HALIE - HYBRID APPROACH TO LUNAR INFLATABLES AND ERECTABLES (HALIE) FOR INITIAL OPERATIONAL CAPABILITY

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ABSTRACT: For decades, space architects and engineers have proposed alternative concepts for construction and evolution of a habitable lunar settlement using a phased approach. A wide range of construction strategies by human crews or robots have been suggested in various past approaches. The HALIE concept proposes a "goldilocks" zone for a swift and early lunar settlement buildup evolution with a hybrid robotics+crew or based approach that could also entail partial telerobotic and autonomous assembly operations.

Using autonomous construction robots, the initial site preparation could be completed before humans arrive. Several terrestrially tried and tested options exist that could be adopted for quickly erecting initial operational capability that can extend the duration, scope, and range of crew and robot assisted lunar surface exploration and related technology, test, and development activities. Advances in autonomous robotics will be explored to build easily erectable structures such as adapting the rapid habitat erection technology the SPRUNG company offers. SPRUNG structures and deployment strategies are widely used around the world, having evolved over a century of building projects. These erectable structures come in an easily assembled kit of parts that could be designed and adapted for lunar surface conditions. A similar erectable structure would be ideal for autonomous robotic assembly and would offer a rapid erection of thermal and micrometeorite shell structures for future pressurized interior structures. Autonomous robots would then be able to deploy the inflatable pressurized structures, complete with airlocks, for crew occupation inside of the thermal and micrometeor protected erectable structures. Creating complicated structures out of regolith, using technologies like In Situ Resource Utilization (ISRU) are planned at later stages of lunar infrastructure development.

The HALIE strategy for initial lunar settlement proposes to erect and commission a lunar surface habitat during the better part of a sunlit lunar day of 14 Earth days. The combination of using solar powered autonomous robots for site preparation and structure assembly allows for a simpler, quicker and more effective early phases of a lunar settlement than fully human supervised structures or other complicated regolith methods. A buildup sequence and options are presented. HALIE is a preliminary concept architecture that seeks quick and easy commission with minimal tools and equipment during early settlement activity. Detailed comparisons and trades with other lunar habitat buildup strategies are warranted.

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Nomenclature

ISRU	-	In-Situ Resource Utilization
IOC	-	Initial Operational Capability
HLS	-	Human Launch System
MMPACT	-	Moon to Mars Planetary Autonomous Construction Technologies
TRL	-	Technology Readiness Level
MMOD	-	Micrometeorites and Orbital Debris
EVA	-	Extravehicular Activity
C&C	-	Certification and Commissioning
R&D	-	Research and Development
ANT	-	Artificial Neural Tissue
C-TOPS	-	Cabin for Teleoperations

I) Introduction

In the current space age, every country aims for the moon. The United States reached the lunar surface first in the primordial space age, but in recent years more countries have entered the outer space activities arena. While the United States plans and executes its Artemis missions, the Indian Space Research Organization (ISRO) recently landed a rover on the lunar surface for the first time with the Chandrayaan-3 mission. The Chinese National Space Administration (CNSA) has been roving the lunar surface for years, bringing back samples from the lunar surface in 2020. These countries (and more) exemplify the upsurgence in lunar fascination, as well as the increased competition for all to stake their claim in the Space exploration arena. The commercialization of the Space industry has only added to this fuel, offering more opportunities for orbital and lunar advancements. With additional launch vehicles (particularly reusable ones), communication satellites, and manufacturing abilities, Space opportunities continue to expand. NASA has retained some design autonomy, such as the Lunar Gateway program, but has contracted many projects such as the Human Launch System (HLS) and the next generation of spacesuits to commercial companies and vendors. Commercialization of Space adds to the flux of opportunity, feeding additional resources and focus onto the mission of expansion. As government and commercial interests coalesce, the competition for Space real estate and the desire to dominate surges. In order to maintain the pre-eminence and lasting leadership on the Moon following the Apollo era, the USA must build the first lunar settlements and hopes to establish a permanent human presence on the lunar surface. Lunar settlements provide permanent habitats for crew and serve as a hub for power operations, communication build up, storage of consumables. Countless other benefits for humanity will follow, just as the Apollo program accelerated wide-ranging developments across our society. Rovers present an important first step in demonstrating technical capabilities and providing initial surveys, but a permanent habitat determines a sustained, lasting human presence. Such a permanent habitat also allows for further exploration and scientific research, as well as enhanced commercialization opportunities.

In the coming decades, NASA aims to foster lunar infrastructure as a gateway to Mars. The Artemis program identifies the pathway to this infrastructure, as seen in Figure 1.

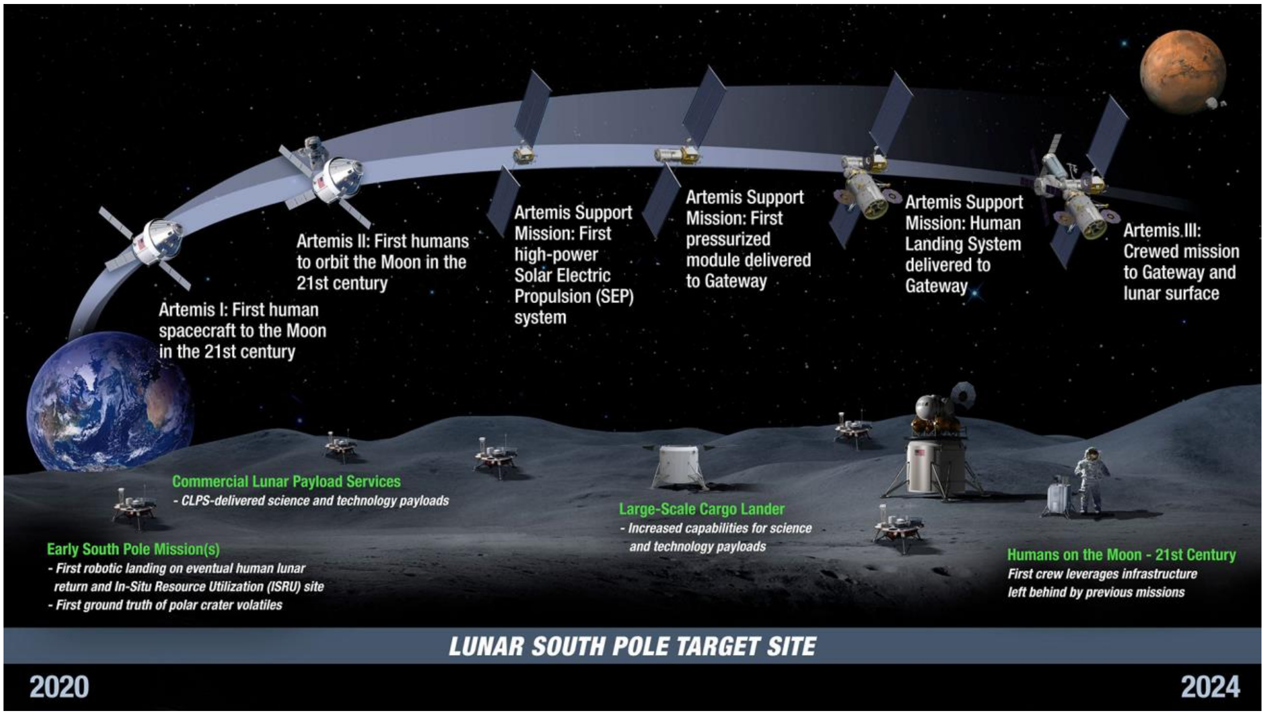

Figure 1. Artemis mission timeline highlights necessary steps to put boots back on the moon [9].

This timeline has Artemis III, returning crew to lunar surface, aiming to launch in 2025 and maps the initial steps to creating a lasting presence on the Moon. It involves pre-deploying large-scale cargo landers containing necessary supplies, followed by a crewed mission to the lunar surface at the south pole. The south pole of the Moon is of particular interest in the current space age due to its unique topography and the higher abundance of regolith resources such as ice and other minerals that offer scientific opportunities and the potential for future ISRU-based technologies.

An initial operational capability (IOC) habitat is where a system can meet the minimum operational capabilities to meet the levied requirements. The operational capability consists of support, training, logistics, and system interoperability. For a lunar habitat, this entails offering a structure that provides life support capabilities for the crew for an extended period of time during surface operations.

NASA’s Artemis Accords provides a starting point for spacefaring nations of the globe and proposes a “best practices” guide to collaborate peacefully and synergetically by highlighting many requirements and capabilities needed to evolve safe and sustainable activities on the Moon.[26]

The Moon to Mars Planetary Autonomous Construction Technologies (MMPACT) program also exemplifies this mission by encouraging new, innovative technologies [2]. Thus far, MMPACT has focused on ISRU technologies in order to utilize the lunar regolith as a fundamental material for creating structural building blocks on the lunar surface. However, many of these technologies are still very early in development, incur high costs, and would involve a lengthy and complicated process to transform regolith into usable material once on the Moon. On the opposite side, missions that launch fully assembled habitats must launch large amounts of mass and face additional risks throughout the mission phases in the form of complex system designs and components with a much higher likelihood of failure. While many viable solutions exist, no optimized solution has been found that utilizes the best aspects of all concepts for an initial operations capability(IOC) habitat, an early phase, quicker and safer surface habitat. An IOC lunar base habitat is similar to a civil engineering project site office or an advanced forward base camp from where early setup operations can be supervised and anomalies corrected through minimal EVA, if ever needed. Crew would use minimal equipment and operate real-time telerobotic agents, preferably using laser communications and line-of sight engagement. Cabin for teleoperations(C-TOPS) is such a concept proposed in an earlier USC Astro studio in which the lander is equipped with C-TOPS control systems.[27] Such consoles are in routine use today. Alternatively, if adjustments can be made for operations from the Lunar Gateway(if deployed in time) then early activities can also be supervised from lunar orbit. If broadband links are established and the 2.77sec time-delay imposed by Earth-Moon distance and system latencies can be accommodated, it may be possible to conduct such activity from mission control on Earth. [Figure 2]

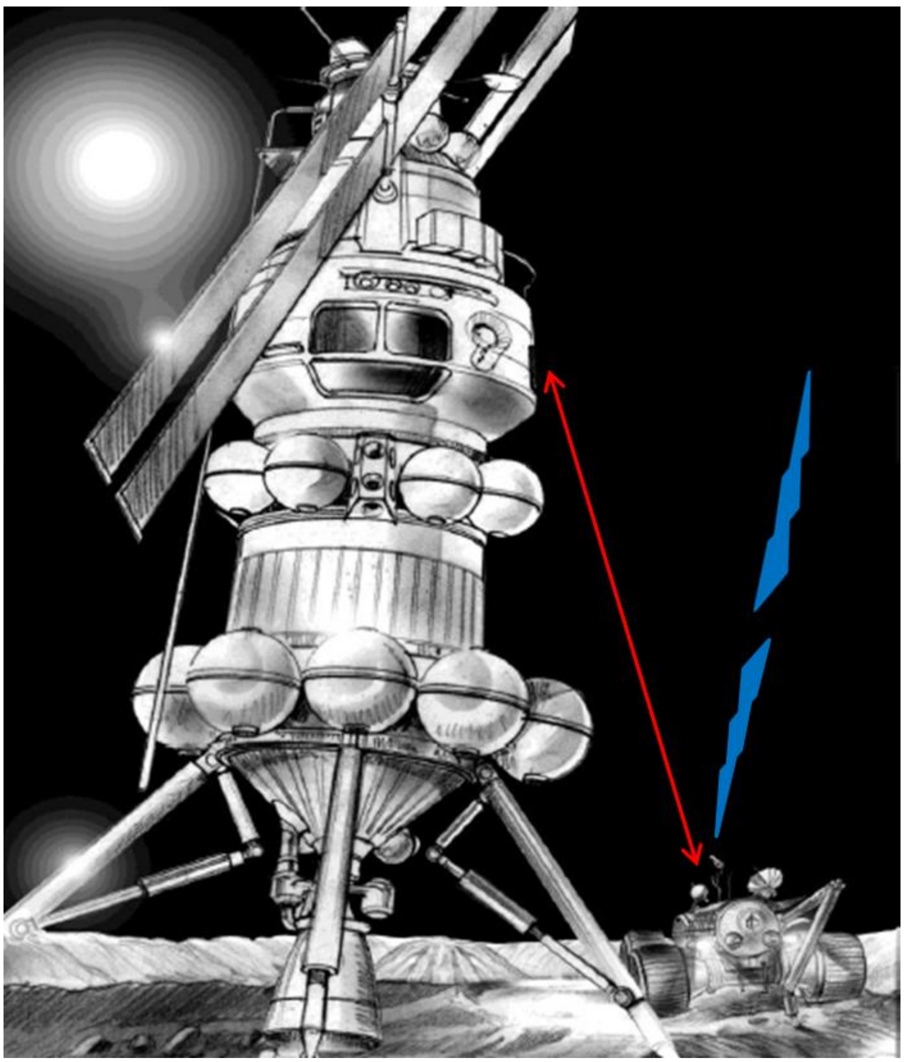

Fig.2 C-TOPS Cabin for teleoperations is a concept that allows laser communication link for line-of sight-control of IOC buildup and commission operations from the lunar lander. Remote links from the Gateway in lunar orbit or Earth mission controlis also possible, allowing crew to guide robot agents. EVAs are proposed only when anomalies arise that require direct crew intervention.

Many of these existing concepts have numerous advantages and disadvantages that can be combined to create the most efficient, cost-effective, and lowest risk initial lunar habitat.

Incorporating crewed systems in a partial capacity as opposed to full responsibility will also optimize initial construction timeline and simplicity. Using the most advantageous aspects of each of these systems, a robotic assembly of inflatable and erectable structures could establish initial operations capability. For the optimal method of constructing a self-sustaining habitat, initial building will rely on modules manufactured terrestrially and assembled on the lunar surface via autonomous construction robots with limited crew support, while later development upon this initial base may incorporate ISRU as increases in technology readiness level (TRL) of these methods allow for advancements in capability. A hybrid solution offers a structure that will survive the loads and environments, while still enabling efficient construction on the lunar surface.

Figure 3. SPRUNG structures offer the possibility of quick deployment and very spacious, unfettered volumes that could prove useful for thermal and micrometeoritic protection on the lunar surface. By erecting pressurized inflatables within such structures, it is possible to combat and ameliorate the harsh lunar environment for crew in activities that extend the IOC activities of early crew.

II) Lunar Environment

Erecting a structure on the lunar surface must take into account many different loads and environments, the first of which includes leaving the Earth and arriving on the lunar surface. Any structure or materials must survive the launch loads of the chosen launch vehicle, which impart extremely high forces on its payload. These include a mixture of vibration, shock, and acceleration forces, which result in a net combined force on the payload [4]. The next challenge involves the loads of landing on the lunar surface. As the moon does not hold an atmosphere, the type of loads will vary from those seen on Earth, though the landing event will still impart large forces due to the necessary deceleration to safely reach the surface. While considering the loads imparted on the structures, determining how the segments of the habitat are attached inside the launch vehicle's fairing will play a large role. Fully assembled structures attach directly to the fairing, and thus must withstand full launch loads as defined by the transfer function from the attachment point. Items that are able to be soft-stowed (packed into boxes with foam to attenuate loading) see much lower forces. The volume and mass available in the fairing also constrain the design of its payload. This affects the available living space and directly influences structure design.

Once on the lunar surface, additional environmental factors must be considered. The lack of atmosphere exposes humans and robotic systems to high vacuum, large thermal gradients as well as constant bombardment of micrometeorites and solar particle and cosmic radiation. Consequently, a habitat must provide a livable atmosphere for its crew, which includes steady cabin pressure, oxygen production, carbon dioxide scrubbing, and trace contaminant removal (ideally with regenerable methods to limit the amount of consumable up-mass). This also entails thermal control to ensure a normal ambient temperature for crew. Creating a stand-alone pressurized structure also necessitates airlocks for crew transfer in and out of the habitat. The lack of atmosphere also provides the lunar surface with no natural protection from solar radiation. These harmful rays can affect electronics' functionality and cause detriment to human crew. Another consequence of the exposed terrain is the susceptibility to micrometeorites and high energy orbital debris (MMOD) impacts. Foreign objects from space impacting Earth will most likely burn up in the atmosphere, whereas on the Moon they impact directly as seen by the numerous craters pocking the surface. To mitigate these vulnerabilities, a habitat must offer adequate protection for its crew and life support.

A large quickly erectable outer shell employing SPRUNG structure technology used widely for various applications on Earth could be adapted for the Moon to provide a large unpressurized volume in which to erect an inflatable pressurized IOC habitat.[Figure 3.]

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In addition to exposure from space threats, the surface itself poses challenges to mechanics and crew. Lunar dust, or "regolith", can cause health issues when accidentally ingested by crew and can also clog tubing and necessary mechanical features throughout the habitat [14]. The libration of the Moon itself also drives design features, limiting communication and power abilities depending on habitat location. All these physical and environmental factors dictate habitat choice and the most optimal structure type. The extreme thermal gradients on the lunar surface exposes structures to thermal stresses that will require specially designed and engineered components and seals, especially to prevent fitting leaks across all susceptible components and systems in habitats and EVA systems, including suits and vehicles. Site selection will depend on the power and thermal constraints caused by this, as well as the lunar topography and proximity to exploration sites.

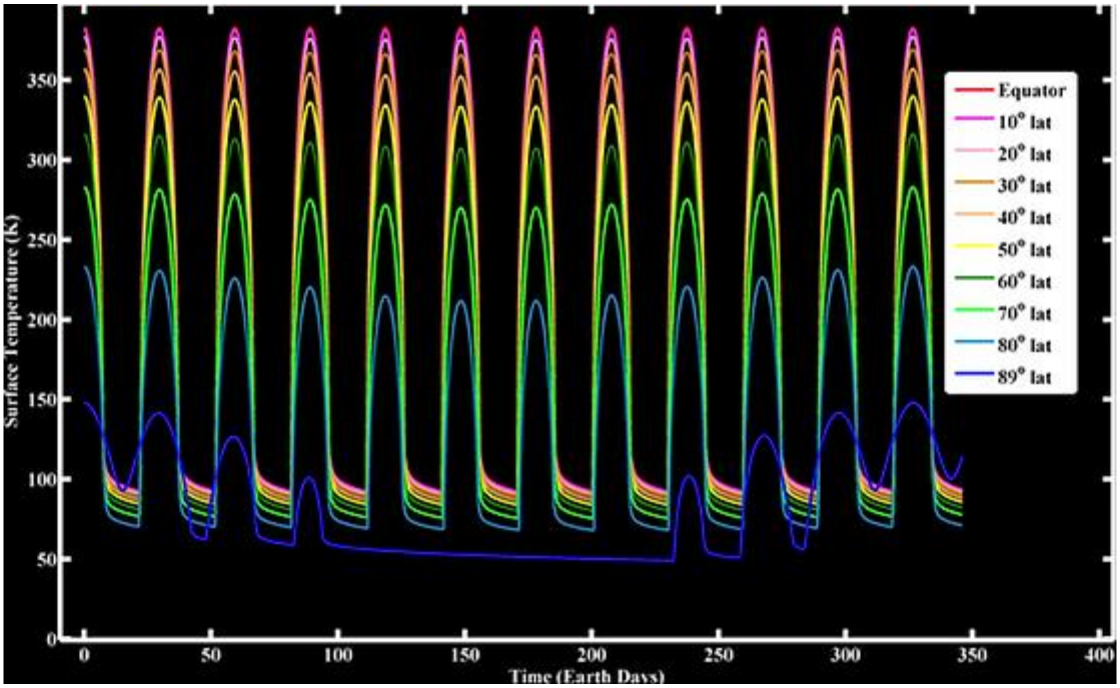


Figure 4. Extreme diurnal thermal variation across the lunar surface requires careful attention during the erection and commission of habitats [data via NASA Diviner payload]

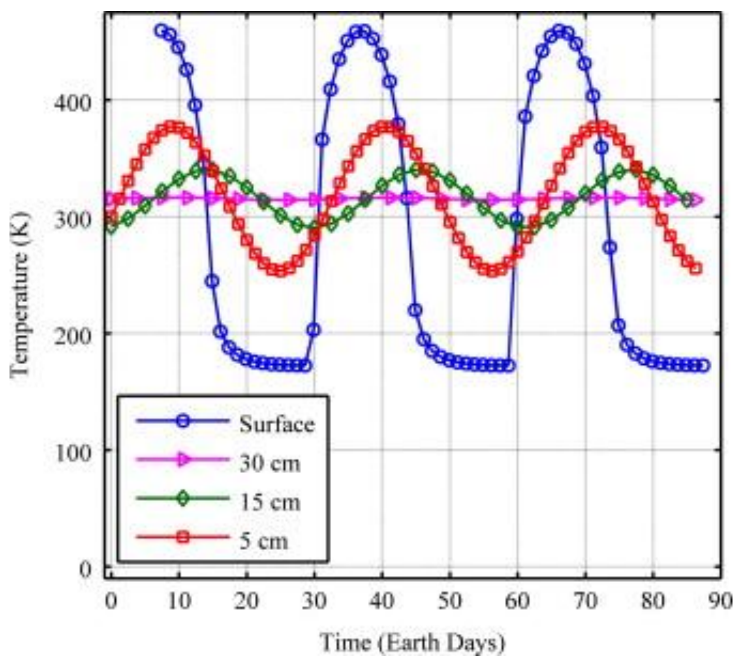


Figure 5. Lunar regolith surface is mostly covered with a fine layer of dust. In the ambient high vacuum, the regolith is a very good insulator, suggesting creative use as a thermal barrier.[10]

III) Types of Structures

There are three basic types of structures: Class 1 (pre-integrated), Class 2 (erectable and deployable), and Class 3 (ISRU based). The requirements, mission types, and use cases are outlined for each class below.

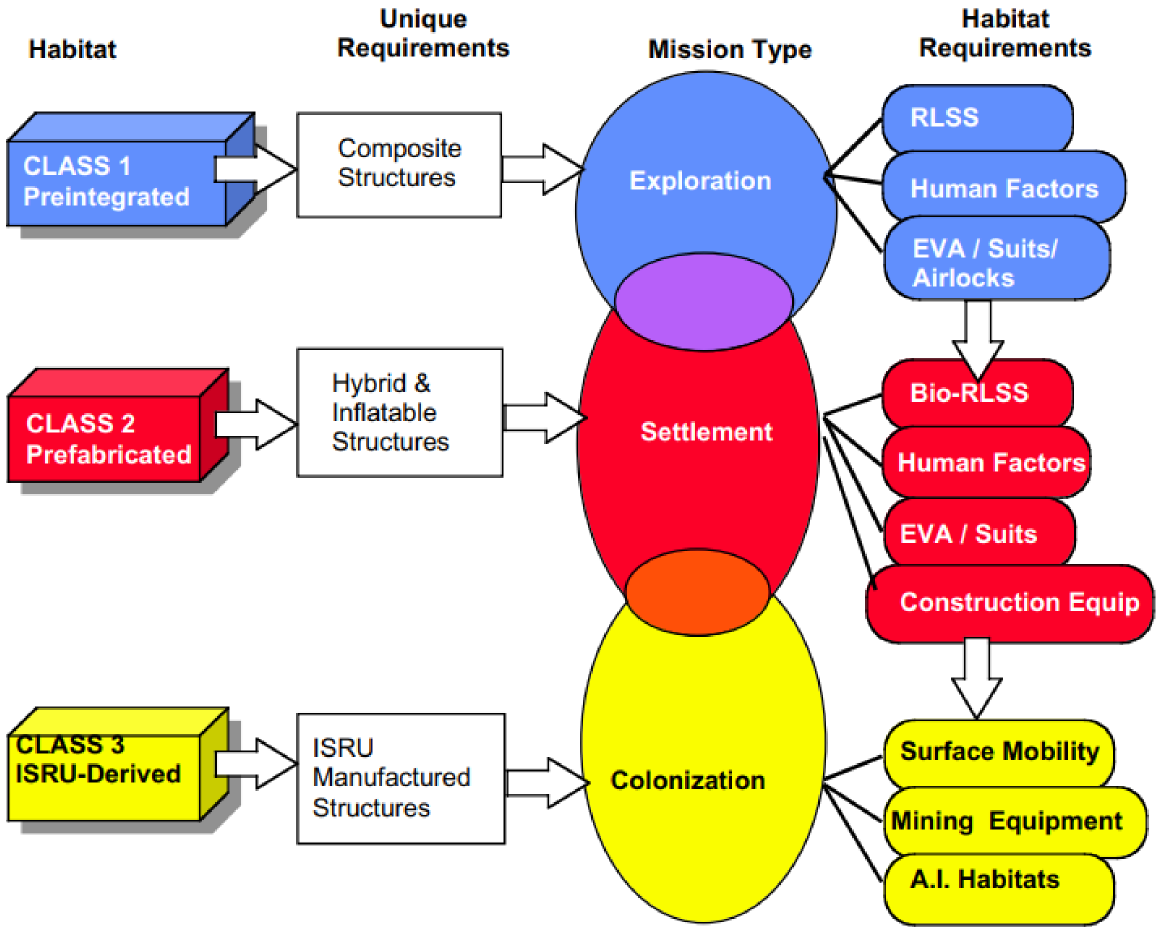
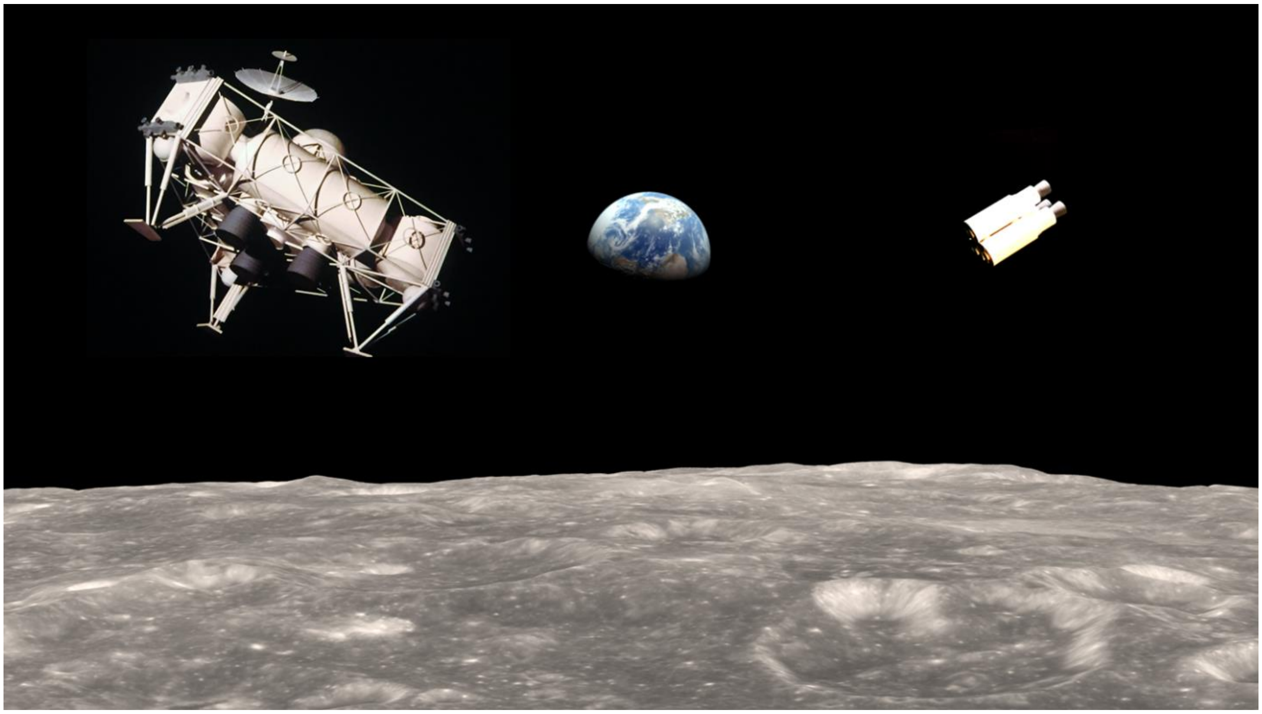


Figure 6. Typology Evolution of lunar habitat structures [3]

Pre-integrated structures (e.g. Apollo and MALEO) refer to those that launch fully assembled.



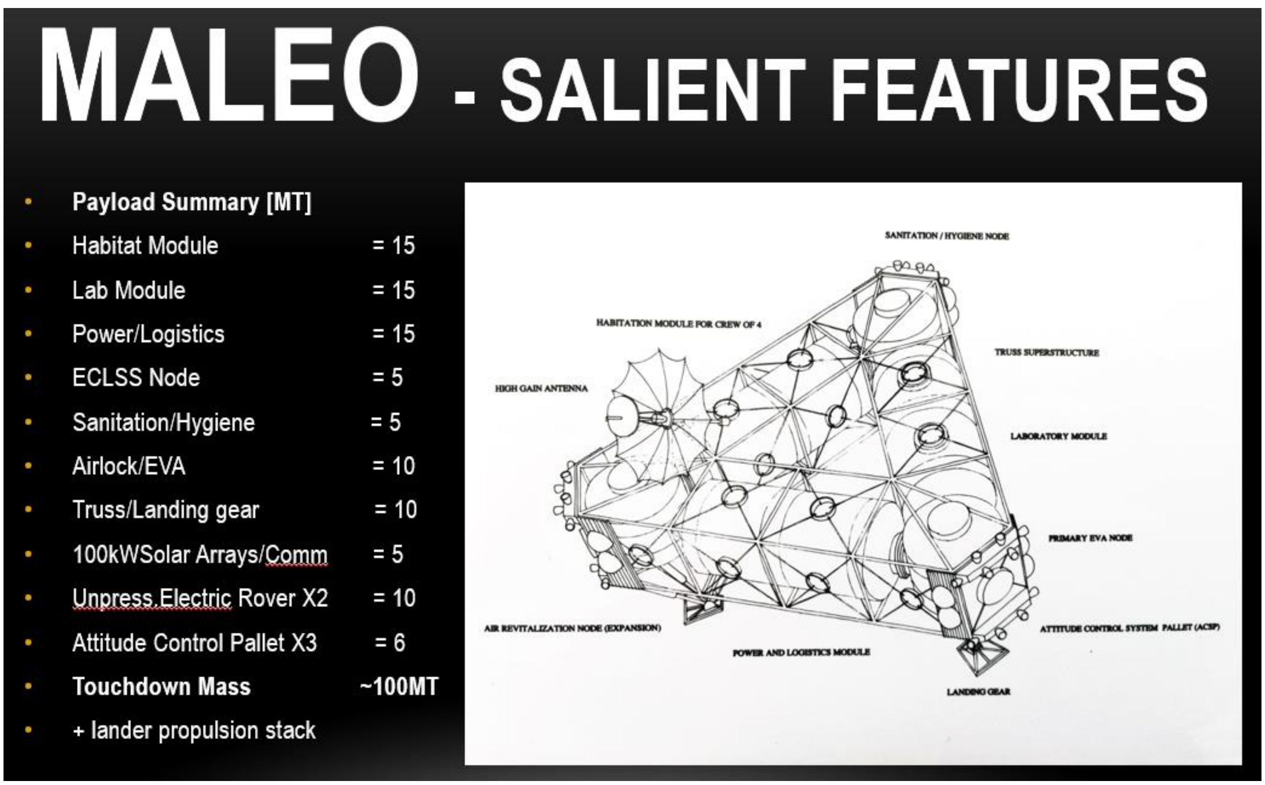


Figure 7. MALEO is a large Type 1 fully pre-integrated lunar lander that is to be built and commissioned in low Earth orbit and docked with lander propulsion in lunar orbit. Upon touchdown, this lander would serve as an initial operational capability base from which lunar activities can commence [18].

It is well established that early lunar habitats be preintegrated structures that are certified and commissioned and ready to function upon touchdown. The Apollo series of lunar landers, spartan as they are, are examples of such early initial operational capability habitats. Such habitats have a narrow scope, range of exploration capabilities, and mission duration that are also constrained by onboard consumables, both for crew and spacecraft operations.

Figure 8. Eugene Cernan tests the lunar rover during the first Apollo 17 EVA on the surface of the Moon. The rover in foreground was deployed from the lander belly after touchdown. Such structures are classified as Type 1 habitats. [7]

This type of structure offers an early-stage solution with no building equipment needed and quick certification and commissioning (C&C). However, a large reason that launching fully assembled habitats incur such expensive launch costs lies in the complexity and structural robustness needed to survive launch and landing loads. Buildings must be engineered with very high factors of safety and extremely sturdy designs to withstand these conditions. A fully assembled, very strong structure increases launch mass substantially, especially when accounting for the mass of the lander needed to safely deliver the habitat to the surface. In addition, the complexity of an all-up habitat increases the likelihood of component or assembly failure (leading to any given capability or crew risk) and thus incurring further downstream costs in the form of crew time needed for repair or expenses and launch mass for deployment of spares or even full modules.

The next class, erectable and deployable, aims to mitigate many of these risks by launching unassembled pieces that do not require the same structural robustness for launch as pre-integrated structures. They are also able to be packaged into smaller volumes, which can in turn reduce mass. These structures are still considered viable for early-stage developments and involve minimum equipment but involve slight additional C&C as the finished product cannot be fully assessed prior to launch. [Figure 9a,b]

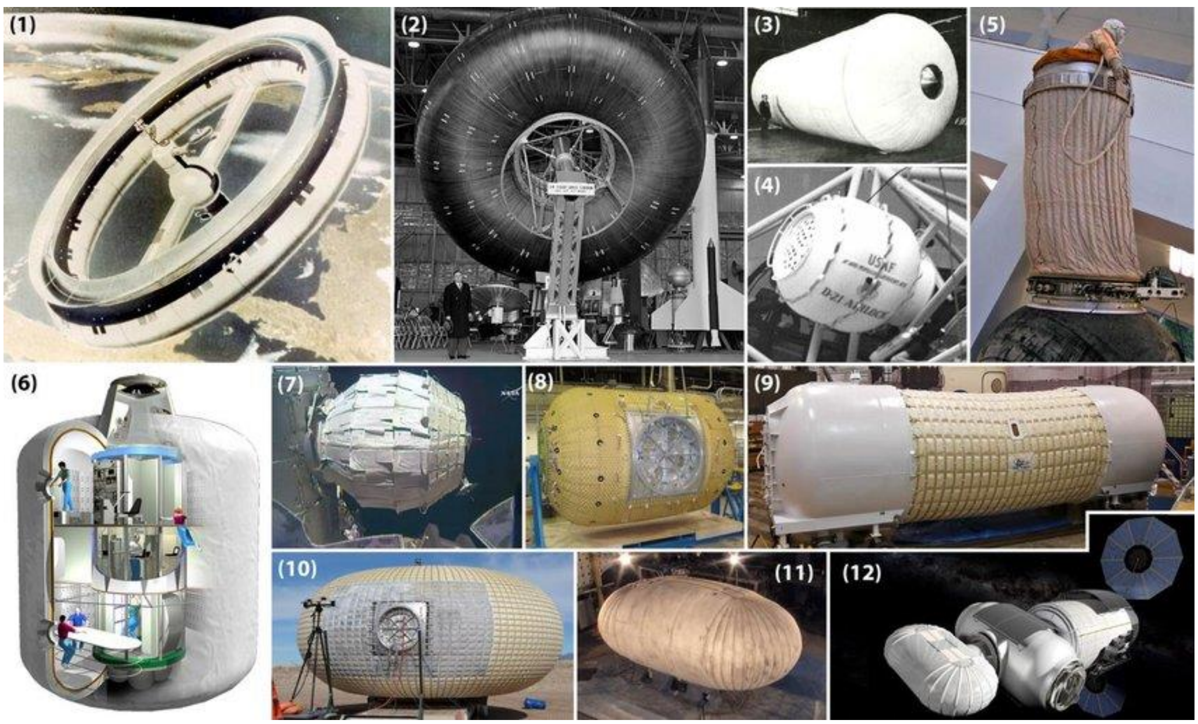


Fig.9a

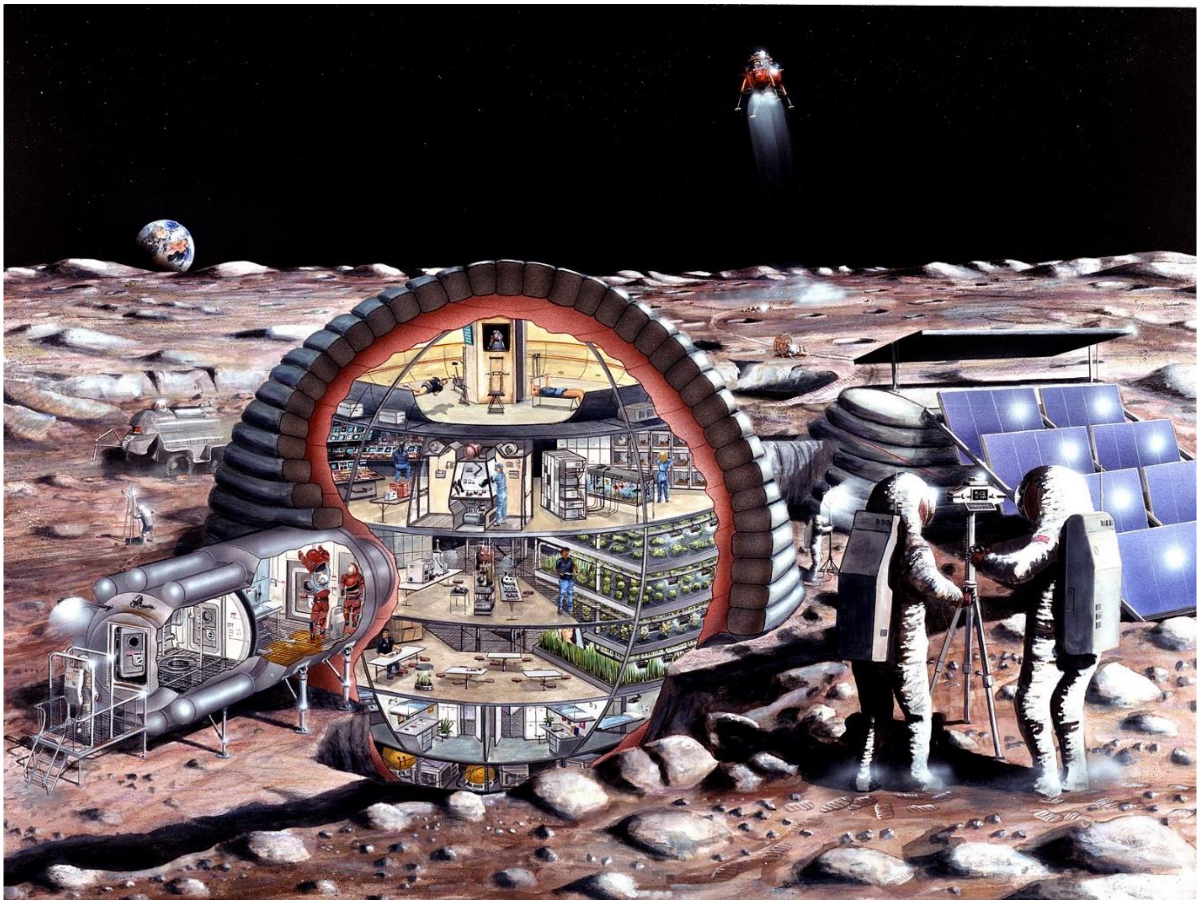


Figure 9b. Type 2 prefabricated structures include a variety of NASA inflatable habitats including Transhab, Bigelow BEAM on the International Space Station or hybrid structures with ISRU derived regolith bags for thermal, micrometeoritic, and radiation protection. [12]

While erectable and inflatables reduce mass, they still involve transporting all building materials from terrestrial to lunar surface which still incurs expense. This dilemma directs the lunar infrastructure technology towards utilizing Class 3 (ISRU) as little up mass cost is necessary as all of the raw building materials existing naturally on the surface. ISRU can be achieved through 3D printing, sintering, or dry packing lunar regolith. [Figure 10a, b]

Though this technology reduces the initial launch costs, it involves complex machinery and has never been demonstrated with lunar regolith and thus incurs high research and development (R&D) costs to raise the TRL. Relying solely on new technology also extends the timeline of the mission for more intensive qualification and acceptance testing, as well as operational concerns. Planning to use this in the initial operational capability habitat increases the risk of mission failure due to low amounts of testing while still risking a timeline delay. In addition, the power consumption for ISRU technology would dominate the needs of a base and necessitate much more mass for a larger power infrastructure [1].

Figure 10a, b. Type 3 habitation and infrastructure development involves heavy robots as well as allied co-robotic protocols and equipment and maintenance facilities that are being studied for advanced lunar infrastructure. Top [ICON], Bottom [8,20].

A hybrid of these approaches, however, can incorporate the beneficial aspects of maintaining terrestrial manufacturing and also include remote operations while mitigating cost and risk. This approach is even adaptable to incorporate ISRU created materials once that technology has been successfully demonstrated on the lunar surface.

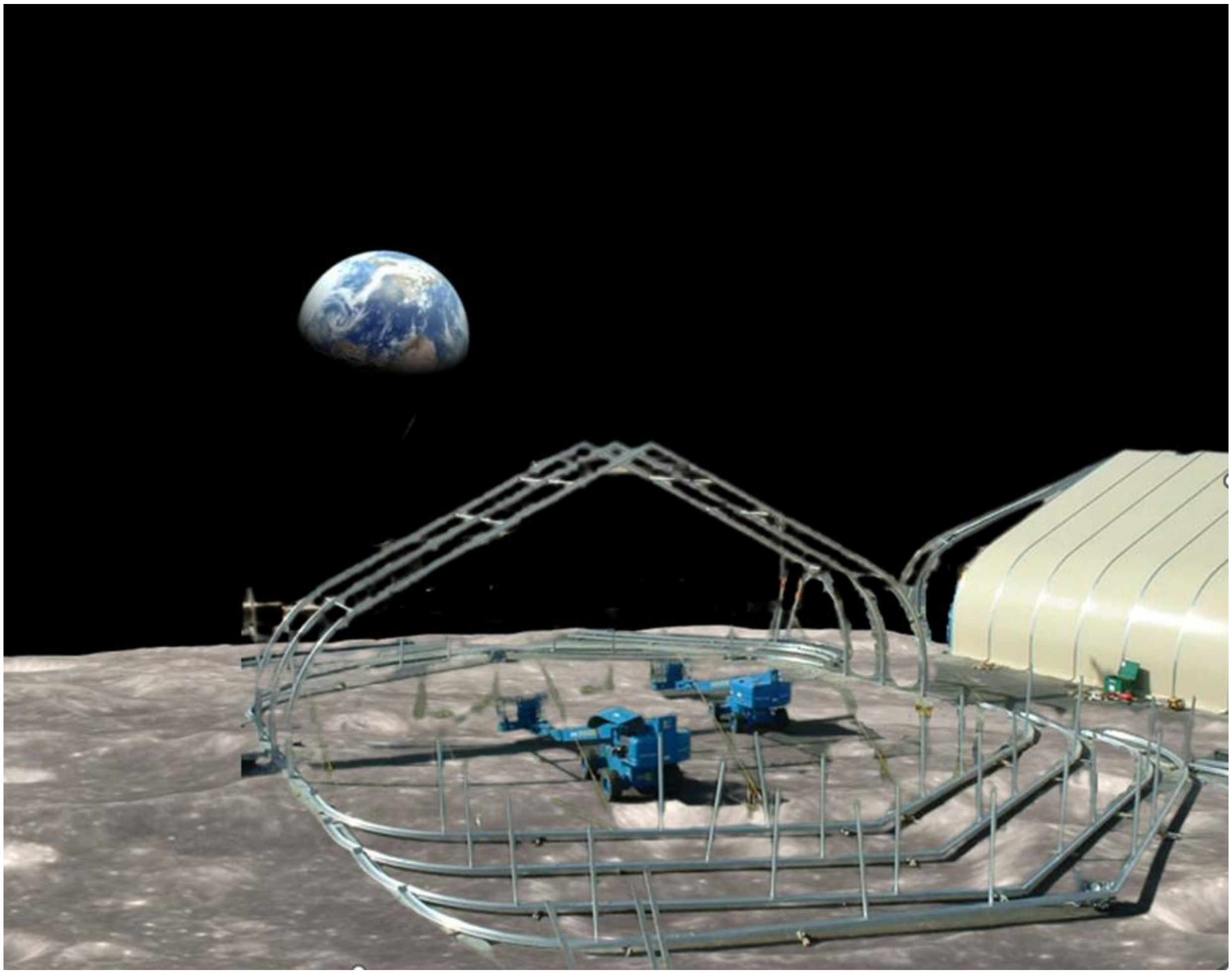


Figure 11. The HALIE hybrid concept proposes to adapt the established and proven SPRUNG technology to erect thermal and micrometeoritic shelter over a pressurized membrane habitat on the Moon to provide early initial operational capability for Artemis crew.

IV) Concept Definition

Using heritage technology greatly reduces risk and shortens timelines. The proposed concept suggests manufacturing kits of components here on Earth that will be assembled on the lunar surface using autonomous rovers. These kits will include easily erectable structures that will form the outer habitat layers, consisting of a dual-layer (Whipple) unpressurized structure to provide MMOD protection, radiation shielding, and thermal insulation. Along with an easily erectable outer structure, the habitat will consist of an inflatable, pressurized inner structure for life sustainment. This inner structure can rely on the outer shell for structural support, as well. These two combined will provide the main structures of the lunar surface habitat. This hybrid approach massively simplifies the construction process which allows for rapid deployment and outfitting. [Figure 11]

The manufacturing capabilities on Earth offer a reliable method for ensuring proper design of systems and subsystems for habitats, and have demonstrated success in the development of spacecraft, space station modules, and lunar landers and rovers. Without needing to launch fully assembled, this approach produces more lightweight components that enable soft stowing in the launch vehicle to provide savings in the form of mass and volume, as well as enhanced load attenuation. Autonomous construction has gained large amounts of traction for large-scale projects in many cities and has proven effectiveness in a variety of projects [11]. They have demonstrated the ability to quickly erect structures using AI learning techniques to enable near to full autonomous operations. Before launching to the lunar surface, these robots can simulate on Earth building the exact structures that they will erect on the lunar surface. This concept has been explored for lunar applications, with the Artificial Neural Tissue (ANT) approach applied to multirobot excavation for lunar base preparation tasks including clearing landing pads and burying of habitat modules [23]. These robots were able to excavate a terrain to match a given three-dimensional blueprint with minimal human input, ideal for IOC construction. Because the rovers start with little pre-programmed knowledge, the controllers discover creative techniques and learn on their own. This autonomous capability enables quicker and safer construction by limiting human reliance. Easily erectable structures are also a verified concept in terrestrial construction, as demonstrated by the company SPRUNG, which offers highly robust buildings that are efficiently erected using similar kits [15]. The modularity also enables future expansion capabilities. These kits are erected in a manner of days or weeks (depending on size) and have been used in some of the most extreme environments on Earth. Overall, these erectable structures offer rapid construction, design flexibility, performance and durability, and lower overall costs.

Inflatables have also gained traction in the space community, as they can also be stowed in a compact configuration and expanded/assembled once at their destination. This technology provides the easiest method for quickly producing a pressurized habitat rather than attempting to assemble one complete structure for all functions. The pressurized inner layer will also be launched with a stowed airlock to be attached on surface, enabling crew transfer for EVA purposes. Immediate deployment via rover provides instant shelter for incoming astronauts with high reliability and little production time. Inflatable habitats also have validated on orbit use, as seen by BEAM [12]. Once the structure has been erected and inflated, crew can perform checkouts and any final operations the autonomous robots are incapable of. The mission for this construction consists of two phases. First, autonomous rovers will perform initial site preparation including excavating and leveling. Then, a 2 week-long expedition to the lunar surface using a heavy launch vehicle containing erectable kits, inflatable habitat and airlocks, and crew for additional supervision of the robotic assembly and parallel EVAs.

V) General Concept of Operations

a) Initial Landing and Unloading

The initial phase of this concept begins with launching a vehicle containing autonomous rovers and supporting equipment. Once landed on the lunar surface, the rovers will conduct an initial survey of the building site. Using preprogrammed blueprints and on surface learning techniques, the rovers will begin surface preparation, including dust clearing and platform erection at the most optimal site. This will provide a lunar demonstration of the rovers’ capabilities before the crew arrives at the site.

b) Inflatable and Erectable Construction

Once the rovers have demonstrated their ability to function remotely, the next phase with the erectable kit and inflatable inner module will launch with an accompanying crew. Once unpacked from the landing vehicle, the autonomous rovers can then begin the assembling process at the chosen site location. The inflatable can also be unloaded and placed within the external shell to be inflated once outer construction concludes. The assembling of the structure will be done using the learning techniques developed terrestrially and built upon during lunar surface operations. This can be aided by an external camera system, as well as crew input. Once all pieces of the external structure have been assembled, the internal inflatable can begin pressurization. This inflatable structure will also connect to an airlock units on each end for crew access. [Figure 12]

c) Crew Functional Checkouts

Following the completion of the erectable and inflatable structures, the crew will perform functional checkouts to verify that the structures were built correctly and the life support system functions sufficiently. The rovers will be responsible for large scale assembly and creating the "backbone" of the structures and placement of the inflatable habitat, while the crews will be able to perform more detailed installation once the life support system is sustaining. This includes suited Once pressure and habitability is verified, unsuited operations will be available. Thus, once all checkouts and final additions are made, the habitat will reach initial operational capability. A plan for this phased approach of this concept of operations is outlined below.[Figure 12]

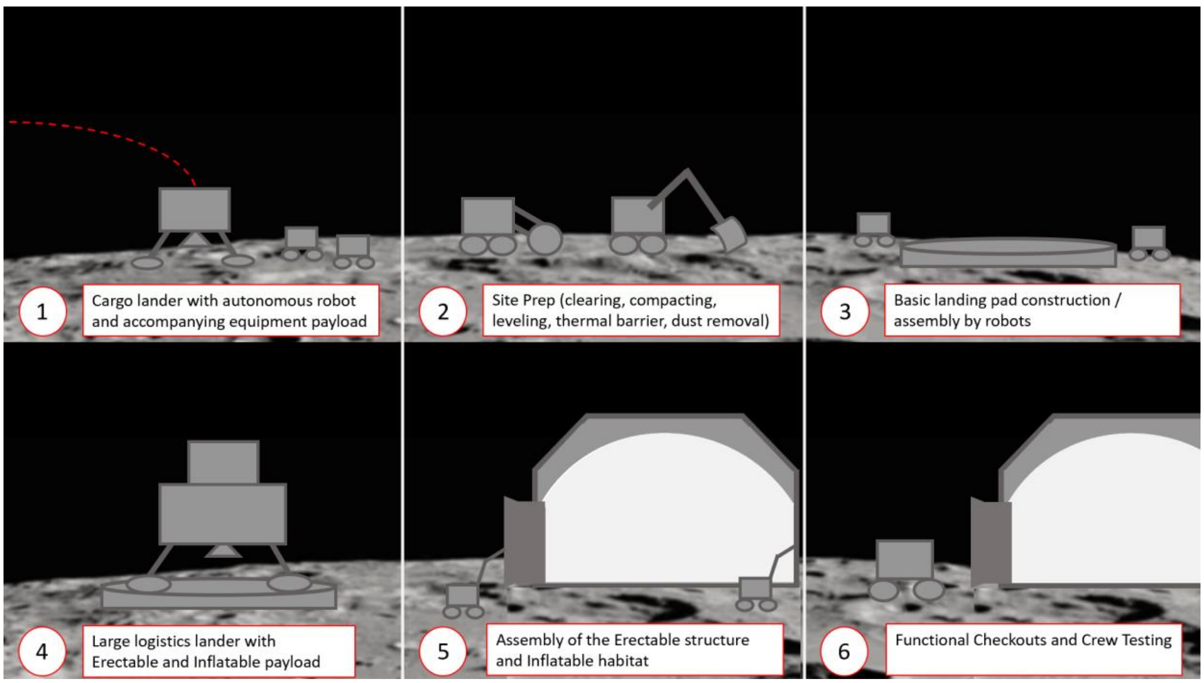


Figure 12. Step-by-step approach of hybrid construction concept of operations.

VI) Conclusion

While many existing lunar habitat concepts exist, the proposed HALIE concept achieves a method for rapidly building up habitable spaces that utilizes existing technology that can be incorporated in the near-term. All portions of habitat construction can be tested here on Earth before launching to the lunar surface, ensuring a higher probability of mission success. Creating easily erectable kits decreases the required up-mass of the system as engineering complete structures to high loads is not as necessary. Remote or automated operational capabilities, as possessed in ISRU construction, are still utilized using automated rovers. Though, this hybrid approach does not need specific minerals or location on the surface and can thus be built at any site. Incorporating crew at the end of the construction process for system checkouts also adds safety as the brunt of the work is achieved robotically. Thus, the Hybrid Approach to Lunar Inflatables and Erectables (HALIE) concept proposes an efficient, effective, and practical method for early-phase lunar habitat deployment and development.

VII) Acknowledgements

This concept architecture was created and developed in the ASTE527 graduate Space System Architecting Studio aka Space Exploration Concept Synthesis Studio in the department of Astronautical Engineering within the Viterbi School of Engineering at the University of Southern California. Original concept presentation of the RALIES project may be accessed at:

[ASTE 527 Home - 2022 - CHASE (google.com)]

Thanks are due to all the discussions, creative lectures, participants and reviewers who helped shape the RALIES concept. Further detailed trades are warranted. NASA partnership is invited to pursue this concept further.

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