Project Olympus: Off-World Additive Construction for Lunar Surface Infrastructure

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In Project Olympus, ICON and SEArch+ have developed design schematics for critical surface infrastructure necessary for a permanent lunar base. In 2020 ICON was awarded an SBIR contribution from Marshall Space Flight Center (MSFC) to contribute to NASA Marshall's Moon-to-Mars Planetary Autonomous Construction Technologies (MMPACT) initiative. ICON will first demonstrate additive manufacturing capabilities for horizontal structures such as roads and landing pads, followed by demonstrations of vertical structures, including unpressurized radiation shelters as well as habitats. In 2020, ICON employed SEArch+ to develop design schematics for mission-critical surface construction elements for a lunar settlement, including concepts for surface-site deployment, construction sequencing, and structural design. The design process was informed by discussions with key ICON engineers and NASA collaborators. The exchange not only ensured the constructibility of designs according to hardware and material processing limitations, but also enabled the architectural process to influence and shape hardware requirements as they were being defined. The ensuing habitat design, titled the "Lunar Lantern" for its double-protective outer shield structure, celebrates and promotes a design approach driven by human factors principles to ensure the safety and security of future crew. As a whole, Project Olympus envisions the construction of durable, self-maintaining, and resilient surface structures enabled by advanced 3D-printing technologies.

Nomenclature

3D	=	3-dimensional
3DP	=	3D-printed
ConOps	=	concept of operations
ECLSS	=	environmental control and life support system
ISRU	=	in-situ resource utilization
LRO	=	Lunar Reconnaissance Orbiter
MMOD	=	Micrometeoroid & Orbital Debris
MMPACT	=	Moon to Mars Planetary Autonomous Construction Technologies
MSFC	=	Marshall Space Flight Center
PSR	=	permanently shadowed region
RLSO2	=	Robotic Lunar Surface Operations 2

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I. Introduction

BY 2028 NASA seeks to deploy surface construction technologies for the development of a permanent lunar base. While lunar construction will undoubtedly depend on multiple advanced construction technologies working in-concert, NASA has committed to developing in-situ resource utilization (ISRU) additive manufacturing (3D-printing) capabilities with excavation and handling technologies to realize surface-site elements. Large-scale additive manufacturing technologies will be applied to autonomously construct surface infrastructure prior to a crew's arrival. Multiple sheltering aspects will be needed for early settlements to reliably protect crews against radiation, micro-meteoroids and provide exhaust plume protection during subsequent launches. Future precursor missions depend on safe, durable, and protective housing and infrastructure and will rely on ISRU-based additive manufacturing to construct landing pads, roads, berms, garages, and habitats.[1]

NASA's Moon to Mars Planetary Autonomous Construction Technologies (MMPACT) is a program developing, delivering, and demonstrating on-demand capabilities to protect astronauts and create infrastructure on the lunar surface via the construction of landing pads, unpressurized and pressurized radiation shelters, roadways, berms, and blast shields using regolith-based materials. Project Olympus is ICON's multi-year initiative to develop an autonomous, large-scale construction system capable of manufacturing both horizontal and vertical construction typologies and surface infrastructure on the Moon and eventually Mars.

In 2020 ICON was awarded an SBIR contribution from MSFC to contribute to the MMPACT program, and employed SEArch+ to develop design schematics for mission-critical surface construction elements for a permanent lunar settlement. The design process was informed by discussions with key ICON engineers and NASA collaborators. The exchange not only ensured the constructibility of designs according to presently known hardware and material processing limitations, but the architectural process was also able to influence and shape hardware requirements and technology capabilities as they were being defined. This model of leveraging the design process to inform systems requirements represents a novel and necessary workflow for accelerating the realization of human habitation concepts within the aerospace industry.

A. Regolith Surface-Site Construction Activities

Future missions to the Moon and Mars will require the use of in-situ planetary materials for the construction and manufacturing of habitats and infrastructure, as use of local and indigenous construction materials will drastically reduce launch and transportation mass. Payload mass-optimization is the principal rationale for ISRU manufacturing of materials, technology, and resources supporting autonomous surface habitat construction. Before 3D-printing is deployed for infrastructure development, site establishments will rely on construction machinery for excavation, leveling, grading, and terrain preparation. Regolith 3D-printing methods and construction activities have previously been surveyed and evaluated in workshops and design reference studies, such as at the W.M. Keck Institute for Space Studies in 2016.[2] A variety of extrusion deposition and layered in-situ binding mechanisms have been considered and compared, such as: cementitious, fused-deposition method, microwave melting, powder spray, laser sintering, solar sintering, and selective inhibition sintering, among others.

B. Critical Infrastructure Elements

A shortlist of critical surface site infrastructure elements was derived from prior research to inform the scope of this study, including the availability of power sources and power generation, landing systems, propellant production, ISRU production, as well as site excavation and preparation activities. Lunar surface construction technologies must support the manufacturing of critical infrastructure elements such as: landing pads, rocket engine blast protection berms, garages, roads, dust-free zones, equipment shelters, and of course human habitats and radiation shelters. 3D-printing provides unprecedented versatility to manufacture a wide range of structural geometries on-demand. ISRU capabilities are necessary to an overall mission architecture in which multiple technical discipline elements such as mobility, material processing, product storage, and distribution are connected and tied to other systems.[2] ICON's construction system is planned to first demonstrate capabilities to manufacture critical horizontal structures such as roads and landing pads, followed by demonstrations of critical vertical structures including unpressurized radiation shelters as well as habitats.

C. Phased Development Timeline

Not only will regolith construction capabilities (including excavation and material processing) need to advance significantly from the current state-of-the-art to deliver autonomously constructed habitats, but it is probable that foundational surface structures will be constructed using a combination of structural typologies and construction methods (see Figure 1).

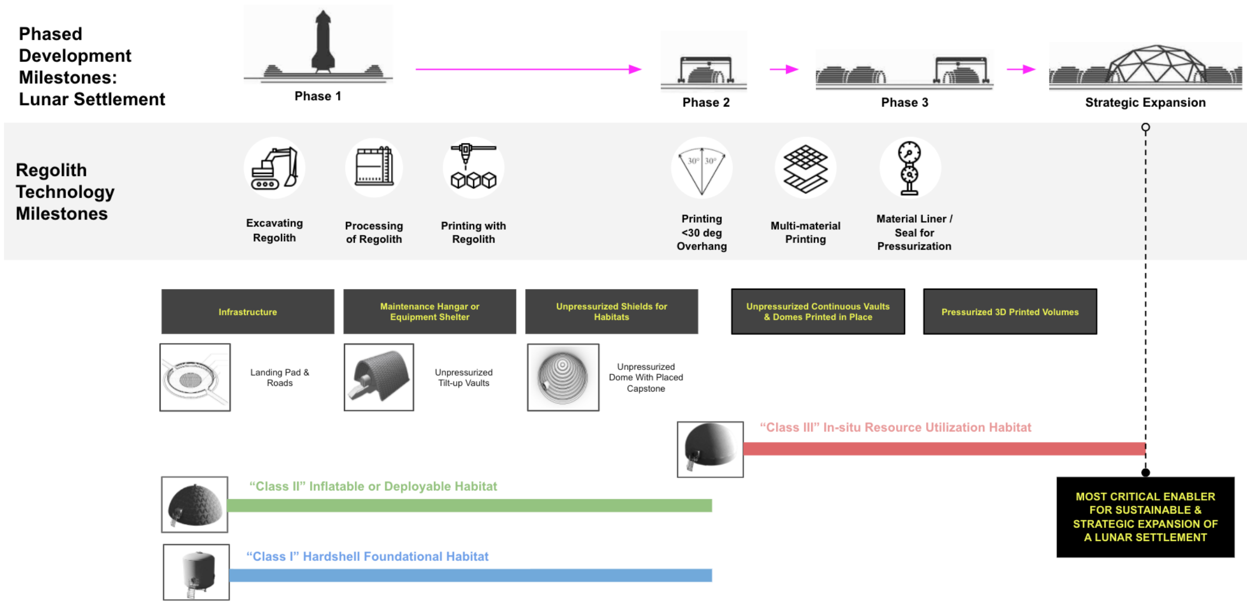


Figure 2. Roadmap demonstrating parallel paths between regolith construction capabilities milestones and phased development milestones for the construction permanent lunar infrastructure.

Research pushing towards the realization of 3D-printed surface habitats will advance in parallel with technology development in construction robotics, ISRU capabilities, and autonomous systems. NASA has designated three classes of space habitat paradigms: Class I consists of hard-shell modules pre-integrated on Earth (i.e. the ISS), Class II habitats are prefabricated and surface-assembled modules (such as inflatable structures), and Class III space habitats utilize ISRU for the autonomous construction of structures that integrate with Class I and II modules.[3] Currently 3D-printed ISRU surface habitats constitute a later-stage initiative with multiple technology milestones needing to be met prior to realization. These milestones include capabilities for printing at greater tangent overhang angles, multi-material printing of composite layups, and the deposition of a non-porous material or installation of a material liner capable of creating a hermetic seal to maintain pressurization (see Figure 3). The current project assumed a 20° tangent-overhang angle as a constraint. Foundational habitats planned by the Artemis program will likely consist of Class I and Class II modules. To advance the viability and technology readiness of additively manufactured ISRU surface habitats, technology development not only depends on the additive deposition technologies themselves but likewise in the robotic integration of pre-integrated hard-surface modules and precision-manufactured elements launched from Earth.

Additive manufacturing on the lunar surface will occur in multiple phases of development (see Figure 4), aligning with expansion of the lunar base itself as well as multiple phases of crewed lunar exploration.[4] Anticipating autonomous robotic operations, initial cargo arrivals will support robotic activities on the lunar surface and precede the arrival of the first crew. Activities supporting robotic site excavation, materials acquisition, and power generation will almost certainly precede regolith construction activities. Sequencing of regolith surface construction activities will depend in large part on integration and interfacing with ISRU activities as well as available power resources.

II. Site Analysis and Master Planning

Architecturally, the project assumed a site-agnostic strategy due to the lack of resolve in regards to landing locations at the lunar South Pole.[5] Despite the fact that site selection may not occur for some time, the design team remained cognizant of the fact that inherent features (topological and otherwise) of the immediate landscape not only impact the design of a foundational habitat, but pose dramatically different concepts of operations (ConOps) for the deployment of surface site infrastructure, adjacencies and distances between resources, as well as surface exploration activities (such as geo-planetary science, ISRU propellant production, etc).

A. The Lunar South Pole

NASA has selected the lunar South Pole for initial Artemis missions. Possible landing locations and regions of interest for future exploration missions have been evaluated by Flahaut et al.[6] In this research, case studies demonstrate that precise landing site selection is highly mission-dependent. NASA is interested in the South Pole for geologic research and in light of increasing evidence for cold-trapped water-ice and volatiles in the region.[6] Flahaut et al. note that illumination and Earth visibility at the South Pole nonetheless remain limited and will strongly impact future mission scenarios.[6] The presence of a highly varied topography at the South Pole presents a challenge which greatly differs from Apollo missions. The nature of seismic activity in the South Pole is comparatively unknown to the mid-latitude regions. But from the limited data we have, one moonquake of Richter 3 magnitude has been observed near the South Pole. As opposed to the 14 day-14 night cycle in the mid-latitudes where the Apollo missions were carried out, being in the polar regions forces us to consider how to design within permanently shadowed regions, permanently lit regions, and everything in between. The perceived day-night cycle for a given region depends greatly on the topography of the area and its surroundings. Construction strategies are hence difficult to generalize for this region—apart from obvious suggestions to place solar power collectors in highly lit areas. The extremely low Sun angles around the poles may result in uneven heating of infrastructure. Also, the regolith in the south pole has different geological and mineralogical characteristics; while the Apollo missions were in the Maria (and/or basins), the south pole is in the Highlands.

B. Site Analysis & Preferred Landing Site Criterion

Site data analysis began with studying imaging from the Lunar Reconnaissance Orbiter (LRO) maps. A site analysis was conducted to determine high-value potential landing site locations that also met site planning requirements. Different site locations at the South Pole introduce different potential advantages for construction; for example, some sites around the ridges between the Shackleton crater and De Gerlache have high solar energy that exceeds 90% illumination over the course of a year. Other permanently shadowed regions (PSRs) at the bottom of craters are known to contain ice deposits. In contrast, other sites have flat topographical features which could ensure better maneuvering for rovers and construction robots.

An integrated analysis was initiated by overlapping the following lunar maps: illumination, topography, and temperature (see Figure 5). Multiple maps were analyzed by pixelating LRO imaging and assigning numerical values according to color. An approximate area of 140,000 m x 140,000 m located near Shackleton crater was analyzed according to this method. A grid of 100,000 points with assigned numerical values for elevation was generated to compare illuminance, topography, and temperature data within the region. Minimum and maximum values were assigned by color, and the maps were graphically "layered" to parse and identify preferred site locations with the lowest temperature deviation, highest illuminance, and minimal slopes. Minimal temperature deviations, greatest illuminance, and flatness of the topography served as the primary criterion for site analysis.

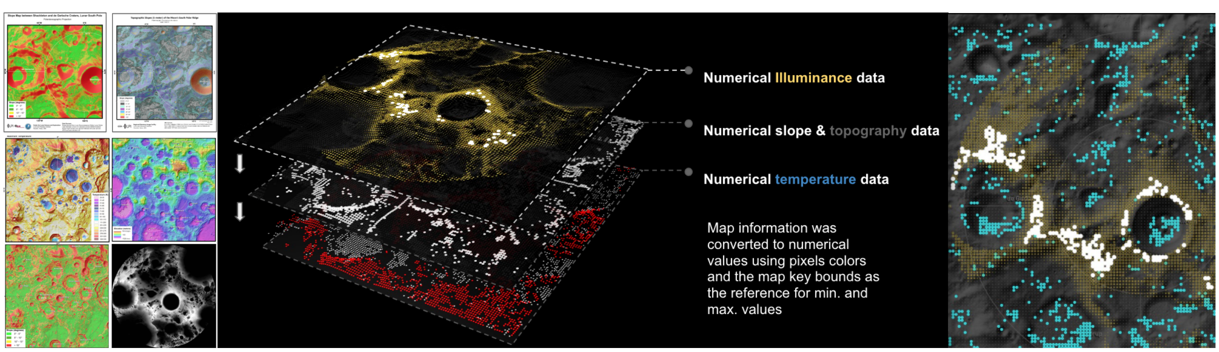


Figure 6. Left: Lunar Reconnaissance Orbiter maps. Center and right: Graphic showing how numerical illuminance, topography, and temperature data from the Lunar Reconnaissance Orbiter maps were layered and quantitatively parsed to identify preferred site locations.

An additional selection criteria was then assigned to further refine site selection results. Using an algorithm-based model, we created a tool that highlights flat sites with green, high illumination sites with yellow, and PSR with green. The criteria evaluated 100 test points (a 2 x 2 km geographic area) from the previously generated grid and identified regions with the following characteristics: flattest terrain (more than 80% of site has a slope less than 5.0 degrees), maximum illumination (more than 50% of site has illumination more than 90% of year), and least temperature deviation (more than 60% of the site has a temperature deviation less than 200 K) (see Figure 7 right).

III. Requirements Definition: A Lunar Base

A. Methodology & Assumptions

The research methodology used to arrive at requirements for master planning consisted of the following: application of baseline principles to site data analysis, evaluation of research precedents and case studies, followed by identification of mission-critical operations, task activities and functions, and designation of rules and principles relative to zoning and expansion. Zoning and expansion rules included sequencing requirements for a phased development timeline, required safety or keep-out zones, required program adjacencies, and minimum/maximum travel distances. Adopting design principles developed by Sherwood et al., baseline principles and assumptions for a permanent lunar outpost within our study included: adaptability (accommodating off-nominal conditions), flexibility (adapting to changing requirements), resilience (accommodating failure), and multi-use (commonality and reuse of hardware and product elements).[7] Functions of a lunar base and facilities to be included in a master plan were evaluated based on research by Koelle et al., including: support for lunar science and technology activities (such as operation of laboratories, observatories), ISRU production of raw materials (such as resource mining, beneficiation of lunar soil, and production of gases, raw materials and feedstock), manufacturing of end-products and commercial services (such as manufacturing of structural components, propellants, energy for export), and direct support operations (such as supervision and control of equipment, communication services, data management, housing of crew, health and recreation for crew, maintenance and repair of facilities and equipment, etc).[8] Earth-brough lunar surface elements were evaluated based on a study by Bodkin et al., which considered multiple utility rovers for construction and maneuvering of base components (habitat modules, airlocks, and cargo containers) on the lunar surface.[9] Additional principles informing requirements for the design and planning of a lunar base focused on: safety, efficiency, and expandability.[10]

B. Historical Precedents and Case Studies

The research phase of the project considered several precedent projects and examples of lunar bases, both historic and contemporary. Multiple examples of lunar base designs were evaluated and studied according to their specified and selected infrastructure elements, equipment and assets, site planning strategy, architectural approach, construction sequencing approach, as well as number of anticipated crewmembers.

1) Project Horizon

   Project Horizon was evaluated for its distinct approach to lunar outpost design. The semi-hypogean U.S. Army base, made of Class 1 horizontal modules, is covered in loose regolith to shield against radiation. The L-shaped master plan is site-agnostic, and it's built around the safety constraints.

2) RLSO1 and RLSO2

   RLSO1 was evaluated for its use of robotic operations on the lunar surface. Some of the key takeaways of this analysis included: the need for a gantry-like asset which could perform multiple functions, the existence of traffic routes highly influenced construction timelines, and lastly base assets must remain protected from lander jet debris.

3) McMurdo Station

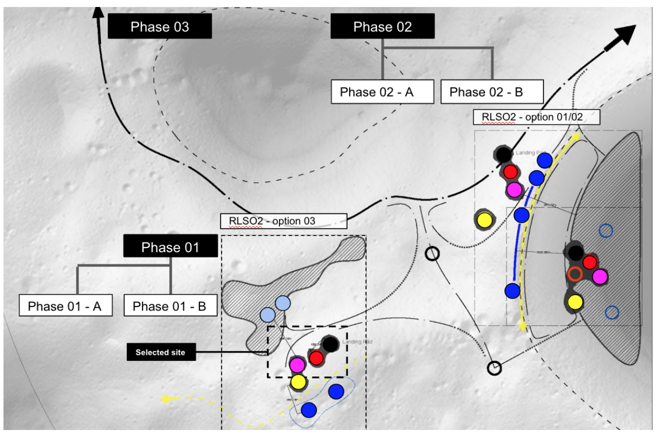
   McMurdo Station was evaluated for its master planning approach within an extreme environment. What started out as a geometric and symmetric site plan with modular structures gradually evolved towards adhering to Antarctica's natural topography, and fewer sloped roads and more compressed habitats were ultimately built.

4) Other Projects

   Other projects evaluated as precedent case studies included NASA's Constellation program, ESA/Liquifer's Regolite project, and ESA/SOM's Moon Village. Regolite in particular was evaluated for its use of solar sintering and the design of an unpressurized, self-supporting additively manufactured shield.[11] Orbital's lunar infrastructure design was evaluated in regards to its approach to habitat programming and functionalities as well as circulation studies.[9] A variety of mobility platforms were evaluated and considered to support the Olympus construction system, including ATHLETE's use within the Constellation program.[12] The final hardware configuration for the Olympus deposition system may be seen in Figures 6 and 22.

C. Master Planning & Expanding on RLSO2

The design team applied the preferred site locations identified within the site analysis phase to three planning and phased development schemes developed by RLSO2.[13] Within RLSO2, criteria for site planning and expansion depended on access to natural features of the landscape (in this case Shackleton crater) for ISRU water mining, excavation, and propellant production. The three site options presented by RLSO2 introduce different options for base location: option one is within the Shackleton crater (permanently shadowed region), option two is on the rim of Shackleton crater (permanently lit region), and option three is several kilometers away from the crater rim (permanently lit region). The three options within the design team's development and adaptation of RLSO2 also introduce different concepts for: excavation locations (two options are within permanently shadowed regions and one a combination of shadowed/lit), regolith characteristics (based on whether there is a higher or lower anticipated concentration of water-ice), and power transmission methods.



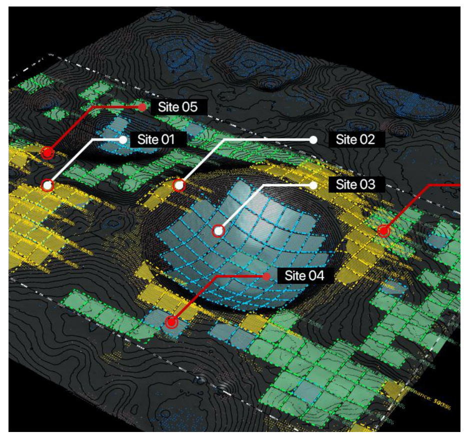


Figure 8. Left: Three possible planning strategies and a phased development approach adopted from and based on RLSO2. Figure 9. Right: Further refined site selection based on additional criteria applied to 2 x 2 km test points at the South Pole.

D. Planning Requirements

The research on historical precedents and case studies was used to determine a logic for zoning and expansion. Zoning adjacencies, minimum travel distances, and safety keep-out zones were determined from these analyses. A planning manual was developed to document initial dependencies for the locations of surface infrastructure elements. For example, lunar landing pads would benefit from being close to an initial Lunar outpost's critical infrastructural elements to allow for efficient off-loading of goods and resources. While logistical proximity to infrastructural elements would increase, safety and keep-out distances must nonetheless be considered.

IV. Printing Horizontal Structures: Lunar Landing Pads

The design and construction of lunar landing and launch pads ranks as a high-priority element of strategic infrastructure to be constructed on the surface of the Moon. To develop civil infrastructure on the Moon and eventually Mars, repeated visits to the same location will be necessary. Landing pads on the Moon would prevent regolith dust from sandblasting other infrastructure at 3 km/s, which would spread over the surface of the Moon and even enter lunar orbit.[14] A landing pad provides a stable zone for a lander's touchdown and would deflect exhaust plumes without excavating a hole under the lander.[14] The Artemis missions will require increased capability over previous Apollo missions for accurate descent and landing systems with greater abilities to detect and avoid hazards. Autonomous space landings and precision landing to a prescribed target on the Moon will present additional challenges unmet in previous spaceflight missions—and the construction of landing pads from in situ resources will mitigate risks posed by frequent and repeated landings to locations close to a lunar outpost.

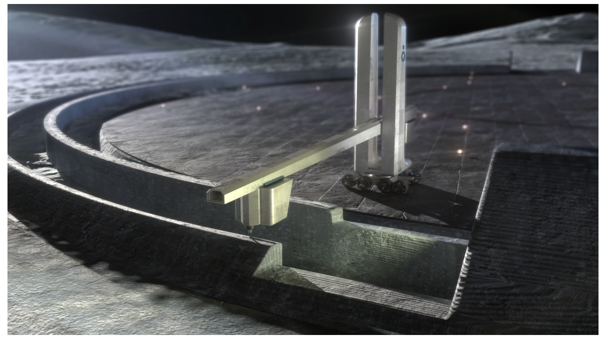
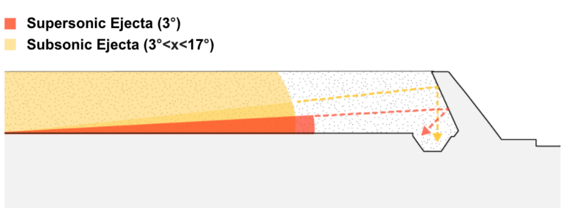


Figure 10. Left: Schematic representation of landing pads designs. Figure 11. Right: The Olympus construction system 3D-printing a landing pad.

A. Landing Distances: Principles & Rationale

Lunar landing pads would benefit from being close to an initial lunar outpost's critical infrastructural elements to allow for safe and efficient off-loading of cargo, goods, and resources. While logistical proximity to infrastructural elements would increase operational efficiency, standoff distances ensuring habitable and occupiable structures' safety remain a critical constraint in site planning. Not only do standoff distances need to be far enough to protect outpost structures from damage against rocket plumes, but also from the acceleration of dust particles during landing and launch. Because high-velocity dust impacts are incredibly damaging to hardware, keep-out zones are of extreme significance. Current research is not yet able to define safe landing distances; while NASA guidelines define an arbitrary 2-km keep-out zone, larger landers may require larger keep-away distances, and sensitive equipment may require additional keep-out specifications.

High-velocity dust impacts are a significant design driver for landing pads. As dust particles become airborne, they can accelerate to supersonic speeds and travel beyond the lunar surface and enter into orbit. We have evidence demonstrating that larger particles, traveling at supersonic speeds, eject at a lower angle of 3 degrees, and slower, smaller particles eject at a higher angle closer to 17 degrees.[15] Smaller particles are more subject to intra-particle collisions, slowing down the travel speed and giving rise to more complex trajectories. Current research indicates that the majority of ejecta can be contained with a blast wall at the height of 17 degrees.[15] Additional variables driving landing distances include the landing accuracy of the descent vehicle as well as the size and thrust of the rocket. Current computational landing accuracies of 100-m[16] necessitate a fairly large landing pad—but as landing accuracies improve, landing pads may become smaller and more efficient. Recent studies indicate 25-m as an achievable landing accuracy using a system of surface beacons.[17]



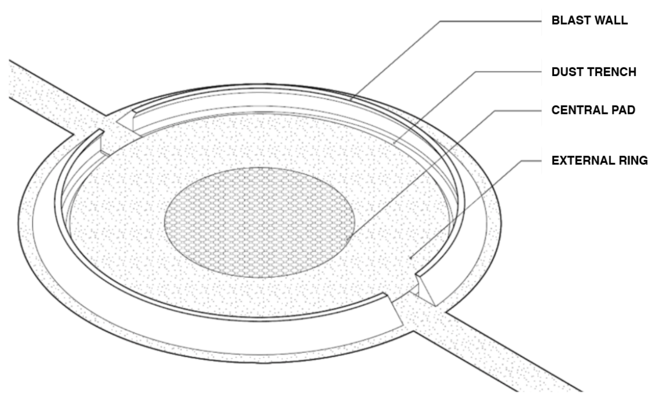


Figure 12. Left: Diagram of the anticipated path of supersonic ejecta between 3-17 degrees from point of touchdown, and the path of supersonic ejecta at 3 degrees from point of touchdown. Figure 13. Right: Components of landing pad design including: blast wall, dust trench, central pad, and external ring.

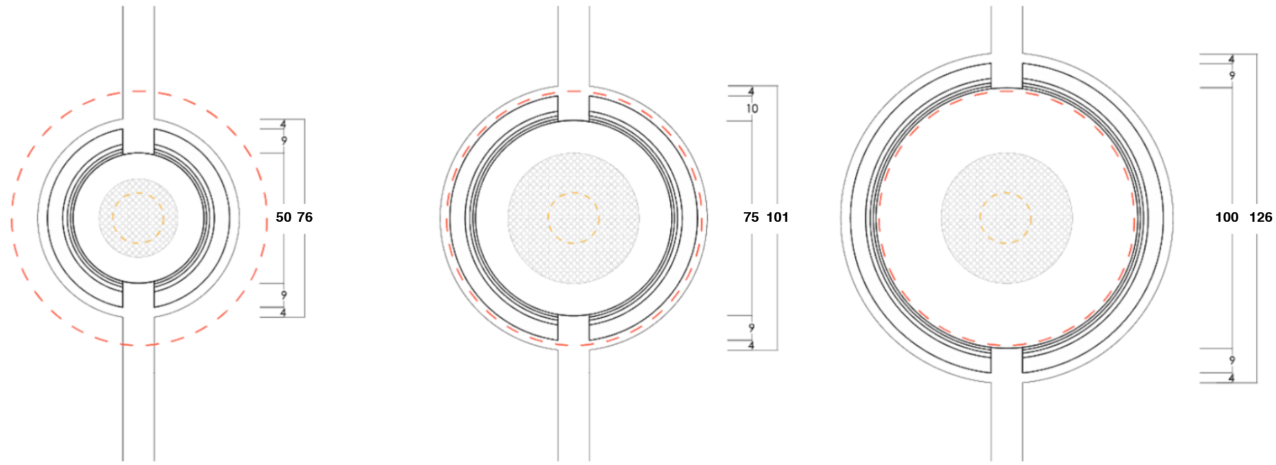


Figure 14. Three landing pad sizes proposed within the design process. *The red dashed circle denotes a 100-m diameter based on recent computationally-modelled landing accuracies determined in research, and the orange circle denotes a 25-m diameter zone, assuming improved landing accuracy with beacons.*

B. Landing Pad Conceptual Design & Construction Methods

This study expands on prior research differentiating the touchdown or center zone of the landing pad from the immediate area surrounding it, described as a secondary zone.[14] Four main components for a landing pad are introduced including: multi-material concentric rings for the central landing surface, a blast wall, a support berm, and a dust trench. Within this study, multiple construction options were considered including: a continuous sintering method, paving options which include a solid paving surface, the creation of interlocking paver elements, and a layer of 3D-printed gravel aggregate. Further study of how solid paving, 3D-printed gravel, and interlocking pavers behave is needed before a final recommendation is made. Pavers have been studied and prototyped in current research such as in NASA's collaboration with PISCES; however additional research is required to determine the exact shape, size and thickness recommended for a durable paver.[18]

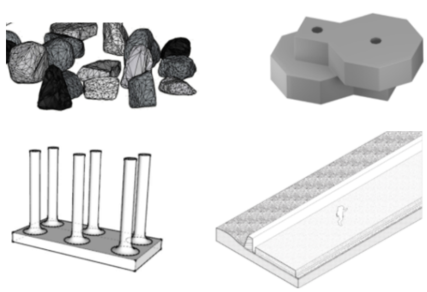
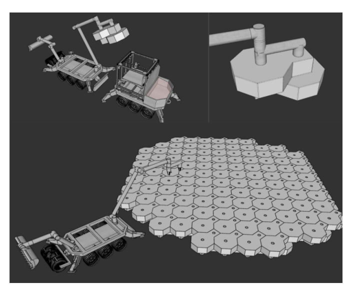



Figure 15. Left: Ideation relative to horizontal construction. *From top left: loose gravel and rocks of various sieve sizes which could be manufactured using the Olympus construction system, stacked pavers for use within landing pad designs, pile pavers (center), sidewalls adjacent to roads which could be modular components or 3D-printed regolith (far right).* **Figure 16. Right: Concept for robotic emplacement of surface pavers.**

Blast walls are a critical functional element of the landing pad. Our study introduces several blast wall options, including a continuously sintered wall, a wall constructed of sintered stacked pavers, and a 3D-printed "box" formwork filled with loose regolith. The blast wall design may include an angled dust barrier or wall with a height determined by the 17 degree angle requirement[15] and a dust trench that would collect most of the supersonic ejecta for later removal. While an understanding of the physics of plume effects drives the design of the blast wall and dust trench, additional trade studies are required to validate these approaches and determine a final recommendation. Additionally, a thorough understanding of the relationship between deposition time and feedstock quantities needed for each design will enable a more successful trade study to be conducted.

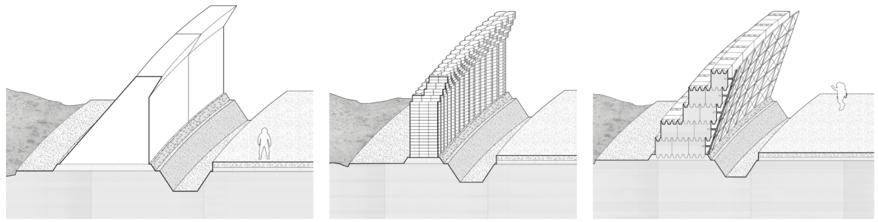


Figure 17. Three design options for landing pad blast walls. *The options represented include: a continuously sintered wall (left), stacked pavers (center), as well as a sintered formwork filled by loose regolith (right).*

C. Environmental Conditions Affecting Landing Pad Construction

Several environmental factors guide the design of a lunar landing and launch pad including but not limited to: temperature swings associated with day/night cycles, a site or location within permanently shadowed or permanently lit regions of the Moon, seismic activity, anticipated frequency of micrometeorite impacts, as well as materials degradation due to thermal swings. Traditional building methods of expansion joints and saw-style cuts may be valuable mitigation strategies to address thermal stress. The introduction of spaces between pavers to allow for expansion and contraction may relieve stress on 3D-printed surfaces and could also channel rocket plume and its associated ejecta toward a blast wall and dust trench. Additionally, using various patterns of alternating or layered contour and deposition tool paths may more reliably control materials failures in 3D-printed horizontal structures. Specifying alternating tooling patterns within a 3D-printed layup may improve strength properties and assist with understanding failure points.

D. Final Design Directions

Two design directions, titled the “sunflower vault” and the “eyelashes” directions, were down-selected at the conclusion of an iterative concept phase. Both designs provide countermeasures to blast ejecta using different strategies. The sunflower vault uses a continuous printed circular wall to contain the ejecta, offering different rebound angles according to the different sizing of the regolith particles: the biggest ejecta will fly on a lower angle but at supersonic speed while the lighter, slower ejecta will fly at an higher angle. The circular wall is shaped in radial petal-vaults, designed to slow the regolith and collect it on the ground where it can be collected by an autonomous robot. Following wall completion, loose regolith may be dumped on the exterior ring to add structural integrity and penetration protection from the fastest ejecta particles. Three tunnels built radially around the landing area allow access to the pad. The three tunnels are oriented on the tangent angle with the internal wall circumference to limit the spread of regolith in the access paths.

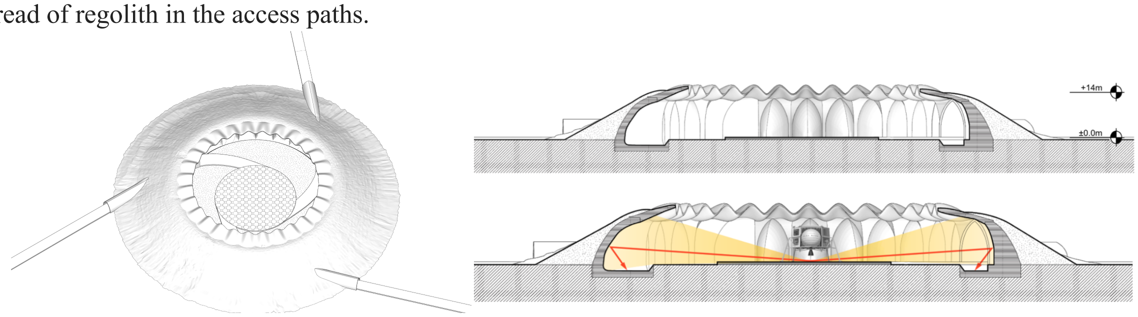


Figure 18. Sunflower vault landing pad design. *Left: axonometric. Right: section.*

The second proposed design, named “eyelashes” performs by absorbing ejecta. The aim of this concept is to force a high level of particle interactions and create a “cloud” of regolith that will exhaust the potential energy in intra-particle collisions. To achieve this objective, a ring will be excavated around the landing pad, after which a pattern of sintered regolith pillars will be constructed to stimulate the particle interaction in a specific area. The exhausted particles will sequentially fall into the collection ring. This direction may require less printing time, but will likely filter fewer particles compared with the sunflower vault option.

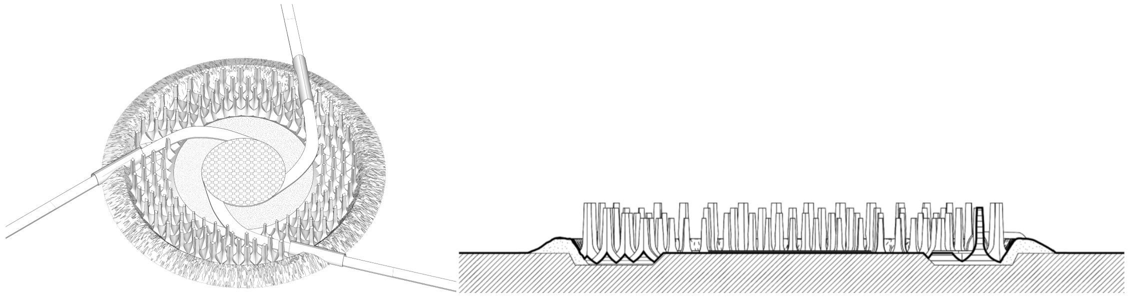


Figure 19. Eyelashes landing pad design direction. *Left: axonometric representation. Right: section.*

The above landing pad design investigations indicate that additional research is necessary to develop solutions which mitigate high-velocity dust impacts for a variety of lander types and lunar outpost configurations. The ejecta behavior is greatly influenced by the footprint of the landing vehicle and its mass; the speed of the particles as well as travelling angles thus have a high impact on landing pad design requirements.

V. Unpressurized Infrastructure & Surface Shielding

As mentioned earlier, multiple regolith-constructed shielding elements will prove critical in the creation of a permanent lunar base; these include rocket engine blast protection berms, garages, roads, dust-free zones, equipment shelters, and of course human habitats and radiation shelters. While foundational habitats launched by NASA's Artemis program will likely consist of Class I and Class II structures, future lunar base structures will include Olympus-constructed Class III structures, and may viably include combinations of Class I, II, and III structures therein.[19] The types of surface structures considered in the project drew from elements outlined within the Regolite consortium, which posed valuable distinctions between pressurized, unpressurized, and external (tertiary) facility types.[11] For example, types of pressurized facilities may include a base habitat, recycling plant, and greenhouse, whereas types of unpressurized facilities may include an electrical power supply facility, gas and fuel and other storage facilities. Benaroya has overviewed key issues and concepts relative to habitat design within the harsh lunar environment, and surveyed examples of Class I, Class II and combinations therein within prior research.[20] Multiple options have been considered relative to locating a habitat on the lunar surface—above the surface and shielded by regolith, inside lava tubes, or partially excavated within the ground plane.[21] Concepts for packed, modular regolith components were investigated and expanded on from a study conducted by Kaplicky, Nixon, and Wernick.[22] Various formal geometries were investigated relative to stacking, filling, and interlocking modularly constructed units with civil engineering applications.

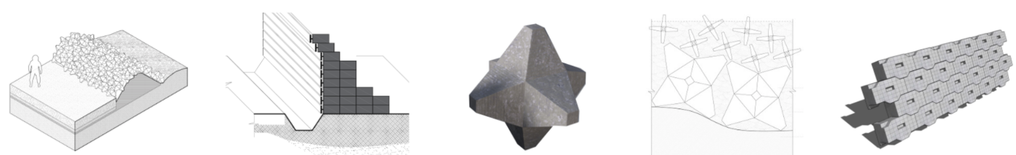


Figure 20. Ideation relative to dust mitigation and various shielding elements. *From right: berm wall constructed from 3D-printed jacks, blast wall constructed of stacked pavers, 3D jack for stacking and filling (center), archway composed of modular brick elements (far right).*

A. Architectural Typologies for Shielding and Sheltering

By combining multiple enclosure types and construction methods the design team sought to alleviate the burden of internal pressurization using 3D-printed regolith alone, and optimize additively manufactured regolith construction for critical structural elements. Additive manufacturing and directed energy sintering technologies under consideration within the MMPACT program are both energy- and time-intensive processes. The design team iterated on structural typologies and approaches which essentialize the use of 3D-printed structure with other, arguably less time and energy intensive construction processes such as regolith infill. Several technology development challenges remain present when considering 3D-printed construction with regolith alone (these challenges have been described as technology development milestones within Figure 1). Firstly, printing tangent overhang angles less than 20° from a previously printed layer without structural support is a present limitation of the state-of-the-art, and thus was assumed as a constraint within the design process. Presently, many 3D-printing technologies incorporate temporary scaffolding and support material to additively manufacture overhangs (although this is highly dependent on the material being utilized as well). Secondly, it is yet unknown whether regolith construction alone may create a hermetic seal structurally sound enough to maintain internal pressurization on the lunar surface. Regolith is materially porous and present research has yet to indicate that it may support the creation of an airtight seal. Alternatives and solutions posed to this problem include deploying a fabric or material liner to the inside of the regolith shell, or applying a spray-on (possibly polymer-based) material to seal the interior of the structure.

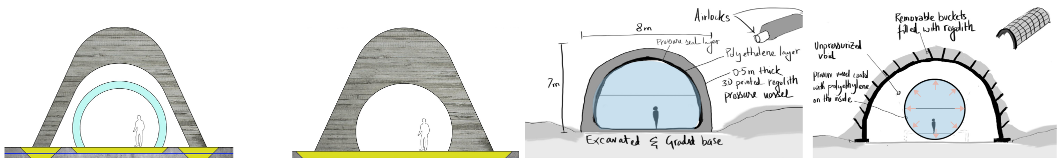
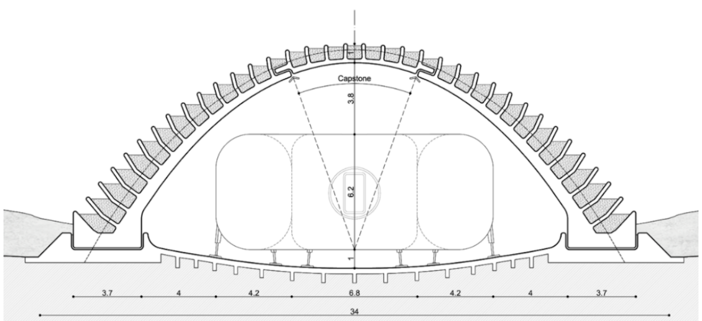


Figure 21. Various typologies for shielding, sheltering and internal pressurization. *From left: an Earth-brought pressurized inflatable surrounded by a partially pressurized 3D-printed enclosure for radiation and ballistic shielding, a 3D-printed pressure membrane, a 3D-printed enclosure relying on a printed polyethylene liner to maintain the pressure seal, an early rendition of the "bucket" scheme representing a hard-shell pressurized structure surrounded by a 3D-printed archway with multiple ledges or "buckets" capable of catching loose regolith for radiation shielding.*

B. Design of Unpressurized Shelters

Multiple types of unpressurized shelters were iterated on and considered in the design process, while relying on various types of inflatable as well as hard-shell surface structures for the purposes of internal pressurization and maintaining a closed hermetic seal to the lunar environment. Habitat geometry for the .707 hardshell structure (Figure 22) was adopted from Bodkin et al.[9] Habitat geometry for the inflatable structure (Figure 23) was adopted from habitable soft-goods inflatable studies by NASA.[23] Within the so-called bucket scheme, a 3D-printed shell is printed in-place through one of two methods: construction with a capstone at the roof of a dome structure, or construction of an unenclosed vault using sectional "slices" that are printed horizontally and tilted up to a vertical orientation (see Figures 19, 20).



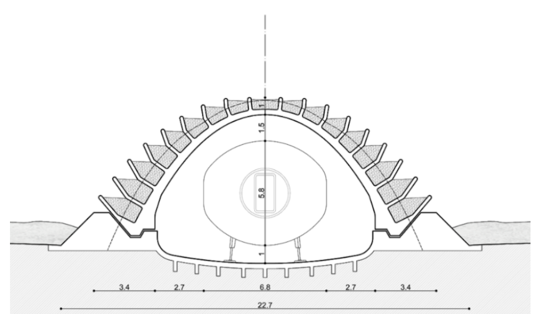
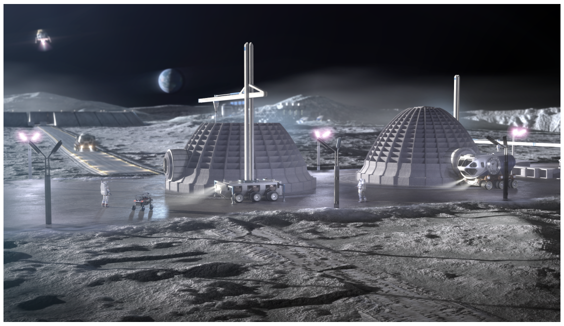


Figure 24. Left: Portrayal of bucket scheme surrounding a pressurized inflatable structure, constructed using an emplaced capstone to enclose the dome. Figure 25. Right: Portrayal of bucket scheme archway surrounding hardshell .707 pressurized structure, constructed using the tilt-up method.

1) Construction with Capstone
   In this design scheme, the construction system prepares the foundation and prints the vault or dome up to the overhang limit. Then the crane places the 3D-printed capstone on top of the dome (Figures 17 and 19). The structure's maximum footprint thus depends on the crane arm size.
2) Tilt-up Construction
   This scheme and construction method may only be used for the vault design. The foundation in this design has railings to move vaults and lock them together (Figure 18 right). The structure's dimension has no limit in extruded length, but its span is limited to the weight capacity of the crane. Figure 20 right shows a gantry system (double crane) tilting the end vault.



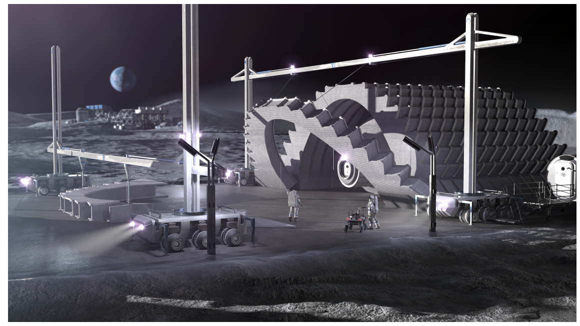
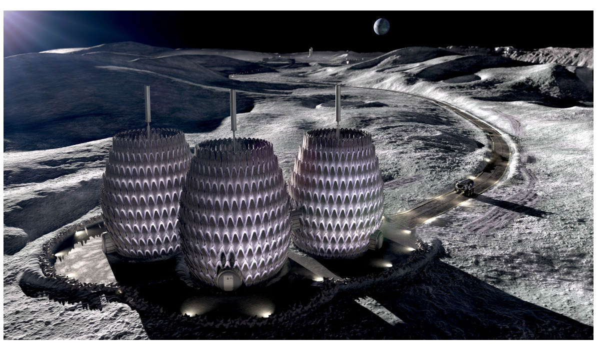


Figure 26. Left: Tilt-up construction of bucket scheme. Figure 27. Right: 3D-printed construction of bucket scheme with emplaced capstone at top.

VI. The Lunar Lantern: Structural Design

The ensuing habitat design is titled the Lunar Lantern and introduces a protective and illuminated outer shield structure surrounding a continuously 3D-printed pressure vessel. The combination of discretely manufactured panels on the outside of the structure surrounding a continuous 3D-print for the pressure seal introduces an added layer of redundancy and protection for the habitat. The form of the continuously printed inner habitat was generated by two drivers: the realization of a formal pressure membrane, and the constraint of only 3D-printing tangent overhang angles less than 20° from a previously printed layer (see Figure 23). A critique afforded to the project in review claimed that it may be possible to print overhangs at greater angles in the future, however the project assumed 20° as a present constraint. Several structural load cases were analyzed for the Lunar Lantern, including the lunar environment's harsh temperature differentials as well as internal pressurization of the structure. The analysis encouraged the team to consider other structural technologies mitigating structural vulnerabilities and validated the necessity of a double-shield structure for the design.



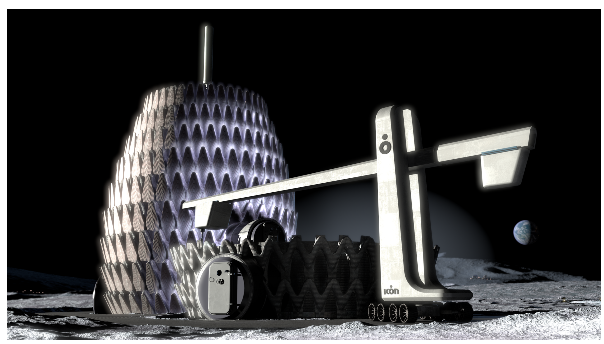
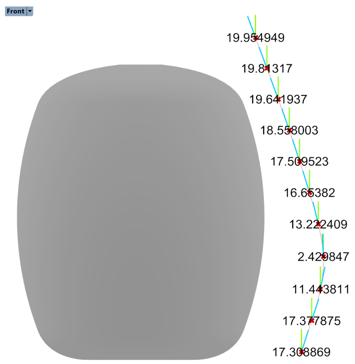


Figure 28. Left: perspective view of the Lunar Lantern. Figure 29. Right: Olympus construction system 3D-printing the habitat design.

A. Habitat Performance Objectives

Throughout the lifecycle of the habitat, the structure will need to prove resilient to cyclic and fatigue loading, long duration seismic events, asymmetrical thermal loading and internal pressurization. For these reasons the sintered regolith material will need to remain elastic; being a brittle material, the design intent is to avoid crack formations under low stress limit states as much as possible. Ensuring structural resilience may be the single most important concept relative to the development of a thriving, self-sufficient and permanent settlement on the lunar surface.[24,25] In order to mitigate the risks of micro-meteorite impacts and secondary impacts that may cause catastrophic failure due to rapid depressurization, habitats must be designed with robust and durable shielding. New failure modes must be anticipated to better evaluate the life cycle of lunar structures and infrastructure. Intelligent structural monitoring must be considered, such as by incorporating embedded sensor networks to monitor structural health and integrity as well as probabilistic risk assessments that may predict anomalies within structures. Some damage may be acceptable to the habitat's structural shell so long as it can be repaired and maintained.



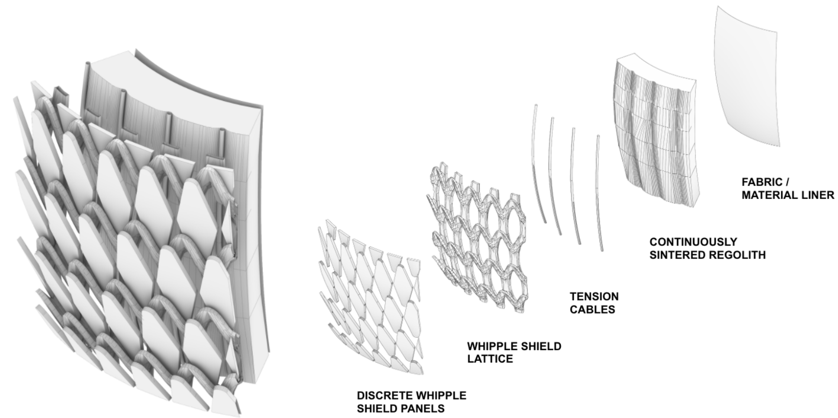


Figure 30. Left: Representation of tangent overhang angles within the cross-section of the habitat. Figure 31. Right: Exploded view of the habitat wall system, including structural technologies incorporated within the design.

B. Habitat Structural Design & Technologies

The risk of extreme temperature fluctuations and seismic activity on the Moon will cause extreme material fatigue. Particular attention must be attributed to assigning factors of safety to structural design. Benaroya et al. have made significant progress modelling temperature extremes at the South Pole, such as between lunar noon and night.[26] The following structural technologies have been introduced in the project to mitigate risks leading to structural failure: parabolic base isolators, discrete whipple shield panels, and post-tensioning of the habitat shell.

1) Base Isolation

To mitigate risks posed by long, shallow moonquakes and seismic activity on the Moon, we introduce base isolation as an approach for earthquake-resistant design, which conceptually reduces seismic demand rather than increasing the resistance capacity of structures.[27] Base isolation uncouples the building response from the damaging action of moonquakes by interposing structural elements with low structural stiffness between the structure and the foundation. Typically, the energy associated with the high frequency components of ground motion is not transferred to the structure. Base isolation reduces seismic demand by a factor of 3-4 compared with a fixed base structure. Base isolation also reduces potential damage to the habitat while concentrating damage to the isolation system, where elements may be substituted.

2) Discrete Whipple Shield Panels

To mitigate the risk of rapid depressurization from micrometeorite impacts, we introduce discrete 3D-printed whipple shield panels additively manufactured on the lunar surface and robotically emplaced in a secondary lattice structure surrounding the habitat (see Figures 22, 24). Whipple shields represent a mature solution with high technology readiness for micrometeoroid and orbital debris (MMOD) aboard the ISS.[28] In current spaceflight operations, high risk areas are found by analysis and shield panels are added by EVA in places where the greatest MMOD hits are anticipated. The whipple shield also serves as a secondary thermal barrier to the habitat. The whipple shield may theoretically provide shading to the pressurized habitat shell during construction, however more research is required to validate a ConOps where this is demonstrated. Incorporating the whipple shield panels as a secondary structure to the continuously 3D-printed pressure shell represents a powerful and strategic structural combination with high redundancy. The potential for repairability and maintainability of the whipple shield panels suggests that shielding of the pressurized habitat may happen with greater reliability.

3) Post-tensioning

Post-tensioning concrete provides critical performance enhancements in seismic resistance, vibration, deflection, and most importantly crack control. Post tensioning keeps the habitat shell in a constant state of compression, which provides critical performance enhancements in seismic resistance, vibration, deflection, and most importantly crack control. A combination of glass fiber and post-tensioning was considered by the design team to mitigate crack propagation.

C. Habitat Construction Sequencing

Unlike Class 1 and Class 2 habitat construction typologies, construction sequencing development is a necessary component for the ConOps of Class 3 architectures to ensure constructability and advance the level of development of additively manufactured habitats. Construction sequencing for the Lunar Lantern is as follows: first, a circular area, 16 m in diameter and 2 m deep, is excavated using unmanned rovers to expose the more stable layer of the lunar terrain. Ramps may be incorporated during this process to make the excavation and later utilization of this excavated area easier. The 3D-printer will then print the foundation in the excavated area. Next, the 3D-printer will transfer the habitat's pre-integrated core from the lander onto the foundation while ensuring the proper connection between the seismic base isolators and the notches on the foundation. Then, the 3D-printer begins printing the walls of the pressure vessel. At this time, airlocks and windows are placed when the print level reaches the bottom level of these perforations in the 3D-printed wall. After printing of the walls is complete, the top cap will be raised and locked into position. The tension cables stored in spools on the top cap are then lowered down and attached to anchors on the bottom cap of the core by unmanned rovers. Finally, the outer shield may be printed, beginning with the lattice structure and followed by the separately printed whipple shield panels, which are placed into the lattice with the 3D-printer.

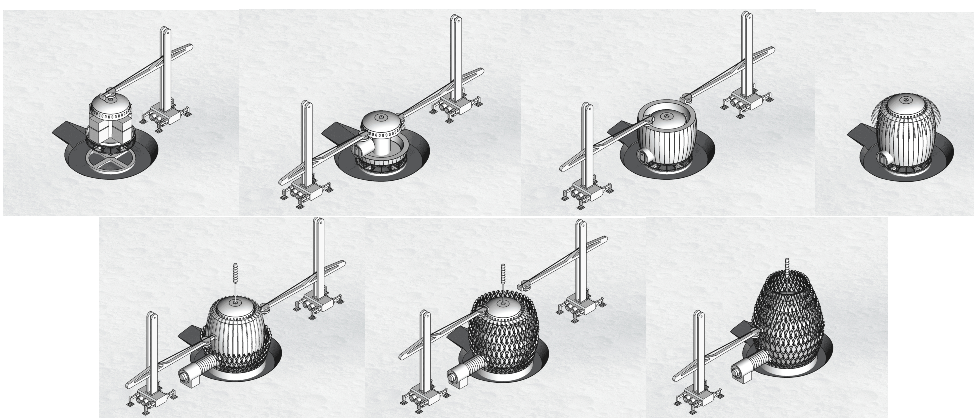


Figure 32. Construction sequence of habitat design. *From top left to bottom right: 1) Placement of core on the foundation, 2) Initiate 3D-printing of the walls and placement of airlocks/windows when necessary, 3) Finish printing the walls and raise the top cap of the core afterwards, 4) Deploy tension cables from the top cap and tie it to anchors on the bottom cap and place the light collection device on the top cap afterwards, 5) Initiate printing outer shell lattice, 6) Finish printing the lattice structure, 7) Install separately printed modular whipple panels.*

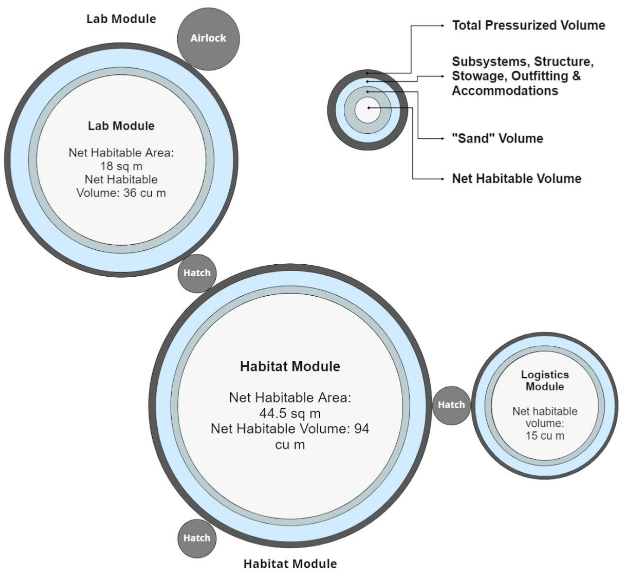
VII. The Lunar Lantern: Habitat Programming & Interior Layout

The interior habitat celebrates and promotes a design approach driven by human factors principles to ensure the safety and security of future crew. The habitat is a three-story structure supporting a crew of four based on the anticipated Artemis missions[29,30] and our analysis of RLSO2.[13] Among the various mission drivers typically used to determine habitat sizing and habitable functions, crew size was the one known parameter within the project, unlike mission duration and activities. A range of surface operations have been evaluated to inform programmatic needs for the habitat; these include resource extraction, planetary and biological sciences, and surface exploration.[31] The design team strove to create functional work and living spaces that could not only be adequate for future long-duration missions of six months or longer, but to introduce functional programming, architectural, and interior design elements that promote crew cohesion, performance, and overall health and well-being.


Figure 33. Left: Crew quarters at the ground floor of the habitat. Figure 34. Right: Wardroom at the top floor of the habitat.

Habitat program areas were adopted from studies developed by Bodkin et al., which separate crew functions into distinct modules: a crew module (including crew quarters for a crew of 4, galley, hygiene areas, dining and wardroom areas, as well as health and medical functions), science module, maintenance module, and logistics module (for storage and maintenance)[9]— a distribution similar to NASA's Constellation program.[32] The design team adopted the aforementioned described module functionalities to separate crew module functions from science and research activities and ensure safety of the crew. The design of the Lunar Lantern incorporates and designs for crew module functions only. Research in habitat sizing and volume estimation places significant emphasis on mission duration, crew size, and scientific objectives for optimal crew performance.[4,33] Additionally, there is no accepted standard for habitable volume at partial gravity which is also applicable to zero-g environments; studies have recommended the standard be alternately approached as a habitable floor area since the crew will be subject to ⅙ gravitational forces.[9] For the purposes of this project, a constraint was not specifically given to the overall floor area within the habitat, but instead focused on separation of programmatic elements based on function. Nonetheless, the design team did adapt a methodology described in Rudisill et al. relative to allotting a certain percentage of floor area to "sand," as well as area for "subsystems, structure, stowage, outfitting and accommodations" (see Figure 28).[33]

The ground floor features private programmatic areas: individual crew quarters for four astronauts, a lounge area, bathroom, and a convertible health-lab / medical station. The hatch on this floor connects to the pressurized rover and also functions as an emergency exit. The second floor features a dedicated area for communications and mission control activities, a restroom/commode, a rack area for environmental control and life support system (ECLSS) hardware, and an exercise area. This mainly public floor has two airlocks to connect to other modules such as the lab or logistics (which again, remained out of scope for the current project). The third and top floor of the habitat features a galley and communal recreation area, kitchen, storage, as well as an aeroponic garden that cascades to the second level of the habitat. The top floor is adaptable in that it can shift from being a public gathering space to a more private space observation and contemplation area. A window is located on every floor of the habitat and positioned to ensure constant visibility to Earth.



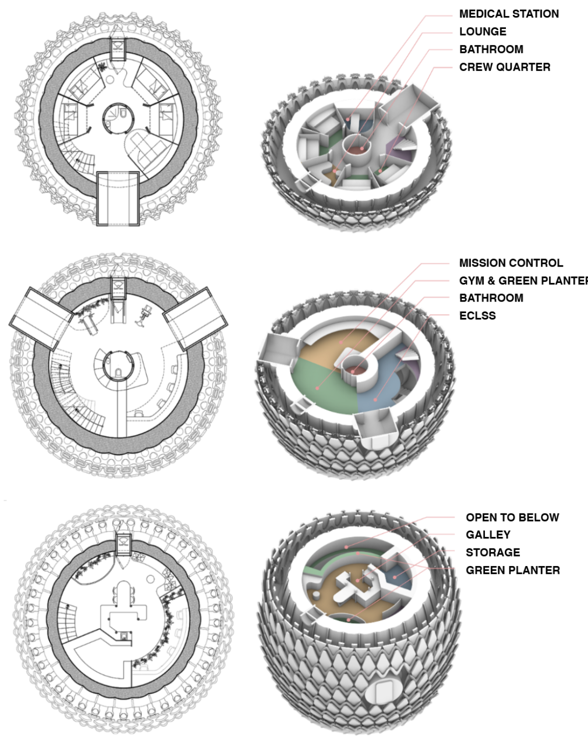
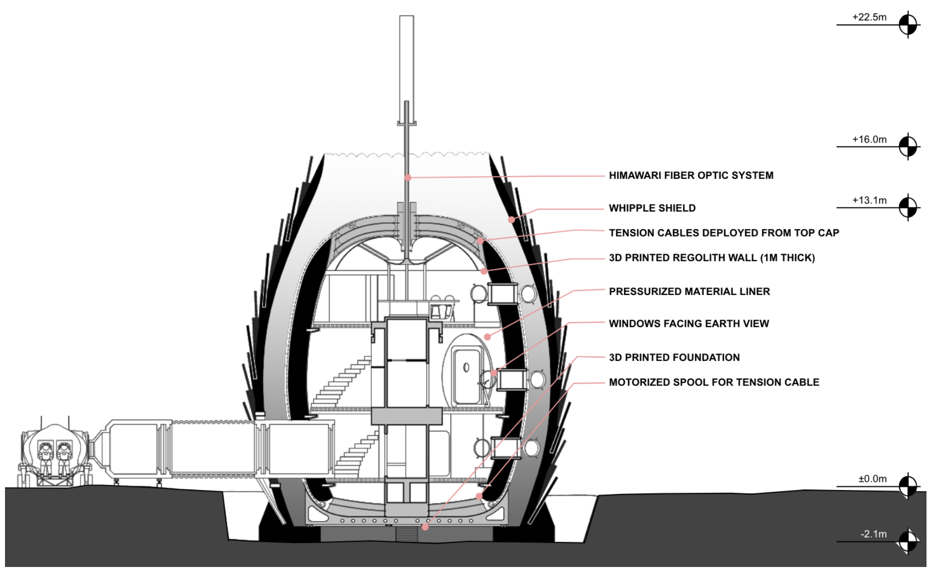


Figure 35. Left: Programmatic breakdown of habitat, logistics, and lab modules. Figure 36. Right: Floor plans and axonometric for the Lunar Lantern.



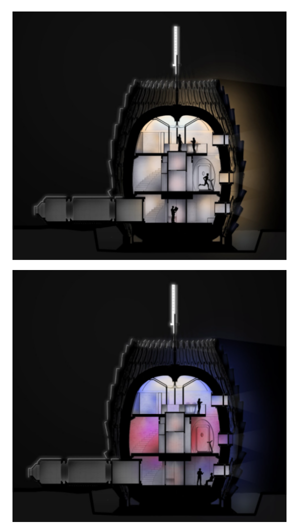


Figure 37. Left: Section of the Lunar Lantern design. Figure 38. Right: Day versus night interior lighting within the Lunar Lantern.

Circulation within the habitat occurs through a ladder, an elevator, and closed corridors within early iterations of the design to maximize efficiency of interior space. Three voids or openings to below were implemented within floor levels of the habitat to provide open views that may enhance user satisfaction and psychological comfort. The most considerable opening is the open staircase that starts from the ground floor and rises to the top floor. It enables the crew to gradually see the entirety of the habitat, lowering the risk of claustrophobia. The other two voids are green spaces between the middle and upper floors. The continuous green wall beside the windows with the earth's view and the hanging garden are designed to provide access to biophilia and ease the crew's communication between the floors. The habitat's interior lighting and design program is based on the Social Zeitgeber Theory; any external or environmental cue synchronizes the crew's biological rhythms to the Earth's 24-hour light/dark cycle and 12-month cycle.[34] The separation of private and public spaces not only enables social interactions with crewmates but is also anticipated to improve work/life balance, ensure crew performance in mission task activities, ensure stable eating and drinking patterns, and promote regular exercises. Meanwhile, the AI-controlled artificial lighting system, controlled atmospheric conditions and temperature helps manage and maintain the crews circadian rhythms.

VIII. Conclusion

Project Olympus introduces design schematics for critical surface infrastructure necessary to realize a permanent Moon base, and envisions the construction of durable, self-maintaining, and resilient surface structures enabled by advanced 3D-printing technologies. Olympus is ICON's autonomous, large-scale construction system capable of delivering a high variety of surface infrastructure elements. ICON's hardware and technology development goals are to develop, deliver, and demonstrate on-demand capabilities for critical surface infrastructure on the lunar surface—including landing pads, habitats, shelters, roadways, berms and blast shields using lunar regolith. As a part of the MMPACT program, NASA is evaluating multiple additive construction technologies, materials, and construction element forms. ICON engaged SEArch+ to develop schematic concepts for both landing pads as well as a foundational habitat as a means of informing and determining key engineering requirements and construction capabilities for the Olympus system. ICON tasked SEArch+ with conceiving of schematic infrastructure elements critical for a 3D-printed lunar base, including concepts for surface-site deployment and construction sequencing development. The schematics developed for the project represent an initial component to ICON's multi-year Project Olympus, which will deploy additive manufacturing construction technologies on the lunar surface.

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References

1. M.R. Fiske, J.E. Edmunson, J.C. Fikes, "The Disruptive Technology That is Additive Construction: System Development Lessons Learned for Terrestrial and Planetary Applications" AIAA SPACE and Astronautics Forum and Exposition, September 2018.
2. R.P. Mueller, S. Howe, D. Kochmann, et al., "Automated Additive Construction (AAC) for Earth and Space Using In-situ Resources." ASCE Aerospace Division International Conference on Engineering, Science, Construction, and Operations in Challenging Environments (Earth & Space 2016), American Society of Civil Engineers, Reston, Virginia, 2016.
3. S. Howe, B. Sherwood, "Out of This World: The New Field of Space Architecture," Vernacular of Space Architecture, Vol. 1, AIAA, Reston, Virginia, 1st ed., 2009, pp. 7–21.
4. Schowalter, David T.; Malone, Thomas B. (1972 February). The Development of a Lunar Habitability System (NASA CR-1676). Washington, DC, USA: National Aeronautics and Space Administration.
5. Chapter 4: Lunar Architecture. Lunar Architecture, 75–216. NASA, 2006 <https://www.nasa.gov/pdf/140635main_ESAS_04.pdf>
6. J. Flahaut, J. Carpenter, J.-P. Williams, M. Anand, I.A. Crawford, W. van Westrenen, E. Füri, L. Xiao, S. Zhao, Regions of interest (ROI) for future exploration missions to the lunar South Pole, Planetary and Space Science, Volume 180, 2020, 104750, ISSN 0032-0633, https://doi.org/10.1016/j.pss.2019.104750.
7. Sherwood, B. (2019 July). Principles for a Practical Moon Base (IAC-18-A3.1.6). 69th International Astronautical Congress (IAC), Bremen, Germany, 1-5 October 2018. In, Acta Astronautica (vol. 160, p. 116–124). Amsterdam, The Netherlands: Elsevier.
8. Koelle, H. H. (1996 January 1). Lunar Base Facilities Development & Operation. Berlin, Germany: Institut für Luft- und Raumfahrt, Technische Universität Berlin.
9. Bodkin, David K.; Escalera, Paul; Bocam, Kenneth J. (2006 September). A Human Lunar Surface Base and Infrastructure Solution (AIAA 2006-7336). 2nd International Space Architecture Symposium (SAS 2006), AIAA Space 2006 Conference & Exposition, San Jose, California, USA, 19-21 September 2006. Reston, Virginia, USA: American Institute of Aeronautics and Astronautics.

10. Petrov, Georgi I.; Inocente, Daniel; Haney, Max; Katz, Neil; Koop, Colin; Makaya, Advenit; Arnhof, Marlies; Lakk, Hanna; Cowley, Aidan; Haignere, Claudie; Messina, Piero; Sumini, Valentina; Hoffman, Jeffrey A. (2019 July). Moon Village Reference Masterplan and Habitat Design (ICES-2019-280). 49th International Conference on Environmental Systems (ICES), Boston, Massachusetts, USA, 7-11 July 2019. Lubbock Texas, USA: Texas Tech University.
11. Imhof, Barbara; Urbina, Diego; Weiss, Peter; Sperl, Matthias; Hoheneder, Waltraut; Waclavicek, René; Madakashira, Hemanth Kumar; Salini, Joseph; Govindaraj, Shashank; Gancet, Jeremi; Peer, Makthoum; Gobert, Thibaud; Fateri, Miranda; Meurisse, Alexandre; Lopez, Olfa; Preisinger, Clemens (2017 October). Advancing Solar Sintering for Building a Base on the Moon (IAC-17-C2.9.13). 68th International Astronautical Congress (IAC), Adelaide, Australia, 25-29 September 2017. Paris, France: International Astronautical Federation.
12. Howe, A. Scott; Wilcox, Brian H.; McQuin, Christopher; Mittman, David; Townsend, Julie; Pólit-Casillas, Raúl; Litwin, Todd (2014 October). Modular Additive Construction Using Native Materials. In L. S. Gertsch, R. B. Malla (Eds.), Earth and Space 2014: Engineering for Extreme Environments (p. 301-312). 14th Biennial ASCE Conference on Engineering, Science, Construction, and Operations in Challenging Environments, St. Louis, Missouri, USA, 27-29 October 2014. Reston, Virginia, USA: American Society of Civil Engineers.
13. Austin, A., Sherwood, B., Elliott, J., Colaprete, A., Zacny, K., Metzger, P., Sims, M., Schmitt, H., Magnus, S., Fong, T., Smith, M., Casillas, R. P., Scott Howe, A., Voecks, G., Parness, A., Vaquero, M., & Vendiola, V. (2019). Robotic lunar surface operations 2. Proceedings of the International Astronautical Congress, IAC, 2019-(October), 21–25.
14. Susante, Paul J., and Metzger, Philip T. "Design Test, and Simulation of Lunar and Mars Landing Pad Soil Stabilization Built with In Situ Rock Utilization." Earth and Space 2016, Orlando, FL, April 11-15, 2016.
15. Lane, John E., Metzger, Philip T., Immer, Christopher D., and Li, Xiaoyi. "Lagrangian Trajectory Modeling of Lunar Dust Particles," Earth & Space 2008, Long Beach, CA, Mar. 3, 2008.
16. Tomohiro Harada, Rie Usami, Keiki Takadama. "Computational Time Reduction of Evolutionary Spacecraft Location Estimation toward Smart Lander for Investigating Moon" 11th International Symposium on Artificial Intelligence, Robotics and Automation in Space (i-SAIRAS) Turin, 2012
17. Anzalone, Evan, Iyer Anand, Statham Tamara. "Use of Navigation Beacons to Support Lunar Vehicle Operations" IEEE Aerospace Conference, Mar. 7, 2020
18. Mueller, Robert P., Fikes, John C., Case, Michael P., Khoshnevis, B., Fiske, Michael R., Edmunson, Jennifer E., Kelso, R., Romo, R., Anderson, C. "Additive Construction with Mobile Emplacement (ACME)." 68th International Astronautical Congress (IAC), Adelaide, Australia, 25-29 September 2017.
19. Benaroya, Haym (2002 October). An Overview of Lunar Base Structures: Past and Future (AIAA 2002-6113). 1st Space Architecture Symposium (SAS 2002), Houston, Texas, USA, 10-11 October 2002. Reston, Virginia, USA: American Institute of Aeronautics and Astronautics.
20. Haym Benaroya, "Lunar habitats: A brief overview of issues and concepts." REACH - Reviews in Human Space Exploration 7–8 (2017) 14–33
21. Pólit-Casillas, Raúl (2012 July). Self-Deployable Lunar Habitat, Part-1: Overall Architectural Design and Deployment (AIAA 2012-3556). 42nd International Conference on Environmental Systems (ICES), San Diego, California, USA, 15-19 July 2012. Reston, Virginia, USA: American Institute of Aeronautics and Astronautics.
22. Kaplicky, Jan; Nixon, David A.; Wernick, Jane (1992). Vertical Regolith Shield Wall Construction for Lunar Base Applications. In W. W. Mendell (Ed.), The Second Conference on Lunar Bases and Space Activities of the 21st Century (NASA CP-3166, Vol. 1, p. 275-279). Houston, Texas, USA, 5-7 April 1988. Houston, Texas, USA: Lunar and Planetary Institute.
23. Valle, G., Litteken, D., & Jones, T. C. (2019). Review of habitable softgoods inflatable design, analysis, testing, and potential space applications. AIAA Scitech 2019 Forum, January 2019. https://doi.org/10.2514/6.2019-1018
24. Maghareh, Amin & Lenjani, Ali & Dyke, Shirley & Marais, Karen & Whitaker, Dawn & Bobet, Antonio & Ramírez, Julio & Modiriasari, Anahita & Theinat, Audai. (2019). Resilience-oriented Design of Extraterrestrial Habitat Systems. 10.2514/6.2019-3972.
25. Dyke, Shirley & Bobet, Antonio & Ramírez, Julio & Melosh, Jay & Gomez, Daniel & Maghareh, Amin & Modiriasari, Anahita & Theinat, Audai. (2018). Resilient ExtraTerrestrial Habitat Engineering. 49th Lunar and Planetary Science Conference, 2018
26. Mottaghi, Sohrob & Benaroya, Haym. (2014). Design of a Lunar Surface Structure. I: Design Configuration and Thermal Analysis. Journal of Aerospace Engineering. 28. 04014052. 10.1061/(ASCE)AS.1943-5525.0000382.
27. Yosio Nakamura, Gary V Latham, H. James Dorman, Abou-Bakr K. Ibrahim , Junji Koyama and Peter Horvath (1979) Shallow Moonquakes : Depth, Distribution and Implications as to the present state of the Lunar Interior. Proc. Lunar Planet. Sci. Conf. 10th (1979) p 2299 - 2309
28. NASA TM-2009-214785, Handbook for Designing MMOD Protection
29. Rumpf, C. M., Bjorkman, O., & Mathias, D. (2020). Risk and Performance Assessment of Generic Mission Architectures: Showcasing the Artemis Mission. IEEE Aerospace Conference Proceedings. https://doi.org/10.1109/AERO47225.2020.9172593
30. NASA. (2020). NASA's Lunar Exploration Program Overview (Issue September). https://www.nasa.gov/sites/default/files/atoms/files/artemis_plan-20200921.pdf

31. Eagle Engineering Inc. (1987 December). Lunar Base Systems Study (LBSS): Lunar Surface Operations Study (NASA CR-172050). Washington, DC, USA: National Aeronautics and Space Administration.
32. Kennedy, K. J., & Toups, L. (2008). Constellation Architecture Team-Lunar Habitation Concepts. AIAA SPACE 2008 Conference & Exposition, September. https://doi.org/10.2514/6.2008-7633
33. Rudisill, Marianne; Howard, Robert; Griffin, Brand Norman; Green, Jennifer; Toups, Larry; Kennedy, Kriss J. (2008 March). Lunar Architecture Team: Phase 2 Habitat Volume Estimation: 'Caution When Using Analogs.' In W. K. Binienda (Ed.), Earth & Space 2008: Engineering, Science, Construction, and Operations in Challenging Environments (p. 1-11). 11th Biennial ASCE Aerospace Division International Conference on Engineering, Science, Construction, and Operations in Challenging Environments, Long Beach, California, USA, 3-5 March 2008. Reston, Virginia, USA: American Society of Civil Engineers.
34. Mark Ott, C., Crabbé, A., Wilson, J. W., Barrila, J., Castro-Wallace, S. L., & Nickerson, C. A. (2020). Stress Challenges and Immunity in Space. In A. Choukèr (Ed.), Stress Challenges and Immunity in Space: From Mechanisms to Monitoring and Preventive Strategies. Springer International Publishing. https://doi.org/10.1007/978-3-030-16996-1