft Shakedown, would be the final integrated test prior to the next step of going to Mars. If a Mars orbital mission were selected, the Mars Spacecraft would have to support a crew for up to 1,200 days away from Earth. A crew of four would be accommodated for this journey with a contingency EVA capability. The propulsion system would be utilized to ferry the crew to Mars and back. One envisioned option, shown in Figure 5, is a hybrid propulsion stage [7], combining solar electric propulsion with chemical propulsion. The use of electric propulsion offers significant advantages for interplanetary missions due to its higher efficiency, allowing vehicles to accelerate for longer periods of time while expending less propellant. These systems allow

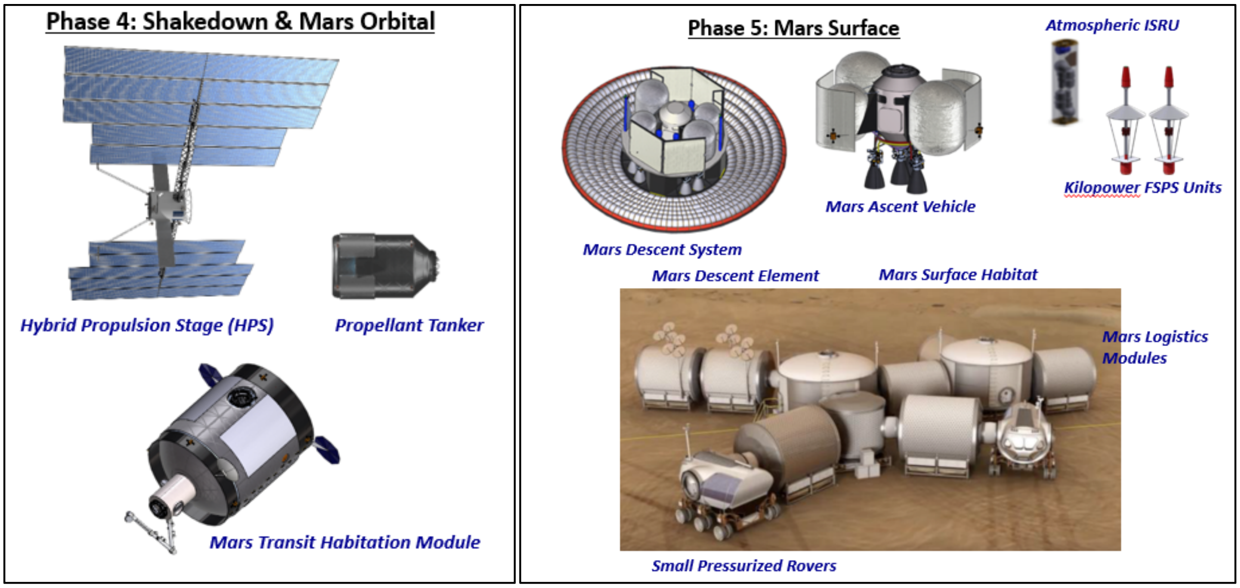


Figure 5. Phase 4 Mars Spacecraft (notional elements) and Phase 5 Mars Surface Approach (notional elements)

a reduction in total vehicle mass compared to a spacecraft using an all-chemical propulsion system. Nuclear propulsion options are also in consideration for propulsion systems. In addition, a propellant tanker is assumed to refuel the Mars Spacecraft between missions, providing an opportunity to use the Mars Spacecraft for multiple missions.

Assumptions for Phase 5: Mars Surface

There have been many studies and approaches published on Mars surface architectures [8, 9]. Generally, these past studies point to the need to get to the surface with an entry, descent, and landing system, infrastructure for the crew surface mission, and an ascent system. Potential surface infrastructure include habitation, mobility, surface power, EVA, and in-situ resource utilization. One notional concept is shown in Figure 5. The Evolvable Mars Campaign was used as guidance for the architecture assumptions for Phase 5 [10]. The surface architecture consisted of multiple kilo-power units, robotic rovers, a monolithic habitat, resupply logistics modules, small pressurized rovers, and unpressurized rovers. These were placed on the Mars surface over a series of landings to enable a crew of four to stay up to 500 days on the surface.

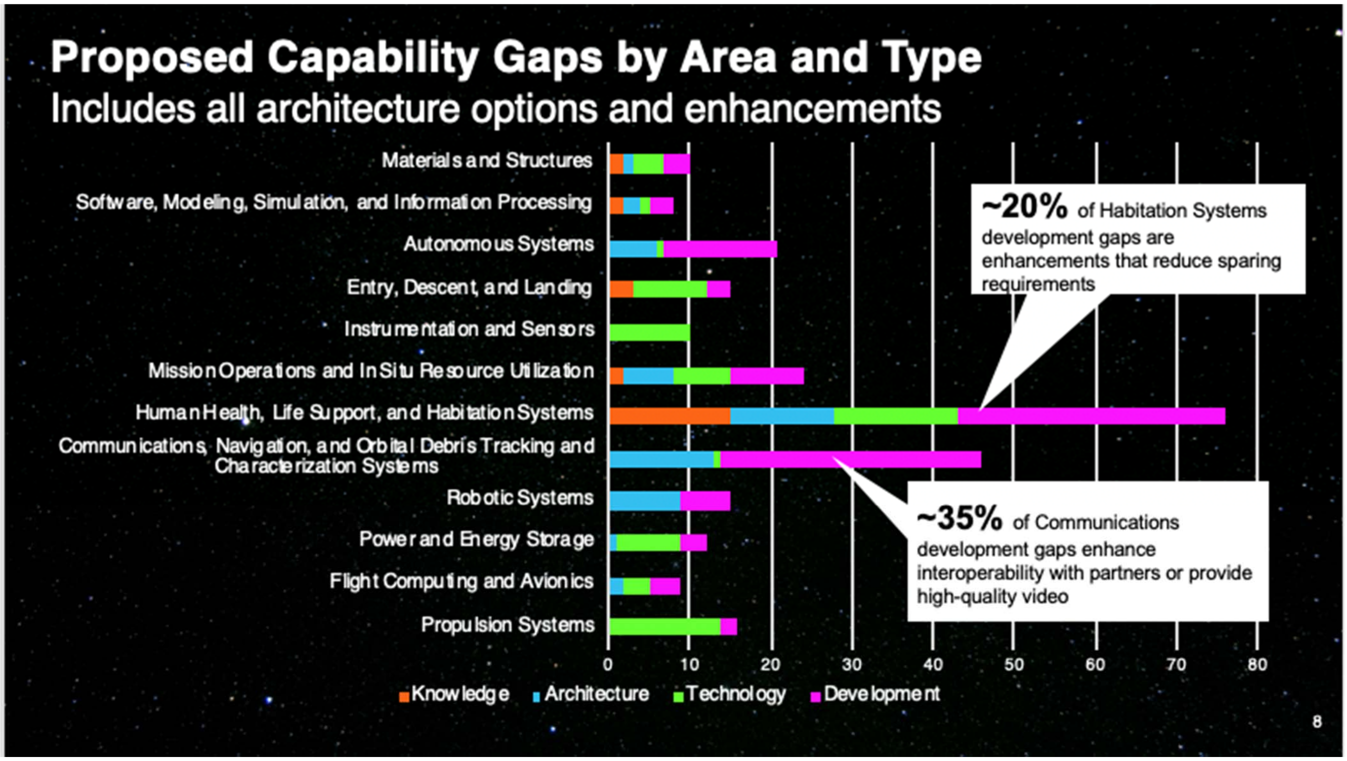
5. CAPABILITY GAPS

Capability gaps are classified as being in one of areas:

- Development – Gaps that are closed through engineering solutions.
- Technology – Gaps that require the development of new technologies in order to close.
- Architecture – Gaps that require further refinement of mission plans to clarify capability needs.
- Knowledge – Gaps that require additional scientific research in order to close.

When all architecture options were considered, 270 capability gaps were identified. The largest portion of these – 44% - were classified as "Development Gaps," representing items that were simply a matter of engineering. 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. Of the remaining gaps, 28% were classified as "Technology Gaps" requiring development of new technologies; 20% were "Architecture Gaps" requiring further refinement of mission plans to clarify the capability need; and the remaining 8% were "Knowledge Gaps" requiring scientific research for closure.

Figure 6 summarizes the capability gaps by capability area and type. The Human Health, Life Support and Habitation Systems Capability area had the largest number of gaps, with a large number of these characterized as development 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 in order to reduce sparing requirements. These items are not strictly enabling for many of the architectural options considered. However, if successful in closing these gaps, the capabilities could enhance the missions by reducing logistics and associated mass and other costs. Similarly, the majority of 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



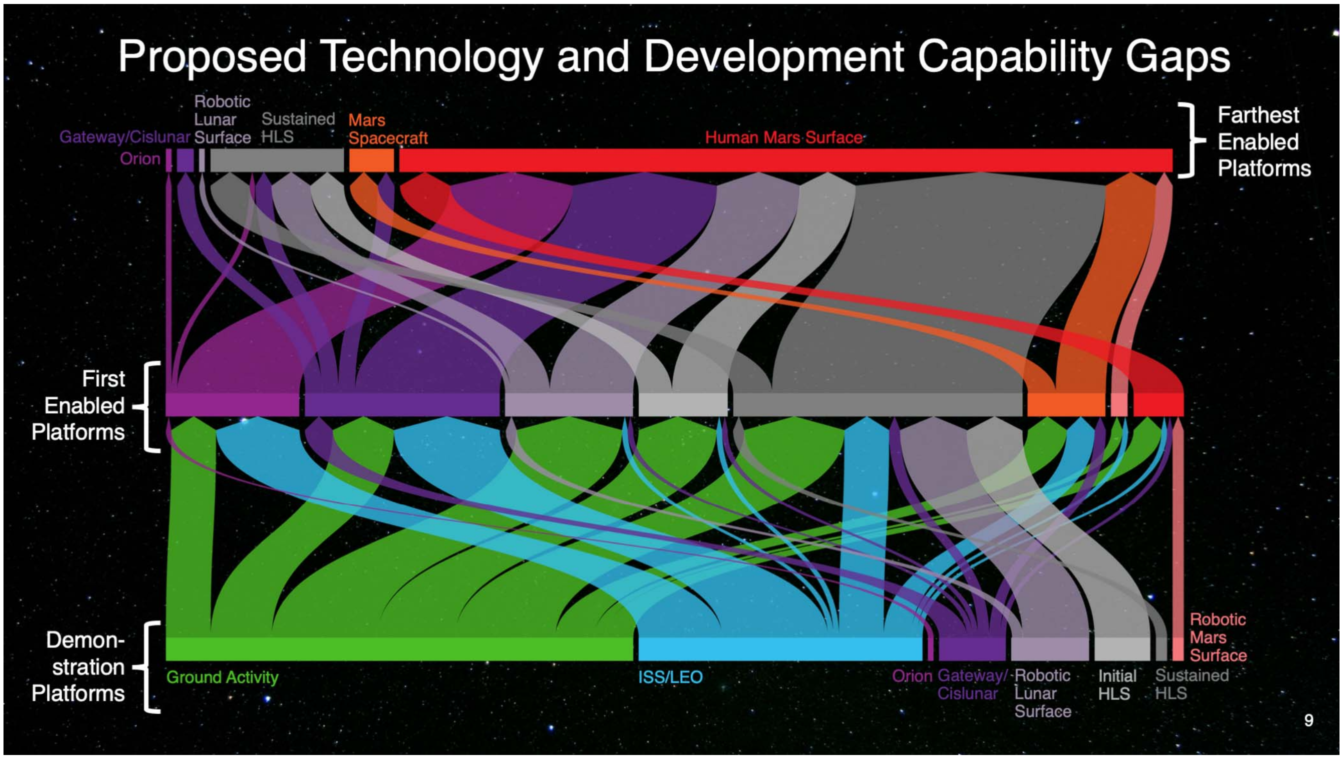
Proposed Capability Gaps by Area and Type

Includes all architecture options and enhancements

~20% of Habitation Systems development gaps are enhancements that reduce sparing requirements

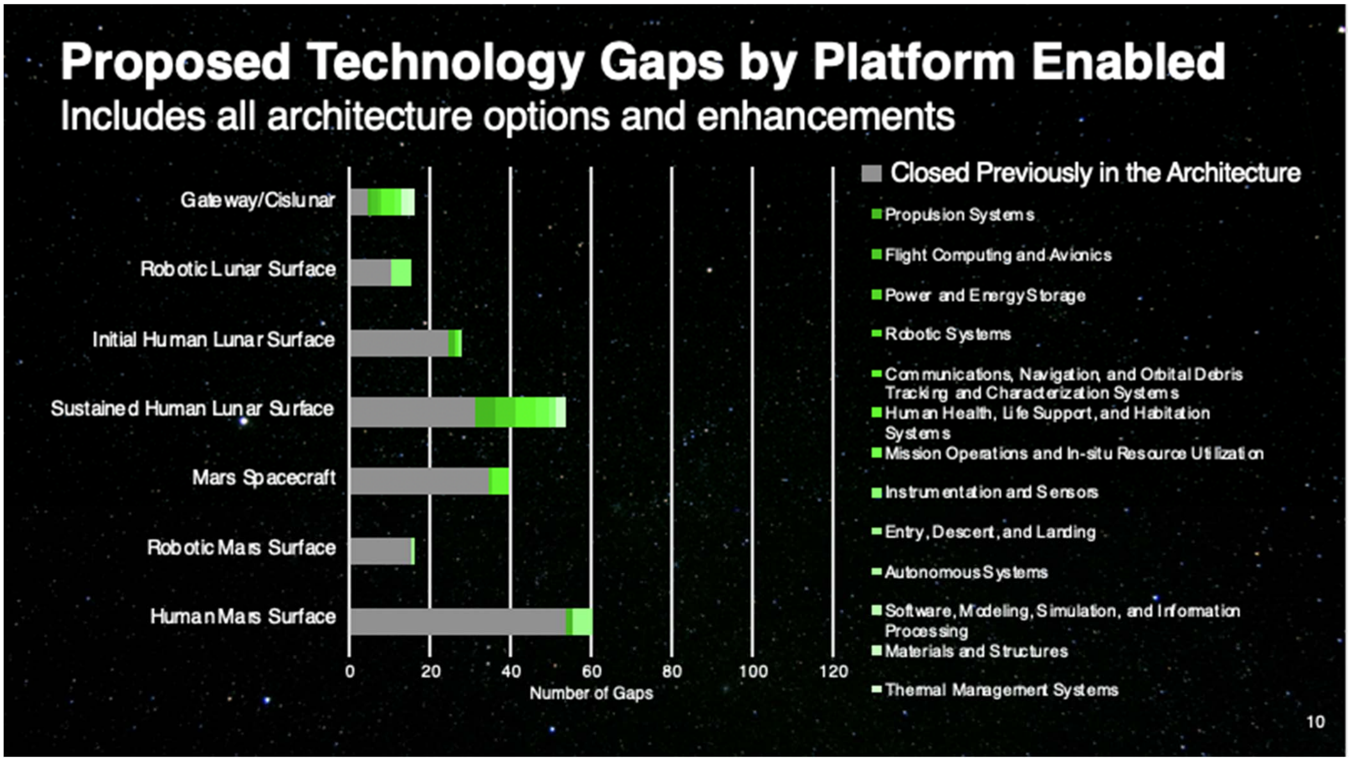
~35% of Communications development gaps enhance interoperability with partners or provide high-quality video

Figure 6. Proposed Capability Gaps by Area and Type



Proposed Technology and Development Capability Gaps

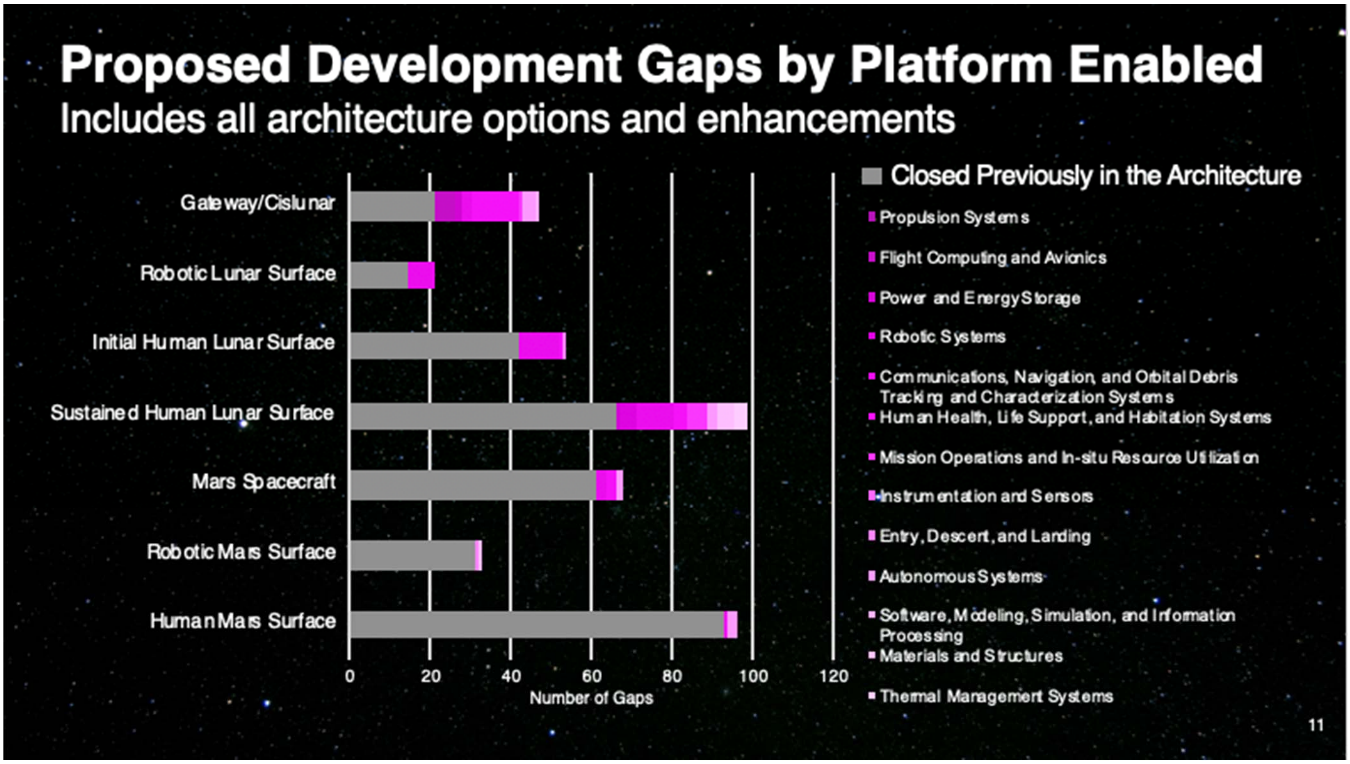
Figure 7. Proposed Technology and Development Capability Gaps



Proposed Technology Gaps by Platform Enabled

Includes all architecture options and enhancements

Figure 8. Proposed Technology Gaps by Platform Enabled



Proposed Development Gaps by Platform Enabled

Includes all architecture options and enhancements

Figure 9. Proposed Development Gaps by Platform Enabled

enable the public to witness the return of humans to the Moon and the first human landing on the Moon.

Figure 7 traces technology and development capability gap closure from the required demonstration platform through the first platform enabled by that demonstration to the ultimate platform enabled by closure of the gap. The width of the lines corresponds to the number of gaps to be closed. In reviewing closure paths, it becomes clear that all of the current proposed platforms in NASA's plans as of now – ISS, Orion, Gateway, and Lunar Surface Assets – are required to enable the eventual human exploration of Mars. 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.

Figures 8 further examines technology gaps and the platforms enabled by closure of those gaps. Similarly, Figures 9 further examines development 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 8 and 9 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 9 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 are 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 both technology and developmental gaps. When comparing the Sustained Human Lunar Surface and the Human Mars Surface, the number of development gaps are similar. This is partially due the differences application of in-situ resource utilization gaps on the lunar surface and on the Mars surface.

6. CONCLUSIONS

For the architecture options presented in this paper, there are a variety of capability gaps that must to be closed. These include gaps relating to knowledge, technology, development, and architecture. The framework presented in this paper allows NASA to identify these capability gaps and to gain an understanding of what actions, including design, development, and testing, must be completed to enable potential missions during each of the identified phases.

Although a majority of the gaps collected in the framework are in the areas of Human Health, Life Support and Habitation Systems Capability; and Communications, Navigation, and Orbital Debris Tracking and Characterization, many of the gaps can be considered enhancing versus enabling. The next step in the overall process to differentiate between these two types of gaps.

The tracking of gaps from demonstration platform 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, a majority 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 invest in technology and risk reduction in enabling Mars missions. Trying to fill all of 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 a sustainable, affordable exploration plan.

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- Center Experts - Dust Mitigation, EVA Systems, Human Health & Performance, Thermal Management
- Office of Safety & Mission Assurance – Planetary Protection
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BIOGRAPHY

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