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# Self-Deployable Lunar Habitat, Part-1: Overall Architectural Design and Deployment

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**To develop a feasible concept for a long-term lunar architecture inevitably requires developing radiation-shielding capabilities in order to settle other planetary surfaces without magnetic field or atmospheric protection, like those on Earth. The use of in situ material, such as regolith, as well as self-deployable robotic configurations could very well become one of the basic strategies to this matter. Nevertheless, both will require more advance design studies to tackle this complex problem. This first publication, within a paper series that follows the design process of this ongoing project presents the early stage of an innovative architectural approach. The following preliminary conceptual study is based on a self-deployable habitat architecture system that uses three meters-thickness layer of regolith for radiation, micrometeorite and thermal protection purposes and only proven technologies. Requirements and constraints are studied in order to design a fully robotic architectural deployment without requiring any previous extra vehicular activity (EVA). To present the overall design and layout is the primary goal of this paper. However structural details, interior configurations, volume and energy budgets as well as deployment mechanisms are taken into account and they will be presented in detail in coming publications. Current European launcher system Ariane V (fairing) sets the parameters for architectural, volumetric and design constraints. A basic mission definition is also given in order to define working parameters. This line of research that uses flexible elements, low-tech and low-energy principles, robotic in situ resources utilization, and adaptable architectures tackles crucial aspects for future manned missions. Adaptable architecture systems like this one could very well help in reducing mass, energy and volume budgets of future human space exploration missions, becoming a basic approach for sustainable, affordable and adaptable settlements on other celestial bodies.**

## I. Introduction and rational

The construction of habitats on other planetary surfaces[1] such as the Moon have been addressed in different studies in the past decades. From both public (e.g., NASA[2]) as well as and private entities such as Boeing[3] or Biguelow Aerospace[4], this problem has been addressed. Certainly this is a complicated problem that requires an interdisciplinary approach in many levels. At the same time during the last decades there have been several key advancements and studies related to adaptable geometries, for instance by the MIT Kinetic Design Group[5] or the use of textiles elements[6] and inflatables[7] in advance habitat design to mention just a few. Since the amount of information and knowledge these previous projects exceed the scope of this publication, it is assumed the reader has some knowledge about these heritage studies in the field. Hence this study presents a preliminary design study build upon some of those concepts as well as proven technologies coming from other construction and architectural areas. Building a habitat on other planetary surfaces, either class I pre-integrated or class III that uses in situ resources[8] requires dealing with several environmental constraints such as radiation, thermal and micrometeorite issues among many more that following paragraphs will elaborate. Among them perhaps radiation is one of the most complicated issues to address and certainly implies a great amount of technical and scientific development. The use of mass in order to mitigate the effects of radiation is a way to deal with the problem[9]. Nevertheless the use of in situ resources requires most likely advance robotics systems and even more an architectural design that can make use of these resources. The problem of tele-operations due to the distance, limitations in terms of mass and volume (components) that can be launched, or the adaptability to different mission and situations certainly makes this a very complex

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matter. Nevertheless, any solution has to provide the same points stated by Vitruvius centuries ago: function, structure and design. Therefore, building on other celestial bodies is a very specialized approach of the space architecture discipline[10]. In the case of the moon, several strategies can be pointed out among the literature on the topic: the use of craters and lava tubes[11], the construction of structures using lunar regolith such as sintering techniques[12] or 3D concrete printing as well as classic pressurized modules. The project presented in this paper is focused on the architectural aspects of a self-deployable habitat. It is a hybrid concept that uses in situ resources (regolith and gravity force) as well as adaptable architecture. Thus the system can be folded and reconfigured once it reaches its destination so mass and volume budgets are reduced. For this preliminary research study, a technical standpoint is taken and several main issues related to lunar constructions today are tackled; such as: radiation, volume constrains (launching system), weight limitation, robotic integration or adaptable design among many others. How to solve these constraints using innovative concepts but proven technologies is the challenge undertook by this study that is currently under detailed development.

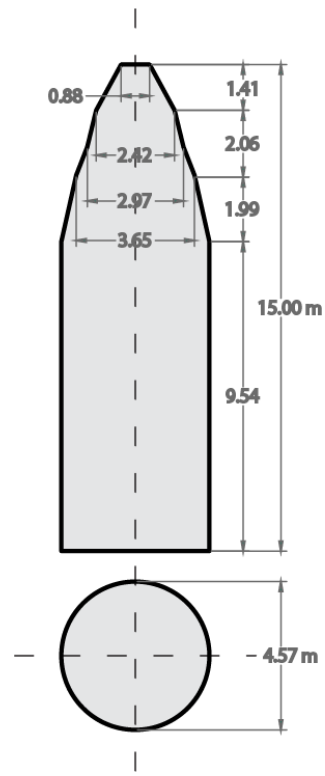


Figure 1Description of Ariane V fairing volume. Measurements are in meters.

## II. Requirements and constraints for a lunar habitat

### A. Launcher and mission architecture

In order to start an architectural and structural study for a long-term habitat on the moon, a mission definition is presented as the starting point with the following requirements:

- Mission: The habitat is launched using one single vehicle. A second launch puts in orbit propulsion and lander units. Once both are in orbit they dock (LEO) and a transfer orbit will send them towards the Moon. Upon arrival, the lander deploys the habitat using a tether system, like the sky crane concept for MSL developed at JPL[13].
- Launch vehicle: Ariane V up to 21 tons of payload[14]. A second launch would be needed for the propulsion systems and lander. The habitat has to fit in one Ariane V fairing volume.
- Crew: 6 astronauts
- Duration: 180 days
- Location: It should be able to adapt to any landing site. It is assumed a sensible flat surface would be chosen.
- Architecture: From the volume within the fairing, the habitat must be unfolded to create an inhabitable volume. Robotic integration and deployment has to be taken into account in this process. The system should not require any previous human presence or activity.
- Operations: It would be tele-operated from Earth and communication systems need to be taken into account.
- Fully autonomous but not fully equipped: Consumables and equipment would be shipped later.
- Analogs: Both technology and concept should be able to be tested on Earth previously (with gravity present)
- Elements: Launcher system (two Ariane V ES), habitat module, propulsion unit and moon lander.

This paper only tackles the most fundamental aspects for the design related to the ability of the folded habitat to survive launch stage, docking process and landing. Adaptors and other parts for the launching process are taken into account but not represented in the graphical documentation.

### B. Lunar environment requirements

Independent from any selected location, the lunar environment presents some specific constraints[14] that the design must address:

- *Radiation:* Major sources of radiation on the moon are high energy galactic cosmic rays (CGR), solar flares, non ionizing sources like UV as well as thermal and visible electromagnetic waves from the Sun. Without the protection of a magnetic field like Earth's, this becomes a major issue in long-term mission on the moon for both humans and electronic devices[15]. Different ways to obtain protection against it are: polymers and water due to the high content of hydrogen, lead and the use of mass as protection, for instance lunar regolith. Radiation dose on the Moon surface is about 30 Rem (30 cSv) and during a solar flare event could be more than 1000 Rem (1000 cSv)[16, 17]. The recommended annual dose for a 30 years old astronaut is 38 Rem (200 life-time limit).

- *Pressure differential*: Moon's atmosphere is very tenuous[18], less than $10^{-13}$ atm, therefore it can be completely neglected[14]. However that means that a pressurized environment needs to sustain the inner pressure from a structural point of view.
- *Extreme temperatures*: A 15 days daylight or darkness conditions are cause by the lunar cycle of 29.53 days. Thermal changes on the surface vary from -53ºC to +100ºC depending on these conditions. This means that structures and materials need to resist extreme conditions: expansion, stress, thermal shocks, etc. will condition the design and selection of materials. Underneath 1 m of regolith the temperature drops to -30ºC, +30ºC [18] reducing thermal problems drastically.
- *Micrometeorites*: With speeds as high as 20 km/s, the impact of even the smallest part could be fatal for a pressurized habitat on the moon. The use of regolith is known to provide multi-shock resistance capability[19].
- *Lunar Gravity*: Gravitational acceleration on the moon (1.62 $m/s^2$) is about one sixth of its value on Earth. Therefore there is gravity stabilization but lesser anchoring effects due to this.
- *Substrate Mechanics*: The regolith is a layer of 5-10 m mostly made of dust and rocks fragments. It has been created over time by meteorite's impacts[15] and other lunar conditions. The bulk density is low in the surface (0.8 – 1.0 $mt/m^3$) and goes up to 1.4 -2.2 $mt/m^3$ below 3 meters in depth. Lunar regolith is very cohesive (0.05 N/cm2) presenting an internal angle of friction[20] around 34º.
- *Dust composition and mechanics*: More than 50% of regolith particles are below 70 micrometers (μm) in diameter. These particles are extremely sticky due to electrostatic forces and some of them are abrasive. This becomes a problem for any kind of mechanical systems[14] and may be hazardous for the astronaut's health.
- *Lunar Tribology*: Friction, lubrication and wear suffer changes in the moon environment due to the hard vacuum, temperature extremes and dust.
- LEO and Orbit-Transfer Environment: Atomic oxygen in the highest parts of the Earth's atmosphere has proven to be very corrosive. Therefore, polymers and epoxy materials need to be protected while crossing the LEO region.
- Isolation: The long distance to Earth, forces to take into account autonomy and adaptability as key aspects in the design, due to the fact that an immediate rescue cannot take place.

### C. Design and architectural constraints

Once the initial requirements where recognized, the next step is based on the subsequent research and creative process. These are some of the requirements added as a consequence to the initial architecture concept:

*1. Radiation and regolith*

Radiation protection is identified as some of the main design drivers. Since the weight is also constraining the launch, a heavy shielding option is not available. Therefore, the use of regolith for radiation shielding is the most feasible approach. Furthermore, this also brings protection for thermal cycles and extremes while it shields against meteorites, bringing structural integrity through ISRU system. In 1992, ESA recommended a shielding of 400 $g/cm^2$ (700 $g/cm^2$) during solar flares. A layer of 2 to 3 meters would suffice, while 4 to 5 meters will protect even during solar flairs. For other authors, a 3 meters thick layer of regolith would be enough to protect against harmful radiation. Therefore 3 meters is an average measure. A layer this thick represents a challenge for the design as well as for the system to fill without human intervention.

The conducted research has shown a variety of project and strategies regarding habitats on the moon. Some examples and strategies are presented in a graphical summary (Figure 2) are the use of: lunar excavated craters and lava tubes[21] for protection, small-deployed hard shell and hybrid inflatable habitat concepts – NASA[22] for habitation or bigger systems.

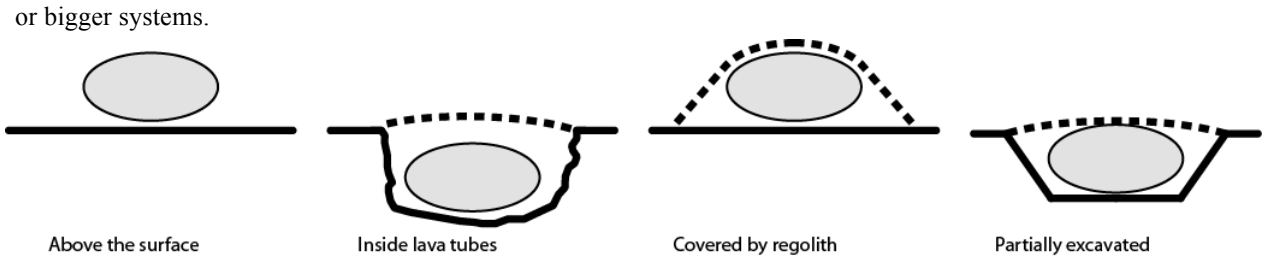



Figure 2. Different options to locate a lunar habitat with regards to a plain surface

*2. Volume*

The selected launch system is the Ariane V SE. The free space (volume) to hold the folded habitat (SDLH) is illustrated in figure 1. This is the biggest fairing available today, however a circumference of 4.5 m represents

another architectural challenge.

*3. Architectural programme*

The system should be expandable using other modules and a modular approach to some of the components like the airlocks. On the other hand the dust and vacuum problems require the inclusion of advanced system for dust control of the inhabited environment and depressurization problems. In order to do so, airlocks that allow direct access to the EVA suits and entryways should be included in the design[23]. From the architectural standpoint, indoor and outdoor spaces should be complemented with intermediate spaces offering partial protection, storage for experiments and goods as well as psychological areas of protection.

*4. Structure*

ISRU approaches include the use of gravity. The system must use gravity as much as it can for the deployment. The structure has to be not only lightweight but also serve a variety of functions. For instance, bearing structures can be also used as deposits and systems storage. The system must also be efficient, for example the internal design of the structure should hold part of its weight as well as the regolith.

*5. Terrain*

The habitat deployment is supposed to occur in a flat or flatten surface. Nevertheless due to the fact that it expands from the original landing area so rocks, small boulders or slight slopes could be present. Figure 3 shows how the structural elements have to adapt to the topography.

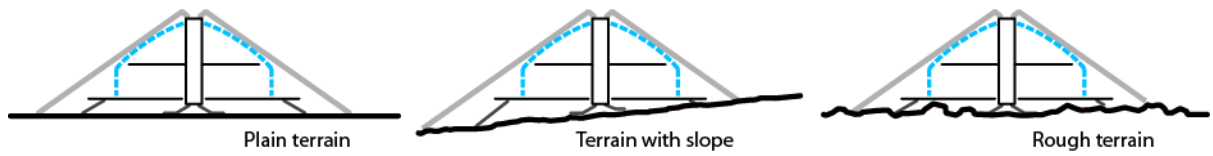



**Figure 1. The sketch shows the adaptability of the concept to any terrain conditions on the lunar surface**

*6. Human Factors*

In a long term mission the design of the architectural concepts need to take into account the creation of adaptable spaces making emphasis on public, semipublic and private spaces. The interior design is not yet part of this study however the volume should create spaces adaptable enough. Entrances, doors and interior volumes should follow long established standards. The distance from ceiling to the floor would be at least 2.5 meters.

*7. Simulation and testing*

The deployment of a habitat like this should be also possible on Earth. The use of regolith could be substituted by sand, earth or even snow for isolation purposes covered or constructed in situ[16, 24].

## III. Architectural constructive design

### A. In situ regolith utilization

After the analysis of the requirements and constraints for the project, the use of lunar regolith (ISRU) for radiation, thermal and micrometeorite protection seems to be the most feasible option. In order to use this in situ regolith on the surface of the moon it is necessary the utilization of a flexible construction element that could hold the regolith. Textiles are one of most efficient option, since they can be folded and cut in any desirable way. Furthermore textiles are very light weighted and durable (tested in space). Therefore some big sacks or bags are designed for this purpose (Fig. 9 and 10).

Nevertheless, the important aspect is to find some basic system to fill those bags with regolith using a very low energy technique that could make use of the partial gravity force on the moon. Archimedes' screws (Fig 4) have been used historically to transfer water and as well as granular materials like cereal grains, sand, etc.

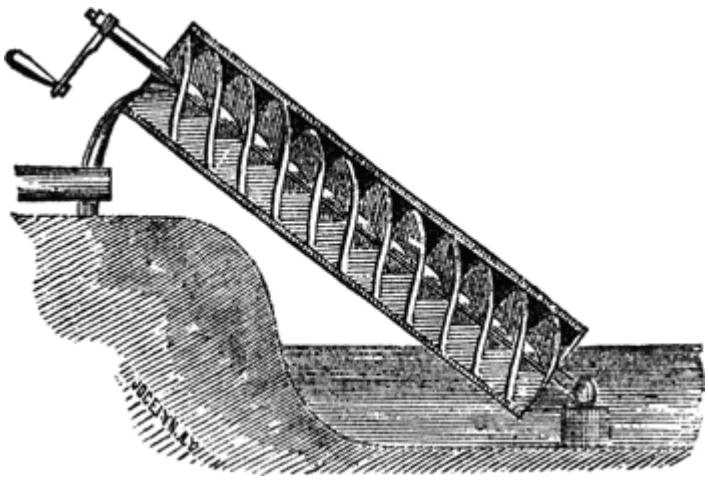


Figure 2. Engraving showing an Archimedes' screw used for lifting fluids and granular materials since long ago. Public domain

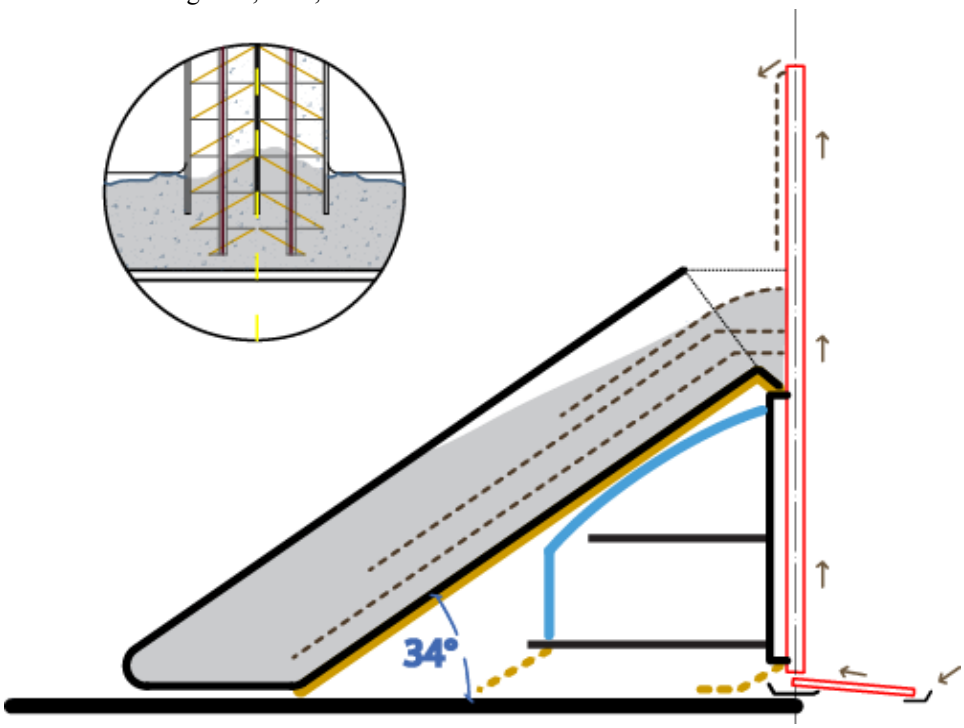



Figure 5. Regolith filling system and architectural constraints for the its design and shape

And its use is well known in civil engineering. This mechanism works only by rotation and gravity, the spiral could be designed to positively use lunar regolith internal angle of friction and tolerances within the pipe. Therefore the mechanism would be integrated in the structural core of the habitat and the process is as follows (Fig. 5).

1. Several rovers integrated in the mission architecture concept could recollect regolith. They can be attached to the landing equipment or sent using another mission. This paper does not develop this area.

2. Rovers pour the regolith into three receptacles, which are deployed before this operation takes place. They are located outside the limits of the regolith bags. Here there is a sieve to control the size of the grain that goes into the pipes.
3. From there, three different pipes equipped with Archimedes' crews transfer the regolith to a central receptacle.
4. Three central pipes (redundancy) integrated in the structural core of the habitat and also equipped with Archimedes' screws elevate the regolith until the upper the part where by gravity it falls down.

On the other hand the filling of the bags is done by gravity, therefore the geometry of the habitat uses the 34º degrees of internal angle of friction to guarantee a smooth filling process. The regolith follows that internal angle of friction, the more regolith there is the more it would push the bags to fill the lower levels. Since there is constant flow of regolith, each layer compresses the lower levels creating a more solid body. The opening in the upper part of the bags also maintains the optimum aperture so the regolith always goes inside the bags. In this sense the habitats covers itself, creating an artificial cave-dove made by three independent vaults (Fig 5). Since the sacks require 3m thick[15] this represents a complex architectural problem to deal with very large volume of 'walls' in comparison with the inside habitable volume. Walls and airlock facing the openings at the main and secondary access have better shielding for radiation. The use of plastic curtains could be a way to reduce radiation through the entrances. However, the openings are minimized to reduce this problem. Better-shielded doors could be placed in the future.

**B. Stowed configuration of the lunar habitat**

Figure 6 shows how the habitat architecture becomes a folded element that's perfectly fits inside the fairing of the Ariane V rocket. The study has taken into account the volume of folded inflatables as well as sacks, so real dimension are being used. The stowed initial configuration of the habitat also allows its deployment using gravity in its advantage. Current research and development of the next design phase is dealing with deploy mechanism and protective parts.

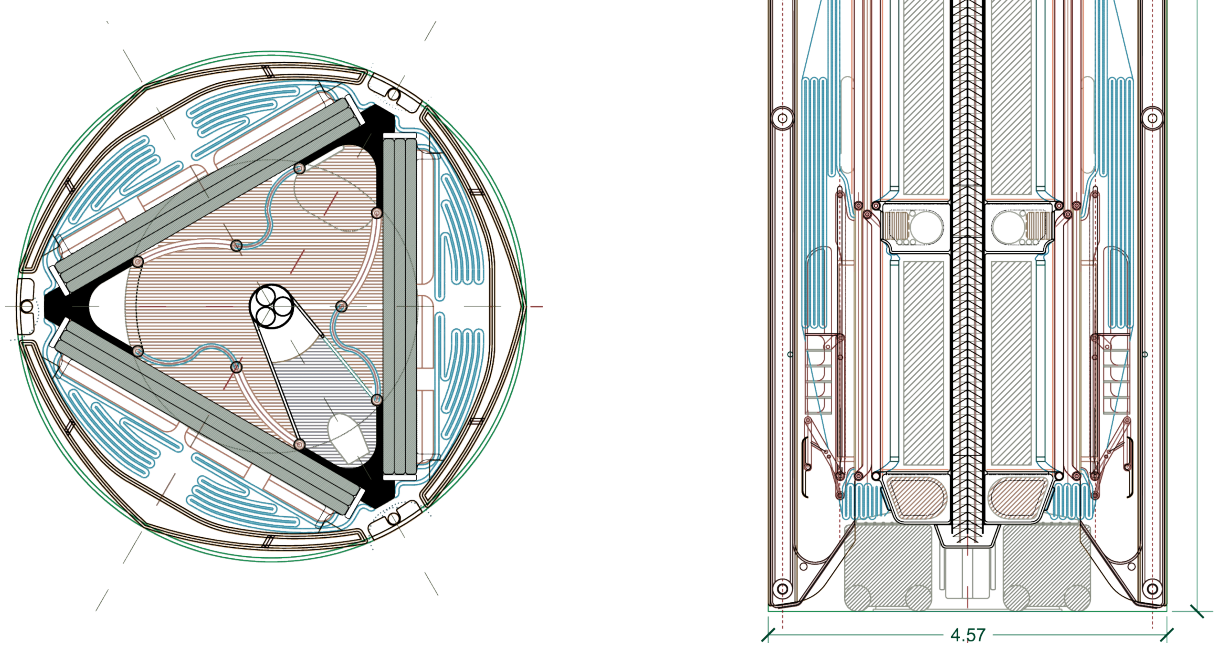



Figure 6.Stowed configuration of the lunar architecture. Measurements are in meters.

## C. Deployment sequence

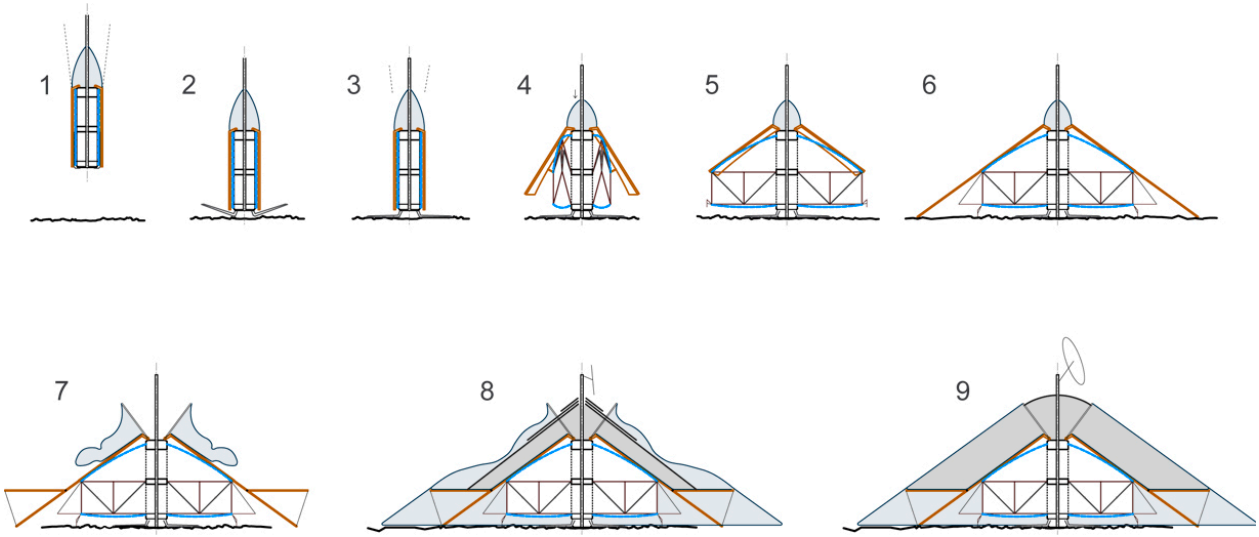



Figure 7. Deployment sequence.

The deployment sequence is presented in Figure 7 as it follows.

1. The habitat approaches the lunar surface using a sky crane type of lander. It hangs from several tethers connected to the lander.
2. Main structural legs are deployed. There are three of them.
3. It lands on the surface and tethers are released.
4. The main internal foldable truss deploys and the vaults are pushed so the habitat opens.
5. Once the main position is reached legs stabilized and level the habitat. Secondary legs on are deployed. The pipes on the core go down as well as the central regolith receptacle. Inflatable walls are also deployed.
6. From the main vaults three internal bodies are deployed using gravity. Once they touch the surface they become a stabilizer for the habitat since they cannot move back. Through them, the load of the regolith on the top of the habitat is transferred to the surface. Secondary parts such us cargo bays are deployed.
7. Regolith sacks are deployed form the upper part of the vaults.
8. The regolith filling process of the sacks starts. The interior of the habitat can be already inhabited.
9. The filling process ends and auxiliary elements like thermal control devices and solar arrays can also be operated.

*1. Structure*

Central composite core, folded floors and walls compose the main structure (fig 7). Three sectors or lobes assure a good structural functioning of the habitat against any possible movement or force. Trusses provide a strong tridimensional lateral support against lateral forces (impacts, sacks on the sides, etc.). Three large surface feet and 2 more points by sector transfer the load to the surface. The structure is made of composite material: Vinilester resin and aramid-carbon fibers for a balance between launch and operational use. Aluminum elements are used for connections and walls. The load is transferred following this sequence: Sacks > Vaults > Inner St. > Truss > Feet. Details on structural behaviors:

- Inflatables: Inflatable surfaces composed of several layers[22] reside between the truss and the sacks. They contain the indoor environment and provide thermal protection, by connecting tubular elements that follow the specific volume. Tight nerves and cables also help to give shape and resistance. The inflatable volumes are only connected to the core and the external wall on each lobe. Therefore, the risk of leaks by the movement is minimized. Division in three sectors allows them to be independent in case of decompression.

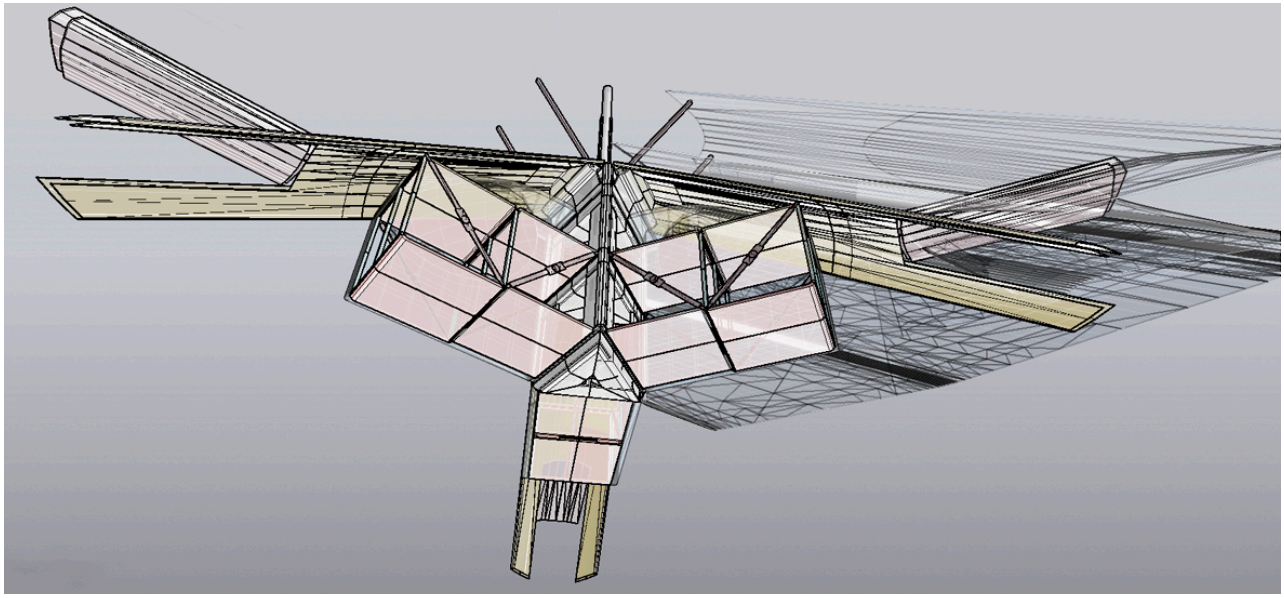


Figure 8. 3D view of the structure seen from the bottom. Sacks are only visible in the right side

- Sacks: The external sacks are made of ceramic fabric. On the inside, there are some composite cables that connect both surfaces, maintaining a specific shape when they are filled. The more the sack is filled, the more rigid it becomes due to the weight. The connection on the top creates an arch vault and allows the weight of the regolith to be partially transferred to the ground through the very same regolith (cohesion is favorable). There are two layers of sacks of 1.5 m thick each one, so the first one can be deployed offering some partial protection, while the second is filled. On the other hand the destruction of the external one by meteorites does not compromise the first layer. The volume of regolith to be collected and poured into the sacks is about 3000m$^3$ .

### D. Deployed configuration of the habitat

Figures 9, 11 and 12 show the volumetric study and basic configuration of the deployed system.

*1. Lower and upper deck layout*

The sectors of the habitat present two levels. The first level (ground floor) is used for working and living spaces, including: access, storage, labs, kitchen, small bathroom, living room and greenhouse, in total 92m$^2$ of public or common areas (see figure 6 on next page). The second level (first floor) is used for more private use and resting. Three main spaces divided in six rooms (although bigger rooms can be made) and a common space for circulation, bathroom (with shower) and systems. This is achieved by a combination of fabrics, inflatable planes and tubes storage in the main core requiring additional work by the astronauts once they arrive.

*2. Cross section and constructive design*

Figures 11 and 12 show measurements and construction details. Inhabited spaces are no shorter than 2.5 m I height. Aisles are no smaller than 0.7 meters in private areas and 0.9 in common areas. Doors and tunnels are at least 2.2 m tall. The section of the folded habitat inside the fairing (Fig. 6), show how the interior doors for the sectors are folded. The central area of the core (triangle) is originally occupied by folded doors and system. Thus, doors can pivot in one side having the other three sides connected by inflatables to the core, recovering that area for human use. Hinge mechanisms and inflatable surfaces hold the doors in position. In figure 11 - detail 1 we can see how the inflatable surface is connected to the external wall. All the mechanisms are within the protective environment of the inside. On the outside, main vaults are connected in several points to the external wall. Therefore the problem of thermal bridges is mitigated by low thermal conductivity of the wall (composite and polymer junction). Details 2 in figure 12 shows the inside of the composite core is used for storage. The core also functions as a big water deposit using this element as extra protection against radiation.

### 3. *Active Systems*

Some of the basic systems such as environmental life support systems (ELSS), thermal control (TCS), water and oxygen storage, dust control airlocks are taken into account. For ECLSS and TCS as well as storage tanks the core provides space for basic systems. More complex operations will require installing part of those systems in the middle space created for that purpose in entrances, greenhouse sector and below the habitat, once it is settled. The cross section (figure 13, double page) presents several key elements such as:

- Radiators are located on the top of the habitat. They are connected to the main tube for regolith deployment purposes. This mast also works as primary structure for the secondary structure systems such as this one.
- Solar panels are radial for an easier deployment. They are connected to the principal mast. Secondary structure actuators allow them to be self-oriented.
- Communication antennas are also connected to the mast.

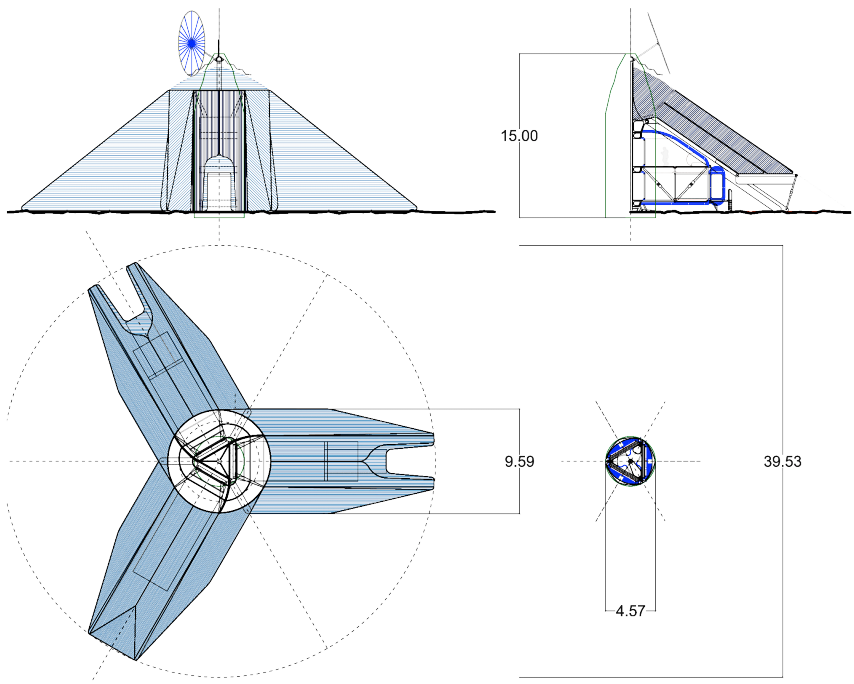



Figure 9. Basic 2D representation of the habitat. Measures are in meters.

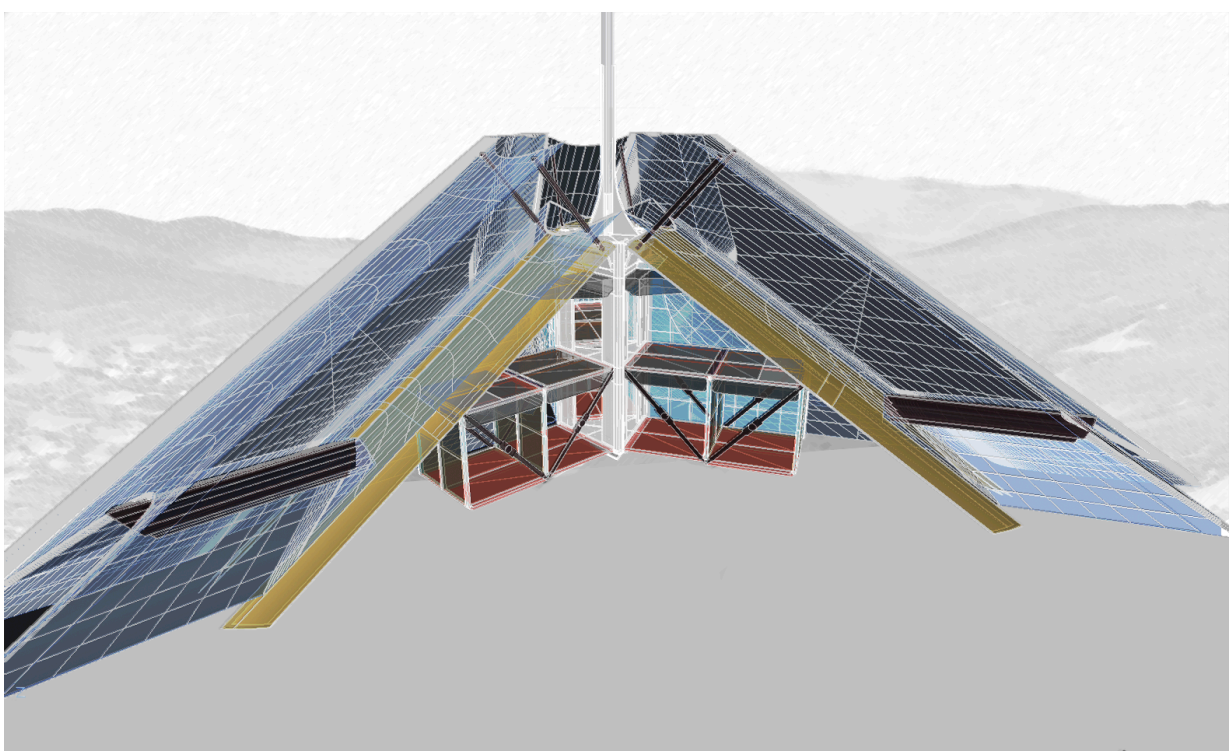


Figure 10. Volumetric study and section of the habitat.

Figure 11. Lower deck plan. Measurements are in meters.

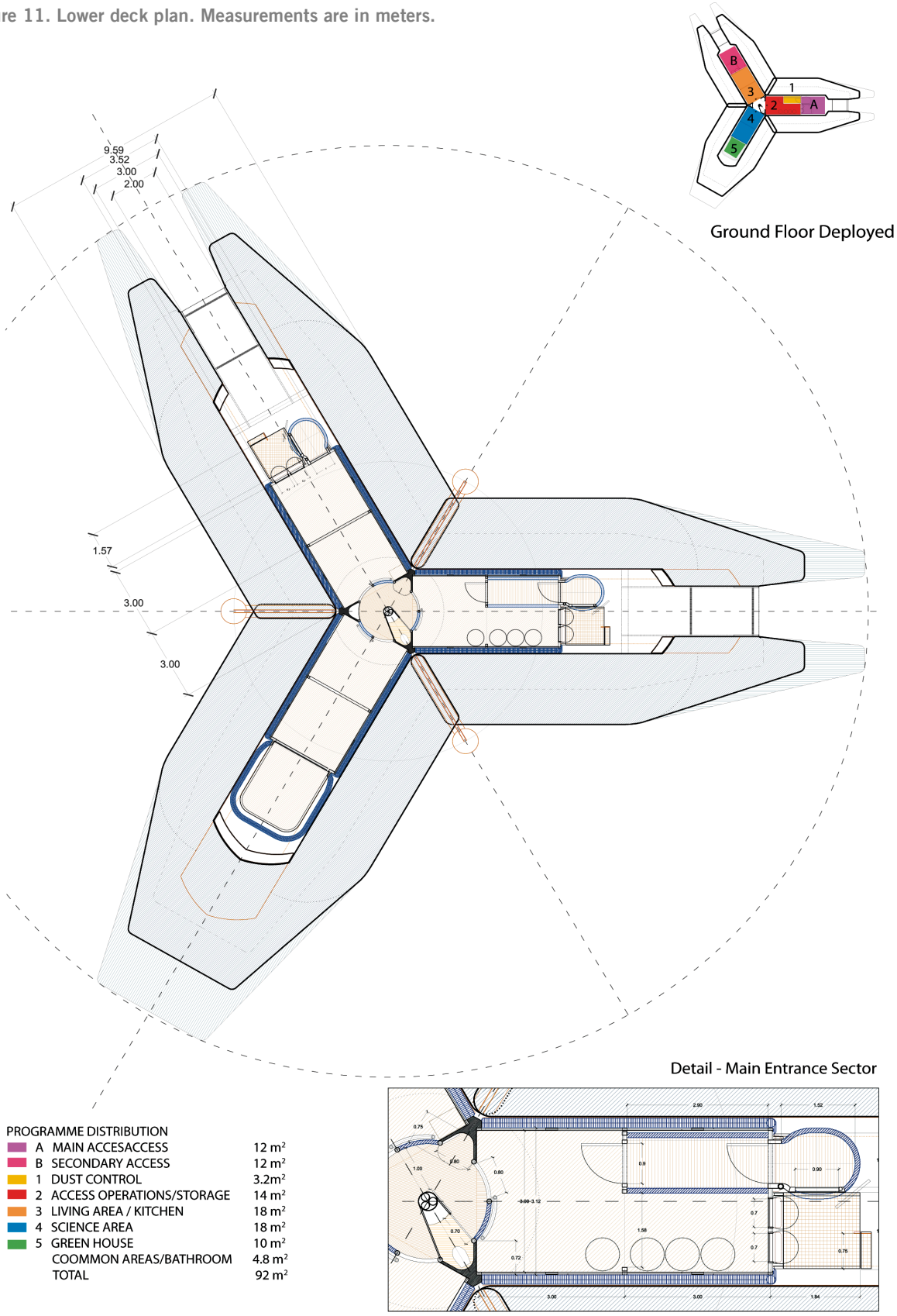


Figure 12. Upper deck plan

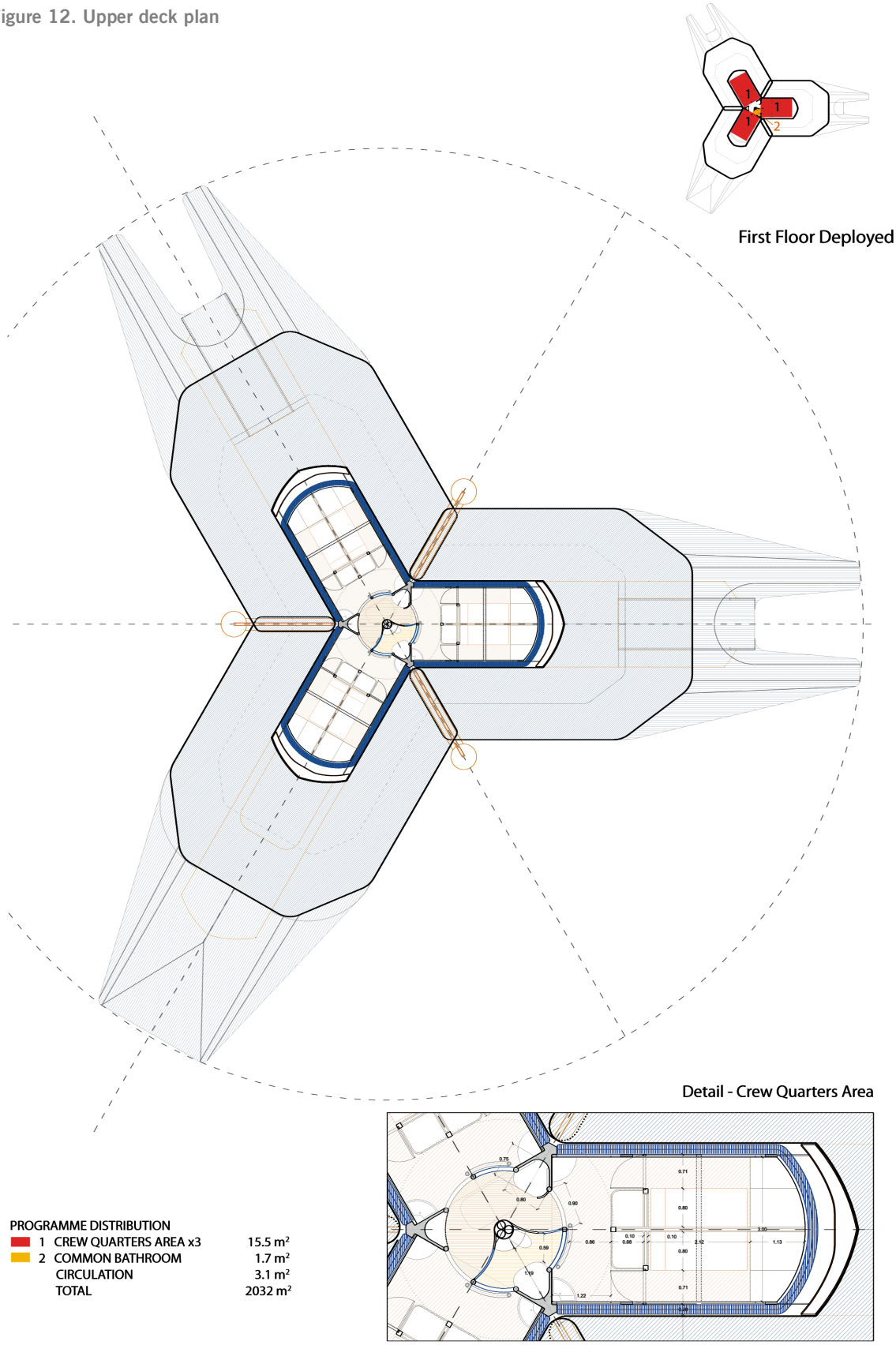
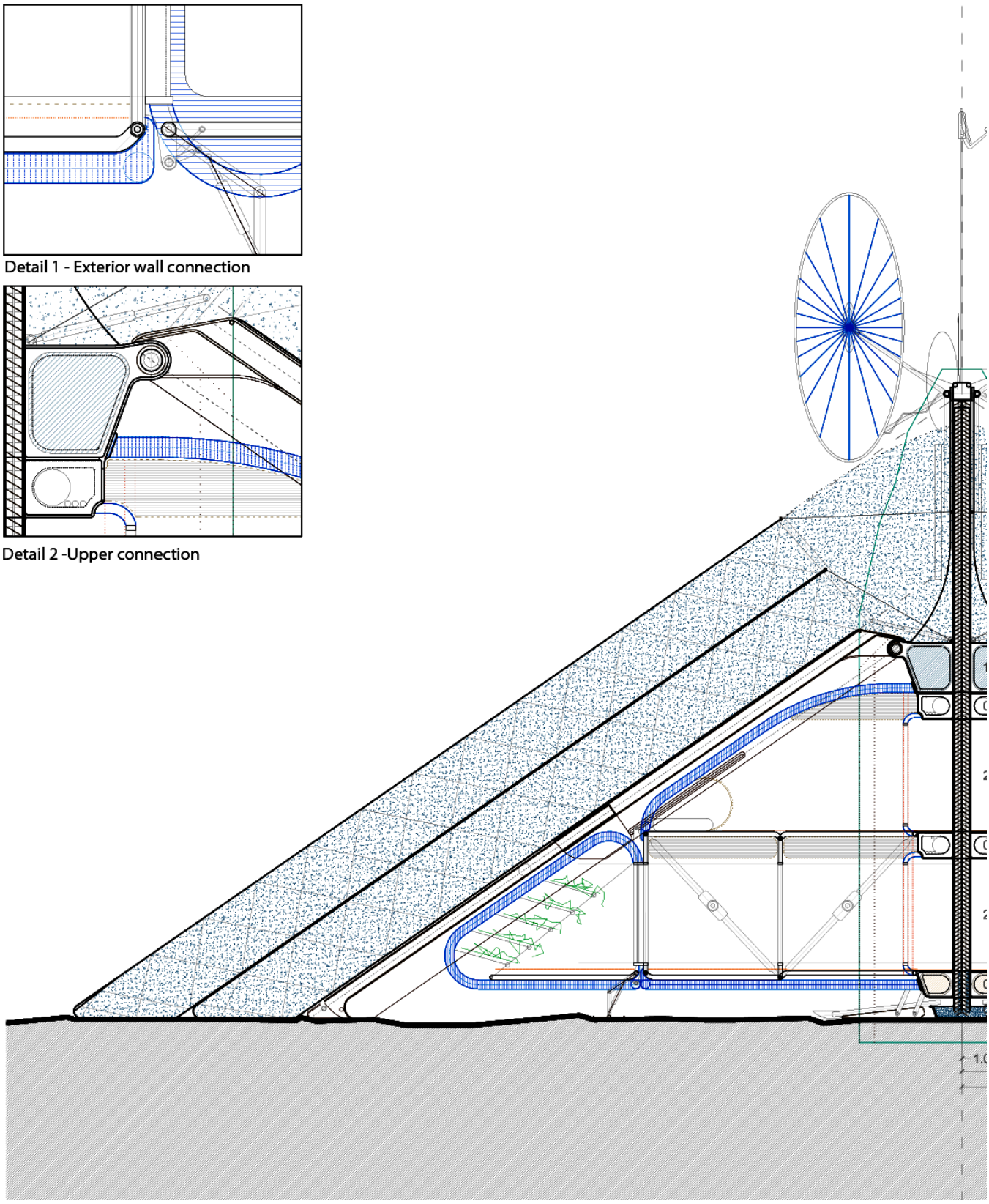
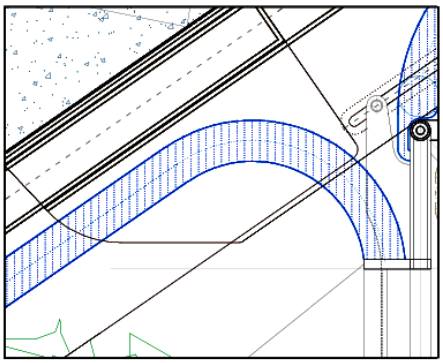
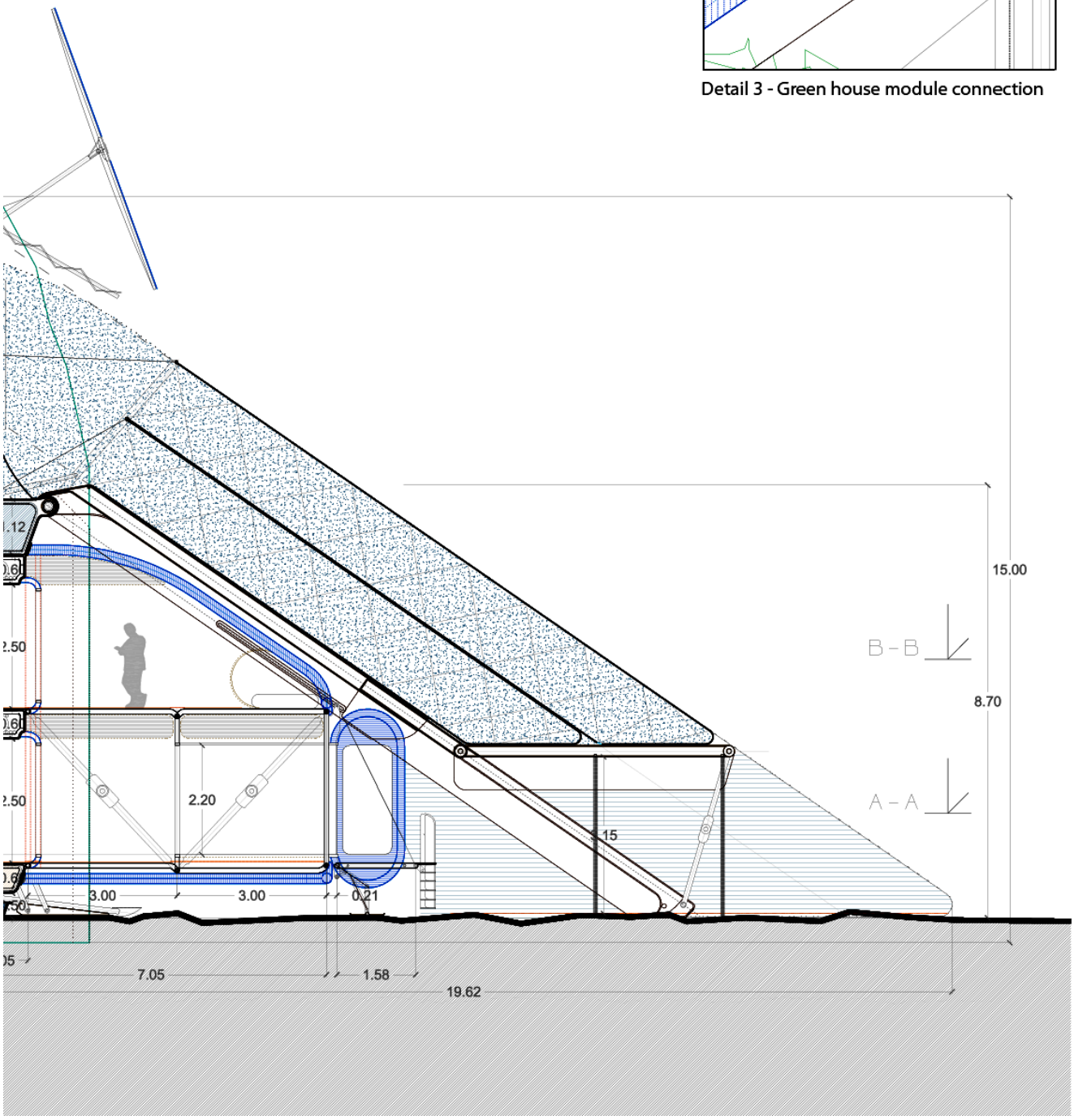


Figure 13. Cross section of the habitat. Measurements are in meters.





Detail 3 - Green house module connection



## IV Conclusion

The analysis of requirements and constraints showed the importance of addressing radiation shielding techniques for a long-term advanced habitat on the Moon surface. For this, the use of in situ regolith as a radiation shield using mass becomes a feasible technique. The architectural design must be adapted to this purpose using robotic assistance. This innovative approach in terms of architectural design, engineering processes and robotic integration for both construction and deployment means that an adaptable architecture should also be required. The preliminary design presented on this paper appears as a feasible concept that can be further developed.

The choice of 3 meters thick wall requires a design which can deal with a large wall volume in comparison to the inhabitable interior. For that matter, not only distributions but also structure and filling system need to be integrated with the habitat environment and design at every level. Since the habitat works as a self-deployment system, the number of elements is limited. Each one of them must be multi-functional. Therefore, rigid elements are combined with fabric and inflatable parts, allowing the initial volume inside the fairing to grow nearly ten times its size. The concept proves to be feasible and further work is being developed to analyze, test and finish its design.

## Acknowledgments (Legal Notes)

The presented research is based on the personal research conducted at ISU by the author while he was a former student of the Master Program 2010-2011. Developing structure, architecture and concept this research was possible thanks to the funds provided by the Caja Madrid Postgraduate International Scholarship. In developing this project I would like to mention Guillaume Tanier, also a former ISU student, who devoted his personal assignment in developing deployment robotic processes and mission design as an independent and complementary study related to this. Author Raul Polit Casillas has develop architectural and structural design, adaptable geometries, human factors and technology concept for this research.

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## Abbreviations

| | |
|---|---|
| *CGR* | *Galactic Cosmic Rays* |
| *ECLSS* | *Environmental Life Support Systems* |
| *ESA* | *European Space Agency* |
| *EVA* | *Extra Vehicular Activity* |
| *ISRU* | *In Situ Resource Utilization* |
| *NASA* | *National Aeronautics and Space Administration* |
| *SDLH* | *Self-Deployable Lunar Habitat* |
| *SLS* | *Space Launch System* |
| *TCS* | *Thermal Control System* |
| *UV* | *Ultraviolet Radiation* |

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