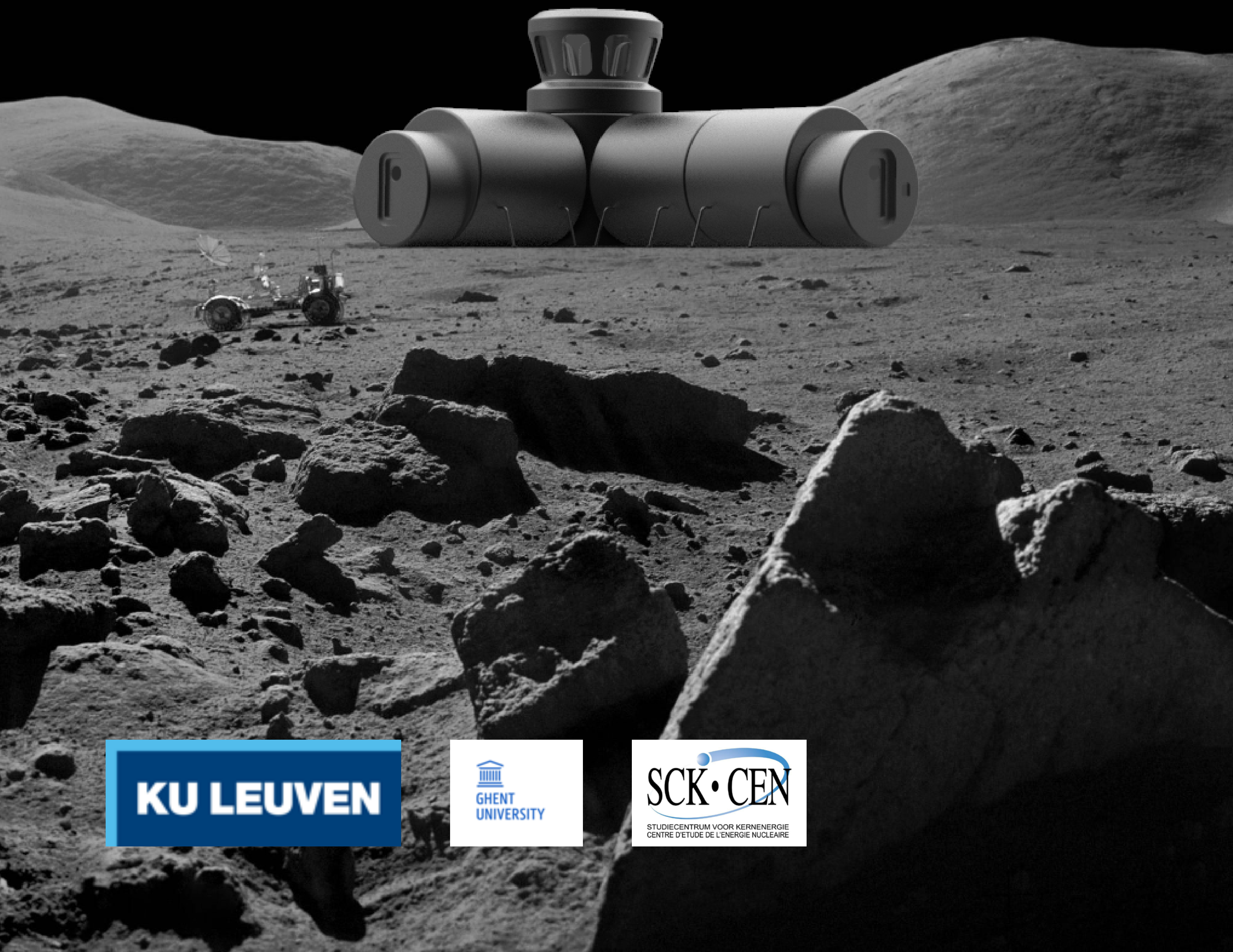
INTERNATIONAL LUNAR OUTPOST

MSc Thesis of Space Studies 2018-2019

Alexander Nieuwborg

Supervisor: Prof. S. Baatout
SCK•CEN – Radiobiology Unit
UGent – Faculty of Bioengineering Sciences
KU Leuven – Institute of Astronomy

Co-supervisor: Dr. M. Moreels
SCK•CEN – Radiobiology Unit



Overview

The vision of the International Lunar Outpost is to build-up a Moon base, in the 2030's, with an heavy emphasis on modularity and expandability. Due to this system, the lunar outpost is gradually build-up, comparable to the ISS, thus providing a realistic, economical and scalable solution. The concept allows for multinational cooperation with modules belonging to for example NASA, ESA and JAXA. Partnering with private industry opens up additional opportunities with modules from SpaceX and Blue Origin contributing to the ever growing outpost.

Although the concept of expandability is not unique, see for example the concept of Grandl (2007) or Bigelow Aerospace (fig. 51), the heavy emphasis and combination with modularity is. Current concepts often present isolated units which have a degree of modularity but these are finite. The ILO should be as expandable as LEGO-bricks thus creating infinite opportunities. By making each module deployable via one launch of a Heavy-Lift Launch Vehicle (HLLV) the financial stays controllable and can be gradually increased. For this project the Falcon Heavy serves as the HLLV but this can change depending of more efficient heavy-lift capabilities in the future.

The first modules will be traditional pre-integrated rigid units since there is extensive experience with them and they provide a solid and safe baseline solution. Systematically new systems can be tested on the lunar surface, such as pre-fabricated and in-situ constructed modules, which is the optimal precursor for operations to Mars.

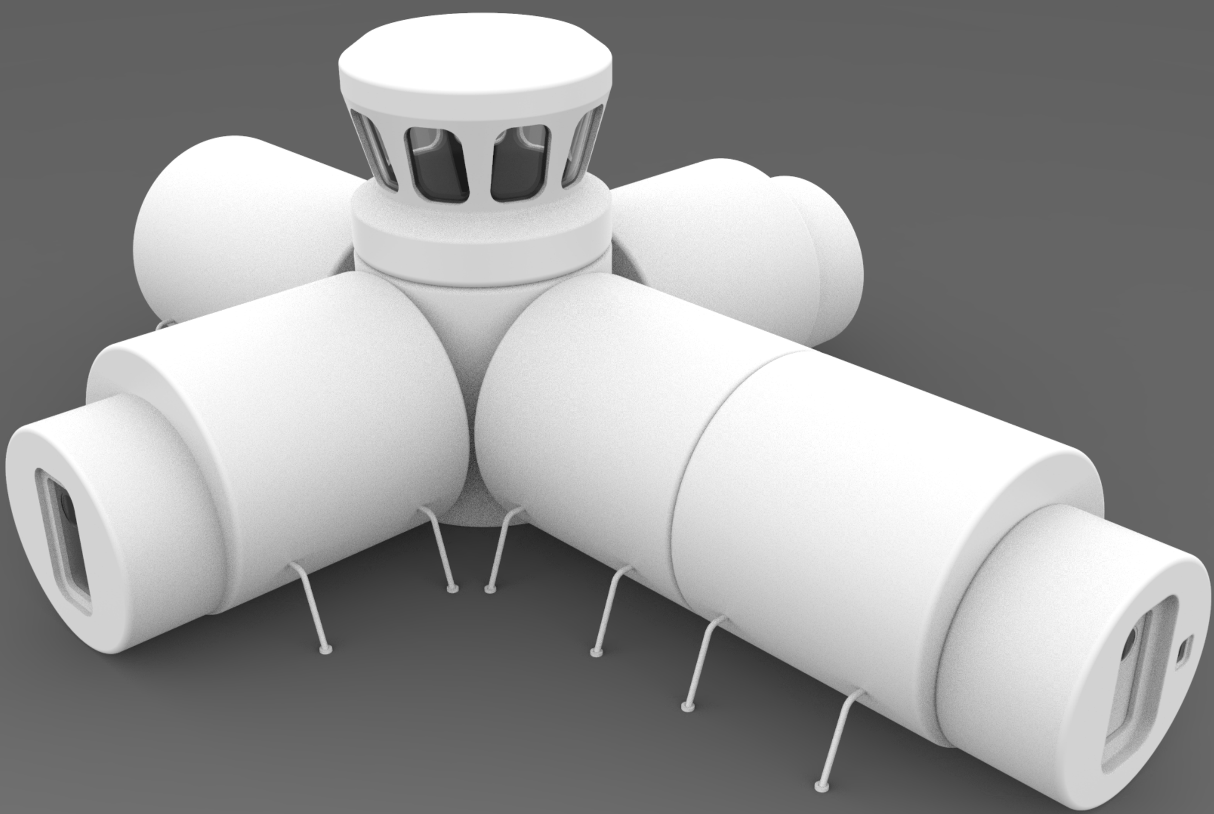


Figure 1. *Early Visualization ILO*

Modules ILO

We propose a combination of three standard modules for the set-up of the outpost. This provides enough possibilities to create a sustainable base for a crew of six. Although the modules have major differences a commonality is essential for cost-effectiveness in for example the interfaces, doors and overall structure. The types are: horizontal, vertical and node module. Note that these are conceptual designs, multiple technical aspects need further development in following design phases.

The baseline horizontal module (fig. 65) has a cylindrical shape with a diameter of 4,6 m and a length of 4,6 m. This fits in the faring of a Falcon Heavy. The baseline horizontal module would predominantly be used as a laboratory or work module. To determine its weight a comparison is made with the ISS's most recent laboratory: the Kibo's pressurized module (JAXA, 2007). This results in a weight of 7,15 ton including all equipment. A similar comparison is made regarding the electrical power. In this case, the module uses 11 kW. Note that these values are estimations based upon technology from the early 2000's. In the context of the ILO a greater efficiency is expected.

All horizontal modules are supported by four adjustable legs which could be deployed from the module itself. At the moment, a rudimentary shape is visualized to point out the importance of this component but further technical development is necessary. Inspiration can be drawn from Moon lander concepts from Lockheed Martin, PT Scientist and Blue Origin.

The internal volume is 50,3 m^3. This is based upon a shell thickness of 30 cm

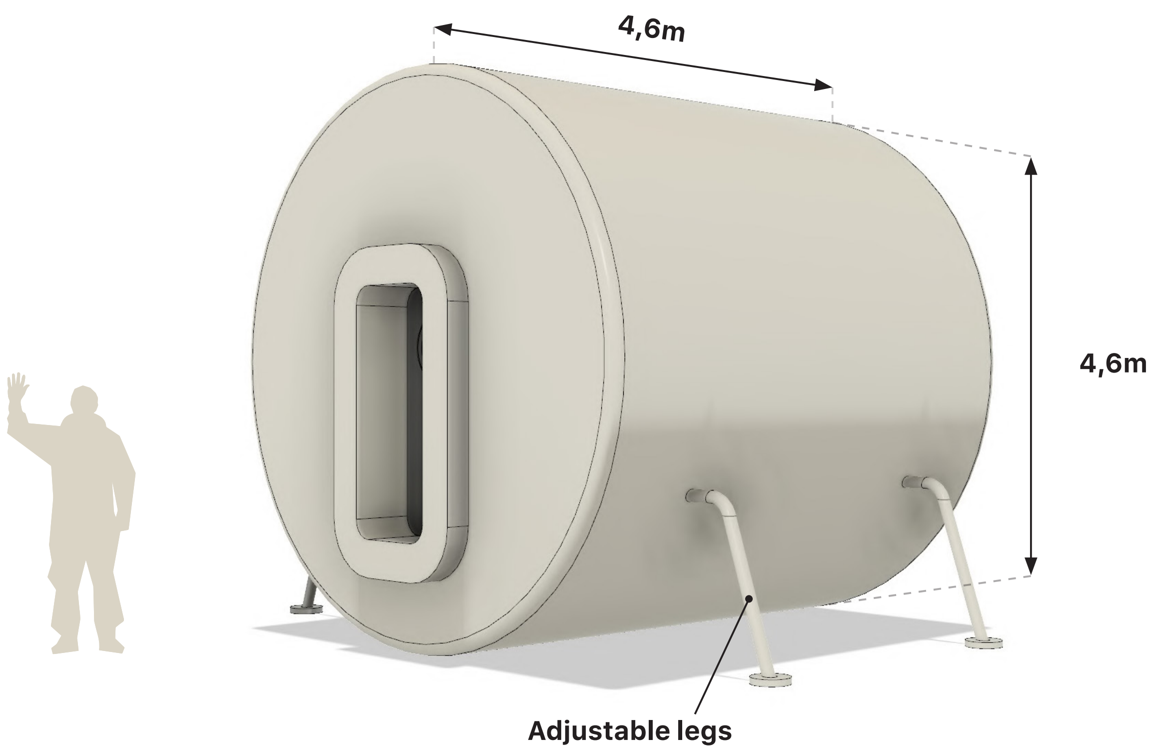


Figure 2. *Overview Horizontal Module*

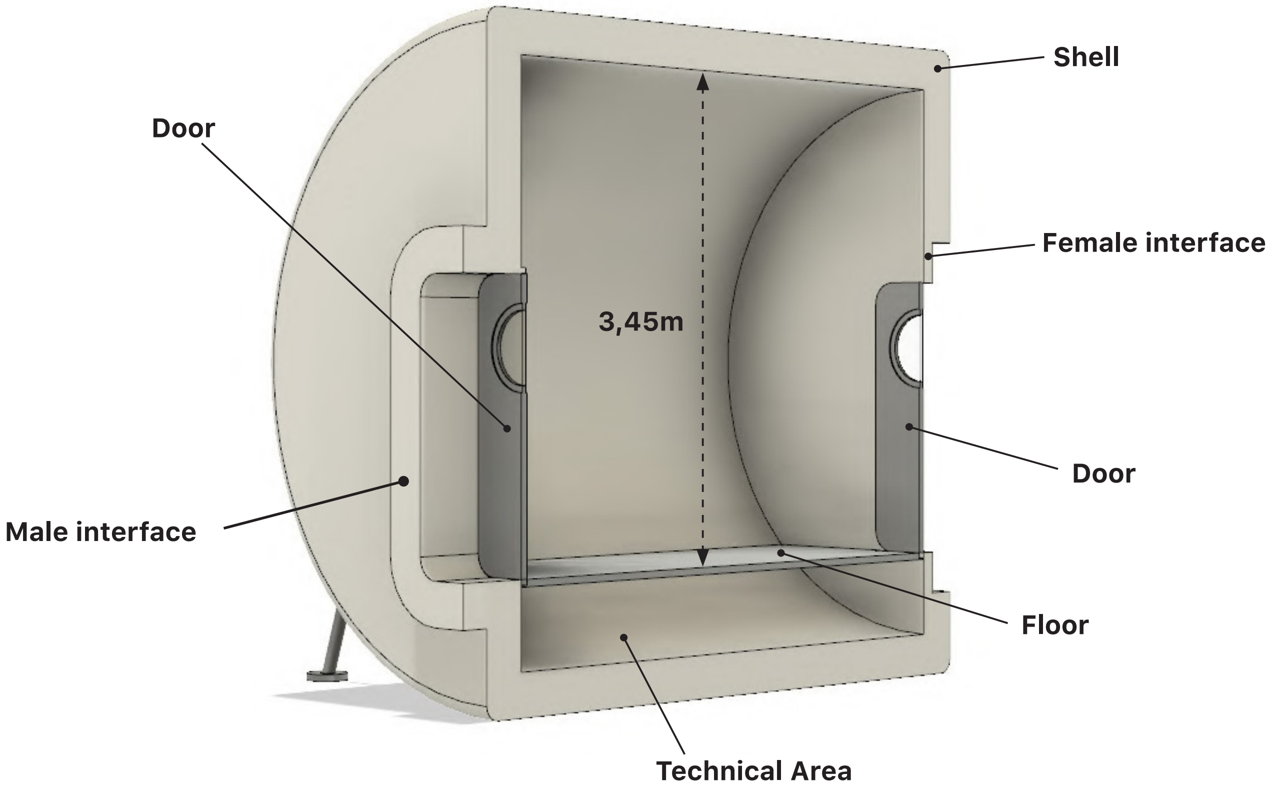


Figure 3. *Section View Horizontal Module*

which is similar as the ISS. The ISS's shell consists of an internal sheet aluminum waffled structure, thermal insulation, equipment and external sheets of aluminum in combination with Kevlar and Nextel to provide micrometeorite and debris shielding (InsideISS, 2014). This shell is the same for all modules. The habitable volume is approximately 20 m^3. The volume calculations are made by measuring the internal volume and estimating the minimum habitable volume inside the CAD software.

The module is outfitted with two sliding doors (fig. 66) thus it is easily locked in case of emergencies. Floor panels are used to provide a flat floor. Space underneath is used as a technical area for life support systems, cabling and stowage. Resulting volume has a maximum height of 3,45 m which is useful in partial gravity. The standard module consists of a male and female interface which allows easy expansion.

Currently two variations of the baseline horizontal module are present in the outpost. Both have two male interfaces but the size varies. Variation one (fig. 67) has equal dimensions, weight and power consumption as the baseline model while variation two (fig. 69) has a length of 6,6 m to provide additional volume for sleeping quarters. The addition of two male interfaces enhances the expandability and modularity.

The total volume of variation two is 75,4 m^3 and the minimum habitable volume contains 32 m^3. To determine the weight a comparison was made with the Kibo module. Originally this was compared with the Node 2 since the ISS crew quarters are based there but this seemed illogical due its main function as utility hub. The module has a predicted mass of 10,25 ton and needs 15,5 kW.

A third variation (fig. 68) was drawn up including a window. This module is not present in current set-up but serves as inspiration for further development. Multiple other designs are possible and could be explored in the future.

The vertical module (fig. 70) has a unique shape comparable to a control tower. The main dimensions are a diameter of 4,6 m and length of 3,6 m. The module has a double function as nerve center for managing all lunar operations and a recreation area to gaze at the lunar environment and Earth. For the determining the weight the Cupola module of the ISS was used as reference (Christiaens, n.d.-a). This results in a weight of 10,8 ton. The Kibo module was used to determine to electrical power needed since no Cupola data was available. This translates to 8,5 kW. The total internal volume is 31 m^3 and minimum habitable volume 14,3 m^3.

The vertical module is accessible via a ladder and connected with a male interface to the node module (fig. 72). Both modules are quick and easily sealable via two hatches in both vertical and node module. To protect the windows against micrometeorites and orbital debris shutters (fig. 71) with a stuffed whipple shield (fig. 74), containing aluminum, kevlar and nextel are needed. Outer dimensions of the windows are 1,4 x 1,0 x 0,15 m. The thickness is based upon NASA guidelines. The vol-

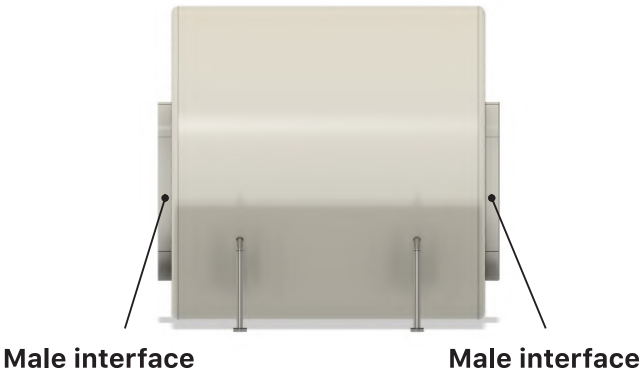


Figure 4. *Overview Variation One*

Figure 5. *Side View Variation Three*

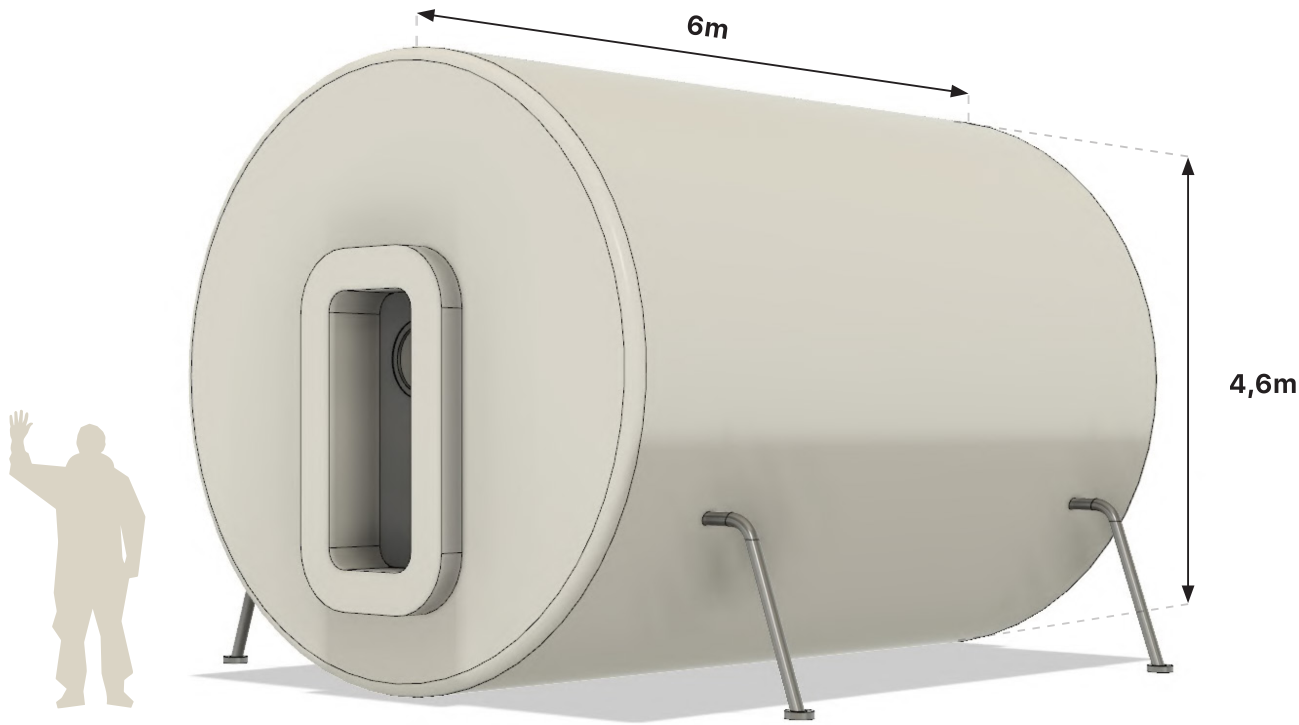


Figure 6. *Overview Variation Two*

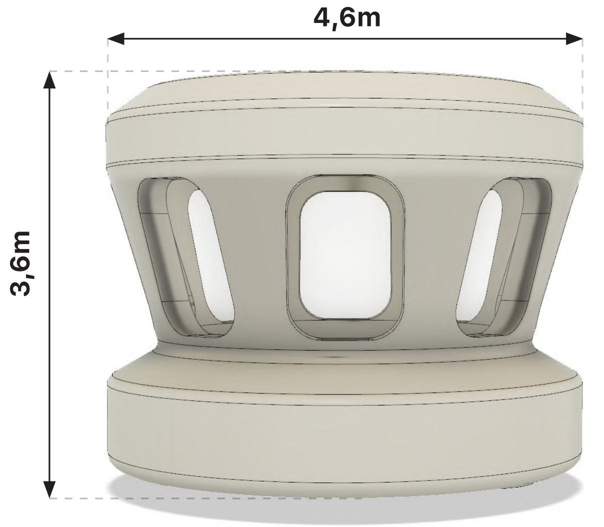


Figure 7. *Overview Vertical Module*

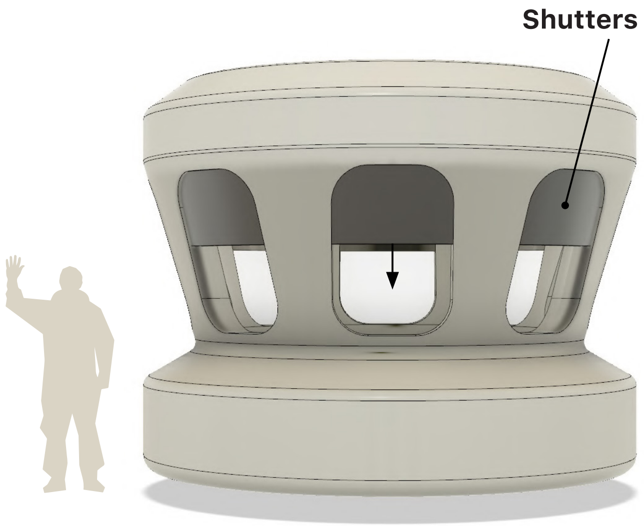


Figure 8. *Vertical Module Shutters*

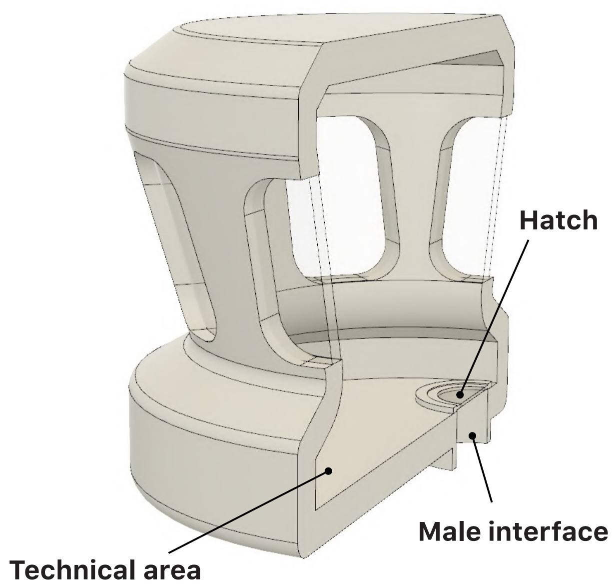


Figure 9. *Section View Vertical Module*

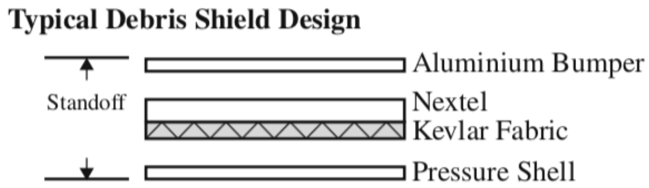


Figure 10. *Section View Whipple Shield (NASA)*

ume underneath the windows can function as a technical area like volume underneath the floor in the horizontal module. (Häuplik-Meusburger & Bannova, 2016)

For current base design only one vertical module is present. In future expansions, more variants could be developed to enhance the verticality of the base thus increasing the degrees of freedom. During the early operations of the base this is not necessary.

The node module provides (fig. 74) the connection between the horizontal and vertical modules with five female interfaces. A ladder connects the node with the vertical module and is easily sealable via a hatch and rail system (fig. 75-76). The unit functions as a central hub containing a food, exercise and stowage area. The dimensions are a diameter of 4,6 m and length of 4,6 m. The internal volume is 50,3 m^3 and a minimum habitable volume of 17 m^3. Like the horizontal module a floor panel is foreseen for a technical area including life support systems, cabling and stowage.

The node module was compared with Node 2 of the ISS. Resulting weight is 11,4 tons. The module needs an estimated 44 kW for electrical power. (ESA, n.d.)

Besides the different modules, airlocks play a crucial role in the lunar outpost. Currently two systems are in use: a regular airlock (fig. 77-78) and a suitport (fig. 79). Both are usable for two persons. When the outpost reaches its complete operational phase three airlocks and one suitport are present. Note that not all airlocks have to be fully used and can serve as a stowage area if not operational. By providing four exits sufficient redundancy is gained. In the case of extreme emergencies, the horizontal modules themselves could be used as airlocks providing room for the complete crew. Subsequently all most outward modules should have space suits for the whole crew stored. Additionally, a rover could be connected to the base to provide a quick emergency exit.

The airlock is in essence a down scaled horizontal module with a diameter of 3,78 m and length of 2 m. The airlock has a floor comparable to previous modules. Internal volume is 11 m^3 and minimum habitable volume is 5 m^3. For the weight a comparison is made with the Quest Joint Airlock resulting in 2,1 ton (Christiaens, n.d.-b). A reference of electrical power of this airlock is not available thus we made an estimation. We compared the internal volumes of both airlock and horizontal modules and translated

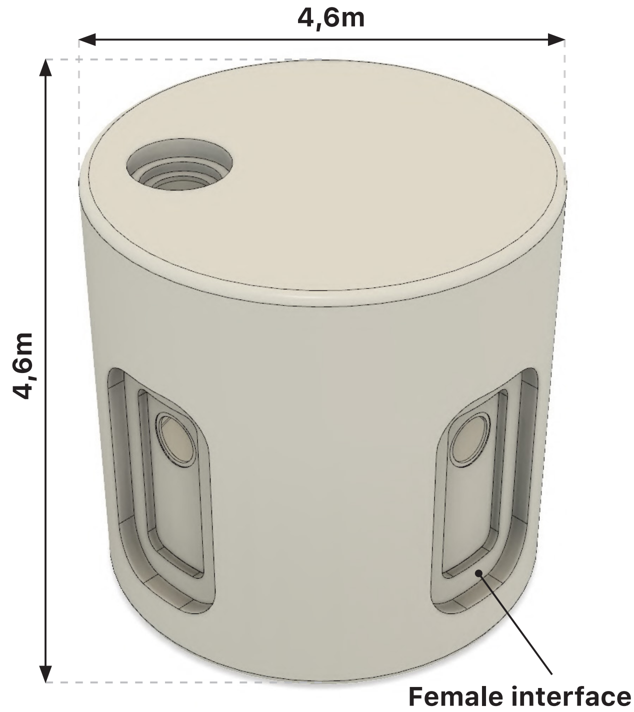


Figure 11. *Overview Node Module*

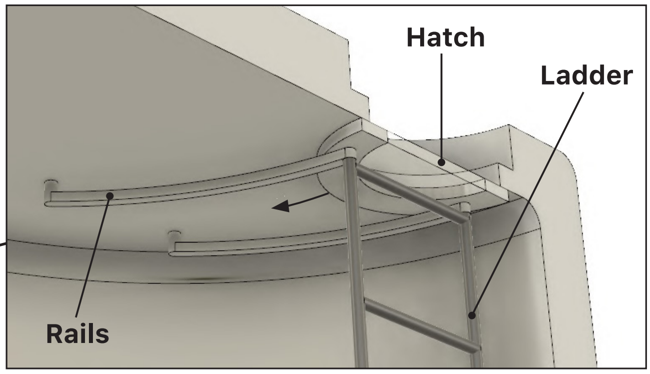


Figure 13. *Detail Node to Vertical Module*

this ratio to the electrical power resulting in 3 kW. A technical airlock is also present in the module allowing for easy transportation of small equipment and samples. Finally, the airlock has a female interface.

The suitport can be combined with any horizontal module. The addition of a suitport saves weight and volume but the constant exposure to the hostile lunar environment increases the possibility of defects in the space suits. To prevent this a construction is provided to protect the suits from the lunar environment. The only functionality of the protection is to shield the suits and allow for maintenance thus weight and power can be kept at a minimum. We foresee a maximum of 1 ton and 1 kW. Pressurization is not necessary thus it does not provide habitable volume.

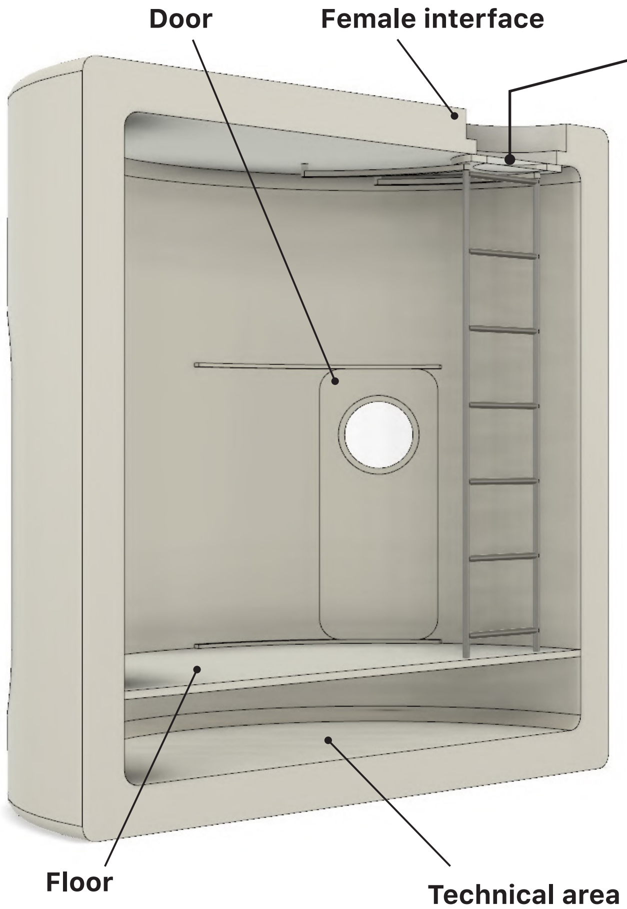


Figure 12. *Section View Node Module*

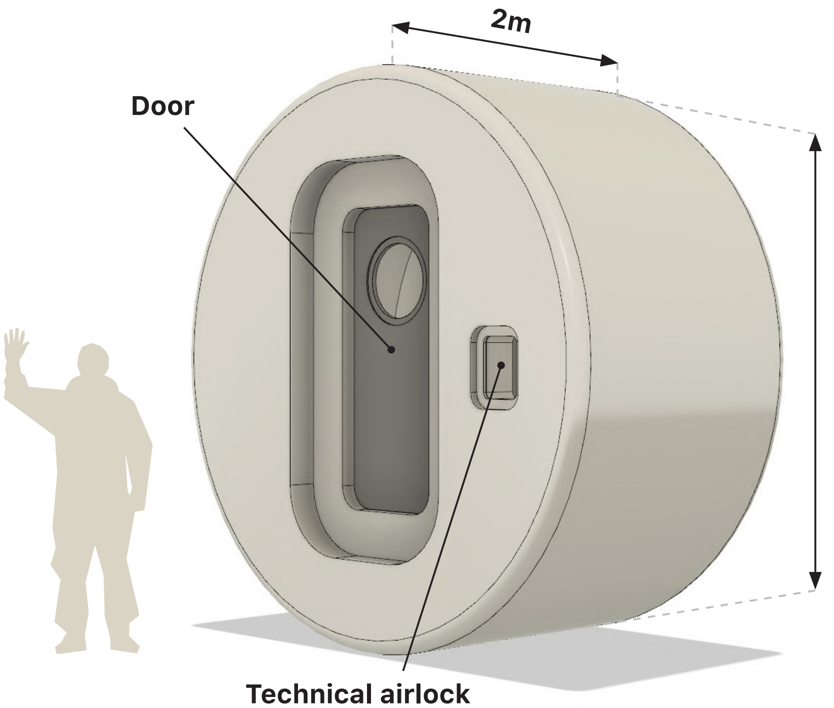


Figure 14. *Overview Airlock*

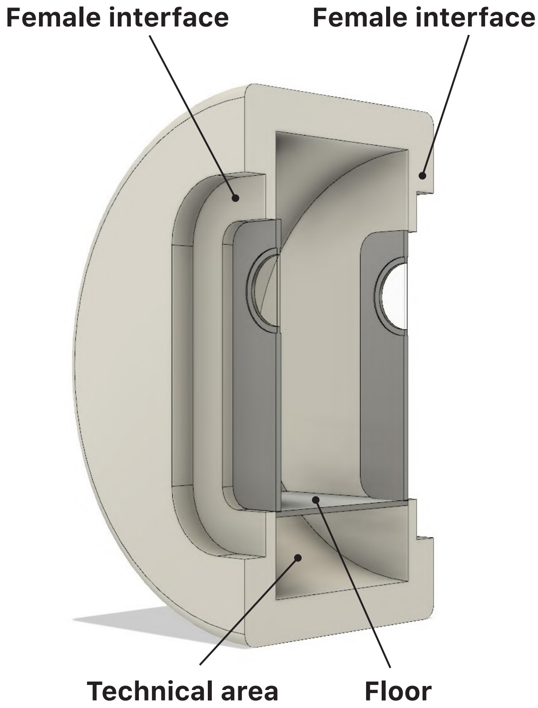


Figure 15. *Section View airlock*

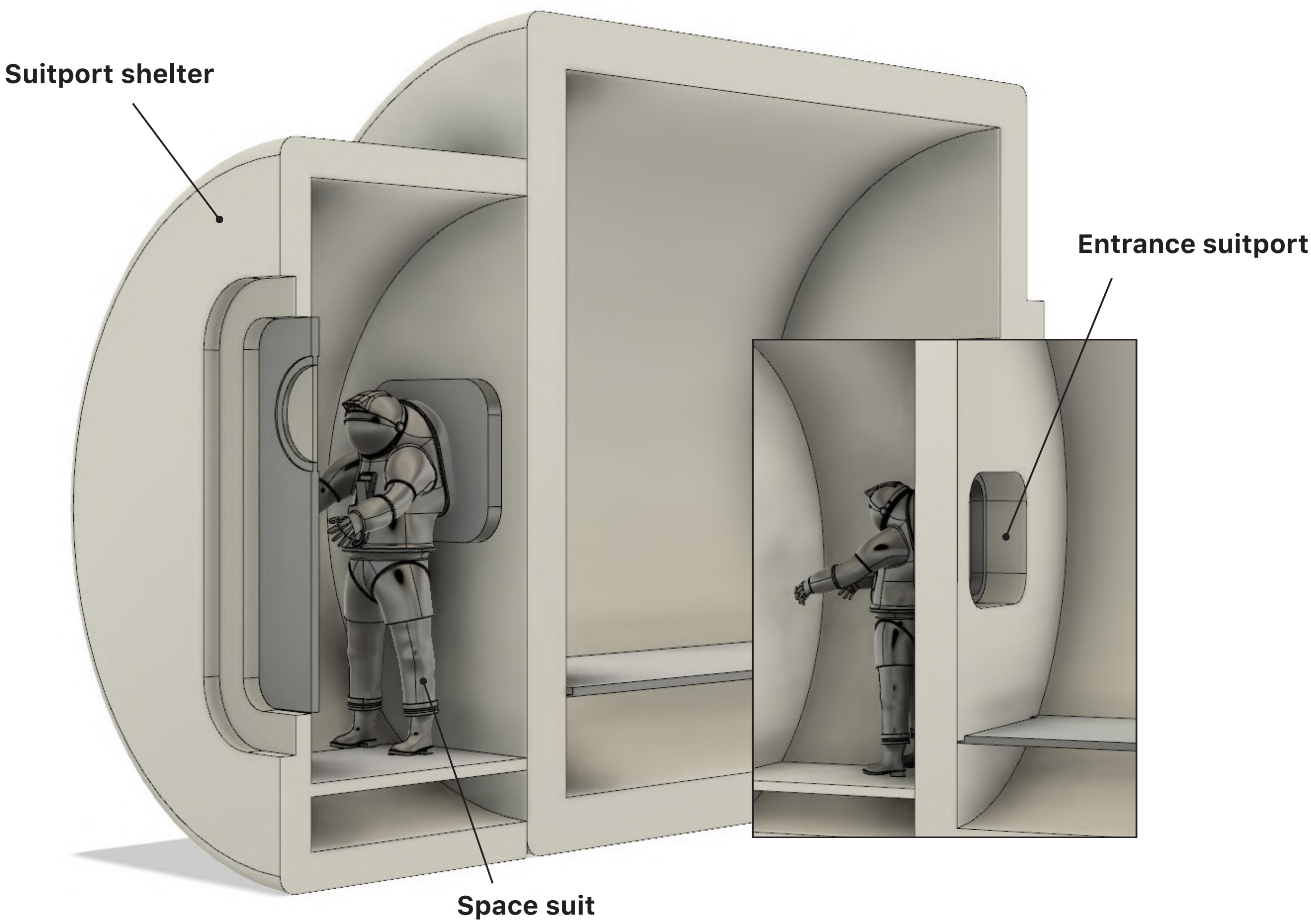


Figure 16. *Overview Suitport*

Outpost Set-Up

Current design will focus itself on an outpost for a crew of six. The duration of operations is maximum six months comparable to the ISS. Before the outpost reaches this capacity, smaller precursor missions are conducted to test the infrastructure and habitability. These missions can vary from two astronauts in one horizontal module for one week until six astronauts in a fully functional base for three months. Since these variations are endless, only the fully functional set-up is presented.

The final outpost set-up consists (fig. 80-81) of four horizontal modules, one node module, one vertical module, one suitport and three airlocks with each of them supporting a functional area. In this case following functional areas are present: four dedicated work areas including a control tower, two wet labs and one dry lab; sleep and private area; hygiene, medical and optional work area; and a food, recreation and exercise area. Stowage areas are foreseen in each module. After the complete deployment, the first level of the ILO will be encapsulated by lunar regolith to provide radiation, micrometeorite and thermal shielding. Further research regarding the interior design, supported by the guidelines in chapter three, is essential for an end-to-end solution.

Functional Areas

The work areas are separated into three units: a control tower, two wet labs and one dry lab. The control tower is inspired

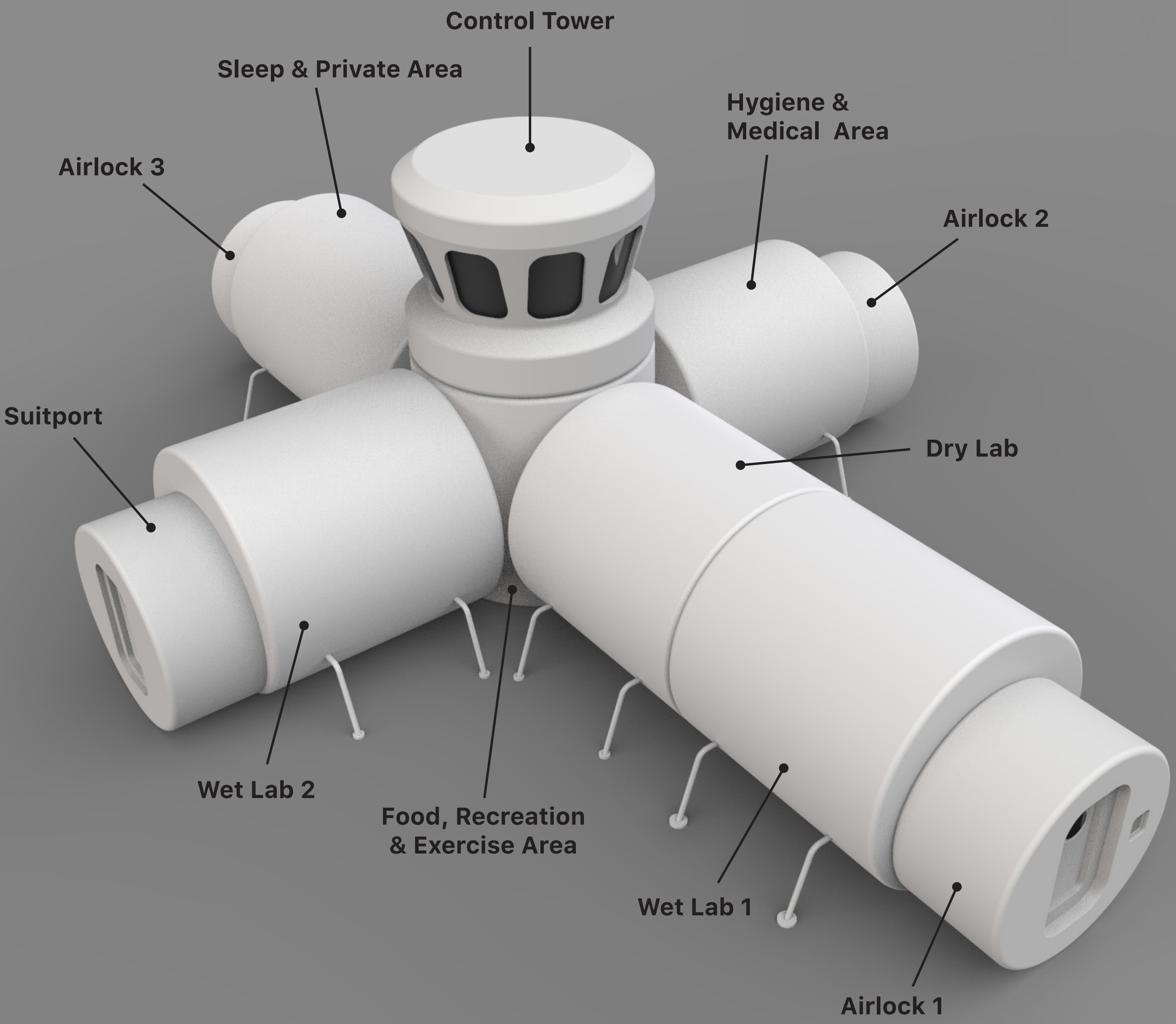


Figure 17. *Modules ILO*

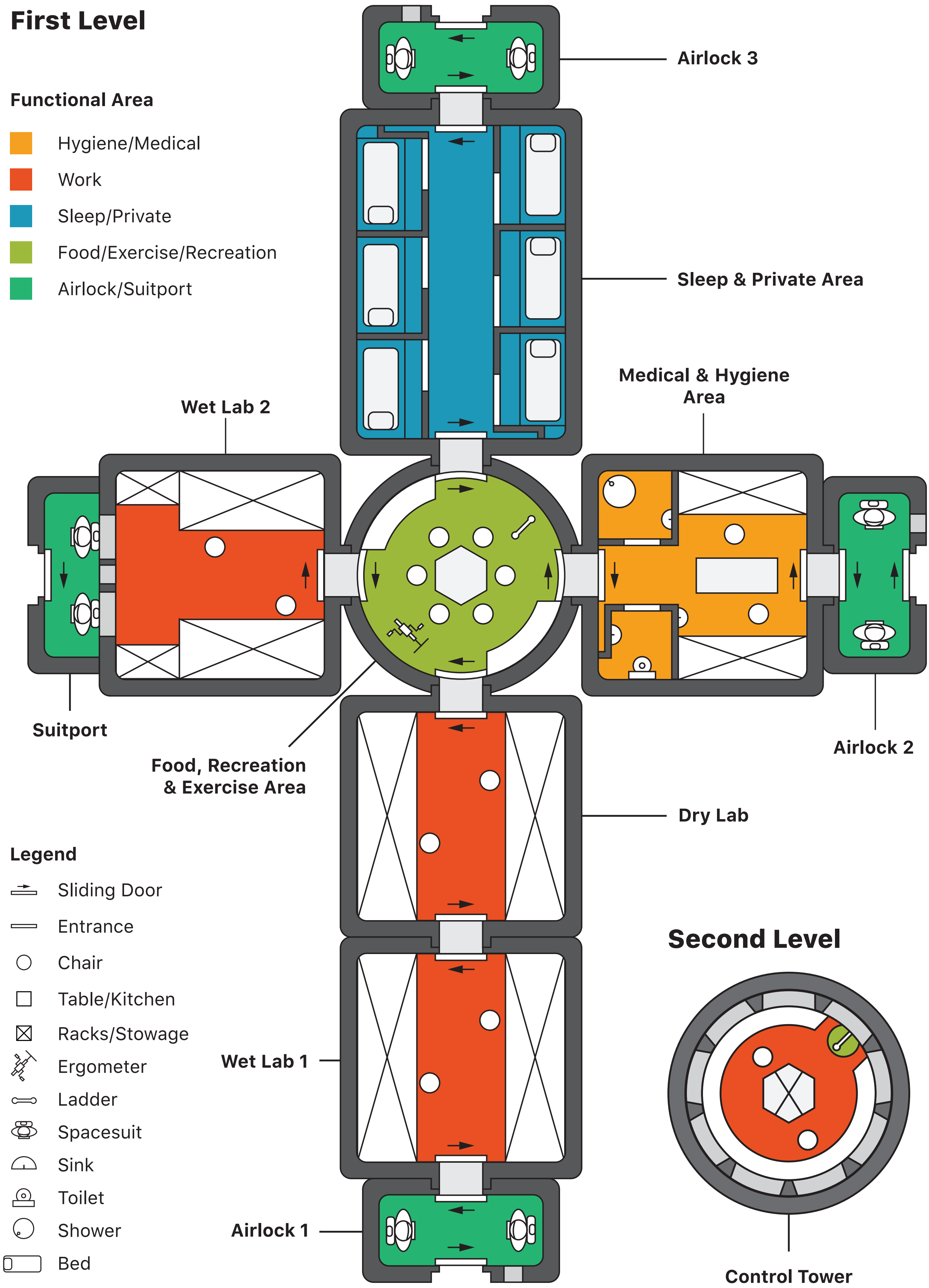


Figure 18. *Schematic Overview ILO*

by aircraft carrier (fig. 82) and airport design and is primarily used as an operational center for EVA's or a recreational area for Moon or Earth gazing. The control tower is situated on the second level and is accessible via the node module.

Both wet labs are directly connected to the outside via airlock 1, the suitport and technical airlocks. By doing this samples for the Moon are directly brought to the corresponding labs thus improving the efficiency, workflow and preventing contamination. A dry lab is present behind wet lab 1. Optionally the medical and hygiene area and control tower can function as additional dry labs.

The central node module is the heart of the outpost containing a kitchen, dinner area and sport equipment. It functions mainly as a recreation area for the crew. A ladder connects the central node to the control tower.

Behind the node module the sleeping quarters are placed. These are divided in six private compartments. The cabins consist of a bed and must provide sufficient personal stowage area. Both bed and desk could be integrated into one piece of furniture thus enabling a multifunctional private quarter which enhances the habitability (fig. 84). By placing the sleeping quarters on a separate branch of the outpost noise is reduced. The module is connected with airlock 3. This airlock should only be used in emergencies. Small stowage can be placed here.

On the right side is the medical and hygiene area consisting of a separated toilet, shower and medical bay. Both toilet and shower are isolated to allow for privacy. The medical bay has a large table on which operations can take place during emergencies. Throughout standard operations the bay functions as an additional dry lab and stowage area. The module is connected to airlock 2. Similar as airlock 3, it functions as a back-up in case of emergencies.

Figure 19. *Reference Control Tower (Getty Images)*

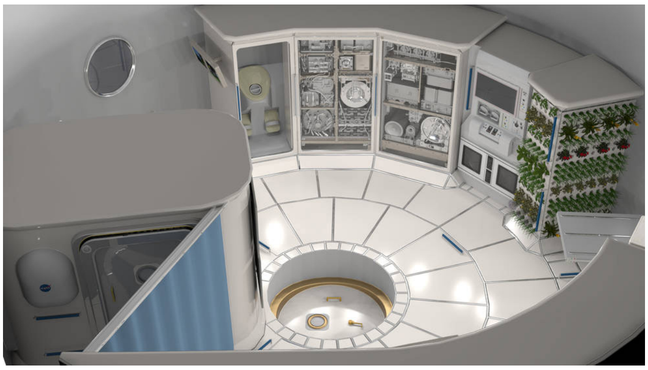


Figure 20. *Inspiration Interior (NASA)*

Figure 21. *Inspiration Desk & Bed (Curbly)*

Safety is an important driver throughout the design. By providing airlocks on every branch sufficient redundancy is added. In the case of one branch being defect the crew can evacuate via the other three branches' airlocks. If multiple branches are compromised and the complete crew is isolated in one module, the module itself can function as an airlock for quick evacuation. To prevent the total destruction of said module, a shutter system (fig. 85) could be used to provide a baseline protection of the present equipment. Additionally, a rover could be permanently docked to the outpost, for example airlock 2, allowing for a quick evacuation for the complete crew without using the modules as airlock (fig. 86). After evacuation, the crew can return to Earth via a spacecraft comparable to the ISS's Soyuz system.

Figure 22. *Visualization Shutters (Roché)*

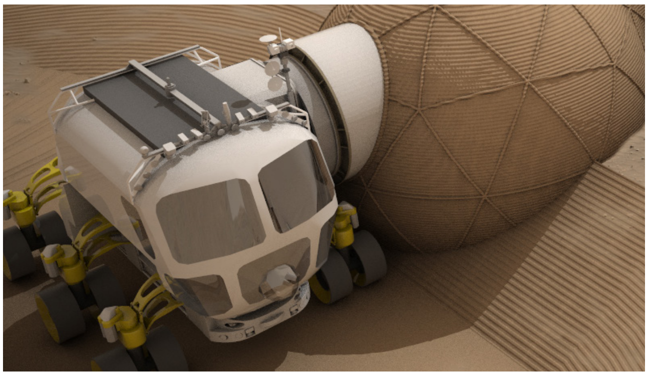


Figure 23. *Evacuation Via Rover (Liquifer Systems Group)*

Build-up

Moon Direct

Build-up of the ILO is heavily inspired by Robert Zubrin's Moon Direct theory (2018). This theory proposes to build a lunar outpost with several Falcon Heavies and shuttle crews with a Lunar Excursion Vehicle (LEV) and Dragon capsule to and from the Moon. Other launch vehicles such as the Space Launch System (SLS) or Big Falcon Rocket (BFR) are not considered yet since they are still in development.

The Moon Direct (fig. 87) consists of three phases: unmanned phase, pilot phase and long-term phase. During the unmanned phase Zubrin suggests that two launches are needed. One launch delivers all equipment to produce liquid hydrogen propellant such as solar panels, communications equipment, an electrolysis unit, a refrigeration unit and robotic and crew rovers. The robotic rovers already do reconnaissance and set-up the solar panels and communication equipment. The next launch delivers the habitat. Construction rovers help installing the base.

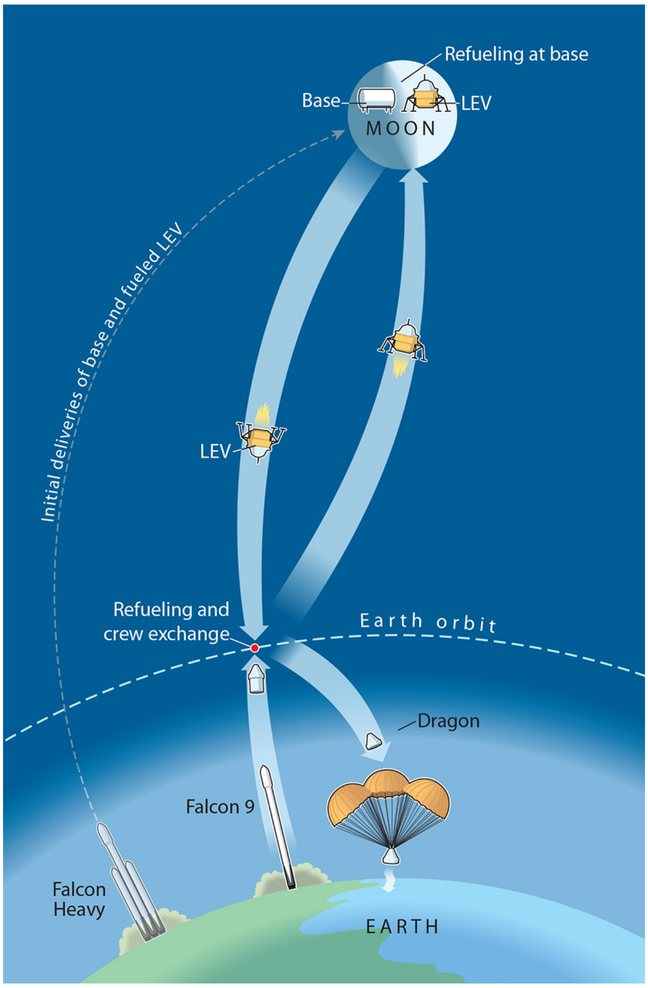


Figure 24. *Moon Direct (Zubrin)*

Phase two consists of launching a LEV to LEO with one Falcon Heavy and then a crewed Dragon 2 capsule with a Falcon 9. In LEO, the crew transfers from the Dragon 2 to the LEV. The LEV brings the crew to the lunar surface and there they set-up the propellant production which then is used to refuel the LEV. This drastically reduces the cost of Earth-Moon transportation and facilitates an easy crew rotation.

Phase three consists of an up and running in-situ fuel, oxygen and water production and a fully functional base with an easy Earth-Moon connection.

ILO

For the build-up of the ILO we use the Falcon Heavy with a payload of 9,9 tons and free faring length of 8,5 m. The variant of 10,8 tons and a free fairing length of 3 m has a too small deliverable volume is for our operations (fig. 88-89). Note that the propellant needed for a lunar surface delivery, both mass and volume, is considered.

The ILO's build-up starts with an unmanned launch bringing all equipment for propellant production, robotic rovers and solar panels. Payload weight is approximately 9,9 tons with four tons of solar panels providing 120 kW. 107 kW is directly dedicated to fuel production (Zubrin, 2018). The rest 13 kW can be used by the rovers. A second cargo launch delivers three crew and a construction rover. Since a single Lunar Electric Rover concept of NASA weighs three tons, we dedicate a complete launch to this (NASA, n.d.). We envision a modular rover that is both used for construction, encapsulation and crew operations. This enhances redundancy and commonality. The rovers will have their own solar panels. The following launches deliver all the ILO modules in eight launches.

Although some modules weigh more than Falcon Heavy's capacity, this is not a problem. Multiple launches are under-capacity thus equipment from the over-capacity launches can be moved there. After this an additional 10,75 tons is available which is used to deliver solar panels for operating the base. We foresee another 4,65 tons of solar panels since the base will consume approximately 122 kW. Note that the actual payload efficiency is higher because the mass is based on ISS's modules from the early 2000's. Since the ILO will be constructed throughout the 2030's improvements are expected but not necessary.

Launcher	*Date available*[15]	*Staging orbit*	*Cargo lander propellant*	*Fairing length used by propellant*	*Fairing length available for cargo*	*Fairing volume available for cargo*	*Payload mass deliverable to lunar surface*
Falcon H.	2018	LEO	LOX/CH_4	3.9 m	7.1 m	118 m^3	8.5 tons
Falcon H.	2018	GTO	LOX/CH_4	1.3	9.7	162	8.6
Falcon H.	2018	LEO	LOX/H_2	8.0	3.0	50	10.8
Falcon H.	2018	GTO	LOX/H_2	2.5	8.5	141	9.9
New Glenn	2020	LEO	LOX/CH_4	1.2	13.8	532	6.0
New Glenn	2020	LEO	LOX/H_2	2.4	12.6	484	7.6
Vulcan	2023	LEO	LOX/CH_4	1.8	18.2	357	4.7
Vulcan	2023	LEO	LOX/H_2	3.7	16.3	320	5.9
SLS	2020	LEO	LOX/CH_4	4.6	7.4	145	12.0
SLS	2020	LEO	LOX/H_2	9.5	2.5	48	15.2
BFR	2022	LEO	LOX/CH_4	3.0	37.0	1859	20.1
BFR	2022	LLO	LOX/CH_4	1.6	38.4	1932	82.7

Figure 25. *Overview Launchers (Zubrin)*

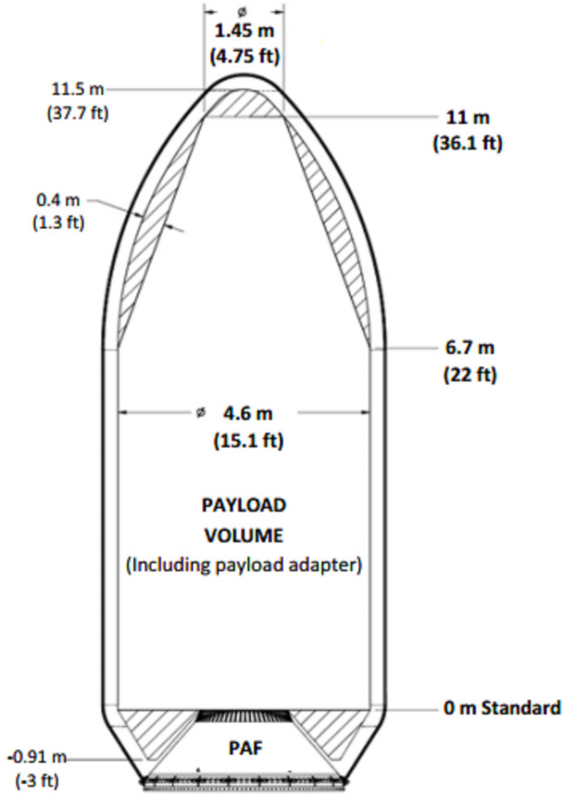


Figure 26. *Fairing Falcon Heavy (SpaceX)*

To provide redundancy an additional power source is needed. Nuclear energy could be used. Since the efficiency, of 33 kg/kW, is equal another 8 tons must be deployed for supporting all lunar operations (Zubrin, 2018). This needs a dedicated 11th launch. Possible free space can be used for additional equipment.

The 12th Falcon Heavy launch delivers all the supplies for six month operations. The 13th Falcon Heavy brings the LEV and additional propellant, in case in-situ propellant production is not up and running, to LEO.

A 14th Falcon 9 and Dragon 2 brings the six crew members to LEO. There they transfer to the LEV and are brought to the lunar surface. After six months of operations a Falcon 9 and Dragon 2 are needed to retrieve the crew from the LEV and bring them back to Earth. A complete overview of the launch campaign is given in figures 90, 91, 92 and 93. Note that these are rough estimations and actual launches, payloads and electrical power needed can differ significantly. We do not calculate in short duration precursor mission, and their supply's, which are needed. We see this estimation as the baseline requirement for our lunar outpost. Its main objective is to show the order of magnitude.

In total, we need 13 Falcon Heavy and two Falcon 9 launches. These vehicles bring 128,7 tons, including an outpost of 68,05 tons, to the lunar surface. Solar panels and a nuclear generator will together provide 549 kW of which 241,5 kW is used. Total habitable volume is 138,3 m^3 with 23,05 m^3/crew, which is 2 m^3/crew larger than required. The launching campaign will cost approximately two billion euro's. This does not include the research and development, production and workforce needed.

Due to the high costs a multilateral approach, combined with commercial partners, is crucial. The ILO easily allows for this cooperation by its modular structure.

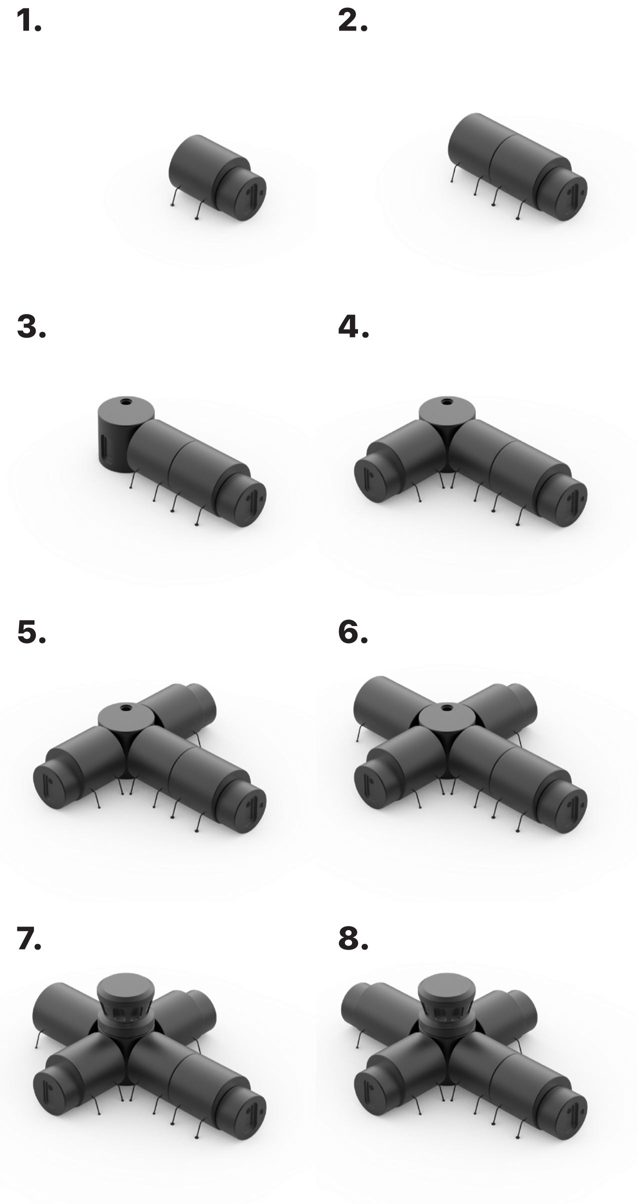


Figure 27. *Build-up ILO*

Figure 28. *Complete ILO*

	Launch Vehicle & Price	Payload Composition	Weight (tons) *(max 9,9 tons)*	Power (kW)	Habitable Volume (m³)
L1	Falcon Heavy *150 M*	Propellant Production, Robotic Rovers Solar panels	3,9 tons 1 tons 4 tons ***9,9 tons***	-107 kW -13 kW +120 kW ***0 kW***	/ / / ***/***
L2	Falcon Heavy *150 M*	3 crew & construction rovers	9,9 tons ***9,9 tons***	/ ***/***	/ ***/***
L3	Falcon Heavy *150 M*	Wet lab 1 Airlock 1 Solar Panels	7,15 tons 2 tons 0,65 ton ***9,9 tons***	- 11 kW - 3 kW + 19,5 kW ***+5,5 kW***	20 m^3 5 m^3 / ***25 m^3***
L4	Falcon Heavy *150 M*	Dry Lab 1 Solar panels	7,15 tons 2,75 tons ***9,9 tons***	- 11 kW + 82,5 kW ***+77 kW***	20 m^3 / ***20 m^3***
L5	Falcon Heavy *150 M*	Food/Recreation/Exercise	11,4 tons - 1,5 tons ***9,9 tons***	- 44 kW / ***+ 33 kW***	17 m^3 / ***17 m^3***
L6	Falcon Heavy *150 M*	Wet lab 2 Suitport Food/Recreation/Exercise Solar Panels	7,15 tons 1 ton 1,5 tons 0,25 ton ***9,9 tons***	- 11 kW - 1 kW / + 7,5 kW ***+ 28,5 kW***	17 m^3 / / / ***17 m^3***
L7	Falcon Heavy *150 M*	Hygiene/Medical Airlock 2 Solar panels	7,15 2 tons 0,65 ton ***9,9 tons***	- 11 kW - 3 kW + 19,5 kW ***+ 34 kW***	20 m^3 5 m^3 / ***25 m^3***
L8	Falcon Heavy *150 M*	Sleep/Private	10,25 tons -0,35 ton ***9,9 tons***	- 15,5 kW / ***+ 18,5 kW***	32 m^3 / ***32 m^3***
L9	Falcon Heavy *150 M*	Control Tower	10,8 tons -0,9 ton ***9,9 tons***	- 8,5 kW / ***+ 10,5 kW***	14,3 m^3 / ***14,3 m^3***
L10	Falcon Heavy *150 M*	Airlock 3 Sleep/Private Control Tower Supplies	2 tons 0,35 ton 0,9 ton 6,65 tons ***9,9 tons***	- 3 kW / / / ***+ 7,5 kW***	5 m^3 / / / ***5 m^3***

Figure 29. *Launch Campaign ILO*

L11	Falcon Heavy *150 M*	Nuclear Reactor	9,9 tons ***9,9 tons***	+ 300 kW ***+ 307,5 kW***	/ ***/***
L12	Falcon Heavy *150 M*	LEV & Propellant	9,9 tons ***9,9 tons***	/ ***+ 307,5 kW***	/ ***/***
L13	Falcon Heavy *150 M*	Supplies	9,9 tons ***9,9 tons***	/ ***+ 307,5 kW***	/ ***/***
L14	Falcon 9 *62 M*	Crew to Moon	6 tons (LEO) ***6 tons***	/ ***+ 307,5 kW***	/ ***/***
L15	Falcon 9 *62 M*	Crew to Earth	6 tons (LEO) ***6 tons***	/ ***+ 307,5 kW***	/ ***/***

Figure 30. *Continued Launch Campaign ILO*

Visualizations

Additional visualizations are provided on the following pages. This includes renders of the concept's encapsulation (fig. 94), expandability (fig. 95) and placement in the lunar environment (fig. 97, 98 & 101).

Feedback

Working iteratively and allowing critical feedback is essential for creating valuable design. After finishing the design, discussions were performed with Marlies Arnhof, Matt Harasymczuk, Sarah Baatout and Marjan Moreels about the ILO concept.

Marlies directly pointed out that the airlock must be bigger to provide sufficient changing and maintenance room. The exercise equipment should be moved to another area then the kitchen module due to unpleasant smells. The control tower is an interesting alternative since it has an additional recreational value.

Different ceiling heights must be explored to more optimally use the modules and offer variation. The ladder in the kitchen area must be placed under an angle. A Viennese ladder could be an interesting solution. Including a quarantine area in the medical bay is essential to prevent the spreading of contagious diseases.

Further exploration of the adjustable legs; interfaces; window shutters; construction and crew rovers; and other technical systems are crucial for creating a fully functional design.

Finally, user journey's must be made. By analyzing the day-to-day operations of the crew many usability flaws can be discovered which are essential when designing the interiors.

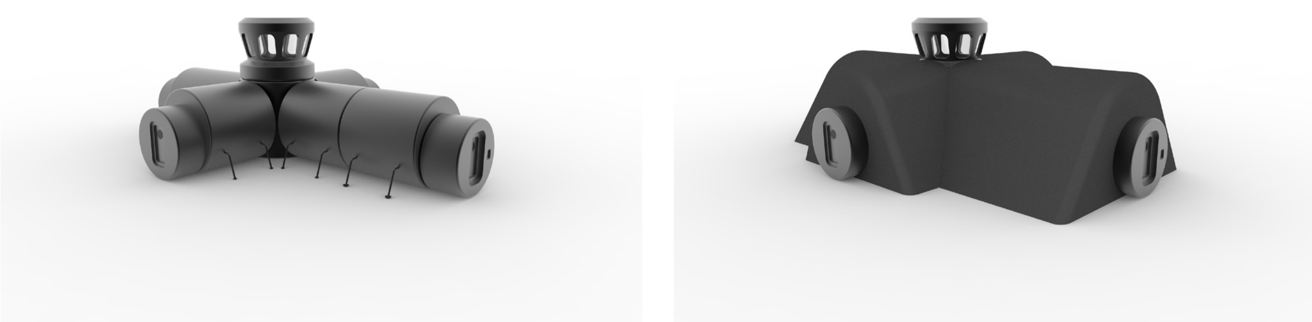


Figure 31. *Encapsulation ILO*

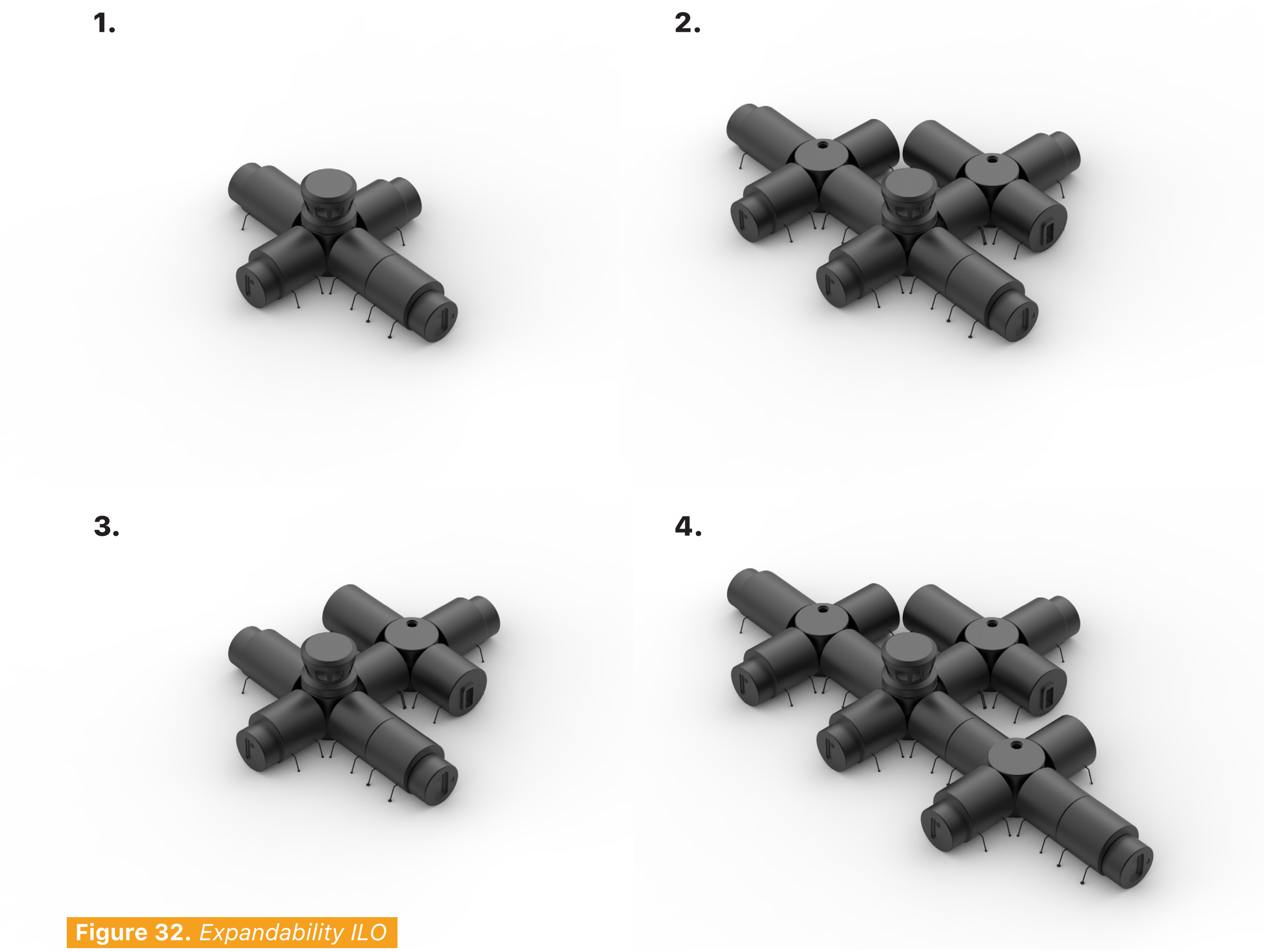


Figure 32. *Expandability ILO*

Figure 33. *ILO*

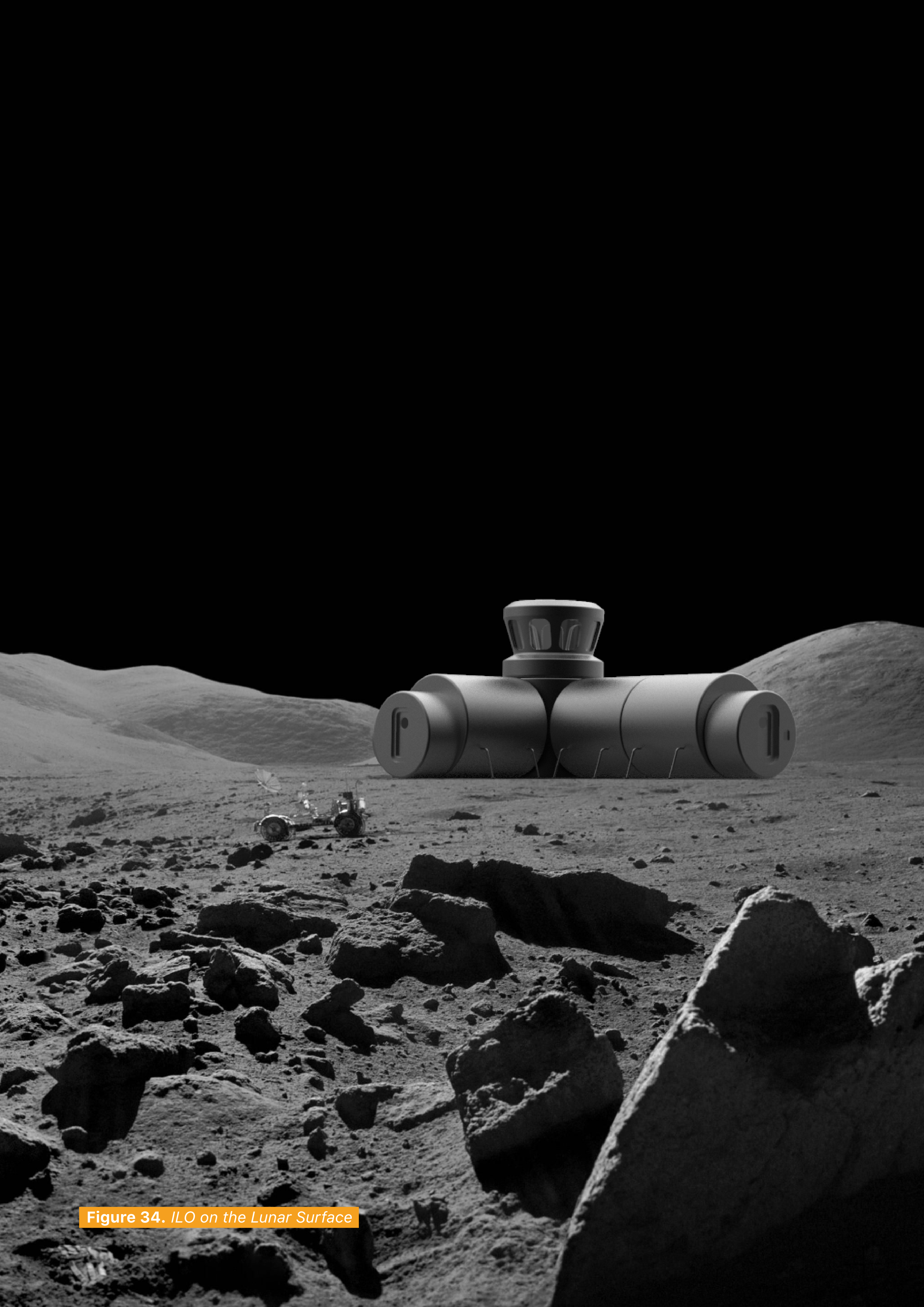


Figure 34. *ILO on the Lunar Surface*

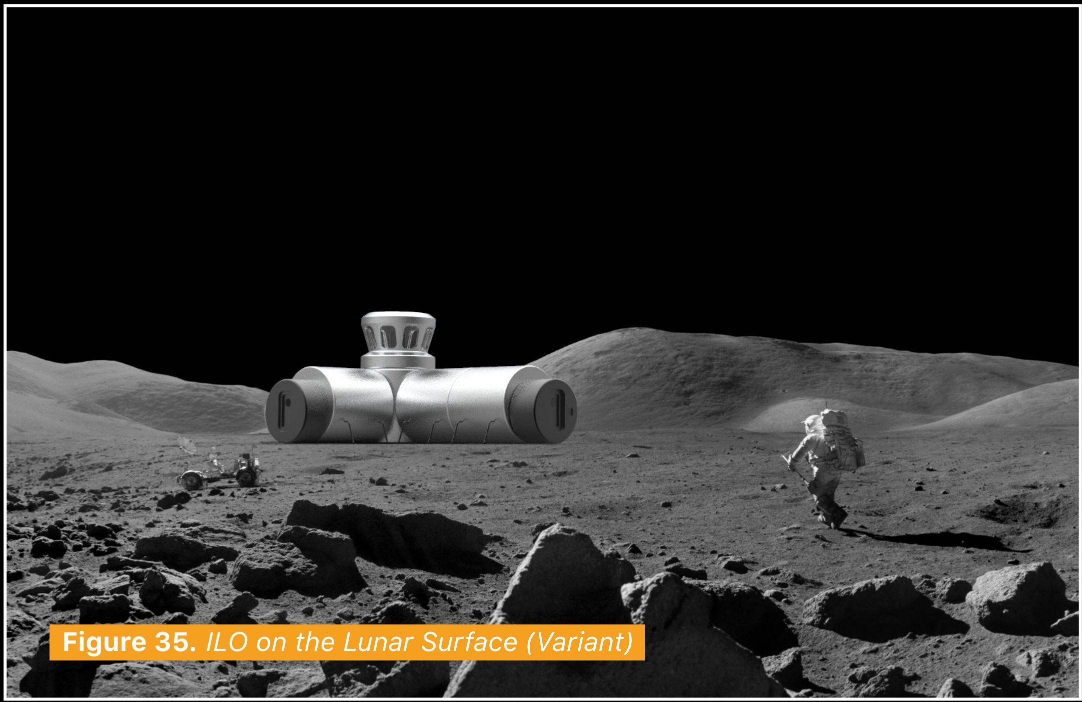


Figure 35. *ILO on the Lunar Surface (Variant)*

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