Design Analysis for Lunar Safe Haven Concepts

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NASA's plan to return humans to the lunar surface faces many challenges, especially in the sustained phases of the Artemis program. In combination with a habitat, a Lunar Safe Haven (LSH) would provide additional protection to crew, electronics, and equipment from the hazards of the space environment such as radiation, thermal extremes, micrometeoroids, and lunar dust. Influenced by the NASA Artemis program goals, the Lunar Safe Haven Study defined the high-level requirements, outlined the trade space for a LSH concept, and evaluated a set of concepts using a decision analysis structure. This paper will provide additional detail for two concepts that were designed and evaluated during the LSH study, the logic behind the choices, and some of the main driving design parameters.

I. Nomenclature

ABC	=	Artemis Base Camp
ALARA	=	As Low As Reasonably Achievable
BFO	=	Blood Forming Organs
Fe	=	Iron
GCR	=	Galactic Cosmic Ray
HEOMD	=	Human Exploration and Operations Mission Directorate
ISRU	=	In-Situ Resource Utilization
LANCE	=	Lunar Attachment Node for Excavation
LEO	=	Low Earth Orbit
LIDAR	=	Light Detection and Ranging
LSH	=	Lunar Safe Haven
LSMS	=	Lightweight Surface Manipulation System
LTV	=	Lunar Terrain Vehicle
MM	=	Micrometeoroid
MMPACT	=	Moon to Mars Planetary Autonomous Construction Technologies

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OLTARIS	=	On-Line Tool for the Assessment of Radiation in Space
RASSOR	=	Regolith Advanced Surface Systems Operations Robot
REID	=	Risk of Exposure Induced Death
SPE	=	Solar Particle Event
STMD	=	Space Technology Mission Directorate
TRL	=	Technology Readiness Level
UV	=	Ultraviolet

II. Introduction

NASA's Artemis program plans to land humans on the surface of the Moon with the intent of conducting long duration exploration missions. Extended presence on the Moon will require engineering and technology developments to allow safe operation on the lunar surface. It is anticipated that long term work on the Moon will provide the opportunities to understand how to support life and work in a hostile environment away from Earth. Lunar surface systems can serve as prototypes for systems that can be used for human missions to Mars [1-2].

Astronaut safety is of paramount importance for sustained planetary presence. Among the environmental hazards of concern are radiation and micrometeoroid impacts; both crew and surface systems must be protected from these hazards as they operate on the lunar surface. Due to mass and volume restrictions, current habitat designs cannot provide enough protection from the space environment to support long-term, sustained presence on the moon. The Lunar Safe Haven (LSH) Seedling Study was a one-year effort aimed at evaluating conceptual designs that can provide additional radiation, thermal, and impact protection to crew and lunar surface systems beyond what is provided by habitation modules; one concept is depicted in Fig. 1. The study team included expertise in areas including site preparation, excavation, construction, in-situ resource utilization (ISRU), in-space assembly, advanced materials and structures, autonomy, robotic servicing, space technology development, and human exploration mission planning and analysis. This paper will present some of the key designs conceived to satisfy Level Zero Requirements developed for the Lunar Safe Haven based on the Artemis Plan. A more thorough overview of the LSH study, with detailed information on requirements and additional concepts, can be found in [3].

Fig. 1 Artist's rendition of LSH - cutaway view of Concept 1.1A

III. Driving Design Decisions

Many different ideas for the LSH concept were generated during a series of brainstorming sessions. Focusing on physical architecture, emplacement methods, and operational phase logistics, a morphological matrix of possibilities was developed [3][4]. Some ideas were culled based on the likelihood of the technology being ready for deployment by the late 2020s as defined in the Artemis program (reasonably high Technology Readiness Level (TRL) required). From the many ideas remaining, the team outlined several alternative concepts for further analysis.

There are many interdependencies between different characteristics of a shelter, not all of which can be implemented concurrently in a single design. This constraint was considered in the development of concept alternatives. Some characteristics can be considered primary drivers – a change in one of these characteristics will drastically affect other characteristics. Others can be changed without affecting the underlying architecture. Here we will discuss several of the primary design drivers, and their effect on downstream choices.

A. Radiation Protection

Radiation protection is a huge driving factor for exploration beyond Low Earth Orbit (LEO), and NASA follows the ALARA (As Low As Reasonably Achievable) principle for radiation exposure. Additionally, the Lunar Safe Haven Level Zero Requirements state:

> LSH **shall** shield crew, electronics (such as computers providing command and control of autonomous systems), and other exploration and habitation systems that require radiation shielding as defined by HEOMD for at least 10 years without exceeding the proxy dose limits for crew and electronics [3].

Career limits are currently based on enhanced risk of death from cancer due to radiation exposure, and acute limits are levied on a 30-day rolling basis to specific organs [5]. Thus, guidance on acceptable doses was needed early in the project to aid design.

There are two major natural sources of radiation – galactic cosmic rays (GCR) and solar particle events (SPE). The GCR spectrum is very difficult to shield from, with particles ranging from low to extremely high energies. Much of the dose attributed to GCRs comes from the relatively rare heavy ions, such as iron (Fe). GCRs can also interact with structural materials, producing secondary showers of neutrons, gammas, and ions. In fact, neutrons are expected to contribute a large percentage to the total dose on the lunar surface simply due to GCR interactions in the regolith [6]. SPEs are comparatively low energy but very high flux streams of primarily protons. Exposure to a SPE without sufficient protection can cause acute radiation sickness or death, besides contributing to crew career dose limits. Thus, the LSH should be able to reduce background dose from GCRs in the long term, but also ensure protection from SPEs which occur on an unpredictable time scale.

For radiation protection, not all materials are created equal; a material that is good at shielding from one source may be problematic for shielding from another. It is well understood that materials with high electron density are better at shielding from GCR particle radiation, so materials with high hydrogen content are preferred [7]. Materials with high atomic weight (such as metals like iron or lead) can be effective at blocking gamma and x-rays, but cause showers of secondary radiation in the GCR environment. This can counterintuitively lead to higher doses behind shielding, if shielding thickness is not optimized via careful calculations of depth-dose curves. In the context of LSH, this means that caution must be exercised when considering making structural supports out of traditional building materials like steel.

As a first approximation of dose inside the LSH concepts, results from the literature [8-11] were compiled with results from our calculations using OLTARIS (On-Line Tool for the Assessment of Radiation in Space) [12]. OLTARIS provides appropriate design reference environments for both GCRs and SPEs, can account for the neutron albedo of the lunar surface, and can output results in several formats (dose, dose equivalent, risk of exposure induced death (REID), etc). For the most accurate calculations, a ray-traced CAD model must be provided to the software; for simpler calculations, layered slabs with material properties (chemical makeup and density) suffice. Table 1 provides guidance on the radiation protection provided by different slab thicknesses of regolith; this material was an obvious choice for our baseline construction material, since maximizing in-situ resource use is another LSH goal. Notably, three meters of regolith results in an approximate annual dose of 50 mSv, which is the Occupational Dose Limit for Radiation Workers [13]. Seven meters of regolith give an annual dose approximately equivalent to Earth background levels, ~5 mSv. Thus, most concepts were designed to the standard of 3-7 meters of regolith overburden.

Areal Density [g/cm^2]	Thickness [m]	Effective Dose [mSv/day]	Notes
0	0	0.51	Can range from 0.3 - 0.7 depending on solar cycle
20	0.12	0.46	Meets typical SPE requirement
100	0.59	0.42	
200	1.2	0.34	
500	2.9	0.12	Roughly equivalent to radiation worker limit on Earth (50 mSv/year)
1000	5.9	0.08	
1200	7.0	0.015	About equal to Earth background
1500	8.8	negligible	

Table 1 Approximate dose to crew from GCRs behind different thicknesses of regolith. It should be noted that a full radiation transport analysis should be performed using the complete geometry and materials list to get accurate dose numbers for any particular concept, but these numbers were used as design guidelines.

NASA-STD-3001 [5] limits the 30-day dose to blood-forming organs (BFO) to 250 mGy-Eq to avoid acute radiation sickness [14].To estimate dose from SPEs, OLTARIS calculations were performed using the free space at 1AU sphere model with the sum of the October 1989 Tylka Band fits as a design reference environment and the FAX human phantom located at the center of the regolith sphere. Results are given in Table 2. Note that these free space calculations should be conservative, especially with thicker regolith; if run on the lunar surface, the moon itself would block about half of incoming radiation but contribute additional albedo neutrons.

Areal Density [g/cm^2]	Thickness [m]	Dose to Blood Forming Organs [mGy-Eq]
0.1		1339
20	0.125	166
80	0.5	43
160	1.0	22
480	3.0	2.8
1120	7.0	0.05

Table 2 Dose to blood-forming organs from the series of 1989 SPE events; calculated using a regolith sphere in free space at 1 AU with the FAX phantom in OLTARIS.

Clearly, regolith thicknesses that provide any significant level of GCR protection "automatically" include SPE protection. However, some designs may not provide equivalent shielding from all directions (for example, an ingress/egress tunnel may be open to space), and careful design is needed to ensure storm shelter areas are readily available to crew during SPEs if there are accessible areas with lower or no shielding.

Also of interest is lowering dose to systems. Materials and components can suffer from total ionizing dose effects, as well as non-ionizing ultraviolet (UV) properties changes. Composites and polymers can suffer from degradation in mechanical properties and color changes that affect optical or heat rejection properties, while metals are much more robust at lunar dose rates. For electronics, single-event effects, stochastic in nature, are of concern. While some systems can reside in the safe haven and benefit from the protection provided to the crew, for robotic construction assets that work primarily outside the confines of the shelter, radiation hardening and robust software development will still need to be incorporated in the design to avoid these problems. But in general, the crew is more susceptible to problems from radiation than are systems.

B. Impact Protection

The lunar environment presents natural and human-made impact hazards. Natural hazards comprise a background flux of primary micrometeoroids (MMs), secondary ejecta, and localized meteor showers. Human-made hazards include errant mobile assets (such as rovers) and plumes from landers. Engineering and site layout controls are likely to provide the best protection from human-made impact hazards. For example, the orientation of any openings in the LSH should be directed away from the line of sight to landing pads; plume ejecta can travel long distances in the near vacuum "atmosphere" of the lunar surface.

For the analysis of the natural environment, the Micrometeoroid Engineering Model 3 (MEM3) [15] was used to generate the primary flux at the lunar south pole for both high and low density populations, from all solid angles, binned by speed up to 85 km/s. MEM3 includes MMs ranging in mass from 10^{-6} g to 10 g; below this range is considered “dust”, and above this range, impactors are exceedingly rare. The total flux is 3.42 impacts/m^2/year, with 70% of that being contributed by the high density population.

The flux was analyzed for angular dependence, as shown in Fig. 2 and Fig. 3. Phi is the angle from the horizon (90 degrees = zenith); theta is the azimuth. The majority of the high-density impactors come in at low-phi angles along the ecliptic, with more than 96% of the flux occurring below 35 degrees. For the low-density impactors, the angular dependence is more even across all angles, with larger contributions from the Oort cloud and deep space. This suggests that berms may be an important part of the final design, providing protection not only from low angle MMs, but also from human-generated impactors. No significant theta dependence exists in the primary flux profile.

Speed distributions are given in Fig 3. For the high density population, faster impactors tend to come in at lower angles. The low density populations have more varied speed distributions, often with bimodal shapes.

phi	flux	% of total flux	
0	7.42E-01	34.5%	34.5%
5	4.93E-01	22.9%	57.4%
10	3.11E-01	14.5%	71.8%
15	1.99E-01	9.3%	81.1%
20	1.30E-01	6.0%	87.1%
25	8.75E-02	4.1%	91.2%
30	5.87E-02	2.7%	93.9%
35	4.17E-02	1.9%	95.9%
40	2.98E-02	1.4%	97.3%
45	2.09E-02	1.0%	98.2%
50	1.45E-02	0.7%	98.9%
55	9.71E-03	0.5%	99.3%
60	6.36E-03	0.3%	99.6%
65	3.73E-03	0.2%	99.8%
70	2.07E-03	0.1%	99.9%
75	1.14E-03	0.1%	100.0%
80	5.43E-04	0.0%	100.0%
85	1.56E-04	0.0%	100.0%

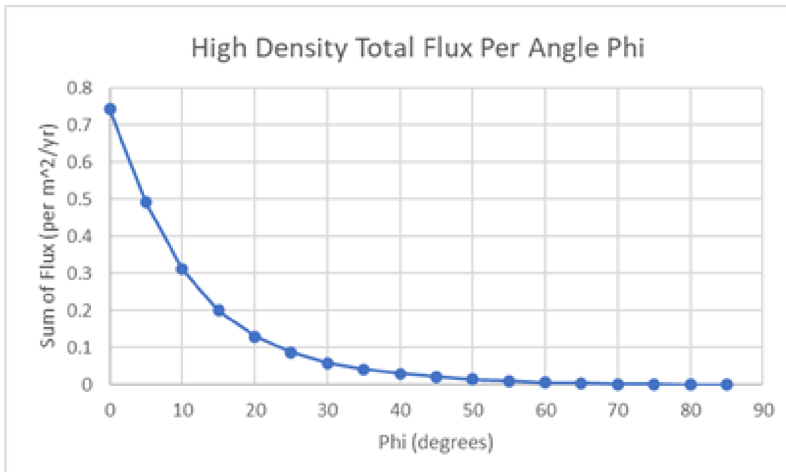

Fig. 2 Angular dependence of the primary high density MM flux at the lunar south pole

phi	flux	% of total flux	
0	1.52E-02	1.5%	1.5%
5	2.60E-02	2.5%	4.0%
10	6.08E-02	6.0%	10.0%
15	7.53E-02	7.4%	17.4%
20	7.80E-02	7.6%	25.0%
25	7.64E-02	7.5%	32.5%
30	7.51E-02	7.4%	39.9%
35	7.93E-02	7.8%	47.6%
40	8.12E-02	8.0%	55.6%
45	8.56E-02	8.4%	64.0%
50	8.58E-02	8.4%	72.4%
55	8.46E-02	8.3%	80.7%
60	7.19E-02	7.0%	87.7%
65	5.34E-02	5.2%	92.9%
70	3.55E-02	3.5%	96.4%
75	2.18E-02	2.1%	98.6%
80	1.14E-02	1.1%	99.7%
85	3.41E-03	0.3%	100.0%

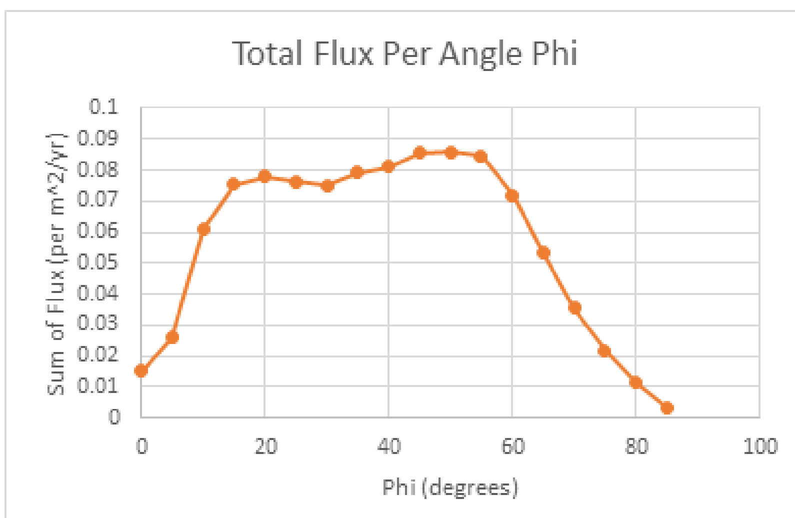

Fig. 3 Angular dependence of the primary low density MM flux at the lunar south pole

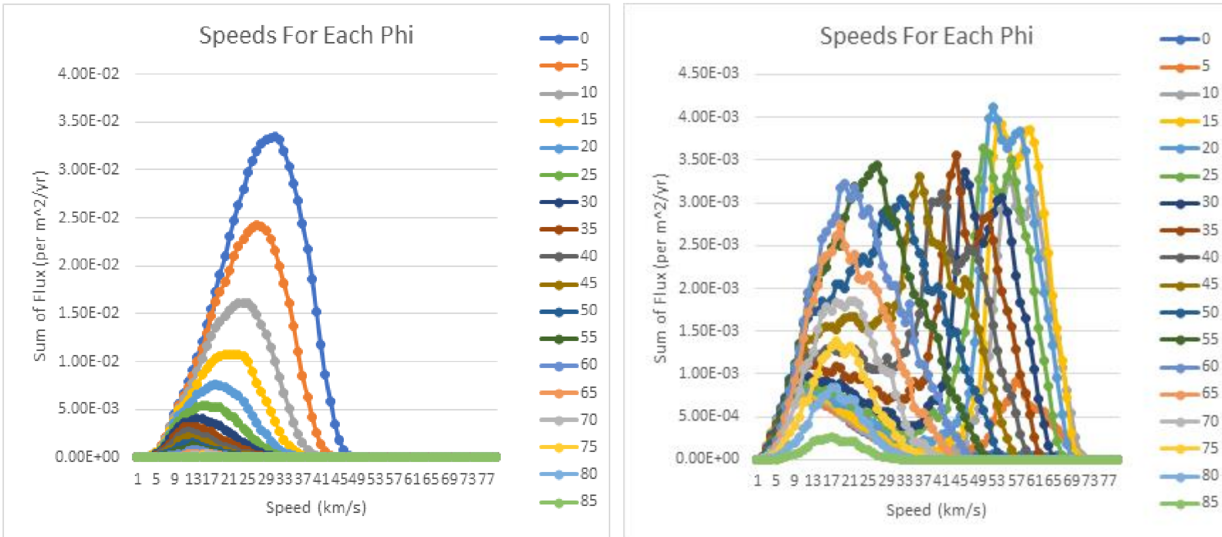

Fig. 4 Speed distributions for high density (left) and low density (right) MM populations

Impactors that hit the LSH will remove material, causing ejecta and cratering. To determine whether this mass loss would be significant, we calculated what size and speed an "average" meteoroid at each density and angle would look like. These data were plugged into the Impact and Explosion Calculator [16], which outputs crater depth, width, and volume. Typical cratering was on the order of 1 mm in depth in regolith at lunar gravity. For our baseline habitat designs with 3-7 meters of regolith cover, surface area is on the order of a few thousand meters squared. At the rate of ~3 impacts/m^2/yr, this cratering results in less than 1000 cm^3 of regolith loss over a 10-year lifetime. This is an insignificant loss, suggesting that no maintenance schedule will be required to replenish the regolith after initial construction.

Finally, we estimated the likelihood "worst case" scenario, in which an impactor causes significant structural damage to the LSH. The definition of catastrophic damage will be very dependent on the final architecture, including materials selection, thickness, and energy absorbing properties. However, as a first order conservative calculation for this seedling study, we define a significant impactor as one that causes cratering of 10% of the depth of the regolith cover. An impactor that would cause 0.3 to 0.7 m depth crater is outside the typical range of the MEM3 flux, so a rescaling of the Grun flux was necessary to determine frequencies and probabilities. Impactors are hundreds to thousands of grams in mass, on the order of tens of centimeters in diameter, and in all cases, occur extremely infrequently – roughly every few trillion years – at a given spot in the south pole region. Further work should be done to analyze the effects of meteor showers, which are very localized in time and space, but can include larger than average impactors.

Although maintenance needs due to impacts are expected to be low with the large regolith overburden required for radiation protection, the LSH would still benefit from a sensor system that can detect significant impacts when and if they do occur. Several ideas are on the table, varying widely in cost, effectiveness, and timeliness of delivering information about strike location and severity. For example, a sensor net that can detects changes in electrical or strain properties could provide real-time information on impacts but would be difficult and costly to implement on the scale of LSH. Crew or robotic visual inspection is straightforward, but not timely. Cameras filming the outside of the LSH may be a good trade, as long as they have the resolution to capture small, high-speed particles in sub-optimal illumination conditions.

C. Habitat Shape and Size

Since LSH is supposed to provide supplemental protection for a habitat, design details of the habitat should ideally inform the LSH concept. However, a single design has not yet been selected, and many possible archetypes are possible, as shown in Fig. 5. For early phases of the Artemis program, the smaller Vertical and Horizontal shapes are most likely to be adopted, and the Vertical Habitat with height between 8 and 12m was chosen as the reference architecture for this study.

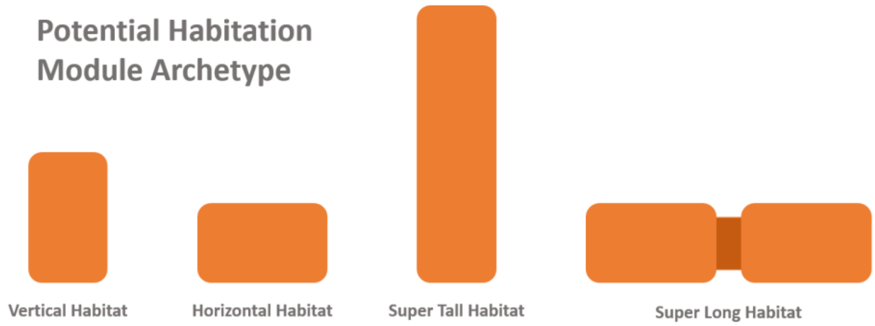

Fig. 5 Habitation Module archetypes

Additionally, the proposed concepts were guided by Level Zero Requirements stating that the LSH should not impact deployment or functionality of the habitat. Effectively, this means that any proposed concept cannot rely on the habitation module for structural support and can ideally be emplaced at any point in the Artemis Base Camp lifecycle without disturbing other operations. Practically, logistical challenges dictate that some modifications to the habitat may be required if it is not initially designed to be surrounded by a large structure; for example, relocating solar panels or radiators.

D. Construction Technology & Equipment Availability

Tele-operated and autonomous robotic system will be key enablers for LSH construction, so the safe haven design will be constrained by access to this equipment on the lunar surface. Construction assets that will be available include a long reach heavy lifting manipulator such as the Lightweight Surface Manipulation System (LSMS) [17] and several rovers with grading, excavating, and bulldozing capabilities such as RASSOR (Regolith Advanced Surface Systems Operations Robot) [18], and LANCE (Lunar Attachment Node for Construction and Excavation, a bulldozer attachment to the Chariot system) [19]. Key construction operations include but are not limited to ground conditioning, excavation, foundation/structural component construction, and various types of regolith transportation/manipulations. We note that the trade study was limited to safe haven concepts that could be constructed above grade, which does not require digging massive pits or dealing with the complexities of lava tube or cave habitation.

IV. Designs

As part of the trade study, the LSH team broke into sub-teams to analyze several different alternative concepts. Two of those concepts are presented below. For more detail on other analyzed concepts, see reference [3]. This analysis was essential to better understand concept feasibility based on technologies available for construction, radiation shielding efficacy, overall functionality, and construction feasibility.

E. Concept 1.1A – Regolith Covered Parabolic Arch

Concept 1.1A utilizes a rigidized arch or dome in compression as a primary inner support structure, with bulk regolith overburden to provide protection, as shown in Fig. 1 and Fig. 6. A parabolic shape was selected because it is ideal to convert all the load into compression load and minimize the structural material needed to hold up the several meters of regolith on top in reduced gravity [20]. The dome would be constructed primarily from material delivered from Earth, which allows for more control over processing and forming. Both metallics and composites are potential candidates for the inner structure, but more analysis is needed to properly scope the strength to weight trades for various materials and evaluate the upmass required for this concept. Due to its compression friendly geometry, it will eventually be possible to build using materials with virtually zero tensile capacity such as regolith-based blocks, taking full advantage of ISRU technologies such as 3D printing with regolith and binder or sintering regolith. These technologies are currently at lower TRL [21], but when available will greatly reduce the need for shipping excessive amounts of materials for the internal structure construction. This concept could also be expanded linearly into a parabolic vault configuration to house a longer habitat, more habitats under the same roof, or additional equipment as shown in Fig. 7.

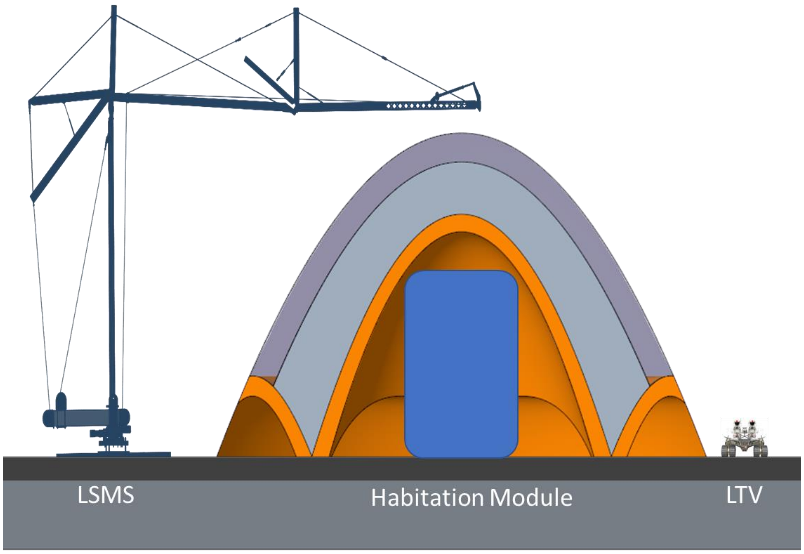

Fig. 6 Notional illustration of Concept 1.1A. Orange areas are structural material brought from Earth; grey areas are loose or compacted regolith infill; notional habitat shown in blue.

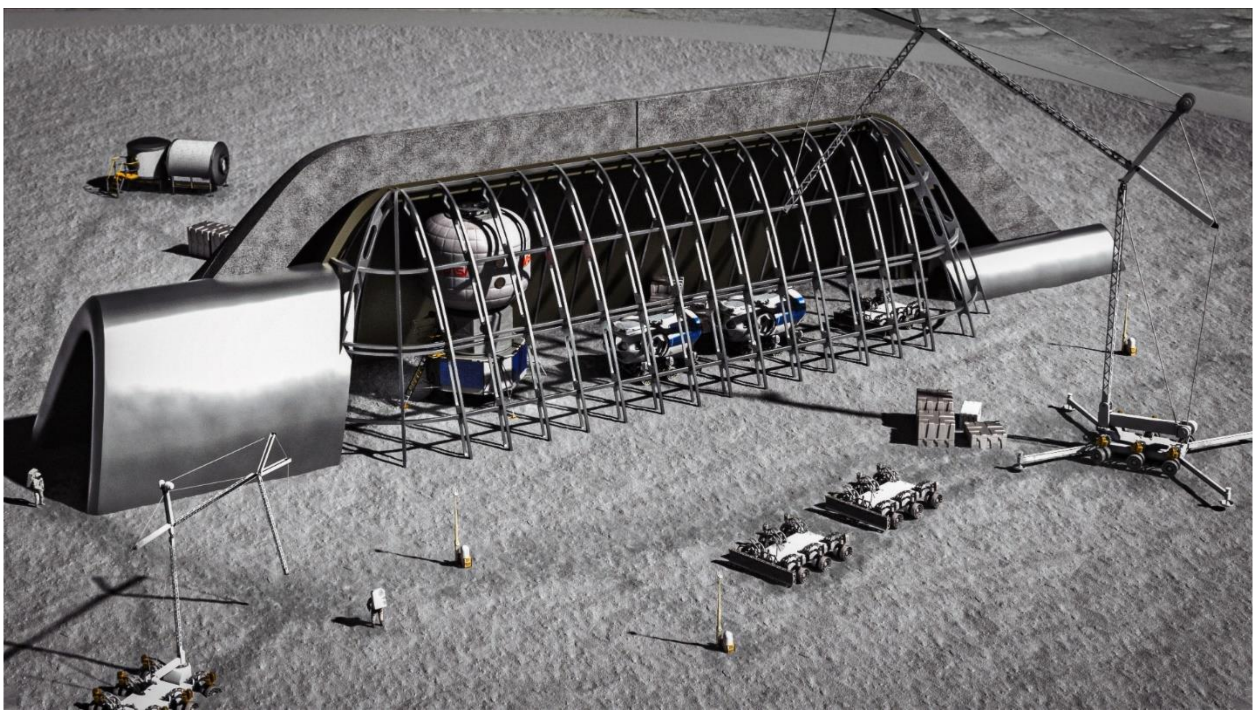

Fig. 7 Artist's rendering of Concept 1.1A. in a vault configuration; cutaway view. Structure shown is notional.

Two tunnels with a parabolic sectional profile provide access for crew and machinery. This design gives equal protection from all directions, with a reduction at both ingress and egress which can be mitigated by considering curved paths and view factors to the sky, as shown in Fig. 8. Alternatively, large detached berms could be built as additional view factor shielding for entrances. Ideally, the ingress tunnel will be large enough for the Lunar Terrain

Vehicle (LTV) or Pressurized Rover to drive inside, providing MM protection in nominal operations, and SPE protection for crew when required.

Fig. 8 Plan concepts for ingress and egress paths for Concept 1.1A

The outer regolith protective layer serves to protect from both micrometeoroids and radiation. Loose regolith can be compacted to higher densities or stabilized with additional material such as geo-mats (erosion control netting made from high-density polyethylene). This could decrease the overall footprint, permitting the building of more vertical walls than could be achieved if the regolith were allowed to assume its natural angle of repose. The dimensions of this concept are generated based on the size needed to house the habitation module and access space needed for crews and machinery to move around and work on the habitat, as shown Fig. 9. The habitat is assumed to be 12 m tall, with some room at the top for clearance, bringing the total inner height is ~15 m, which is equivalent to a 5 story building. A 4 m clear zone around the entire habitat provides enough room for two astronauts in EVA suits to be able to walk next to each and perform maintenance tasks. The habitation module itself is assumed to have a diameter of 7 m, leading to a minimum base footprint diameter of ~15 m (although it may indeed be larger to keep the dome's parabolic profile). Optimally, there would be additional sheltered space for storage, electronics, and other hardware. We note that a non-trivial amount of regolith is required to bring this concept to fruition – approximately three football fields dug to a depth of 0.5 m must be excavated and emplaced on top of the structure to reach the goal of 7 m of regolith overburden (another ~2 stories of height). Building large open span structures without interior support columns is challenging even on Earth, with access to traditional building methods, and we should not underestimate the difficulty of building a similar structure on the lunar surface. Availability of construction assets such as LSMS will be imperative.

We assume the habitation module is already in place when construction of the LSH begins, which carries some inherent risk. This is especially true of this concept, which requires building overhead of the habitat. Temporary scaffolding or netting to contain construction debris must be considered when calculating upmass requirements, and provisions must be made for emergency shelter in the event that any habitation systems are damaged. Additionally, although the overhead environment provides fantastic protection from impacts and radiation, it necessitates changes to some of the habitat module systems. Current baseline habitat designs have radiators and solar panels protruding from the top; these would need to be physically moved outside the LSH, introducing additional challenges.

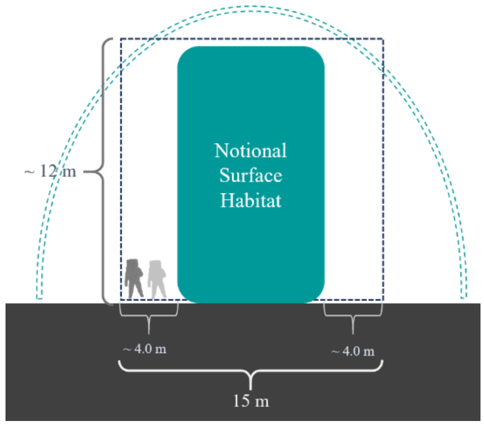

Fig. 9 Notional, estimated dimensions for a tall, cylindrical surface habitat to be protected by an LSH

F. Concept 1.1B – Round Cake with Polyethylene Bean Topping

Concept 1.1B eschews the concept of a regolith dome in favor of a structural cylinder. The inner support structure will be constructed of a cylinder-shaped frame surrounding the habitat, all of which is surrounded by a regolith infill, as shown in Fig. 10. Similar to the first concept, two tunnels are used for crew and machinery access at ground level. Unlike the first concept, there is minimal roofing material overhead. This design reduces the level of protection but lowers construction risk and may be more achievable with available resources.

On top of the cylinder will be a high-strength net or tank used to support multiple bean bags filled with polyethylene or polypropylene pellets/products. If an initial protective layer is deemed necessary, it would need to be upmassed. But eventually, as Artemis moves into the sustained phase, increasing amounts of trash will be generated on a more regular basis. Food packaging and other consumables contain large quantities of polyethylene, aluminum, and other low-Z materials that can provide excellent radiation shielding from what would otherwise be waste mass [22]. Having a pre-built roof structure has several additional benefits, such as potentially easy direct access and connection between the top of the LSH shelter and the interior. This could be useful either for power or communication equipment that is already integrated into the habitat or for other Artemis Base Camp elements that require a tall base structure (<10m) for lineofsight purposes. The overall span of the roof would be around 14m in diameter; a long span structure will need to be in place to support the bean tank, but this is still a reasonable span.

The establishment of 1.1B has several logistical differences with respect to the arched structure of 1.1A. First, design 1.1A is riskier to construct if the habitat is already in place when LSH is being built, especially during the emplacement of the overhead inner structural layer. But since Concept 1.1B is basically a vertical cylinder, it has a natural geometrical advantage on its structural stability. This makes it simple to build, which may reduce the construction steps, shorten the construction time, and require less complicated machinery, all of which are advantageous for risk reduction for the overall project. One key advantage in terms of risk reduction is that this scheme does not involve using heavy equipment and less understood materials directly above the habitat for structural emplacement, given everything directly above the habitat can be well tested and verified here on Earth. This bean-bag concept allows for zenith-facing radiation protection to be added more flexibly around any protruding structures.

With respect to both radiation and impacts, view factor is a defining characteristic for determining risk. Given that the incident angle of most impact hazards is less than 40 degrees from the horizon, the cylinder would provide protection from the most dangerous impactors. However, GCRs and SPEs (when fully developed) are isotropic phenomena, and dose would still be delivered from above. The final design would need to ensure that storm shelter protection was adequate to avoid acute radiation sickness by accounting for all habitat materials between the crew member and deep space. But radiation protection would improve over time as waste material was added overhead, and it does not take too much material to block SPEs.

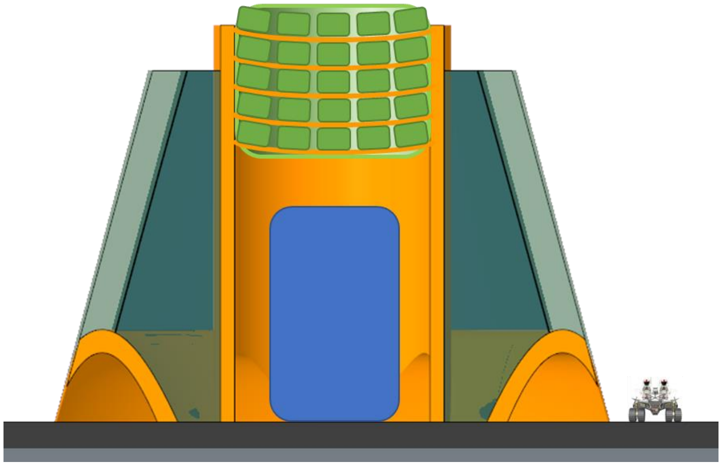

Fig. 10 Notional illustration of Concept 1.1B. Orange areas are rigid structure; teal is regolith infill; green blocks are polyethylene beanbags held up by tensioned membranes; notional habitat is blue.

G. Development Phases

Given the scale of the LSH shelter described above, it is important to break the initial development into phases to prove and advance certain technologies to effectively implement these concepts at full scale. In this case five different phases have been identified with associated critical technologies, as described in Table 3 and depicted in Fig. 11.

Phase	Name	Description and Use Case
Phase 0	Initial Ground Preparation	Leveled ground prepared for landing, as well as serving as the foundation for future construction.
Phase I	Small Scale Shelter Structure	Smaller scale shelter constructed with primarily Earth shipped materials providing some degree of immediate protection for equipment such as rovers, or other small equipment present in near term missions.
Phase II	Small Scale Shelter w/ Regolith Protection	Smaller scale shelter expanded from phase II with additional cover of regolith to further enhance its protection capability. This shelter could later be adopted for use as the ingress / egress tunnel for the habitation shelter and double as an emergency SPE storm shelter for rovers.
Phase III	Full Scale Shelter for Habitation Module	A full-scale shelter for a single habitation module with sufficient radiation protection, access, and dust mitigation measures for long-term stay.
Phase IV	Interconnected Shelters for the Moon Camp (The Lunar Safe Haven)	A long-term presence strategic solution which combines all critical technologies from previous phases providing sufficient protection and resources to support long duration surface lunar activities.

Table 3 Proposed phases of development for the Lunar Safe Haven

With near-term needs in mind, these phases provide a development strategy that matches well with the Artemis Program. By proving technologies while providing capabilities along the way, it would speed up the development process, allowing more rapid and fail-safe opportunities early on, making it more attractive for industry to invest in such technologies, and eliminating the need and the risk for super long development cycles associated with monolithic projects.

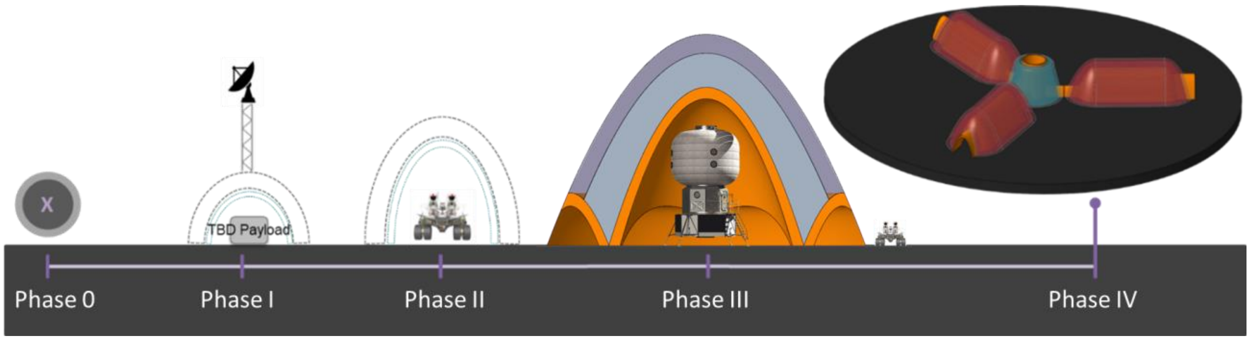

Fig. 11 Proposed phases of development for LSH, notionally illustrated

V. Conclusion

The Lunar Safe Haven Seedling study was conducted to understand the trade space around building supplemental protection for a lunar surface habitation module. To meet the Level Zero requirements, radiation analysis, impact protection, habitat size and shape, and construction asset availability must be carefully considered in the early phases, as they are some of the main drivers of the overall design. From the many concepts proposed during LSH brainstorming sessions, further analysis on two designs is presented in this paper. We conclude that although building the LSH still has many engineering challenges to overcome, building a protective safe haven is reasonably achievable within the "sustainable presence" timeframe laid out by NASA's Artemis program.

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