MOON EXPLORATION HABITAT USING IN-SITU SULFUR CONCRETE
V. Sumini and C. Chesi

ABSTRACT: Concepts for space exploration habitats have been proposed since longtime before the dawn of the space age. Twenty years after the original manned Moon landing, a group of scientists and engineers at the Johnson Space Center (JSC) started to consider the return to the Moon for living purposes. Since 1986, several types of structures have been proposed for both Moon and Mars concept settlements. The possibility of utilizing unprocessed or minimally processed in-situ materials for these structures, as well as for shielding from the cosmic radiations, may be possible by adopting and extending terrestrial techniques developed for harsh environments. Therefore, this research leads to evaluate the structural performance of a possible Moon architecture layout thanks to the recent discoveries related to the possibility of using in-situ materials, such as the Moon regolith. In this paper, an architectural layout is proposed for a human habitat on Moon; specifically, shells structures are designed, making use of mixed and self-assembled regolith, thanks also to robotic fabrication processes (such as 3D printers).

1 INTRODUCTION

Space missions have always focused their interest on scientific and commercial goals to be exploited by humans, strongly placed on Earth. This research proposal tries widening this point of view, developing a space program concept that sees the humans moved in space, becoming themselves the payload and the goal of the space mission itself.

The aim of the project is the analysis and the design of an interplanetary Space Habitat on the Moon. Studying this project feasibility completely upsets the classical space mission targets and requirements: in this case, comfort and users-customers' satisfaction are the must. When dealing with space missions, the most important aspects to be considered are: technology, safety, and costs. As an addiction to these ones, a habitat project can increase the relevance of other aspects such as ergonomics, psychological and physical problems and all the aspects related to human wellbeing in a hostile environment.

Concepts for space exploration habitats have been proposed since longtime before the dawn of the space age. Twenty years after the original manned Moon landing, a group of scientists and engineers at the Johnson Space Center (JSC) started to consider the return to the Moon. The return would not be merely to explore but to learn to live and work on another planetary surface.

Since 1986, a number of concepts for going to the Moon, living on its surface and adapting to its unique environment have been developed at JSC. Significant studies have been developed and several types of structures have been proposed for both Moon and Mars concept settlements. The first step of the analysis is the identification of the main constraints and their influence over the entire project.

The Lunar environment analysis leads to the habitat subsystems sizing and to the settlement location selection. The hostile characteristics are linked with the development of shielding and protection systems and with in-situ resources utilization. Moreover, there are many environmental factors affecting lunar structural design and construction, such as: one-sixth g, the need for internal air pressurization of habitation related structures, the requirement for shielding against radiation and micrometeorites, the hard vacuum and its effects on some exotic materials, a significant dust mitigation problem for ma-

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chines and airlocks, severe temperatures and temperature gradients, and numerous loading conditions—anticipated and accidental. The structure on the Moon must be maintainable, functional, compatible, easily constructed, and made of as much local materials as possible. A mission costs analysis with the payload fairing volume constraint precedes the identification of the best modules layout in terms of number, size, shape and materials. The transportation of modules creates different constraints on the design. The weight is limited by the capacity of the launcher fairing. The geometry constraints are due to the launcher payload volume. An extended study related to a possible Moon habitat has already been developed during the interdisciplinary project thesis at Alta Scuola Politecnica, where the goal was designing a Space Hotel on the Moon environment (M. Kinran, U. Melia, L. Milani, A. Minelli, V. Sumini, *Space Hotel Design: Moorea Moon Resort Architecture*. Advisor: Prof. Michèle Lavagna – Politecnico di Milano, Dept. of Science and Aerospace Technology).

2 DESIGNING A LUNAR HABITAT

2.1 Environmental requirements

Designing a structure for construction on the lunar surface includes several topics, such as: the relationships between severe lunar temperature cycles and structural and material fatigue (this problem is related to exposed structures); the structural sensitivity to temperature differentials between different sections of the same component; the very low-temperature effects and the possibility of brittle fractures; the out-gassing for exposed steels and other effects of high vacuum on steel, alloys, and advanced materials; the factors of safety; the reliability (and risk) which must be major components for lunar structures as they are for significant Earth structures; the dead loads/live loads under lunar gravity; the buckling, stiffening, bracing requirements for lunar structures, which will be internallpressurized; consideration of new failure modes such as those due to high-velocity micrometeorite impacts and the selection of a proper site for a lunar astronomical facility (for example, choosing a polar location would include the possibility to have half sky continuously visible). Another crucial aspect of a lunar structural design involves an evaluation of the total life cycle that is, taking a system from conception through retirement and disposition or the recycling of the system and its components. Many factors affecting system life cannot be predicted due to the nature of the lunar environment and the inability to realistically assess the system before it is built and utilized. Any lunar structure will be designed for and built with the following prime considerations:

- Safety and reliability: human safety and the minimization of risk to "acceptable" levels are always at the top of the list of considerations for any engineering project. The Moon offers new challenges to the engineering designer. Minimization of risk implies in particular structural redundancy, and when all else fails, easy escape for the inhabitants. The key word is "acceptable." It is a subjective consideration, deeply rooted in economics. Such questions go beyond engineering considerations and must include policy considerations: Can we afford to fail?
- One-sixth-g gravity: a structure will have six times the weight bearing capacity on the Moon as on the Earth. Or, to support a certain loading condition, one-sixth of the load bearing strength is required on the Moon as on the Earth. In order to maximize the utility of concepts developed for lunar structural design, mass-based rather than weight-based criteria should be the approach of lunar structural engineers. All of NASA's calculations have been done in [kg-force] rather than [N]. Calculations are always without the gravity component; use [kgf/cm²] as pressure, for example. A note against assuming
that less gravity means a footing can support more load: if soil can be assumed to be linearly elastic, then the elastic modulus is not affected by gravity. However, the load bearing capacity of a real soil depends on the confining stress around it. If the soil surrounding the point of interest is heavier because of a larger gravity, the confining stress would be higher and the soil at the point of interest can support a higher load without collapsing. Lunar soil (regolith) mechanics has been exhaustively explored in the 1970s.

- Internal air pressurization: the lunar structure will be a life-supporting closed environment. It will enclose a pressurized volume with an internal pressure of $6.9 \times 10^4$ to $10.3 \times 10^4$ Pa. The enclosure structure must contain this pressure, and must be designed to be "failsafe" against catastrophic events and decompression caused by accidental and natural impacts. Internal pressurization offers challenges to all lunar structures, but especially the inflatable concept.

- Shielding: the structure has to be able to shield against the types of hazards found on the lunar surface: continuous solar/cosmic radiations, meteorites impact, and extreme variations in temperature and radiation. In the likely situation that a layer of regolith (lunar soil) is placed atop the structure for shielding, the added weight would only partially (in the range of 10-20%) balance the forces on the structure due to internal pressurization mentioned above. In addition to general shielding, special radiation shelters will be needed during periods of increased solar activity. Shielding against micrometeorites impact is done by providing dense and heavy materials, in this case compacted regolith, to absorb the kinetic energy. Lunar rocks would be more effective than regolith because of their fracture toughness, but rocks are more difficult to obtain and much more difficult to place atop surface structures. Some suggest that for shielding purposes alone, it is better to design and place human-rated structures underground even if it is more expensive. Much effort has been devoted to determining the damage effects on human beings and electronics components resulting from nuclear weapon detonation and little is being done to determine long-term sustainable low-level radiation effects, such as those that would be encountered on the Moon. According to Silberberg, during the times of low solar activity, the annual dose-equivalent on humans on the exposed lunar surface may be about 0.3 Sv and the dose-equivalent over an 11-year solar cycle is about 10 Sv, with most of the particles arriving in one or two gigantic fares lasting one to two days. It appears that at least 2.5 m of regolith cover would be required to keep the annual dose of radiation at 0.05 Sv, which is the allowable exposure limit for radiation workers (0.005 Sv for the general public). Moreover, in recent years, there is a move away from silicon and germanium-based electronic components towards the use of gallium arsenide.

Lower current and voltage demand, and miniaturization of electronic components and machines would make devices more radiation hardened. Radiation transport codes can be used to simulate cosmic radiation effects since it is not possible to do that in the laboratory. One such code that has been found to be effective is MCNP6 developed at the Los Alamos National Laboratory.

- Vacuum: the Moon is surrounded by a hard vacuum. This fact precludes the use of certain materials that may not be chemically or molecularly stable under such conditions. One of the main problems of constructing in a vacuum is the possibility of outgassing of oil, vapors, and lubricants from pneumatic systems. Hydraulic systems are not used in space for this reason. The outgassing is detrimental to astronomical mirrors, solar panels, and any other moving machine parts because they tend to cause dust particles to form pods. Another problem is that surface-to-surface contact becomes much more abrasive because of the absence of atmosphere. The increase in dynamic friction would cause fusion at the interfaces (a drill bit fusing with the lunar rock). This is of course aggravated by the fact that the vacuum is a bad conductor of heat. Blasting in a vacuum is another interesting problem to consider. When the explosive in a blast hole is red, it is transformed into a gas, the pressure of which may sometimes exceed 100,000 terrestrial atmospheres. How this would affect the area around the blast on the Moon.
and the impact of eject resulting from the blast is difficult to predict. Keeping in mind that a particle set in motion from the firing of a rocket from a lander could theoretically travel half way around the Moon, the effects of surface blasting on the Moon would be something to be concerned about.

- Dust: The lunar surface has a layer of fine particles that are disturbed and placed into suspension easily. These particles cling to all surfaces and pose serious challenges for the utility of construction equipment, air locks, and all exposed surfaces. Lunar dust consists of pulverized regolith and appears to be charged. The charge may be from the fractured crystalline structure of the material or it may be of a superficial nature, for example, charged particles from the solar wind attaching themselves to the dust particles. It was reported that the dust particles levitated at the lunar terminator (line between lunar day and lunar night) may be due to a change in polarity of the superficial materials.

- Ease of construction: The remoteness of the lunar site, in conjunction with the high costs associated with launches from Earth, suggests that lunar structures be designed for ease of construction so that the extravehicular activity of the astronaut construction team is minimized. Construction components must be practical and, in a sense, modular, in order to minimize local fabrication for initial structural outposts. More detail is provided in a subsequent section on construction.

- Use of local materials: This is to be viewed as extremely important in the long-term view of extraterrestrial habitation. But feasibility will have to wait until a minimal presence has been established on the Moon. Initial lunar structures will be transported for the most part in components from the Earth. The use of local resources, normally referred to as ISRU (in situ resource utilization) is a topic that has been studied, now more intensely because of the possibility of actually establishing human presence on the Moon, Near-earth-orbit (NEO) and Mars.

- Water on the Moon: In a recent development, it appears that there may be water-ice in some craters near the poles of the Moon. It was suggested that water/water-laden comets and asteroids may have deposited the water. If water exists in those craters, the moisture distribution may consist of water-ice mixing with the regolith to saturation or near saturation. The Lunar Prospector Mission team indicated that the moisture content in the regolith at the bottom of the crater might be between 0.3% and 1%. Lunar environment poses also a series of constraints on the infrastructures configuration in particular on the subsystem sizing and definition. Moon surface is characterized by great irregularity, with many craters due to meteorites impacts. Lunar soil is covered by a fragmented material called regolith. The physical characteristics of regolith are similar to terrestrial basalt. Lunar soil has enough static bearing capacity to support virtually all structures and wheeled or tracked vehicles.

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<tr>
<th>Table 1. Moon environment parameters.</th>
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<tr>
<td><strong>Moon environment</strong></td>
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<tr>
<td><strong>Temperature average</strong></td>
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<td><strong>Temperature day</strong></td>
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<td><strong>Temperature night</strong></td>
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<td><strong>Equatorial gravity</strong></td>
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<td><strong>Atmospheric pressure</strong></td>
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<td><strong>Mean distance from Earth</strong></td>
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**2.2 Design requirements**

The concept for the Moon Space Habitat has begun with basic requirements: first and foremost, the habitat needs to be transported to the lunar surface. A modular system that meets the optimal solution (not only thanks to ease of transportability but also because of the convenience of expansion) has been developed. We assume that the scenario of
2030 on which we focus can change in a further future. So in case of any redesign process, new modules can easily be inserted for additional activities, accommodation units and life support systems. The module transportation creates different constraints on the design. The weight is limited by the fairing capacity of the launcher. The geometry constraints are due to the Ares V payload volume. A study has been performed to evaluate habitat module shape, determining the optimal configuration and trying to transport more than one module in the same launch. Another constraint refers to the hotel layout in order to maximize the interfaces between different modules and permit the access to other habitat modules in case of habitat or airlock failure. Therefore, the resulting layout came out analyzing the advantages of an "hive system" as hexagonal shape; in fact, it maximizes the number of connections between different modules minimizing, at the same time, the "dead zones". As a consequence, the final designed shape is an adaptation of this concept to the Ares V payload volume: the hexagon has been modified according to the launcher profile, but maintaining the same connection properties.

**Figure 1. Scheme of modules connections.**

As shown in the Figure 1, each module is connected to the other adjacent ones. The module configuration has been developed to reduce the payload fairing and to increase, at the same time, the organized habitation volume. Consequently, the habitat modules are composed by a rigid part (Wall Organizer Room Management system, W.O.R.M.) and an inflatable one. The shell is designed in order to satisfy the launcher fairing constraints, optimizing its internal volume. Therefore, two modules can be transported together inside Ares V payload fairing. In addition, the circular arch section of the shell solves also a structural problem, as in the arch no bending moments are introduced.

**Figure 2. Architectural drawings of the module.**

The inflatable parts will be deployed and fixed after having shaped the ground. The choice to place the inflatable part of the structure under the ground level responds to the problem that surface-to-surface contact becomes very abrasive in absence of an air lay-
er, such as in the lunar environment. The increase in dynamic friction would cause fusion at the interfaces (a drill bit fusing with the lunar rock). This is of course worsened by the fact that the vacuum is a bad conductor of heat. The pressurized enclosed volume will have an internal pressure of 69 kPa and will be "fail-safe" against catastrophic and other decompression caused by accidental and natural impacts. The internal walls of the inflatable parts are obtained translating and rotating homothetically parts of the module floor. In this way, these walls can be compacted, during the launch, to the WORM, avoiding any lose of internal volume inside the launcher payload fairing.

The structure has to be shielded against solar and cosmic radiations that could create harms or diseases on the lunar surface (radiations can damage DNA and increase the risks of cancer and other maladies). Therefore, a layer of regolith (1 m of thickness) will be placed atop the entire structure. The regolith shell will be realized through the use of robotic fabrication processes (such as 3D printers). At the moment the state of the art, in relation the rapid prototyping of building blocks on the Moon, highlights the research made by Enrico Dini (Monolite Ltd.) who designed a 3D-printer, D-shape technology, and built a section of a Moon outpost (designed by Foster & Partners in close collaboration with Alta-Space) through a regolith simulant. The mechanical properties of the regolith simulant appears very interesting from a structural point of view, as the compression resistance is about 20 N/mm² and the Elastic module is equal to 2350 N/mm². So that, regolith is not too different respect the concrete we are used to realize on Earth.

2.3 Habitat layout

The habitat layout has been designed to host 16 astronauts. Determining the dimensions of a lunar base habitat is a very complex task. Numerous factors like crew size, mission duration and function of the base, influence the necessary habitat size. In this case, each crewmember will spend 5 weeks in the Moon outpost.

![Habitat layout](image)

*Figure 3. Habitat layout.*

The habitable volume (it is interpreted as free volume, excluding volume occupied by equipment and storage) per person considered for developing the project is 70 m³. The modules are classified according to 4 essential tasks as maintenance, logistics, accommodation and leisure. So the diversified modules can be listed as Maintenance Module, Logistic Module, Sleeping Accommodation Module, and Leisure Module. The project
requires four Sleeping Accommodation Module, each one containing four rooms, two Logistic Modules, one Maintenance Module and three Leisure Modules. As a consequence, the habitat is composed by 2 rigid and 8 rigid/inflatable modules which have been transported by 5 Ares V launches. Furthermore an inflatable reception module is successively added. An additional launch will be required to transport the 9 security modules, located at the extremities of each modules row, and 2 rovers.

\[ \text{Figure 4. View of the lunar habitat.} \]

3 MOON HABITAT STRUCTURAL PERFORMANCE

In order to determine the geometry of the module and evaluate its structural behaviour a parametric model of the rigid part of the WORM system has been scripted in Grasshopper© and Karamba©, a visual programming language developed by David Rutten at Robert McNeel & Associates, that runs within the Rhinoceros 3D©. An image of the script has been reported in Fig. 5.

\[ \text{Figure 5. Script implemented in Grasshopper and Karamba.} \]

The script defines the surface discretization in order to assign different steel section properties to the arch system of the WORM. Two different types of loads are applied on the gridshell. The loads applied on the top of the structure are mainly the reduced gravity (1/6 g) and the weight of the regolith layer, 1 meter thick, that covers the entire struc-
ture on top for shielding against cosmic radiations. Therefore, the final load on the external mesh is equal to 3.58 kN/m². Instead, on the floor grishell, the loads are related to a pressurized environment, such as the one on the Earth. Consequently 1.5 kN/m² are considered, as prescribed by Eurocode 0.

Figure 6. WORM gridshell cross sections.

In Fig. 7 the displacement distribution shows that the most challenged part of the structure is the floor system. The maximum displacement value is 0.34 cm that is acceptable considering the span of 8 meters. The stress flow in Fig. 8 highlights that the arch structure is mainly subjected to compression (in red) whereas the floor, due to bending, has also tension stresses (in blue).
Another model has been implemented, considering the possibility to have an inflatable structure on top of the module while maintaining a rigid steel gridshell for the floor system. The dome is considered to be 3D printed in situ, using the regolith as construction material. Therefore, the external grid has been substituted with shell elements, with a thickness of 1 meter. The material properties are the ones of the regolith (as reported in Table 2).

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<th>Regolith</th>
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<tr>
<td><strong>Young’s modulus</strong></td>
<td>2350 N/mm²</td>
</tr>
<tr>
<td><strong>Linear thermal expansion coefficient</strong></td>
<td>$68.3 \times 10^{-6} , ^\circ C^{-1}$</td>
</tr>
<tr>
<td><strong>Compression resistance</strong></td>
<td>20 N/mm²</td>
</tr>
<tr>
<td><strong>Density</strong></td>
<td>2200 kg/m³</td>
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In this analysis the external load is given by reduced gravity while the internal one (on the floor gridshell) is still 1.5 kN/m². In this simulation the shell is subjected to different stress states: compression on the outer level, both compression and tension in the middle one, while tension in the central part of the dome and compression laterally in the inner layer. Where the maximum tension is present in the dome shell, the displacement is about 2.6 cm.
The floor displacement increases (from the previous model) with a maximum deflection of 0.56 cm. From the linear elastic analysis, that considers the regolith as an isotropic material, it appears that the maximum utilization factor in compression is about 2.5% while in tension is 3%. The tension is, therefore, higher than compression and is present in the central part of the dome. Consequently, further analyses on the material performance and mechanical properties of regolith are required in order to estimate its tension resistance. Assuming a resistance similar to the one of stone materials, the solicitation values are relatively low.

4 CONCLUSIONS

This research explores a possible interplanetary habitat, considering the opportunity to use in situ resources, such as the Moon regolith. Two different kinds of numerical models have been implemented in order to understand which could be the lighter structural solution for decreasing the selfweight to be launched from the Earth. Therefore, an entire steel gridshell solution (in which the regolith layer is applied as a permanent load on the structure) is compared to a mixed one, composed by a steel floor structure, an inflatable membrane and a regolith dome (3D printed in situ). The structural performance of the mixed solution appears to be acceptable even if further analyses are required in order to estimate the mechanical properties and the tension resistance of regolith. Concluding, this paper investigates the nowadays highest level of computational design and construction technology trying to export it for establishing an interplanetary human outpost. Moreover, this research could be also extended to Mars, taking into account recent studies related to the sulfur based Martian concrete, that highlight its easy handling, fast curing, high strength, recyclability and adaptability in a dry and cold environment. Quoting J.F. Kennedy at the launch of the Apollo program: “it’s the time to undertake this kind of project not because it is easy, but because it is difficult and this goal will help us to organize and measure the best of our energies and abilities”.

REFERENCES

Campbell, B.A., Campbell, D.B. (2005). Regolith properties in the south polar region of the Moon from 70-cm radar polarimetry, ICARUS.


