Artemis Deep Space Habitation: Enabling a Sustained Human Presence on the Moon and Beyond

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Abstract— **As NASA and its partners' capabilities for human exploration of deep space continue to mature, so too does its roadmap toward a sustained crewed presence on the surface of the Moon and eventual human missions to Mars. The first launch of the Space Launch System and Orion crew vehicle, the contract award for the first demonstrations of a Human Landing System, and the beginning of construction on the initial elements of the lunar Gateway have marked major milestones toward NASA's near-term exploration goals: a long-duration outpost in orbit around the Moon and the next footsteps on the lunar surface. At the same time, NASA is in the early phases of planning the capabilities that will be needed for long-term exploration. Among the common elements that will be required by long-duration stays on the lunar surface, transit to Mars, and Martian surface expeditions will be new habitats unlike any flown to date. NASA is currently working on development of both architectures for those habitats and on the technological advancements that will enable them, with an eye toward systems that will not only extend mission operations but also provide for living quarters that will keep the crew happy and healthy throughout their expeditions.**

Beyond the Gateway habitation needs, these capabilities will need to be defined and advanced to support the initial lunar surface missions and to prepare for human missions to the Mars system. The Surface Habitat is the current concept in consideration to serve as this initial surface habitat that will extend the crew mission durations. It will provide 30-to-60-day habitability for a crew of up to four allowing for the astronauts to explore farther and longer on each visit to the lunar surface. NASA is also currently reviewing opportunities to use current or near-term in-space habitation systems as proving grounds or precursors for keeping astronauts safe and healthy during future transits to Mars. Already, the International Space Station (ISS) is being used for implementation of next-generation life-support systems that will inform those used in exploration habitats, and the operations approach for ISS is providing lessons-learned for future science operations around or on the Moon.

While a suite of habitation concepts is currently under study within NASA, the agency is also working closely with U.S. industry through the Next Space Technologies for Exploration Partnerships (NextSTEP) activity to understand their concepts for commercially provided habitation capabilities as well as close coordination with international partners to understand their desires for in-space and surface habitation. This paper will provide a status of these concepts and partnership activities as well as potential future technology and architecture development paths.[1]

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1. Introduction

NASA is making significant progress on its human lunar exploration plans under the Artemis program toward sending the first woman and first person of color to the surface of the Moon, and the agency is also laying the groundwork toward its longer-term goal of establishing sustainable exploration by the end of the decade.

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At the time of this writing, NASA's Space Launch System rocket and Orion crew vehicle are preparing for their first integrated launch, Artemis I, supported by Exploration Ground Systems at Kennedy Space Center in Florida. After the uncrewed Artemis I test flight, the next launch, Artemis II, will carry astronauts farther into space than any human being has previously ventured. Current plans call for Orion, on its third flight, to rendezvous with a commercially provided Human Landing System (HLS) for the first human lunar landing since Apollo.

Concurrent with preparations for that landing, NASA will also be working with industry and international partners to develop and deploy a lunar-orbiting outpost, Gateway, that will be able to host human-tended long-duration stays in deep-space as well as serve as a platform for autonomous scientific research and serve as a waypoint for missions to the lunar surface or beyond. The first two US-developed elements of Gateway are scheduled for launch in November 2024 and will be followed by international contributions to the outpost [1].

Together, these developments will pave the way for the primary focus of the Artemis missions – a sustained human presence on the lunar surface, a significant exploration milestone in its own right and a vital steppingstone toward Mars [2]. Following deployment of the initial Gateway elements and a human return to the lunar surface, NASA will begin establishment of an Artemis Base Camp on the lunar surface, enabling long-duration stays and untended science operations on the Moon.

To accomplish this bold mission, NASA is working with international partners and commercial industry to both establish this permanent human presence on the Moon within the next decade and to uncover new scientific discoveries while laying the foundation for private companies to build a lunar economy. Since the era of Apollo, NASA has developed strong collaborations with international partners. This has fostered a new era of major scientific advancements and more robust exploration systems and operations. Additionally, an innovative and experienced commercial industry has emerged with capabilities unheard of in the era of Apollo, ISS, or the Shuttle program that further advances this cause of humanity to explore space. This increased capability and reduced cost further lays the groundwork for not only human exploration of the Moon, but other planets like Mars.

Previous missions to the Moon under the Apollo program were smaller sorties in the equatorial regions with shorter total mission durations. The missions under Artemis are intended to increase the duration with sustained operations in the south polar region where lighting conditions have shorter periods of darkness (~4 days) and longer periods of daylight (~200 days), such that longer missions requiring solar power generation are possible and surface elements are more capable to survive through the night for follow-on missions. Under Apollo, equatorial operations were completed during the 14 days of daylight, with a return home prior to the following 14 days of darkness. The longer duration missions of Artemis allow for extended EVA opportunity that is greater than four times the total EVA duration on the Apollo 17 mission (~22 hrs.). Longer duration missions on the lunar surface or in lunar orbit can also serve as a test bed for technologies to support future Mars exploration campaigns. Depending on the trajectory chosen for a Mars mission, the total mission time could extend to over 3 years/1,000 days [3]. The agency will use the lessons learned from these long-duration missions on the Moon to prepare for humanity's next giant leap – sending humans to Mars.

As the Artemis sustained architecture is being matured, this paper will provide a look at the challenges that must be overcome to establish a sustained deep-space presence, current thinking on approaches to address those challenges, and discussion of open trades still being worked. It is not intended to represent a final architecture solution for Artemis, and the approaches outlined here are subject to change.

2. Artemis Base Camp

NASA intends to establish a sustained lunar presence with the development of the Artemis Base Camp by the end of the decade. The base camp core elements include the Lunar Terrain Vehicle (LTV), Pressurized Rover (PR), Surface Habitat (SH), power systems, and in-situ resource utilization (ISRU) systems. Figure 1 shows the cadence of flights and surface element deployments anticipated as part of the Artemis missions to establish a sustained lunar presence.

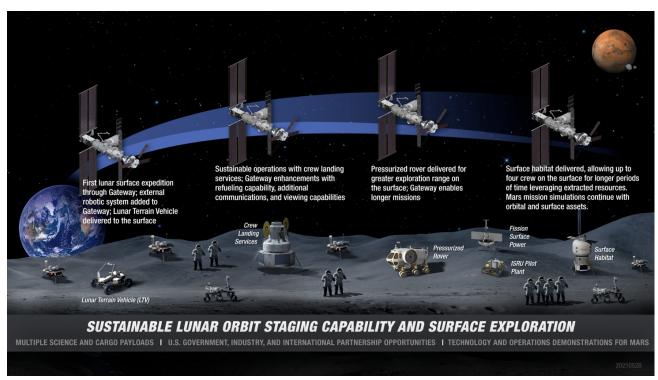

Figure 1: An artist's concept of the missions and activities to build up the Artemis Base Camp

The Artemis Base Camp approach represents a paradigm shift from Apollo, where missions were designed around landing at multiple regions of greatest scientific interest with one-time use systems, in favor of revisiting sites and conducting sustainable operations. The Artemis approach thus requires the establishment of a base of operations similar to ISS (where reuse is a major factor), but on a planetary surface. Unlike ISS, reuse within the context of Artemis missions does require resupply operations much farther from Earth, which drives larger propellant needs and vehicle delivery capabilities. This supply chain must then evolve to meet the needs of Mars missions, where additional resupply becomes a less viable option and the majority of supply is carried with crew throughout the entire mission or prepositioned on the surface.

An artistic rendering of the Artemis Base Camp with several mission elements is shown in Figure 2. Key elements in the base camp architecture include:

Surface Habitat (SH)

The SH, which can accommodate a maximum of four crew, serves as the core habitation capability for the Artemis Base Camp. Capable of being self-sufficient, the SH must provide communications, power, thermal control, radiation shielding, environmental control, life support, waste management, and science utilization. The current SH concept is further detailed in section 3.

Lunar Terrain Vehicle (LTV)

The LTV is an unpressurized rover used to transport two suited crewmembers across the lunar surface. It will greatly expand scientific capabilities by increasing the scale of the region from which geologic samples can be collected. Crew performing ambulatory science are typically limited to 1-2 kilometers surrounding the habitation and/or landing location. The LTV offers autonomous operations and can also support cargo transport, scientific instruments, and even technology demonstration payloads. A Request for Information related to the LTV released by NASA in 2020 indicates a desired cargo capacity of 800 kg, traversal distances of up to 20 km without battery recharging, and continuous operations for 8 hours within a 24-hour period [4]. The sustained operation of the LTV in the Artemis Base Camp requires a design which can survive the lunar night. The location of the Artemis Base Camp in the South Polar region of the Moon also poses traversal challenges. The terrain is relatively steep (grades as high as +/- 20 degrees) and can be highly cratered.

Pressurized Rover (PR)

The pressurized rover enables longer duration trips from the Artemis Base Camp relative to the aforementioned LTV. The PR is anticipated to extend the range for scientific exploration by tens of kilometers relative to LTV. With the addition of the PR to the Artemis Base Camp, mission durations on the lunar surface could additionally be extended by up to 45 days, enabling use of the base camp as a testbed for analog missions which simulate extended operations on the Martian surface. The PR offers opportunities for mission scenarios where some crew members reside in the surface habitat while others conduct operations in the PR; crew may swap habitable platforms during the mission as required by the operational scenario. As with the LTV, autonomous and/or teleoperation capabilities could allow operations with the base camp if untended.

In-Situ Resource Utilization (ISRU)

Currently NASA’s Space Technology Mission Directorate (STMD) has plans for an in situ resource utilization (ISRU) pilot plant as part of the Artemis program. In the long-term sustainability phase of Artemis, the extraction and processing of water and oxygen from regolith could augment crew consumables and potentially provide water for additional radiation protection. The initial ISRU pilot plant will use knowledge gained from the Volatiles Investigating Polar Exploration Rover (VIPER) and Polar Resources Ice Mining Experiment (PRIME-1) missions, to inform process selection and operations [5]. These missions prospect the lunar surface to determine composition of the regolith in the South Pole region and characterize the presence of volatiles. Their results are key to understanding reserves and targeting the specific processes which can be deployed for the purposes of ISRU based on the resources available. The pilot plant will demonstrate core capabilities and subsystems for production of water and/or oxygen from indigenous materials, with the goal of scaling up to full scale mission production rates with further development. While not part of the baseline logistics planning approach for the Artemis Base Camp, ISRU has the potential to reduce logistics requirements for future missions.

The Artemis Base Camp also serves as a key platform for technology development. Other mission-enhancing capabilities which may be initially demonstrated at the Artemis Base Camp include advanced solar and fission power systems and autonomous manufacturing technologies such as 3D printing with regolith-based materials for construction [6].

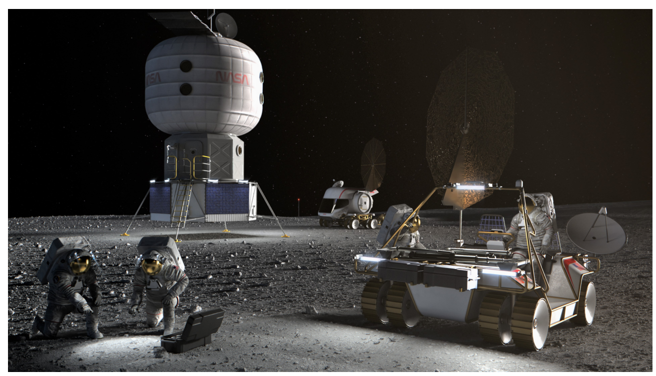

Figure 2: An artist's concept of the Artemis Base Camp with the three proposed primary mission elements – the Lunar Terrain Vehicle (unpressurized rover), the habitable mobility platform (pressurized rover), and the Surface Habitat.

3. Surface Habitat Concept

Anchoring the long-term, human-led exploration at the lunar South Pole is the lunar Surface Habitat (SH). The SH is a fixed surface habitat offering a home base for astronauts, a hub for communications, a science facility, an extravehicular activity (EVA) equipment repair site, a waste processing facility, a supply hub, a surface operations base, and a test bed for sustained surface presence and preparation for Mars missions. Operating in conjunction with Gateway and the Mars Transit Habitat (TH), it is possible to carry out long-duration missions with SH that simulate operations on the Martian surface to test out operations and understand the needed conditioning to prepare for those operations.

The SH will be self-sufficient for operations on the lunar surface, providing its own power generation, energy storage to survive periods of darkness, and capability to communicate with surface assets, orbital assets, and directly with Earth ground stations. The habitat is designed to support two crew for approximately 30-days with the potential for crew swap-outs occurring mid-mission, in which the PR crew trades places with the habitat crew. During these swap-outs, the habitat will nominally support four crew for a short period of time. Long-term, the SH will have the capability to evolve to support up to four crew for up to 60-days. The habitat offers more volume than is slated for the PR given their differing functions in the architecture. The PR is designed to extend surface exploration distances and the habitat to offer utilization, repair and maintenance, and evolvable living space for additional crew.

The SH also houses advanced Environmental Control and Life Support Systems (ECLSS) with assumed regenerative capability that will reduce the amount of consumable items, such as gases and water, that need to be delivered to the surface. The advanced ECLSS is intended to perform water processing, urine and condensate processing, CO_2 reduction and recovery, and oxygen generation. These gases and fluids are also expected to be processed for the PR and interchanged between the two elements at different points in the mission. The urine and condensate from the rover would be transferred and processed on the habitat; subsequently generated gases and potable water would be transferred back to the PR. The SH is assumed to operate at a nominal atmospheric operating pressure of 10.2 psia and 26.5% oxygen concentration and a capability of operating at 8.2 psia and 34% oxygen. On-going trade analyses are currently assessing the viability and impacts of transitioning the SH to a nominal operating pressure of 8.2 psia but it is assumed the SH would still need to retain the capability of supporting both pressures.

The habitat structure is designed with a two-story inflatable section oriented in a vertical fashion, with a metallic core and a lower metallic section that enables ingress/egress of EVA crew and logistics. There is a two-chamber airlock between the outer EVA hatch and the interior section. Suit maintenance would be performed either inside of the airlock or within the main volume of the habitat. The habitat is 7.8 m tall (excluding solar arrays and lander), with an inflated diameter of 6.5 m (Fig. 3), and is designed to be launched within a 5 m fairing. The structure consists of an interior air bladder followed by restraint layers, micro-meteoroid and orbital debris (MMOD) resistant materials, and Multi-Layer Insulation (MLI). The habitat is designed for a 15-year life with 10 years of total operation, which allows for launch delays.

The active thermal control system is composed of a low temperature loop, medium temperature loop, two radiators using HFE 7200, a sublimator for cooling prior to deployment, and fluid pumps for transporting the waste heat. It is expected that during transit up to deployment that the metallic portion would be thermally conditioned and fluids kept above freezing point. [7]

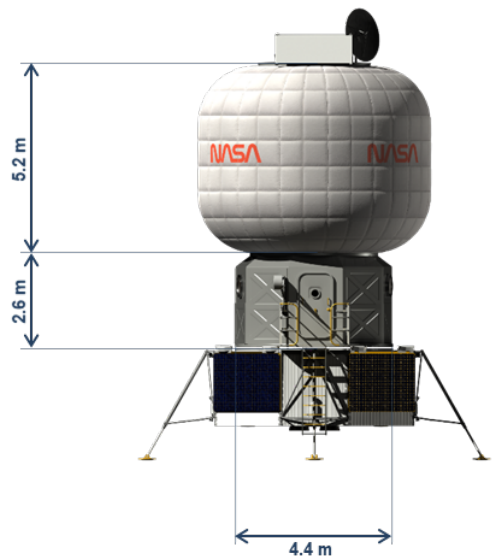

Figure 3: Surface Habitat representative dimensions

The power system is composed of a solar array wing consisting of GaAs cells designed for a 15-year life. A regenerative fuel cell system is used for energy storage. The regenerative fuel cell offers savings for launched and landed system mass over traditional batteries given the duration of darkness and provides supplemental heat during those periods that offset heater power loads.

Lifting equipment is also required on the lander deck to facilitate crew loading of logistics from the lander into the habitat. The LTV and PR are also expected to help transport the logistics and supplies from the lander to the SH to be loaded.

4. Concept of Operations

The Concept of Operations (ConOps) are notional and subject to change as trades and assessments continue. The current ConOps has the SH launched, landed, deployed, and checked out in an uncrewed state. Additional checkout would occur at different stages prior to entering the habitat and once the crew enters.

In the packaged and stowed state, the habitat would rely on the lander to provide the needed power and communications while in transit, which would vary with the delivery vehicle operation design. In the transit state, the habitat is expected to be in a deflated configuration and vented to vacuum, with the metallic at operational atmospheric conditions and thermally conditioned to support the supplies housed there that cannot be maintained at vacuum. Once landed (during daylight), the habitat would have a settling period and the lander would perform leveling functions to within a required range. The habitat would deploy the solar array wing to establish power generation and distribution and deploy communications systems to establish links. Additionally, the solar array would begin charging the regenerative fuel cell system to prepare for night-period quiescent operations. Any additional leveling required beyond what the lander accomplished would be conducted by the habitat. Finally, softgoods inflation would occur, followed by the activation of other systems.

During the approximately 30 days of operation on the lunar surface, it is expected that the crew of four would split into two groups, with one using the LTV and transferring to the Surface Habitat to prepare for long-term habitation and the other crew transferring with the PR to a logistics lander for logistics operations. The crew on the surface habitat would begin work by ensuring floors are properly deployed, move supplies around onboard, adjust system locations, setup crew areas, and prepare for the receipt of logistics from the PR crew.

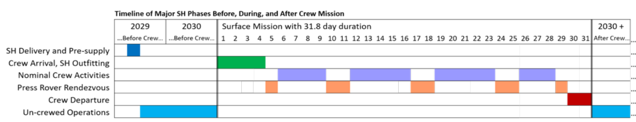

Figure 4: Notional operations timeline for delivery and nominal operations

Once the PR crew has loaded logistics they would bring an additional logistics carrier to the SH for loading. During nominal operations, it is currently assumed that the PR and SH crews would swap locations mid-mission and continue exploration of the surface.

In the case of Mars analog missions, the SH could be used in conjunction with a Mars Transit Habitat (TH) in cislunar space. It is expected that the crew would launch and interface with the TH either as a free flyer or connected to the Gateway during an initial demonstration period to simulate the long-duration transit to Mars. Then, the crew would descend to the surface to perform lunar operations that would mimic Mars surface activity. Next, the crew would return to the TH to complete the simulation of transit back to Earth from Mars. Finally, the crew would transfer back to Earth for the return. Gateway could offer an additional safe haven for these types of operations in-space. The SH would be used to test out operations for Mars surface habitation and offer additional safety to lunar surface crew during simulated operations.

5. Habitation Challenges and Capability Needs

There are many operational and environmental challenges the SH will face in extended operations on the lunar surface, including surviving the lunar night. The SH must be designed to ensure the safety of the crew and enable mission success. In order to establish a framework for addressing these challenges, a Technical Memorandum, "Moon to Mars (M2M) Habitation Strategy" [9] has been written outlining ground rules and assumptions for the SH and TH. The following are factors the SH design must take into consideration:

Survive the Night

The lack of power generation during the 100hr+ eclipse periods will drive energy storage needs. During this period, systems will operate in either a power conservation mode or unpowered altogether if not critical to the operation of the habitat. Power conservation may drive a drop in internal temperatures, presenting a risk of condensation and potential damage to systems/subsystems. One area of consideration is maintaining working thermal fluids above freezing point to ensure that operations can proceed effectively when additional heat rejection is required. Varying heat rejection capabilities can significantly enhance survive the night operations where makeup heat is required with less rejection needed.

Dust Contamination

Contamination of systems by lunar dust and the potential entrance of dust into habitable environments represents an overarching, critical challenge for sustained lunar operations. There is a need to understand the impacts of dust to both internal and external systems. Seals, mechanisms, and thermal systems are particularly susceptible to dust accumulation. Long-term exposure to dust can significantly degrade the performance of radiators and compromise seal integrity. During the Apollo missions, dust on the lunar surface was a source of significant problems: mechanisms became clogged with it, camera lenses became covered/obscured, the astronauts' suit seals were degraded, and dust (which is a significant respiration hazard) was able to enter the habitable environment of the lunar excursion module through EVAs. The morphology of the fine and ultrafine particles is sharp/jagged and glassy, enabling abrasion of most materials it comes in contact with. Under Mars operations, the dust becomes a bigger health hazard to astronauts and the lessons learned from mitigation on the lunar surface can offer greater opportunity to advance systems and operations for Mars.

Both active and passive strategies for dust mitigation are being explored through NASA STMD and the Lunar Science Innovation Institute (LSII). Active approaches require power and actuation, whereas passive approaches rely on surface modification or dust tolerant materials and coatings which can improve the tribological resistance of materials to lunar dust. Some passive strategies explored by NASA Langley Research Center modify surfaces with laser ablative patterning to prevent adhesion of dust particles [8]. NASA's Kennedy Space Center has developed the electrostatic dust shield (EDS), which applies dynamic electric fields to loft dust from surfaces [10]. The Dust Solution Testing Initiative (DuSTI) is evaluating the potential for commercial off the shelf technologies, developed for consumer applications and military aircraft landings (among other terrestrial applications) to meet the needs for dust mitigation on lunar missions [11].

This is one of the most critical technology gaps for habitation, as dust effects every element of the habitat, including solar arrays, hatch seals, joints and interlocks, EVA suits, and radiators. Dust accumulation may also drive increased crew time for system maintenance and repair. Sustained dust exposure represents a significant human health risk, as continued irritation and damage from dust inhalation can increase the risk of cancer.

Resource Transfer

Trades regarding resource sharing and transfer for SH and PR are ongoing. If the PR does not carry the ability to process wastewater, it will rely on either prepositioned logistics or the SH. In the scenario where the SH and PR can exchange resources, the SH would be used to process wastewater from the PR and provide potable water and O2 for EVA charging. There are also considerations for potential safety concerns with resource sharing (allowable materials, types of storage tanks and allowable pressures, contamination filtration, etc.) More efficient transfers that can offload crew time from the activity is an important consideration in these transfers so as to optimize crew availability for exploration and science.

Dormancy

At the Artemis Base Camp, the SH will not be continuously crewed. The significant periods of dormancy anticipated, ranging from months to even years, present engineering challenges. These include long-term storage and preservation of water, strategies to safeguard against the formation of biomass (which drives a need for detection and mitigation solutions), and ensuring nominal operation of systems upon re-activation following a dormant period. Given these new constraints, some aspects of ISS systems (which are designed to operate with crew continually present and able to intervene in the event of an anomaly or failure) may not be readily transferable to a lunar surface habitation application. Thermal control systems must protect against freezing of tubes during dormancy and have automated leak detection systems. Longer system lifetimes, with less frequent repairs and maintenance, are also needed. Microbial growth must be assessed following periods of dormancy; downmass of samples to Earth may not be feasible, driving new capabilities for in situ analyses. Designing systems which can tolerate long periods of dormancy is also extensible to Mars surface habitation and operations where systems will be pre-deployed years prior to crew arrival.

Higher O2 Concentration and Material Flammability

Most heritage materials for ISS were evaluated for flammability using the upward propagation flammability test (NASA-STD-6001) at the nominal ISS environment of 14.7 psia and 20.9% O_2 [12]. This data set, archived in NASA's Materials and Processes Technical Information System (MAPTIS), currently forms the basis for materials selection in habitable environments. In the flame propagation test, the material is exposed to a standard ignition source. A-rated materials, which are strongly preferred for habitation applications, will self-extinguish in the worst-case atmospheric environment the material will be exposed to when in use. A-rated materials also fail to transfer burning debris. Materials which are not A-rated can still be used with appropriate mitigations and engineering rationale (ex. no ignition source or propagation path).

There is some uncertainty regarding the operational environment of surface habitation that creates complexities in evaluating the safety of materials based on existing data. Higher oxygen concentrations and lower-pressure environments (relative to ISS) are advantageous in reducing the time requirements for prebreathe prior to EVAs. The potential differences in environments between ISS and surface habitation means that heritage flammability data may not be valid or extensible, as the flammability characteristics of materials are highly sensitive to the combined pressure and oxygen environment; additionally, partial gravity also impacts material performance.

As future exploration architectures consider various atmospheric environments for habitation systems in partial and microgravity, this uncertainty requires a different approach to flammability testing campaigns. There may be mismatches between desirable (heritage) materials and those which can be used safely in habitation scenarios with an enriched oxygen environment. A test campaign is needed to evaluate material flammability in intended use environments for habitation, including lower pressures, higher oxygen concentrations, and reduced gravity. Testing of this nature would also be relevant to Mars surface habitation where the same environments are planned.

Constrained Delivery Mass

Delivery of the SH will rely on a lunar lander capability. Because the habitat and landing capabilities are being developed in parallel, with SH currently in a conceptual design phase, it is possible that the mass of the SH may exceed lander capabilities (although this depends on the lander system ultimately selected to deliver SH). Constraints on delivery mass and mass growth of the SH must be carefully managed to mitigate this risk. The challenge for the design of SH under these conditions is that the uncertainty in the geometric configuration of the lander and performance could result in significantly different designs. Without this information current designs are limited to traditional landing configurations and specific performance assumptions for launch vehicles and landers. Further trades from this baseline design are expected to provide insight to other potential lander concepts but are no guarantee that all possible configurations will be accounted for sufficiently.

Spares

The sparing philosophy for lunar surface operations is still in development. With many new and newly modified technologies expected in the SH architecture, few will have vetted reliability estimates. Accelerated design, development, testing, and evaluation (DDT&E) cycles may not allow for the extensive reliability testing needed to robustly characterize mean time between failure (MTBF), mean time to repair (MTTR), and mean time to failure (MTTF), among other metrics, for many systems. To compensate for this uncertainty, additional spares may be required. Better probabilistic spares modeling tools and more robust test campaigns will aid in improved characterization of system/subsystem reliability, particularly of low TRL technologies. A combination of modeling and testing will help to define the optimal spares manifest and ensure adequate probability of sufficiency in sparing is maintained on longer duration missions where both upmass and resupply are severely constrained relative to ISS. It is also important to work toward a high degree of interchangeability and commonality of systems within each element, but also look across the broader architecture to drive additional mass savings by considering whether some elements could share spares. There are also opportunities for emerging capabilities such as in-space manufacturing to provide on-demand production of spares once technologies have been developed and vetted on ISS. This approach may be extensible to Mars Transit Habitat mission scenarios [13].

Maintenance and Repair of External Systems

With a sustained presence on the lunar surface, all supporting assets and external elements of the habitat will require some degree of maintenance and repair (M&R). The need for M&R can be necessitated by a system or component exceeding its use life (scheduled M&R), debris generated by movement of other surface assets (ex. landers) which can accumulate on surfaces and degrade performance, and damage due to lunar dust, radiation, or impact events. Repair of external systems will require EVA or robotic servicing capabilities. In some cases, external systems may be difficult for crew to access (for example, consider damage to a solar array which may be deployed from the top of the habitat). Designs which permit crew access to external systems and development of processes and procedures to support external M&R are a key need for surface habitation. With longer mission durations and sustained operation on the lunar surface, the primary mitigation strategy for failure of these systems should not be a return to Earth. The ability to respond to unplanned failures of external systems and assets with repair will enable recovery from major faults, mitigating the risk of loss of mission or loss of crew.

Maintenance Time

Maintenance crew time requirements for lunar surface operations are currently unknown. Data on frequency of replacement of components in heritage systems which will be adapted for lunar surface operations may be used to generate initial estimates. Some categories of maintenance time, such as planned replacement of parts at regular intervals based on their use life, will be anticipated, and planned for. Other maintenance needs will be probabilistic in nature and emerge in response to random failures [14]. To minimize maintenance time, systems should be designed with a high degree of interchangeability and commonality when possible and be accessible to crew. High resource requirements for maintenance may compromise the ability of the crew to perform EVAs and science utilization activities. Reducing maintenance time through design, mission planning, and testing is critical to maximize scientific outputs and increase crew productivity [15]. On ISS, maintenance time has been significantly higher than anticipated, particularly for ECLSS operations. Moving away from the orbital replacement unit model (where one unit is changed out for another without repair at the component level) for future habitation scenarios is one option, but the reduction in logistics mass that can be achieved with this approach (spare components are lower mass than entire systems) must be weighed against potential increases in crew time associated with component level repair.

Outfitting

Outfitting is "the process by which a structural system is transformed into a usable system by in situ installation of subsystems as well as the associated planning and preparation required for this process" [15]. Habitat outfitting generally refers to the supplies and equipment which provide crew with a livable, safe environment during a mission and enable the performance of mission tasks. Outfitting can include installation of hardware (such as environmental control and life support systems, science equipment), internal structures (such as walls, partitions, furniture, storage space, and crew quarters), personal items for the crew (food utensils, clothing, etc.), and utilities (lighting, ventilation, electrical systems). To minimize crew time and crew safety concerns, new approaches must be employed to successfully outfit the SH in the initial missions. Inflatable habitats in particular will require significant outfitting, since many elements will not launch pre-integrated (as they would in a metallic habitat) and will be installed by crew once the habitat is pressurized on the surface. The ability to outfit new system capabilities in subsequent missions is also needed. Outfitting as an area of technology development also includes exploration of autonomous deployment technologies. In places where crew must be utilized for outfitting, the tools and aids required to facilitate the transport of systems into and around the habitat and the installation of those systems is also a consideration. Outfitting in partial gravity (1/6 g for lunar and 1/3 g for Mars) also introduces new human factors considerations relative to microgravity or 1g environments.

In the 2020-2021 academic year, the Habitat Systems Development office at NASA Marshall Space Flight Center partnered with the In-Space Manufacturing (ISM) project and the Moon to Mars Planetary Autonomous Construction Project (MMPACT) to sponsor two university projects focused on approaches for habitat outfitting. This work is through NASA's XHab program, which seeks innovative design ideas for Moon to Mars exploration objectives. The University of Maryland College Park will consider approaches to outfitting inflatable habitats using space robotics and crew. Results of human factors testing will inform best practices for future inflatable habitat design and crew tasking. Colorado School of Mines will study in situ production methods to support habitat outfitting and design an external shielding structure for an inflatable habitat which would be produced with large scale autonomous manufacturing. Results of these activities will be published as NASA technical reports following completion of the respective projects.

While some habitat systems development work such as the XHab projects focus primarily on outfitting of inflatable habitat structures, outfitting also represents a technology gap for “vertically constructed” habitats. These habitats would be constructed on the lunar or Martian surface using large-scale manufacturing technologies, such as 3D printing, with manufacturing feedstock consisting of indigenous resources (ex. raw or processed regolith). Examples of vertically constructed habitats are AI Space Factory’s MARSHA (winner of the NASA’s Centennial Challenge 3D Printed Habitat Challenge) and designs from ICON, Bjarke Ingalls Group (BIG, and SEArch+ for NASA’s MMPACT project [6, 16, 17]. In situ manufacturing techniques provide the core habitat outer structure, but it subsequently requires sealing and pressurization. Like inflatable habitats, the interior must then be outfitted with wiring, insulation, payloads, ECLS, lighting, gas or fluids lines, water hydraulics, and lifting aids.

Within the NASA taxonomy, a structure which requires little to no outfitting (such as a metallic habitat where most systems launch pre-integrated) is a class I structure. A habitat that requires some significant outfitting, such as an inflatable habitat, is class II. Vertically constructed habitats, which require full outfitting and contain no pre-integrated systems, are class III.

Outfitting is a relatively new area of technology development related to habitation. Current top priority gaps include conductor/cable and piping/tubing (coolant, gases, hydraulics, etc.) line management, interfaces, and penetration management (as penetrations, such as windows or passthroughs, introduce discontinuities) [15]. In some definitions, outfitting may also extend to on-demand manufacturing of parts to support outfitting needs. The Lunar Surface Innovation Consortium (LSIC) is currently developing specific concepts/design reference missions related to outfitting and corresponding concepts of operations under its excavation and construction focus group.

Human/system interaction

The history of operations for ISS shows that there is a large amount of time spent on mission operations, with continuous support from ground-based mission control centers. There is a small latency for ground-based communication to the lunar surface (~2.5 second delay), but signal transit time for a Mars habitation scenario represents a more significant challenge, with delays ranging from 4 minutes to 24 minutes. As distance from Earth increases, the ability to rely on Earth-based communications and continual, real-time monitoring of crew and systems via ground control centers will decrease.

With Lunar and Mars missions, a fundamental shift in approaches to mission operations and human/system interaction is needed. Long-duration, long-endurance missions must be equipped with systems with some degree of autonomy, which allow crew to identify issues and respond to them quickly. Significant human in the loop testing will be required to simulate communications delays and develop resilient systems, which would eventually be able to diagnose and respond to unanticipated faults with little or no crew intervention. Quick abort and rapid resupply are not options on exploration class missions and thus new approaches for maintainability, diagnosis, and repair must be developed.

Radiation protection

NASA-STD-3001 “NASA Space Flight Human System Standards” governs crew health and performance considerations for human spaceflight, including medical care, nutrition, exercise, and radiation exposure limits [18]. In 2021, the U.S. National Academics of Sciences, Engineering and Medicine endorsed NASA’s plan to adopt a new radiation standard that would limit a crew member’s lifetime cumulative radiation dose on space missions to 600 mSv. In situ measurements of the lunar radiation environment will be obtained from instruments on the NASA Commercial Lunar Payload Services (CLPS) missions, which will help define anticipated radiation exposure for crew operating in specific regions of the lunar surface. As the Artemis campaign advances, dose estimates for lunar exploration will continue to be developed and refined through models and empirical data.

While some radiation environments can be relatively stable, one major concern with crew radiation exposure is solar particle events (SPE) which occur when particles from solar flares or coronal mass ejections are accelerated through the space environment. These infrequent events discharge highly energetic particles that could expose crew to very high levels of radiation with little warning. Various storm shelter designs or wearable shielding systems (such as vests made of materials to provide radiation shielding) have been considered as options to provide additional protection in the event of an SPE. The Lunar Safe Haven concept developed by NASA MSFC, NASA Langley Research Center, and NASA Kennedy Space Center, is a freestanding structure which can provide additional radiation shielding. Lunar Safe Haven represents one approach to enabling longer duration missions on the lunar surface without exceeding radiation exposure limits [19]. Other concepts for radiation mitigation include active shielding, such as incorporation of a surrounding water wall or magnetic shielding into the habitat design.

These strategies, while potentially very effective, may be mass prohibitive without a significant reduction in the size of systems. Development of enhanced sensors and better space weather prediction capabilities will provide relevant measurements to better plan missions and protect crew residing in surface habitation systems. Materials for radiation shielding and the amount of materials that are needed to effectively limit radiation exposure are an ongoing consideration in habitation system development. Radiation strategies developed for lunar surface habitation are also extensible to Mars transit habitation and a Mars long-duration surface habitat.

6. Commercial Partnerships

NASA has had commercial partnerships with U.S. industry since 2015 to advance deep space habitat concepts through a public-private partnership known as the Next Space Technologies for Exploration Partnerships, or NextSTEP, Broad Agency Announcement (BAA) Appendix A [20]. The initial objective in Phase 1 of this activity was to design and investigate concepts for initial habitation capabilities in cislunar space. In this initial phase, industry partners were able to mature their concepts, initial requirements, and concept of operations while helping NASA understand what capabilities would be required for the initial Gateway configuration [21, 22].

In Phase 2 of the effort in 2018, the Appendix A partners developed high-fidelity ground prototypes of their habitat modules. These ground prototypes allowed NASA and the partners to evaluate configurations, assess various systems interactions together, and use these test platforms to assess standards and common interfaces under consideration. [23, 24, 25]

From 2019 – 2020, Phase 3 of the NextSTEP Appendix A effort focused on continuing to advance the U.S. industry concepts using the analysis from the ground tests and initial Gateway analysis cycles to refine the architectures. Key focus areas for Phase 3 included:

• Advancing Gateway habitation module requirements and system definition to system requirements review (SRR) and system definition review (SDR) maturity with an emphasis on maximizing relevance to extensibility.

• Additional habitat ground prototype development or other risk reduction activities to address key risk areas.

• Extensibility studies to assess use of Gateway habitation concept(s) and technologies for lunar surface and Mars transport habitat applications.

As with previous phases, the results from Phase 3 will continue to feed forward for future habitation applications, including future potential solicitations for an SH and/or a Mars Transit Habitat. In 2020-2021, Phase 3 extensions with NextSTEP partners Boeing, Sierra Space, and Lockheed Martin continued activities to reduce habitation development risks.

In addition to work with American industry under NextSTEP Appendix A, NASA also continues to collaborate with its international partners to advance concepts for deep space habitation. Partnerships across Gateway have allowed for the expansion of habitation capabilities. As NASA looks toward the next generation habitation needs in the deep space architecture, international partners will play a critical role in defining and contributing to those systems.

Figure 5: Contractor Ground Prototypes

Additionally, the LEO marketplace continues to grow, and U.S. commercial companies have sufficiently matured their capabilities for NASA to create partnerships that utilize industry expertise to demonstrate technologies in a commercial LEO habitat module. In July 2021, NASA released the Commercial LEO Destinations (CLD) proposal opportunity [26]. CLD is a two-phase approach, where phase 1 consists of a period of formulation and initial vetting of design concepts, with phase 2 including certification by NASA of a contractor provided CLD habitation system. The overall CLD goals are to accommodate crew and payloads for multiple customers, provide a continuous human presence, encourage development of the LEO economy, provide “turnkey” operations to customers, and demonstrate hardware, subsystems, and key technologies. The system must accommodate at least two crew, internal pressurized payloads, facilities, and at least six external unpressurized payloads. Stretch service goals include exploration analog services (capacity of up to four crew members, crew volume of 100 cubic meters, in situ sample processing and analysis, ability to isolate a portion of the habitat from CLD activities, and providing testbeds for food cold stowage, exercise equipment, and medical equipment for exploration). Another stretch service goal is the capability to perform human-scale artificial gravity research to assess the ability of an AG system to provide countermeasures for sustained microgravity or partial gravity effects on the human body. Based on ISS experience, these effects include vision changes, muscle atrophy and bone loss. In December 2021, NASA announced three awards for commercial companies to pursue development of commercial LEO platforms. Awarded concepts included Northrup Grumman, Nanoracks’ Starlab, and Blue Origin’s Orbital Reef. [27]

7. Summary

The first crewed and uncrewed flights of SLS and Orion, the launch of the initial Gateway elements, and the use of HLS for the next footsteps on the Moon will all mark significant milestones in NASA’s Artemis program toward the goal of a sustained human presence on the lunar surface. Toward that end, NASA is maturing concepts for new systems, including a lunar Surface Habitat, capable of supporting long-duration missions on the Moon. The agency’s more than two decades of astronauts living and working aboard the International Space Station provide valuable lessons and capabilities that will also contribute toward that goal, but the environment of the lunar surface and its remoteness from Earth create unique challenges not faced aboard the ISS. In collaboration with commercial and international partners, NASA is working today to overcome those challenges as it matures plans for Artemis Base Camp, humanity’s first long-term home on another world, with the goal of ultimately enabling human missions to Mars.

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Biographies

Paul Kessler *received a Bachelor's in Biology and an M.S. in Aerospace Engineering from the University of Colorado in 2005 and has worked for DoD since 2006 and NASA since 2008 as both a contractor and civil servant. He is the current lead of the design team for the Lunar Surface Habitat (SH) for the agency working in Habitation Formulation Systems for MSFC. Prior to MSFC he was a systems analyst at NASA Langley where he conducted mission and concept design and analysis, campaign analysis, and architectural design. He also worked as the lead analyst for the Committee on Earth Observation Satellites (CEOS) System Engineering Office (SEO) at Langley Research Center.*

Tracie Prater *received a Ph.D. in mechanical engineering from Vanderbilt University in 2012. She worked in private sector aerospace before joining NASA in 2013. From 2013-2021, she was in the materials engineering division at NASA Marshall Space Flight Center, primarily supporting the in-space manufacturing project and the Centennial Challenges prize competition program. In 2021, she joined the habitation systems development branch, where she is supporting commercial habitation development activities. She is also a senior member of the American Institute of Aeronautics and Astronautics.*

Tiffany Nickens *currently serves as the Systems Engineering & Integration (SE&I) Lead for NASA's Habitation Formulation Team supporting the Human Exploration and Operations Mission Directorate (HEOMD). In this role, she supports technical and programmatic integration of habitation government reference architectures, as well as engagement with commercial partners. She previously supported Avionics/Flight Software design and development on the Space Launch System (SLS) program. Prior to joining NASA in 2017, she worked in the private sector on primary flight displays for rotorcraft and fixed-wing aircraft. She received a M.S. in Human Factors & Systems and a B.S. in Human Factors, both from Embry-Riddle Aeronautical University.*

Danny Harris *is the NASA Marshall Space Flight Center Manager for Habitation Systems Development. In addition, Mr. Harris also serves as the NASA Human Exploration and Operations Mission Directorate Strategy and Architecture Lead for Habitation and manager for the Next Space Technologies for Exploration Partnerships (NextSTEP) Habitation Systems, a program which uses public-private partnerships to enable commercial development of deep space exploration habitats. Prior to this work, Mr. Harris held a variety of program/project management and engineering leadership positions including serving as the NASA Headquarters Space Technology Mission Directorate (STMD) Deputy Chief Engineer, the Science Mission Directorate Deputy Chief Engineer, overseeing the implementation of the STMD Technology Demonstration Missions program portfolio of technology projects, as well as work on the Lunar Atmosphere and Dust Environment Explorer (LADEE) and Lunar CRater Observation and Sensing Satellite (LCROSS) missions, International Space Station (ISS) Environmental Control and Life Support Systems (ECLSS), and ISS flight element development.*

Before joining NASA, Mr. Harris worked for McDonnell Douglas and The Boeing Company, following the merger of the two companies, as a Thermal Control and ECLSS engineer on the Spacelab and International Space Station programs.