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CTEF: Communicating Tiered Evaluation Framework

For Quantitative Investigations of Lunar Surface Habitat Technologies

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Abstract

With a renewed global interest in lunar activities, the establishment of a lunar settlement represents a critical milestone in space exploration and resource utilization. The lunar environment presents unique engineering challenges such as reduced gravity, a lack of atmosphere, abrasive dust, seismic activity, meteoroid impacts, and extreme temperature variations. Additional constraints such as transportation, construction, and structural adequacy must also be considered. Lunar surface habitats can be categorized into three primary classifications: Class I (pre-integrated), Class II (deployable/prefabricated), and Class III (in situ resource utilization, or ISRU). This review examines past concepts for lunar surface habitat technologies and provides a framework for a quantitative evaluation.

This review introduces the Communicating Tiered Evaluation Framework (CTEF), a quantitative evaluation framework to assess concept feasibility and potential. The framework builds on previously established criteria, including: structural strength, pressure resistance, radiation shielding capability, experience, technology readiness level (TRL), research & development difficulty, construction, foundation, excavation, transportation, resources savings, dust mitigation, repairability, and habitability. By establishing a robust assessment framework, this paper aims to provide a consistent reference point for advancing sustainable lunar habitats and other extraterrestrial settlements. It is intended to support both space agencies and internal project teams in assessing mission feasibility and informing mission decision-making.

Initial findings suggest that initial lunar missions will likely rely on Class I and II structures, with a gradual transition toward Class III habitats as ISRU technologies mature. Class I concepts are based on well-established engineering principles and immediate deployability, making them suitable for initial missions. However, they remain limited by their dependence on Earth-based manufacturing and logistical support for long-term missions. Class II structures offer increased adaptability and habitable volume through prefabrication and deployable components, though they introduce additional on-site construction and durability challenges. Class III concepts see the greatest promise for long-term sustainability and operational autonomy with ISRU techniques. This includes 3D-printed regolith shielding and subsurface habitats within lava tubes. However, ISRU technologies remain underdeveloped and require further research to reach the necessary technology readiness levels.

This review highlights the evolution from Class I to Class III habitat concepts and emphasizes the importance of a consistent, structured evaluation framework to guide the development, comparison, and selection of habitat technologies for future mission objectives.

Keywords: Lunar Habitat, Pre-integrated, Prefabricated, ISRU, Framework, Threshold

Contents

1 Introduction

There has been a newfound interest in establishing a settlement on the Moon since the Artemis Accords were launched in 2020 by NASA. The Chinese National Space Administration (CNSA) and Russia's ROSCOSMOS also followed suit in 2021 by initiating their joint International Lunar Research Station (ILRS). Several commercial companies have also taken an interest in the Moon. However, settling on the Moon had been of interest well before the first Apollo astronauts landed there in 1969.

The Moon serves as a symbolic milestone for the explo-

Figure 1: First Quarter Moon [1]

Moon and Earth Properties

Property	Moon	Earth
Surface Area [km^2]	37.9 x 10^6	510.1 x 10^6
Gravity at Equator [m/s^2]	1.62	9.81
Surface Temperature [°C]	-173 to 127	-89 to 58
Surface atm pressure [kPa]	0	101.3
Day Length [Earth days]	29.5	1

Table 1: Comparison of Earth to Lunar Physical Parameters, adapted for engineering considerations [2]

ration of our Solar System and beyond. Maintaining a habitat on the Moon can provide more extensive space exploration by serving as a base for astronomical, geological, and scientific observations. It is an ideal test bed to develop new technologies that can benefit life back on Earth. Innovative projects can create jobs and inspire future generations of students to follow STEM fields. Based on its proximity to Earth and certain desirable materials, the Moon is the more logical and strategic option when compared to Mars.

This review of the literature will discuss the environmental and engineering challenges associated with building a habitat on the Moon. Various concepts from the last 60 years will be introduced and examined. Lastly, an attempt to develop a quantitative evaluation metric will be introduced to compare the advantages and disadvantages of different technologies that are presented. With an unprecedented amount of new concepts being developed today, its important to begin cataloging different technologies to assess their feasibility, which can also serve as a tool for future space habitat development.

2 Lunar Environment

To understand the difficulties of establishing a lunar habitat, we must acknowledge the environmental conditions that are present on the Moon. It is no secret that the physical lunar environment is significantly different than that of the Earth. Table 1 adapted from [2] shows a quantitative list of the physical differences, which highlights some of the design challenges for the moon.

For a habitat design, some of the lunar environment properties seen in Table 1 need to be broken down into design parameters. Previous literature has identified the following as key considerations of the lunar environment: gravity, lack of atmosphere, dust or regolith, meteoroids, long day duration, and seismicity. ([2], [3])

- The gravity on the Moon is $1.62 m/s^2$ or about $1/6th$ of that on the Earth. This introduces many changes in the dynamics. Instead of load-based criteria, mass-based lunar structural design codes should be implemented. The decrease in gravitational load allows for a longer spanning structure where pressure will govern the overall design. Depending on the structure used, it needs to be able to withstand the launch loads. The difference in gravity also has many effects on human physiology.
- There is no atmospheric pressure on the Moon, but the interior of the habitat needs to be pressurized to support human life. This differential between the inside and outside of the habitat means there will consistently be a higher pressure inside the habitat, causing a vacuum. This also creates an important problem to overcome of entering and exiting the habitat.
- Additionally, since there is no atmosphere, there are no layers of protection against radiation like on Earth. Solar winds, galactic cosmic rays, and solar flares all contribute to radiation exposure. Not only is this radiation harmful to humans, but it also degrades material over time and presents a risk to loss of structural integrity.
- Dust presents a unique and important issue. Lunar dust is unlike dust on Earth in that it is abrasive and sharp. This means it can prematurely damage components and presents a constant challenge for construction equipment, airlocks, and exposed surfaces. It is also toxic if breathed in and will stay suspended in the air longer due to the reduced gravity.
- Long day duration is not an issue to the structure by itself, however the change in extreme temperatures does. On the Moon, the temperature will range from -173 C to 127 C. This presents a challenge for structural and mechanical components, as thermal cycling can cause fatigue and long-term stress. There are also 100hr+ eclipse periods, which drive energy storage demands.

- Lastly, roughly 12,000 recorded ground motions on the moon during the Apollo missions. 4 seismometers were left on the lunar surface and detected deep, shallow, and thermal moonquakes, as well as meteoroid impacts. Although these moonquakes are much lower magnitude compared to Earth, they raise fatigue and dynamic loading concerns ([4]). Meteoroid impacts pose a very rare failure event, but are extremely dangerous if they hit the lunar habitat.

While considering the environmental conditions on the Moon is straightforward and self-explanatory, there are also several engineering requirements to consider. Structural adequacy, material, maintenance, functionality, compatibility, transportation, construction ease, excavation, foundation, and local materials are requirements that are familiar on Earth [2]. Due to the nature of a space mission and the lunar environment, we cannot take the same approach to planning and construction as we do on Earth.

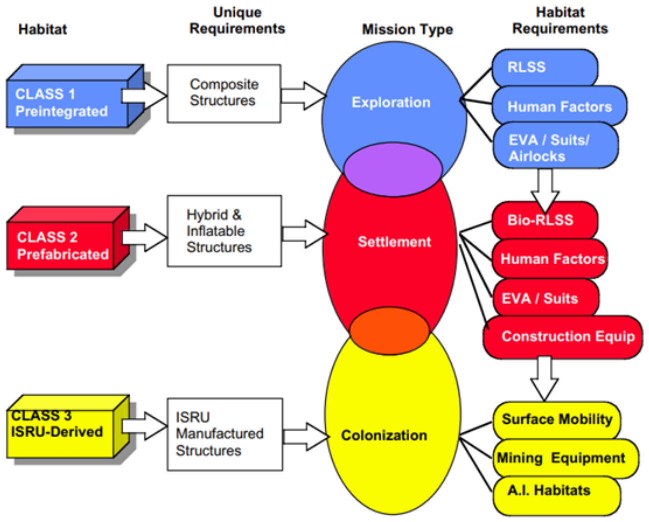

Figure 2: Surface Habitats and Construction Roadmap: Diagram of Three Classes of Lunar / Planetary Construction and their Application to progressive stages of Development [3]

3 Habitat Concepts

Habitat technologies are not limited to a single design or classification. Three main classifications were identified in NASA's Habitats and Surface Construction Technology and Development Roadmap in 1997 [3]. Figure 2 summarizes the three classes proposed by the Roadmap. Consider the Roadmap as a timeline; as technologies advance and we build a stronger presence on the Moon, the types of structures will evolve. Hence, these classifications can also be referred to as phases, and are defined as follows:

1. *Class I – Pre-integrated*
2. *Class II – Deployable or Prefabricated*
3. *Class III – In Situ Resource Utilization*

Most of the literature accepts this hierarchy and attempts to fit the developing narrative on habitat design into this roadmap.

3.1 Class I - Pre-ingegrated

Class I is a pre-integrated design classification, where a rigid structure is entirely built and integrated on Earth. Once on the lunar surface, it will stay in one place. Pre-integrated habitats require a composite of structures and will most likely be used for initial exploration missions. This structure can be pre-deployed and operated. Class I concepts have already been built and are well understood, though the only flight proven instance of these structures is the Apollo missions, where Apollo 17 spent just over 3 days on the Moon [5].

3.2 Class II – Deployable/Prefabricated

Class II structures are deployable or prefabricated structures that are assembled, deployed, erected, inflated, or reconfigured on the lunar surface. However, the original structure is still built on Earth. These prefabricated habitats are likely to include a hybrid for pre-integrated components and inflatable structures, which will be used for maintaining a more permanent settlement on the lunar surface. In a paper for the Journal of Aerospace Engineering, four main structural types are identified that the Class II habitats can be constructed with [6]:

- *Inflatables* are meant to provide a more efficient construction process while decreasing costs and weight simultaneously. These structures are very fragile because the high likelihood of puncture can result in a pressure loss event. While inflatables allow for increased volume, they will need to be combined with other structural systems to achieve functionality.

- *Cable Structures* refer to tension systems such as cables, reinforced fabrics, nets, and stiffened trusses using cables. The greatest advantage of such systems is being able to carry high intended axial tension loads across a habitat. Construction on Earth has significant experience with these types of structures, allowing for more straightforward repair and higher reliability.

- *Rigid Structures* are ideal for achieving a certain robustness and puncture resistance and can be used without the need for a secondary system. Much like a pre-integrated approach, these structures require a higher mass and transportation volume.

- *Underground Construction* refers to using existing lava tubes under the lunar surface to provide natural spaces for a habitat. For this report, underground construction is considered a Class III system (see Class III section).

3.3 Class III - In Situ Resource Utilization (ISRU)

Class III follows an In Situ Resource Utilization (ISRU) method. This means that the habitat incorporates in situ materials and is manufactured on the lunar surface using a variety of approaches. ISRU is most likely to be used if colonization on the Moon takes place. The goal is to decrease the required materials and achieve self-sufficiency from Earth.

Until recently, much of the technology focus was on developing Class II structures. With the rapid development of 3D printing and additive manufacturing technologies, many companies and researchers have looked ahead to using such methods for utilizing indigenous lunar materials. However, this technology is still not ready for use on its own to satisfy engineering requirements [7]. Rather, ISRU methods should be combined with other configurations to achieve desired specifications. Another perspective is that Class III structures incorporate aspects from the previous classes.

ISRU should not be limited to reworking materials but should include taking advantage of natural structures such as lava tubes or craters. Underground construction refers to the use of lava tubes that will naturally provide meteoroid and radiation protection and much of the thermal fatigue and other exposures can be moderated. Combining lava tubes with inflatables appears to be a promising beginning [6]. This approach borderlines Class II into Class III structures, as indigenous materials are incorporated into the design. Because of this, concepts utilizing underground methods or regolith are identified as Class III structures in this report.

4 Evaluation Framework

4.1 Existing Evaluation Metrics

Since each concept is very different and there has been no functioning habitat tested on the Moon (with the exception of the Apollo Lunar Lander), it is not easy to establish a quantitative comparison and evaluation. Many of the considerations are more qualitative than quantitative. Previous research has attempted to establish a quantitative approach to evaluating structures. Much of the existing literature, such as [8] and [9] focuses on the internal habitability and comfort of the space. These are important and relevant metrics, however they disregards most of the required technology achieve this. The concepts covered in this review will be subject to evaluation using an approach that combines the evaluation methods established by [6] and [7].

Ruess et al [6] gives quantitative evaluations to qualitative criteria for Class II structures: transportation, ease of construction, experience with structural systems, excavation, and foundations. They used a point system from 1 (worst) to 6 (best) and attempted to create an objective evaluation for selected concepts. They assume that each criterion is equally important for the habitat, but acknowledge that the weighting for each will change with advances in rockets, materials, and lunar science. [6] also notes that it is impossible to achieve a 100% objective quantitative evaluation.

Bodiford [7] uses a different criterion to evaluate ISRU concepts. Their criteria include systems integration, risk levels, current technology readiness level (TRL), degree of research and development (R+D) difficulty, required resources, modularity, and environment-specific criteria such as radiation shielding and pressure differential. For this study, they weighed factors from 1 (lowest priority) to 3 (highest priority). Safety and programmatic issues were given higher priority.

Further studies such as [8] focuses on the habitability of the structures and identified the following metrics: of elements, total volume & habitable volume, mass, and surface area. While these metrics are important for the long term health of the crew, not all are considered in this initial list of criterion as they are considered more design choices. There are also existing databases for all known lunar habitat concepts, for example [9]. However, this database only considers crew capacity, surface area, and volume.

4.2 CTEF: Communicating Tiered Evaluation Framework

In this updated approach, all criteria are evaluated on a scale from 1 to 6 (TRL is normalized to 6 to be consistent with other metrics). 1 represents the worst possible fulfillment of the category, and 6 is the best possible. Each criterion is assigned into 6 groups: Safety & Protection, Technology Maturity, Surface Construction Complexity, Logistical Efficiency, Maintainability Durability, and Habitability, shown in table 2. Criteria are weighed within the Group they are assigned to. The intention of the evaluation is to require a certain level of performance to be used as a feasible lunar habitat.

Initially, each group was also assigned a weight to prioritize crew safety, but this approach resulted in each concept achieving similar overall scores and it was impossible to discern any information. Instead, each group is given a minimum threshold that it is required to score. In this sense, each group acts as a vessel that needs to be filled to a certain level so the next group can be filled. This approach is inspired by the Principle of Communicating Vessels.

Figure 4 visualizes the approach in which a group should be evaluated. Each criterion is assigned to a single group and given a corresponding weight. The framework is intended to allow for additional criteria as they are identified in the future, and this approach enables concepts to be easily re-evaluated for new criteria. Whenever a new criterion is identified, the weights for that group should be recalculated.

Each criterion needs extensive design, analysis, and testing to assign an appropriate score for each criterion and should be peer-reviewed. For example, for *Structural Strength and Pressure Resistance*, the primary structural system should undergo full mock up testing until failure, to determine a safety factor and expected performance over time[1].
Once each criterion is evaluated and assigned individual scores, they are weighted to the group they fall under and the group score represents the sum of those weighted scores. This final group score is then compared to the minimum threshold. If the score does not exceed the threshold, the habitat cannot be further evaluated for the later groups. See Figure 3 to visualize this process.

This ensures a habitable cannot be feasible if the previous group does not meet its threshold. The minimum thresholds follow the same order of the groups. For example, Group 1 is Safety and Protection, and requires a minimum score of 5.5. If based on the individual Criteria scores for Safey and Protection, the overall Group score does not meet 5.5, the crew is automatically unfeasible and cannot be assessed for the next group of Technology Maturity. In order for a habitat to be deemed feasible for a long term lunar habitat, it should fulfill the threshold for all groups.

4.3 Groups and currently identified criterion

The following list organizes the 6 groups which the criteria are assigned to. Each criteria is described and scoring rubrics are provided. Individual metrics require indepth investigation in order to properly assign appropriate scores. This is not meant to be an exhaustive list, and is designed to be expanded; if new criteria are added, the entire group it is included in needs to be re-weighed. A full rubric with descriptions for each score are given in the appendix.

1. Safety & Protection - *Threshold: 5.5*
    - SP – Structural Strength and Pressure Resistance
      Capacity to maintain structural function under loads, stresses, and impacts
      Weight: 0.55
    - RSC – Radiation Shielding Capability
      Effectiveness in protecting crew against radiation
      Weight: 0.45
2. Technology Maturity - *Threshold: 5.0*
    - XP – Experience
      Extent of prior testing, heritage, or mission use
      Weight: 0.25
    - TRL – Technology Readiness Level
      Maturity of technology/system (normalized to 6)
      Weight: 0.50
    - RD – Research and Development Difficulty
      Level of research and innovation required to mature the concept
      Weight: 0.25
3. Surface Construction Complexity - *Threshold: 4.5*
    - CO – Construction
      Complexity and resource demand of assembly
      Weight: 0.50
    - FO – Foundation
      Need for and difficulty of anchoring or stabilizing foundations
      Weight: 0.25
    - EX – Excavation
      Effort, equipment, and energy required to excavate local materials
      Weight: 0.25
4. Logistical Efficiency - *Threshold: 4.0*
    - TR – Transportation
      Difficulty of transporting the system to the lunar surface in terms of mass, volume, and cost
      Weight: 0.45
    - RS - Resource Savings
      Reduction in Earth-supplied materials through ISRU
      Weight: 0.55
5. Maintenance & Durability - *Threshold: 3.5*
    - DM – Dust Mitigation
      Effectiveness in limiting contamination or wear from Lunar dust
      Weight: 0.55
    - RE - Repairability
      Ease of inspection, maintenance by crew or robots
      Weight: 0.45
6. Habitability - *Threshold: 3.0*
    - MO - Modularity
      Flexibility to be scaled, reconfigured, or integrated with other units
      Weight: 1.00

[1] The case study scores in this report are based on assumptions of the intended performance for each criteria and do not reflect accurate values

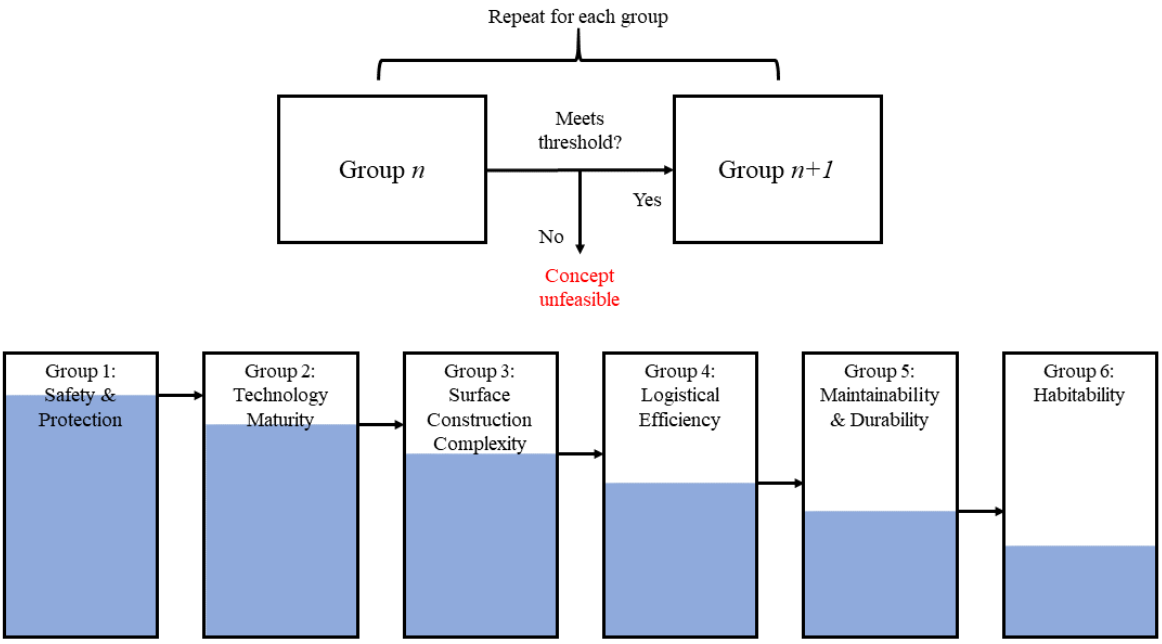

Figure 3: Communicating Vessels Flowchart

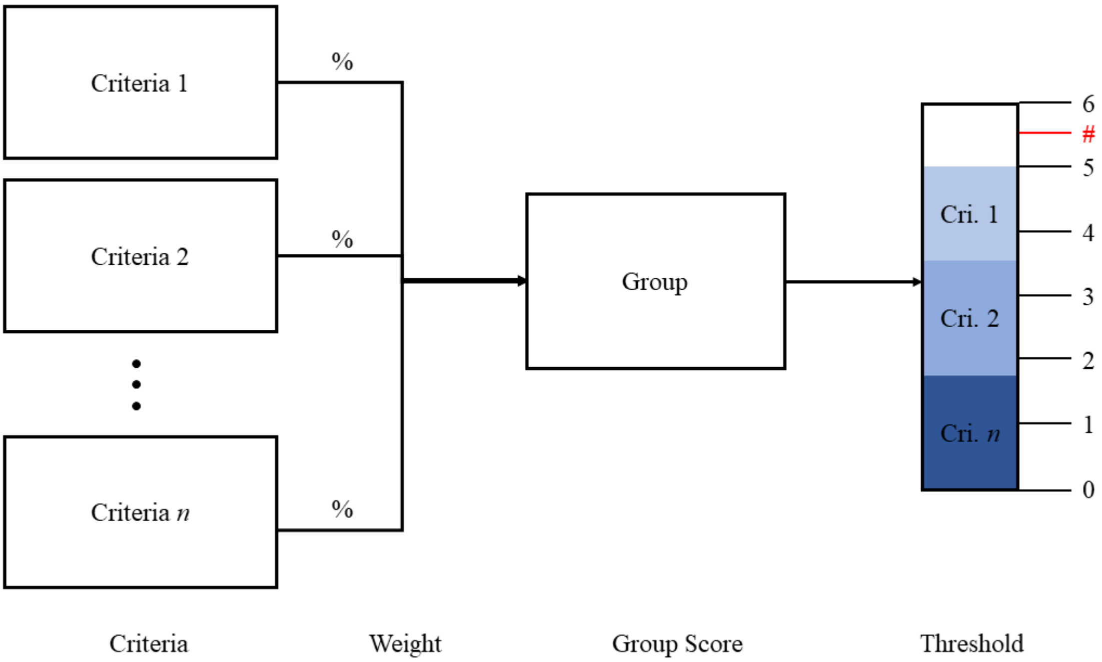

Figure 4: Evaluation Flowchart

Weighted Evaluation Criteria

Group	Criterion	Description	Weight	Weight Justification
1. Safety & Protection *Threshold: 5.5*	**SP** Structural Strength & Pressure Resistance	Capacity to maintain structural function under loads, stresses, and impacts	0.55	Life safety depends on structural integrity and pressurization.
	RSC Radiation Shielding Capability	Ability to protect crew from galactic cosmic rays and solar particle events.	0.45	Long-term crew survival depends on shielding from GCRs/SPEs.
2. Technology Maturity *Threshold: 5.0*	**XP** Experience	Degree of mission heritage and past use of similar systems.	0.25	Proven technologies reduce mission risk.
	TRL Technology Readiness Level	Normalized TRL (1–9 scaled to 1–6) representing technology maturity	0.50	Higher readiness reduces development risk. .
	RD Research and Development Difficulty	Difficulty and resources required to advance technology to deployment.	0.25	High R&D effort can delay deployment and increase cost.
3. Surface Construction Complexity *Threshold: 4.5*	**CO** Construction	Complexity of assembling or fabricating habitat on the surface.	0.50	Complexity affects mission duration, crew effort, and feasibility.
	FO Foundation	Need for and difficulty of anchoring or stabilizing foundations.	0.25	Stability is essential on uneven or regolith-covered terrain.
	EX Excavation	Effort required to prepare site or excavate regolith for installation.	0.25	Required for shielding, ISRU, and anchoring.
4. Logistical Efficiency *Threshold: 4.0*	**TR** Transportation	Ease of transporting components from Earth to the lunar surface	0.45	Launch costs and cargo capacity are critical constraints for early missions. .
	RS Resource Savings	Ability to use in-situ resources to reduce Earth resupply needs.	0.55	Reducing dependence on Earth is crucial for long-term sustainability.
5. Maintainability & Durability *Threshold: 3.5*	**DM** Dust Mitigation	Resistance to performance degradation from lunar dust.	0.55	Dust can degrade systems, but it is manageable with mitigation measures.
	RE Repairability	Ease of inspecting, maintaining, and repairing habitat systems.	0.45	Important for maintenance, but less critical if systems are redundant.
6. Habitability *Threshold: 3.0*	**MO** Modularity	Ability to expand, reconfigure, and integrate with mission infrastructure.	1.00	Flexibility is important but less critical than life safety.

Table 2: Weighted evaluation with current identified criteria with justifications and descriptions. Groups, weights, and threshold values are in order of priority of crew life safety.

5 Case Studies

This section introduces a small collection of past lunar habitat concepts for each of the three classes. This section simply introduces these concepts at a higher level; justifications for the evaluation are included in the appendix. These case studies are just examples of how this methodology can be applied to existing and future concepts, and do not reflect a singular approach to establishing settlements on the Moon.

5.1 Class I

Even before landing on the Moon was proven to be possible, concepts to establish a permanent lunar settlement were already being developed. After the beginning of the Apollo program in 1961, original concepts recognized the need for a pre-integrated design that would allow for integration in the Saturn V system [10]. This review will cover the LESA System and the recently announced Lunar MPH to make comparisons of Class I structures.

- *Lunar Exploration Systems for Apollo (LESA) – NASA 1963*

  The most ambitious and popular design during the Apollo missions was the Lunar Exploration Systems for Apollo (LESA) by NASA in 1963. The concept is continually referenced and would have likely provided the beginnings of a larger settlement had it been accomplished. The initial design accomodates up to six people for a six-month mission. While the overall design of the 25,000 lb. (11340 kg) module is relatively simple and elegant, it would still require additional material for radiation shielding.

  Figure 5 shows initial illustrations of this concept. The module sits on four lets that allow for minimal excavation. The image on the right shows regolith shielding placed on top of the module.

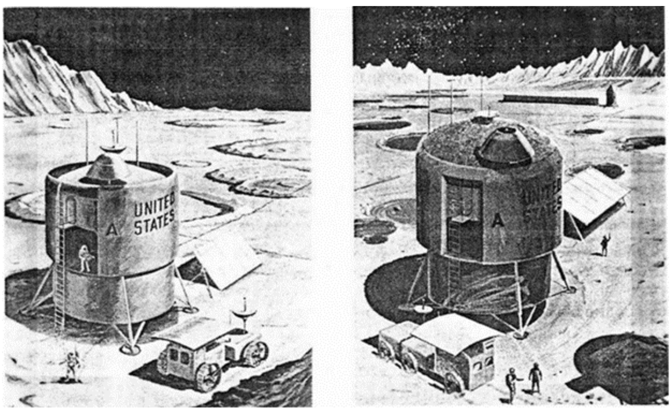

Figure 5: Lunar Exploration System for Apollo (LESA) concept illustrations [2]

Figure 6 shows the evaluation chart for the LESA concept. Having been modeled after the Apollo missions, the LESA meets the threshold for Technology Maturity, and additionally does not require extensive surface construction. However, the LESA lacks the structural strength and radiation shielding required to protect astronauts long-term.

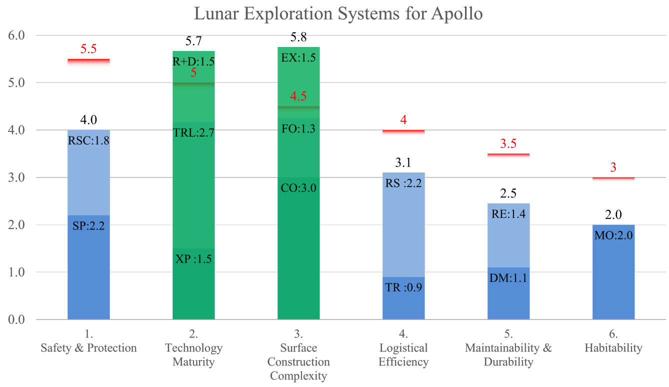

Figure 6: LESA Evaluation Chart

- *Lunar Multi-Purpose Habitat (LMPH) – Thales Alenia Space 2023*

  A more modern concept is the Lunar Multi-Purpose Habitat (MPH) by Thales Alenia Space. The project was announced in November of 2023 and is under contract by the Italian Space Agency in collaboration with the Artemis Program. Though limited information on this design is available, Figure 3 shows a simple modular design that is pre-integrated for lunar interface simplicity. The company comepleted its Mission Concept Review in September 2024, allowing Thales to further develop the habitats life support systems, and technologies to provide protection from the lunar environmental conditions.

  Figure 7 is a rendering offered by Thales. It highlights the simple geometry and includes solar panels. This design sits on the lunar surface lengthwise, which likely allows for more habitable volume.[11].

  The LMPH scores very similarly to the LESA concept. As seen in Figure 8, the distribution of scores are similar to that of LESA. The structure is fully integrated

5.2 Class II

Deployable structures are the logical next step after a fully pre-integrated module concept. Once a module on the Moon is established, Class II structures can be utilized to expand and establish a permanent lunar settlement. While there is an abundance of studies and concepts, this review covers only the BEAM and Artemis Lunar Surface Habitat.

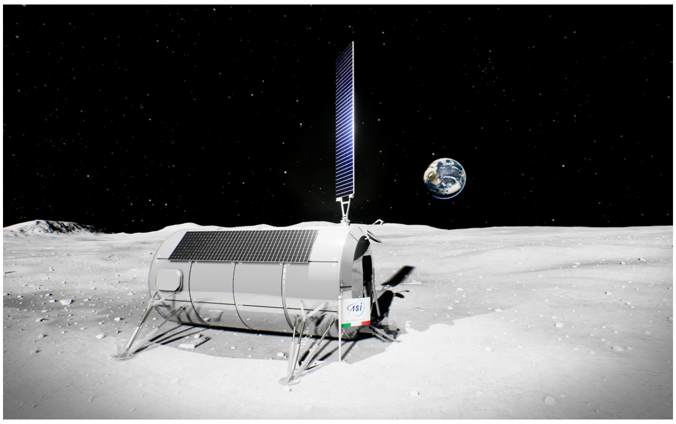

Figure 7: Lunar Multi-Purpose Habitat Concept rendering [11]

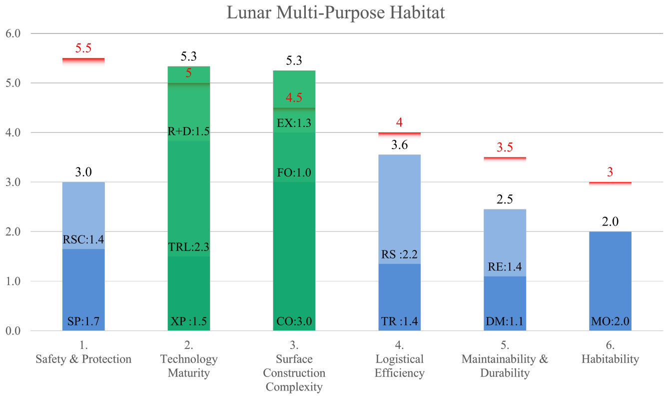

Figure 8: LMPH Evaluation Chart

- *Bigelow Expandable Activity Module (BEAM, originally TransHab) – Bigelow 2016*

  Although not designed to land on the Moon, the BEAM is worth mentioning as a proven example of an inflatable structure operating in the space environment. Initially a study under the name TransHab, it was abandoned by NASA. The project was later taken over by Bigelow Aerospace and reached the ISS in 2016. It is considered as a first step in creating habitable structures on the Moon and the design could easily be adapted to a lunar structure [2]. The BEAM has a central rigid core which includes bulkheads and radiation shielding water tanks. Once this structure reached orbit, it inflated its multi-shell layer of micro-meteoroid orbital debris (MMOD) protection shielding.

  The BEAM module can be seen fully inflated and attached to the ISS in figure 9. This study showed how: to protect an inflatable structure from micrometeoroids, a structure can be packaged and deployed in space, and to pressurize an inflatable in the vacuum of space.

Figure 9: Bigelow Expandable Activity Module (BEAM) is pictured attached to the ISS [12]

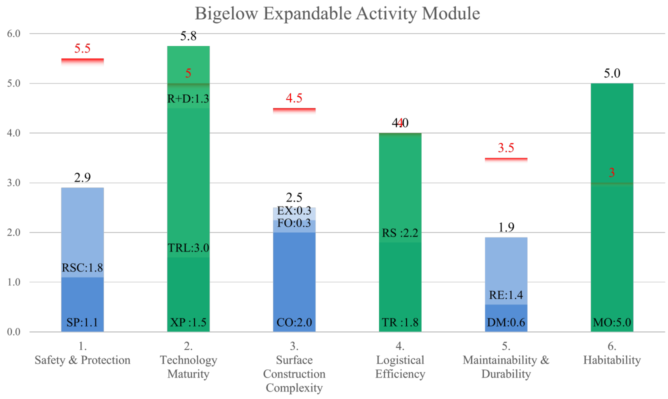

Figure 10: BEAM Evaluation Chart

- *Artemis Lunar Surface Habitat (ALSH) – NASA 2022*

  Under the Artemis Program, NASA is refocusing its efforts to send humans back to the moon and establish a permanent lunar presence. After the Gateway lunar orbiting outpost is established, the Artemis basecamp will follow. This includes the lunar Surface Habitat (SH) to accommodate a crew of up to four astronauts. Many similarities can be taken from the TransHab. The structure is designed with a metallic core and a two-story inflatable section. The membrane consists of restraint layers, MMOD resistant layers, and multi-layer insulation (MLI) [13]. Further challenges that this design faces are surviving the 100+hr eclipse periods without access to solar power, dust contamination, resource transfer, dormancy, oxygen concentrations (flammability), mass delivery, spares, maintenance, outfitting, human factors, and radiation.

  Figure 11 shows an elevation view of the Surface Habitat design. The habitat inflates to 6.5m in diameter after fitting in a 5m fairing for launch. The lower section is rigid and allows for ingress and egress. Similar to other concepts, the habitat sits on 4 legs and minimizes the need for excavation.

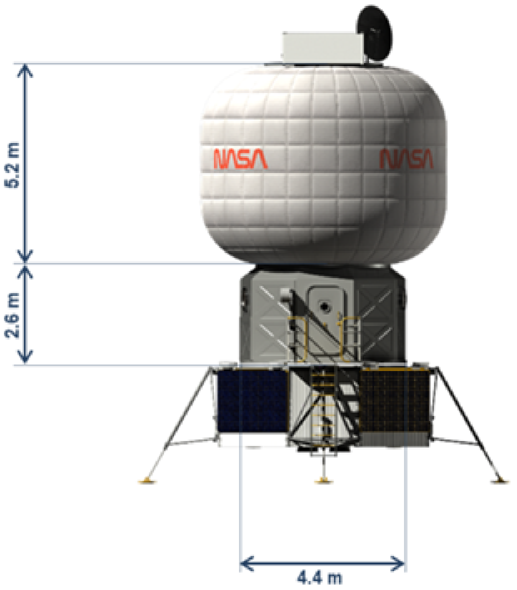

Figure 11: Surface Habitat Dimensions[13]

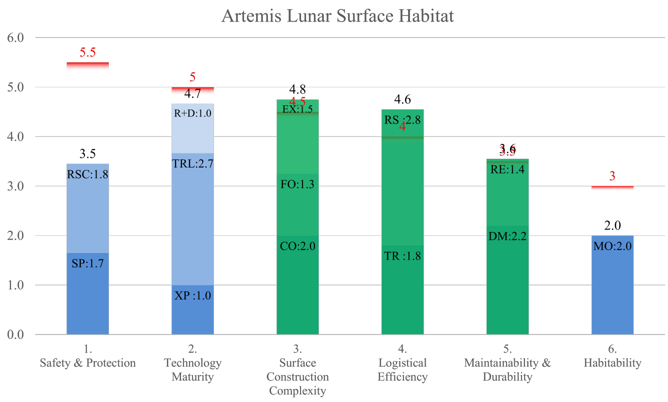

Figure 12: ALSH Evaluation Chart

5.3 Class III

There are still a lot of uncertainties in the literature surrounding the use of 3D-printed techniques. As mentioned, ISRU methods should be confined to previous classification concepts. Due to this, this report will cover more feasible concepts that do not rely solely on the use of 3D printing. The case studies include the Spherical Inflatable and Lunar Outpost Design.

- *Spherical Inflatable (SI) – Roberts 1988*

  A popular early concept of an inflatable class II structure is the Spherical Inflatable concept by M. Roberts in 1988. The habitat allows engineering principles to guide its shape and design. The objective of this design was to establish a baseline and flexible design for future concepts, hence its spherical shape. The most significant structural concerns are membrane stress, leakage, and puncture resistance. The concern is that if the inflatable membrane collapses, the entire structure will collapse on itself. Therefore, there is an additional internal structure. In this case, the membrane also supports regolith shielding. The regolith shielding helps protect the structure against radiation, meteoroids, and extreme temperature changes [14].

  Figure 13 presents an artist's illustration of the spherical inflatable concept. Its diameter is 16 m and includes an airlock, clean room, life science lab, hydroponic gardens, wardroom, and private quarters.

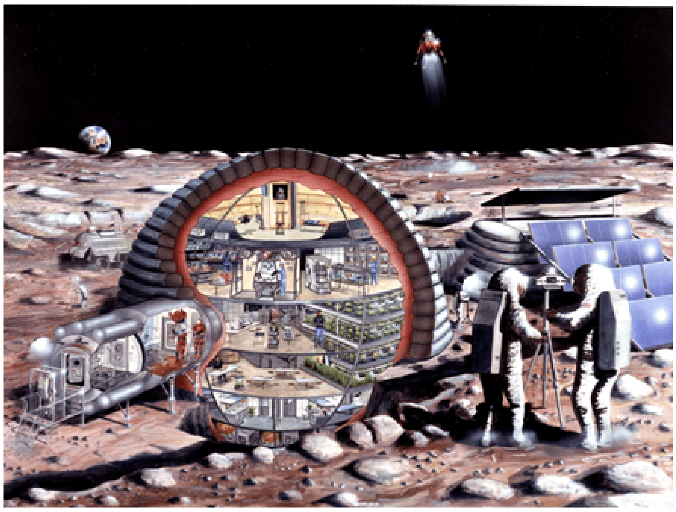

Figure 13: Spherical Inflatable habitat concept [2]

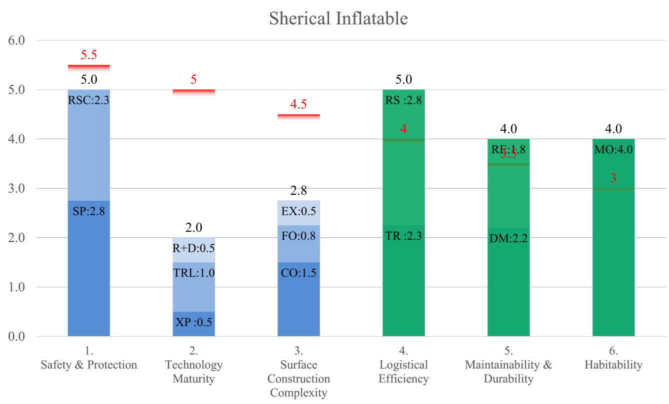

Figure 14: SI Evaluation Chart

- *Lunar Outpost Design (LOD) – Foster + Partners 2015*

A more recent concept utilizing in-situ materials is the 2015 Lunar Outpost by renowned architectural firm, Foster + Partners. The design includes an integrated module and 3D-printed regolith. The integrated module offers access to the outside through an airlock and interface with additional inflatables for future expansion. The inflatable structure provides atmospheric pressure and habitable volume. However, the team recognized that the inflatable would be a fragile structure, so it utilized a 3D-printed dome shell for protection. The regolith shell protects against radiation and meteorite impacts. They mention D-shape 3D printing technology being used on smaller robots to slowly build up the maximum 1500mm thick regolith catenary structure over the inflated structure [15].

The rendering in Figure 15 shows a section of the proposed design. Notice the rigid module connected to the inflatable membrane. Like masonry structures on Earth, regolith has low tensile strength. The geometry of the 3D-printed regolith is in a catenary, which ensures that it remains purely in compression to maintain structural integrity.

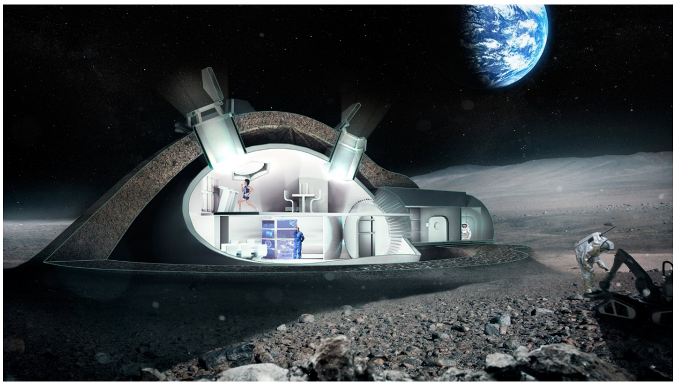

Figure 15: Rednering of the Lunar Outpost Design by Foster + Partners [15]

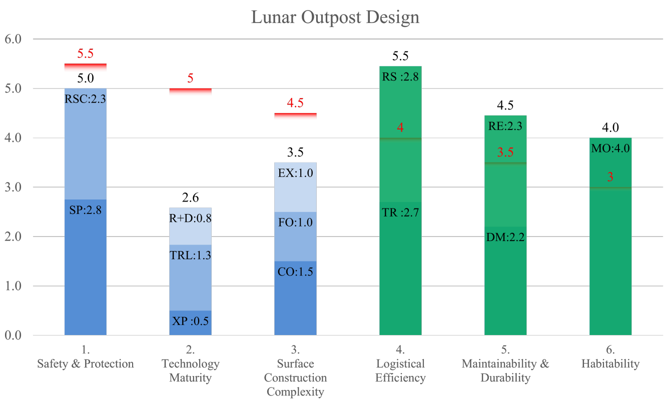

Figure 16: LOD Evaluation Chart

6 Discussion

Class I concepts examined in this literature review scored an average unweighted score of 53.0, while Class II and Class III scored 49.7 and 49.3 respectively. This suggests that Class I concepts are still the favored option for establishing an initial lunar settlement and confirms the validity of the Roadmap created in 1997 [3]. It should be noted that although the BEAM concept could not be evaluated for the foundation and excavation criteria, it is unlikely that the Class II score would go higher than Class I.

Class I structures are overall better understood, and their basic engineering has been extensively used in several other applications on Earth (submarines, water tanks, etc). However, they are limited in their further development and expandability for growing and sustaining a settlement on the Moon. Because they are fully integrated on Earth, they also fully require significant support from Earth as well. This limits the capacity at which pre-integrated structures can operate independently.

Class II concepts are the bridge of moving from Class I to Class III structures. These concepts take the first step into expanding and reaching operational independence. This review focused on inflatable Class II structures. However, other methods incorporate different structure types that must be considered as well, for example, using cable structures for support systems and going underground into lava tubes.

Although they are not at the required level of understanding and lack the technology readiness level, Class III structures have the most potential for growth and expansion. Once regolith construction techniques are reliable and well understood, it becomes obvious that ISRU is essential to maintain a permanent presence on the Moon. Without learning how to utilize the local resources, a lunar habitat will always be reliant on resupply missions from Earth.

7 Conclusion and Recommendations

This paper reviewed habitat concepts from as early as 1963 and demonstrated how the ideas and approaches to Lunar settlements have evolved. Studying and understanding how these ideas have developed provides insight into how to best advance in the direction of a permanent lunar settlement.

Classification of different technologies helps to make comparisons; however, it is unreasonable to assume that one structure fits perfectly into one classification. An example of this is the LESA structure which still needs some regolith to satisfy its radiation shielding capability. The ideal scenario is a structure that incorporates each phase

Summary of Case Study Evaluation - Unweighted Scores

Group	Criteria	Weight	LESA	LMPH	BEAM	ALSH	SI	LOD
1. Safety & Protection	**SP**	0.55	3	3	2	3	5	5
	RSC	0.45	4	3	4	4	5	5
2. Technology Matuirity	**XP**	0.25	6	6	6	4	2	2
	TRL	0.50	5.33	4.67	6.00	5.33	2.00	2.67
	R+D	0.25	6	6	5	4	2	3
3. Surface Construction Complexity	**CO**	0.50	6	6	4	4	3	3
	FO	0.25	5	4	1	5	3	4
	EX	0.25	6	5	1	6	2	4
4. Logistical Efficiency	**TR**	0.45	2	3	4	4	5	6
	RS	0.55	4	4	4	5	5	5
5. Maintenance & Durability	**DM**	0.55	2	2	1	4	4	4
	RE	0.45	3	3	3	3	4	5
6. Habitability	**MO**	1.00	2	2	5	2	4	4
Total Unweighted Score			54.3	51.67	46.0	53.33	46.0	52.67

Table 3: Evaluation Matrix of selected case studies. Criteria are rows. Scores range from 1 (worst) to 6 (best). TRL normalized to 6.

or classification that can gradually evolve. The LOD is a great example of this, where a structure can start as a pre-integrated module and serve as a nucleus from which a colony can develop and expand.

The evaluation method introduced is far from complete. Although the criterion are weighed to prioritize crew safety, the actual values require further study and investigation. This review only considered 6 case studies, but should be expanded to consider more concepts, especially those which overlap classes. It is important to aim for a standardized and quantitative evaluation method. The more technologies are explored the more our understanding will grow. If a standard database is established, it could be applied and repeated for Mars habitats in the future. The Moon has been and should continue to be a muse for space exploration.

7.1 Future Work

Based on the literature and conclusions made, my recommendations for future work are:

1. **Define full scope of standardized evaluation metrics.** This framework establishes which criteria need to be evaluated, but does not provide a proper method for how the evaluation for each criterion should be performed. Each criterion requires further research to assign an evaluation score more accurately.
2. **Create a standardized database of concepts to make more accurate comparisons.** There exists a lot of other literature that each has its own metrics of evaluation, very often focusing only on the habitability of the crew. Establishing a database with standardized criteria could be used to catalog new concepts and provide a great reference for future projects in areas that require further development. This is also useful in additional parameters that become known with flight experience and can be documented.
3. **Repeat a similar process of evaluation for Mars habitats.** Once we have flight heritage with successful lunar habitats, it would not be difficult to extrapolate similar metric for Mars. This could prove to be useful as a baseline for new concepts. The strategic goal is to focus on lunar habitats, but eventually habitats on Mars will want to be pursued.
4. **Explore concepts that can evolve from a Class I to a Class III structure.** By synthesising data from all existing concepts, ideas can be shared and combined to develop innovative technologies that allow for structures to evolve from Class I to Class III as they see more use. This could be an innovative and sustainable approach to starting a lunar colony, and should include further feasibility studies for ISRU.

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Appendix - Individual Scoring Justifications

The values given to each concept need a qualitative justification in order to support the score. Tables 4 to 16 gived detailed arguments for each criteria. This follows a similar format that [6] uses in their initial evaluation. 1 represents the worst possible performance; 6 is the best performance.

Structural Strength & Pressure Resistance			
Class	**Concept**	**Score**	**Justification**
I	LESA	3	Rigid Structure
	MPH	3	Rigid Structure
II	BEAM	2	May load integrity if loss of pressure
	SH	3	May load integrity if loss of pressure
III	Roberts	5	Interior structure supports shell in case of pressure loss
	LOD	5	Regolith does not rely on inflatable structure, however minimal interior structure to support in event of pressure loss

Table 4: Pressure Differential Criteria Scoring Justifcation

Radiation Shielding Capability			
Class	**Concept**	**Score**	**Justification**
I	LESA	4	Module requires additional regolith shielding
	MPH	3	Shielding capability unknown, assumed to include minimum
II	BEAM	4	MMOD Layer should provide minimum shielding
	SH	4	MMOD Layer should provide minimum shielding
III	Roberts	5	Regolith layer should provide sufficient shielding
	LOD	5	Regolith layer should provide sufficient shielding

Table 5: Radiation Shielding Capability Criteria Scoring Justifcation

Experience			
Class	**Concept**	**Score**	**Justification**
I	LESA	6	Rigid pressure vessels well understood
	MPH	6	Rigid pressure vessels well understood
II	BEAM	6	Structure has been launched and tested
	SH	4	Similar to BEAM, however, may behave differently on lunar surface
III	Roberts	2	Minimal experience with inflatable membrane
	LOD	2	Minimal experience with inflatable membrane

Table 6: Experience Criteria Scoring Justifcation

Technology Readiness Level			
Class	**Concept**	**Score**	**Justification**
I	LESA	5.33	Similar to Lunar Module, structurally similar to ISS module
	MPH	4.67	Structurally similar to ISS module
II	BEAM	6.00	Flight Proven
	SH	5.33	Similar to Lunar Module and BEAM
III	Roberts	2.00	Only proof of concept provided
	LOD	2.67	Limited experience working with inflatables in space, 3D printed regolith only proven in lab environment

Table 7: Technology Readiness Level Criteria Scoring Justifcation. In order to be consistent with other metrics, this criteria is normalized to 6.

Research and Development			
Class	**Concept**	**Score**	**Justification**
I	LESA	6	Pressure module, well understood
	MPH	6	Pressure module, well understood
II	BEAM	5	Additional testing may be useful but is flight proven
	SH	4	Additional research required for landing inflatable on surface
III	Roberts	2	Extensive additional research required
	LOD	3	Additional research and technology development required

Table 8: Research and Development Criteria Scoring Justifcation

Construction			
Class	**Concept**	**Score**	**Justification**
I	LESA	6	Structure is pre-integrated
	MPH	6	Structure is pre-integrated
II	BEAM	4	Structure built on Earth but requires inflation
	SH	4	Structure built on Earth but requires inflation
III	Roberts	3	Careful when working with membranes
	LOD	3	Careful when working with membranes

Table 9: Construction Criteria Scoring Justifcation

Foundation			
Class	**Concept**	**Score**	**Justification**
I	LESA	5	Minor foundations assumed. The structure sits on legs
	MPH	4	Minor foundations assumed. The structure sits lengthwise on surface
II	BEAM	0	NA, are not designed for the lunar surface. Would not be feasible.
	SH	5	Minor foundations assumed. The structure sits on legs
III	Roberts	3	Foundations not considered in concept. Minor foundations assumed
	LOD	4	Minor foundations assumed

Table 10: Foundation Criteria Scoring Justifcation

Excavation			
Class	**Concept**	**Score**	**Justification**
I	LESA	6	Minimal leveling required
	MPH	5	Minimal leveling required, however, due to its orientation it may need additional
II	BEAM	0	NA, are not designed for the lunar surface. Would not be feasible.
	SH	6	Minimal leveling required
III	Roberts	2	Half structure if below ground
	LOD	4	Ground leveling and resource extraction required

Table 11: Excavation Criteria Scoring Justifcation

Transportation			
Class	**Concept**	**Score**	**Justification**
I	LESA	2	High mass, Adequate volume
	MPH	2	High mass, Adequate volume
II	BEAM	4	Medium Mass, Larger volume
	SH	4	Medium Mass, Larger volume
III	Roberts	5	Low mass, but internal structure results in additional mass
	LOD	6	Low mass and small stowage volume

Table 12: Transportation Criteria Scoring Justifcation

Resource Savings			
Class	**Concept**	**Score**	**Justification**
I	LESA	4	Easy to establish several modules, however difficult to integrate together
	MPH	4	Easy to establish several modules and could be aligned to integrate together
II	BEAM	4	Though not designed for the lunar surface, the concept could be used to expand volume as seen on the ISS.
	SH	5	Easy to establish several modules, however difficult to integrate together
III	Roberts	5	Additional airlock could be provided to support expandabilty
	LOD	5	Airlock module allows for expandability for additional inflatable structures

Table 13: Resource Savings Criteria Scoring Justifcation

Dust Mitigation			
Class	**Concept**	**Score**	**Justification**
I	LESA	2	Single module habitat, no indication of dust management
	MPH	2	Single module habitat, no indication of dust management
II	BEAM	1	Not designed for lunar environment
	SH	4	Lower rigid structure can serve as airlock to include a separate for dust
III	Roberts	4	Airlock can be used to separate out dust
	LOD	4	Airlock can be used to separate out dust

Table 14: Dust Mitigation Criteria Scoring Justifcation

Repairability			
Class	**Concept**	**Score**	**Justification**
I	LESA	3	Single rigid module, would only be able to perform minor repairs at a given time
	MPH	3	Single rigid module, would only be able to perform minor repairs at a given time
II	BEAM	3	Single module, would only be able to perform minor repairs at a given time. Major damage would be very difficult to repair.
	SH	3	Dual module can help with larger repairs, as crew can separate themselves from damaged area if needed.
III	Roberts	4	Large enough space to block of certain areas for repairs, ISRU utilization
	LOD	5	Large enough space to block of certain areas for repairs, ISRU utilization

Table 15: Modularity Criteria Scoring Justifcation

Modularity			
Class	**Concept**	**Score**	**Justification**
I	LESA	2	Easy to establish several modules, however difficult to integrate together
	MPH	2	Easy to establish several modules and could be aligned to integrate together
II	BEAM	5	Though not designed for the lunar surface, the concept could be used to expand volume as seen on the ISS.
	SH	2	Easy to establish several modules, however difficult to integrate together
III	Roberts	4	Additional airlock could be provided to support expandabilty
	LOD	4	Airlock module allows for expandability for additional inflatable structures

Table 16: Modularity Criteria Scoring Justifcation

Criteria Description Rubric

Group	**Criterion**	Weight	**1**	**2**	**3**	**4**	**5**	**6**
1. Safety & Protection *Threshold: 5.5*	**SP** Structural Strength & Pressure Resistance	*0.55*	Fails under pressure or environmental stress	Weak; survives only mild loads/pressure	Adequate but vulnerable to micrometeoroids or fatigue over time	Strong; reliable against most mission stresses	Very robust; resists pressure, impacts, and seismic events	Exceptional; redundant, resilient, long-duration structural safety
	RSC Radiation Shielding Capability	*0.45*	No shielding; unsafe exposure	Minimal shielding; only partial SPE protection	Basic shielding; reduces exposure but not safe for long stays	Meets minimum crew safety thresholds	Strong protection; suitable for long-duration habitation	Exceptional protection (e.g., regolith/lava tube); near-Earth radiation levels
2. Technology Maturity *Threshold: 5.0*	**XP** Experience	*0.25*	Purely conceptual; no testing or prototypes	Analytical models only; no hardware	Limited lab-scale testing in analog environments	Prototype demonstrated in partial-relevant environments (e.g., ISS, analog sites)	Flight-tested in space or high-fidelity lunar/Mars analogs	Operational heritage; proven in mission-relevant conditions
	TRL Technology Readiness Level	*0.50*	Basic concept; physical principles observed	Technology concept formulated	Proof-of-concept; analytical/lab validation	Component validated in lunar analog conditions	Habitat prototype tested in relevant environments (vacuum, regolith)	Fully operational habitat proven in mission
	RD Research and Development Difficulty	*0.25*	Requires breakthrough discoveries (e.g., new materials)	Very high risk; long-term development needed	Significant technical gaps but solvable with focused effort	Feasible; requires incremental advances in existing technologies	Low difficulty; only minor adaptations needed	No new R&D; ready for immediate application
3. Surface Construction Complexity *Threshold: 4.5*	**CO** Construction	*0.50*	Impossible without massive crew/Earth support	Extremely difficult; heavy equipment and long crew time required	Complex; feasible but with high robotic/crew involvement	Straightforward; achievable with available tools or partial automation	Easy; mostly robotic/automated deployment, minimal crew effort	Plug-and-play or fully autonomous construction or no construction required.
	FO Foundation	*0.25*	Cannot achieve stable placement; high instability risk	Weak or temporary stability; vulnerable to shifting	Stable in limited terrain types but sensitive to seismic/vibration events	Generally stable; handles most regolith conditions with precautions	Strong foundation adaptable to diverse terrains	Exceptional; robust against seismic events, slopes, and regolith variability
	EX Excavation	*0.25*	Not feasible; excavation impossible with foreseeable tools	Extremely difficult; high energy and complex machinery needed	Possible but very resource/crew intensive	Moderately efficient; achievable with specialized robotics	Easy; low energy cost and scalable with existing tools	Highly favorable; regolith excavation nearly effortless or naturally prepared (e.g., lava tubes)
4. Logistical Efficiency *Threshold: 4.0*	**TR** Transportation	*0.45*	Extremely heavy/bulky; requires numerous launches or oversized landers	Very challenging; multiple launches with complex logistics	Manageable but requires dedicated cargo missions and specialized landers	Moderately efficient; compatible with near-term heavy-lift systems	Lightweight/compact; fits within existing launch/landing constraints	Minimal transport burden; largely built from in-situ resources
	RS Resource Savings	*0.55*	Fully dependent on Earth-supplied materials	Minimal savings (<10%)	Partial ISRU/recycling (∼25%)	Moderate ISRU (∼50%)	High ISRU (∼75%)	Nearly self-sufficient (>90% ISRU)
5. Maintenance & Durability *Threshold: 3.5*	**DM** Dust Mitigation	*0.55*	No protection; dust causes major failures	Minimal protection; frequent clogging/abrasion	Basic mitigation; requires constant maintenance	Effective; manageable dust accumulation	Strong mitigation; dust has little effect on performance	Exceptional; habitat nearly immune to dust intrusion
	RE Repairability	*0.45*	Impossible to repair on-site; requires replacement	Very difficult; crew-intensive and resource-heavy	Repair possible but slow and tool-dependent	Moderately easy; components accessible with EVA/IVA tools	Easy to repair with minimal crew effort	Designed for rapid or autonomous repair/replacement
6. Habitability *Threshold: 3.0*	**MO** Modularity	*1.0*	Rigid; cannot be adapted	Very limited modularity	Some modular features; constrained adaptability	Expandable; scalable with additional modules	Highly modular; easily reconfigurable and integrable	Fully modular; universal plug-and-play design

Table 17: Evaluation Matrix of selected case studies. Scores range from 1 (worst) to 6 (best) performance to satisfy category (TRL scores normalized to 6).