Lunar Base Construction and Layout

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Abstract

This paper elucidates a construction and layout of a base on the moon for research and exploration. First the decision on the location is examined, yielding the conclusion that the South Pole should be the construction site for the Lunar Base. The construction of 3D printed domes is also explained and discussed as a reliable solution for the base fabrication. On layout design, the necessary minimum space of 540 m^3 is clarified and use of pre-built modules for emergency and power supply is addressed as a complementary structure for the printed base. The schedule and logistics of transportation of materials, supplies for the crew, and construction of the base is introduced and delineated.

Introduction

In over 50 years mankind have explored the mysteries of space. With one step at a time science answers the questions of what lies beyond the surface of earth. The biggest achievement until this day, the International Space Station (ISS), is what brought together nations across the globe in cooperation to accomplish mutual goals. By the time it was announced that by year 2024 ISS will no longer be in use, a new mission arose, to return to the Moon. As of today, 40 years has passed since the end of lunar exploration. The difference now is that astronauts going there will be staying and living as if they were on ISS. They are going to be six people, live there for six months at a time, and employ themselves with building the lunar base. Where on the moon would it be best to build a base, what requirements are there, and what supplies are there on the market today that can be used. These are some questions to keep in mind during this proposal for a human lunar base. This report is aimed towards those with basic knowledge in space, physics and interest in the progress of human spaceflight.

Location

Process

The mission specifications do not explicitly dictate a location for the lunar base. The location will determine the environment that the structures, devices, and humans must face. Consequently, this is one of the first decisions that must be made and each group within the team will have a preference in the matter. As the current technology and the scientific objectives decide the location which in turn governs the required technology and possible scientific investigations, an iterative process must be used to come to a final and suitable conclusion.

The first step is to define the options. The lunar surface does not seem to offer much variety. Because the greatest differences will exist between the equatorial and polar regions, these two are chosen for comparison. The next step is to examine the advantages and disadvantages of the two alternatives. After this stage it is critical to involve the other groups in discussing the facts. The input from an overall coordination, human aspect, and on-site mobility perspective will help determine the most appropriate lunar base location for the entire team. With a final decision, it is possible to further investigate the selected region and choose a specific location.

Each group will then have to reevaluate their formulated specifications to make sure they are still relevant to the final lunar base location. This group, specifically, must determine a feasible construction method and its respective necessary and locally available resources, an appropriate layout, and construction schedule.

Options

The two most distinctive regions of the moon are the equator and the poles. Both are harsh and inhospitable to human life, but each also provides its own characteristic challenges and benefits. This section will detail the numerous factors taken into account while deciding between these two regions.

The Equator

The equator offers a certain sense of nostalgia and security. This region alone has been previously explored by mankind. For one, significant sites of the past can be revisited. It is, however, unlikely that anything that could be repurposed remains. Thus this is a purely sentimental motivation in this sense. More important is the fact that the composition and conditions of this region are known. A crew landing here could be relatively assured of what they would find. Meanwhile, exploration of the polar surfaces has been more “hands-off”. This plays a significant role in the selection of the construction method and the determination of its inherent risks.

Radiation can be extremely harmful to biological material as well as unqualified electronics. The Earth is protected from most radiation by its magnetic field. The moon benefits from the Earth’s magnetic field only when the Earth is between it and the sun. The moon is also more prone to other sources of radiation such as cosmic rays. Taking all of these factors into account, the equator on the side of the moon always facing the Earth is the safest from radiation. This would mean that the possibility for extravehicular activity both for humans and robots would be greater at the equator. Furthermore, any structures intended for human use would require less shielding against radiation.

The most prominent characteristic of the equatorial region is perhaps the lunar night. The equator experiences approximately 14 days of sunlight followed by 14 days of night. This cycle has a multitude of consequences that must be taken into account when designing a lunar base. Most obvious is the potential lack of a power source since solar panels are the most common power supply used in space. Additional batteries or alternative power supplies such as nuclear power would need to be considered. Both could have a drastic adverse impact on the mass budget. The temperature oscillations caused by these extended periods of light and dark also create numerous problems. The surface temperature at the equator of the moon can fluctuate between -170°C and 140°C [1]. This range is not compatible with human habitation; consequently, shielding must be used to ensure a more suitable environment. Fortunately, a study shows that a thin layer of lunar regolith can have a very positive protective impact [1]. The effect of these temperature fluctuations on materials must also be considered. Construction materials must provide reliable support throughout the entire temperature range and be able to survive the fatigue of multiple temperature cycles throughout their lifetime. The additional factor of safety required of any manned spaceflight mission along with the overall mission mass budget creates a very stringent standard for the construction materials.

The Poles

By comparison, the poles experience relatively small temperature fluctuations. This stems from the more stable light and dark conditions. Areas of near constant sunlight, which offer consistent solar power, and areas of near constant darkness, which are of scientific interest for such purposes as telescopes that require cool temperatures for proper lens function, exist near both poles. Furthermore, the average lunar night duration can be decreased by relatively small increases in altitude from the lunar surface [2]. Most interesting, perhaps, is the existence of adjacent areas of light and dark. This would enable a single lunar base to reap the benefits of both environments.

Despite steady temperatures, shielding would be required for a lunar base at the poles. As mentioned previously, the poles do not provide much safety in the way of radiation. However, a small layer of locally available lunar regolith could provide the necessary protection [3].

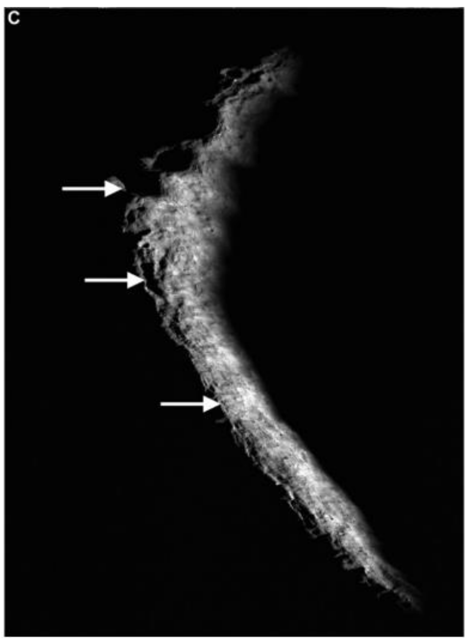
Finally, the poles offer an exciting new possibility for exploration, a chance to extend human knowledge of the region. The promising existence of enhanced hydrogen or even water as well as volatiles at the poles could be conclusively investigated [4]. The existence of these resources near the lunar base could provide future scientific study and useful assets.

Decision

The entire team came to the conclusion that the poles would provide the most suitable location for a lunar base. This decision was based mainly on the desire for a consistent power supply and exploration of the potential resources.

Many studies have been performed on the polar terrain. The area generating the most interest is undoubtedly the Shackleton crater located on the south pole. One study suggests it receives sunlight 86% of the year, making it the most illuminated area on the south pole [5]. Another claims that the crater never experiences more than 1.5 consecutive days of lunar night [2]. The image below designates potential locations for solar power stations on the Shackleton crater. The corresponding study determines that these stations together receive illumination 92% of the year and are never eclipsed longer than 43 hours [6].

Figure 1: Shackleton Crater Power Stations



The conditions at the Shackleton crater determine the potential lunar base layout and construction methods that will be further discussed in the following sections.

Construction

Requirements

The construction of the moon base shall allow the astronauts to live in decent and comfortable enough conditions, despite the rough environment of the moon. Therefore, the construction shall protect the astronauts from temperature fluctuations, radiation, and meteorites. Moreover the moon base shall offer the astronauts a livable – pressurized and oxygenated – environment.

Another constraint is, of course, that the moon base project shall be the as inexpensive as possible, while fulfilling the high standard of requirements in terms of security, delays, and goals. Reducing the cost of such a project works in pair with reducing the mass needed to be sent from the Earth to the Moon. Thus, the more the moon base utilizes materials directly available from the moon and recycles what is consumed, the less expensive the project will be.

Alternatives

Different alternatives should be under investigation for building a permanent habitation on the Moon. To fulfill the previous requirements, one can possibly consider digging up a cave and settling a habitation brought from Earth underground. This solution is interesting since once underground, the lunar soil offers a suitable protection against radiation, but also against temperature variations and meteorites. The problem of the breathable environment could be solved using an inflatable structure that would be put inside the dug cave. One issue is the possible risk for the structure to collapse under its own weight. The main remaining problem is the cost for digging. Heavy machinery is required, and these machines consume a lot of energy. This solution would be too expensive considering the amount of energy and machines needed.

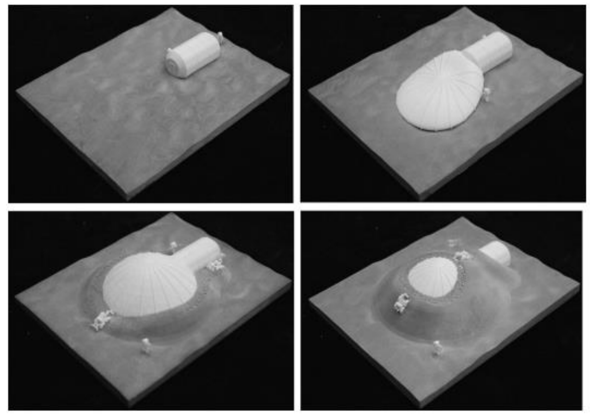
Another reasonable solution would be to send already prefabricated and ready to use modules directly from Earth. Of course this solution presents numerous advantages. The technology already exists and has proven to be reliable in the past. With this alternative, there are only a few unknowns, and a crew would have, from day 1, a fully operational structure. Yet this solution is also very costly in terms of weight. Since this project is aiming for a long-term mission, astronauts cannot possibly be expected to live in a restricted volume for long periods of time. Offering a decent volume for everyday life, safety, and work would require sending many small modules, to build a larger moon base by connecting them together.

The last alternative would be to use materials directly from the Moon to build a structure. It obviously offers several advantages, such as a gain in weight since despite the machines needed to build the structure, the materials already exist on site. Moreover, the use of on-site materials can provide sufficient protection if the thickness of the wall is adequate. Nevertheless, the technology used must be reliable enough, without an excessive need in term of energy and heavy machinery.

Solution

Several studies have been made to assess the possibility of building a moon habitation using the lunar soil, also called regolith, through a 3D printing process. Regolith is an abundant compound on the moon, and added to special binding material, solid and resistant walls can be built [9]. Yet, this technology is not fully autonomous and could benefit from human supervision on site.

Figure 2: Example Sequence of the Lunar Outpost [9]



The chosen solution will then be a mixture between the second and last alternative. Indeed, the 3D printing technology cannot provide the astronauts a shelter starting from day 1. A temporary base used during a transition phase will be needed, in which the astronauts will live and work, while the permanent base will be built. From this temporary base the astronauts will also supervise the ongoing work on the 3D printed structures. Once the permanent base is ready for habitation the astronauts can move to it. The temporary module will be used as an emergency structure in case of unexpected events in the main one.

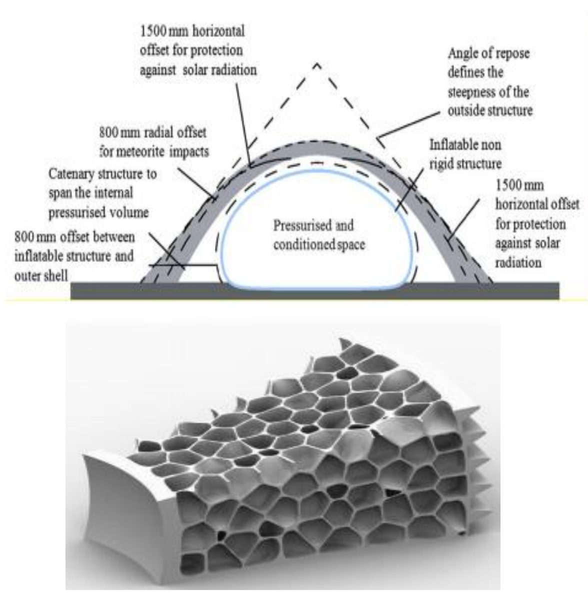
Temporary base module

This module will be based on already existing technologies, with additional characteristics to provide a proper shield against radiations on the Moon. The temporary base module will be explained in further details in the Layout part.

Permanent base construction

The permanent base will consist of two different parts; the external regolith shelter, which will cover the inner habitation as a dome. This external part will offer protection against thermal variations, temperature, and micrometeorites. The inner part will consist of an inflatable structure that will be sent from the ground and will provide the astronauts a pressurized and oxygenated atmosphere. This inner part will have a dome shape, and will be linked to a solid module that can, for example, be used as an airlock. The dome will be built step-by-step by rovers equipped with the necessary devices in order to 3D print the structure. One rover will print the structure using regolith and binding material through a 3D printing extruder, and the other rover will collect and feed the printing one with continuous regolith.

Figure 3: Lunar Outpost Structural Elements [9]



The outer regolith structure must protect the inflatable structure from temperature, radiation, and micrometeorites but also features some mechanical properties. To do so, the wall will have a defined thickness and shape, as one can see in Figure 3. One can note that a honeycomb structure is used, to bring mechanical properties, protection characteristics, but also lightness.

Mass budget at day 1

In order to offer the astronauts an operational Moon base at day 1, several parts of the projects should be brought with the first launch, and will determine the amount of payload necessary and influence the organization of the project. First, a transitory habitation module is necessary. Its characteristics will be detailed in the next part of this report. Then the inflatable structure will represent approximately a mass of 1500 kg and a volume of 40 m^3. The two rovers necessary for printing weigh approximately 1000 kg each and have a volume of 3 m^3. All these assumptions concerning mass and volume budget can be found in [9]. Finally, even if most of the materials required for printing the dome will be found on the Moon, some dry salts to make the binding materials have to be brought from Earth. According to [9], it represents 6 m^3 and a weight of 3800 kg per dome.

Layout

Requirements

In this part, the designs and layout of the Lunar Base will be discussed. At first instance the design for this mission is based on achieving at least a 90 m^3 space per astronaut for comfortable living and working at the facilities. Since the station requirements is to have a six-astronaut operation, the minimum space on the whole station has to be above 540 m^3. These values correspond to the needs of a crew for a mission duration of more than 6 months, to live and work comfortably.

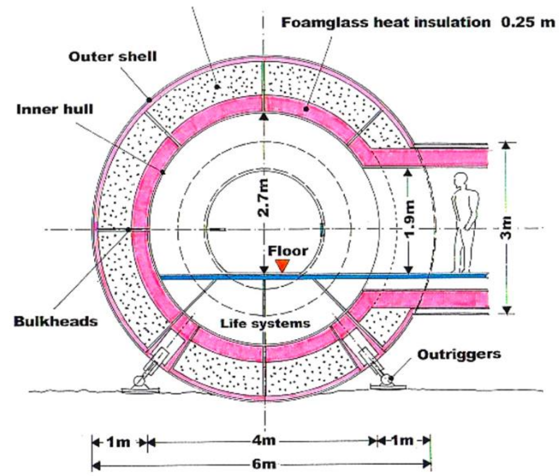
The final layout will of the base will include one emergency module, three power modules, and three printed domes. These domes will be divided into one dome for living, one for research, and the third one for a greenhouse experiment.

Dealing with the many uncertainties of mission success, especially taking into consideration the possibility of failure on the printed module construction compounding the numerous other dangers related to the mission, the safest strategy will be to bring an Emergency Module, where 3 astronauts will live for the initial period when the first dome is being printed.

Emergency Module

The Emergency Module will be developed based on Grand Lunar Base study, with the use of water instead of regolith for shielding. First this module will be used as a living and working space for the first crew. After the construction of the first dome, the module will serve as a storage and safe room for any emergency. The module has a cylindrical shape, with a 10 m length and a 6 m diameter. The total weight is around 10.2 ton. The double wall compartment is filled with water for radiation protection, thermal isolation, and water storage as can be seen in Figure 4. [7]

Figure 4: Emergency Module Cut View



The cylinder is made of aluminum and the length of the filling gap in between the double wall is 0.65 m.

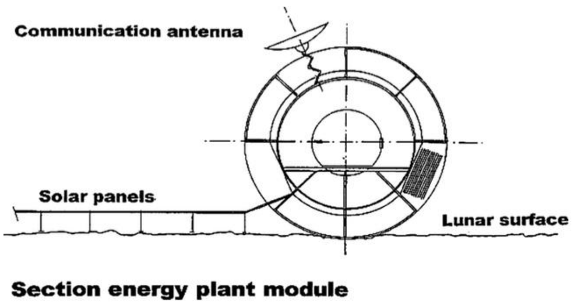
The module will have an independent temperature control and life support system. Also, it will rely on the first energy plant module for power supply.

On this module the first crew in the initial period of the mission will be able to sleep, eat, exercise, and do limited work.

Energy Plant

The Energy Plant Module will be similar in shape and size to the Emergency Module. It will consist of solar panels as its main source of energy production. Also it will include a battery bank and a nuclear reactor as a backup source. This can be seen on Figure 5 The module will also contain the antennas and communication system for the base. [7]

Figure 5: Energy Module



Three similar modules will be sent according to the construction of each dome. The first energy cylinder will power up the emergency module and the first dome after this been built. All the modules will be connected to each other, working together, forming a big energy supply plant. For safety reasons and versatility, each module can also work independently of the others.

Each module's solar panels will be folded for a compact size on launch and they will unfold once the module lands on the moon.

Utilizing the energy consumption and solar panel size on the ISS, each module will have a panel total area of 1000 m^2, that will generate 33 to 48 kW of electrical energy. [8]

Part of this energy will be used to maintain the life-support systems and the station upkeep and the remainder for battery recharge. A good amount of the energy will also be used to power up the greenhouse lights.

The bank of batteries will be similar to those of ISS, using rechargeable nickel-hydrogen batteries.

Printed Domes

This printed domes are inflatables covered with 3D printed lunar material. Each one has an average size of 250 m^3. [9]

The first module built will have two floors – Figure 6 – and serve as the living module. The top floor has separate rooms for each one of the six astronauts. A common area and work space to interact, share meals, and for communication with family or some entertainment can be seen on Figure 7.

Figure 6: Two-Floor Inflatable Building

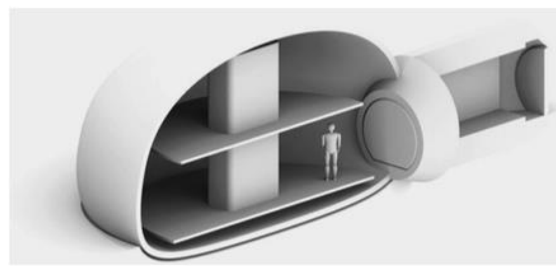
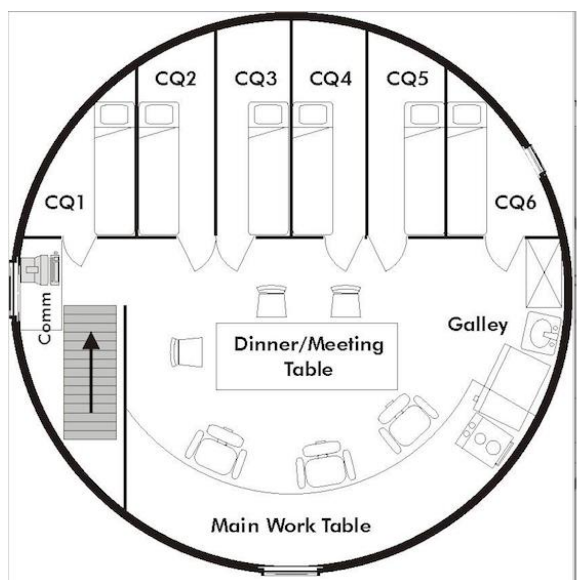


Figure 7: Living Module Top Floor



The bottom floor has two toilets, one shower, and an exercise facility.

The second module will contain an airlock room on the bottom floor for external exploration, where the pressure is lower than the other part of the module in order to control dust entrance into the lunar station. The other bottom part of the module will have a storage facility for food, water, and other products.

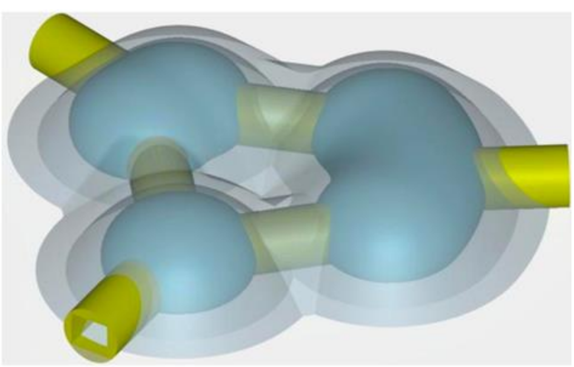
The top floor is the laboratory, where the inside experiments will be performed by the crew.

The third module will be a greenhouse for biological experiments, such as plant growing. The module will not have any windows thus artificial light will be used.

The module has a bottom part with racks where the small plants can be placed and a top floor for a small lab for other biological testing.

All the modules, besides the energy plant, will be connected by corridors that are also protect by the 3D printed walls. The lunar structure will have similar layout as an anthill, such as in Figure 8.

Figure 8: Modules Attached in an anthill configuration



Due to its modular configuration, the station can be easily isolated thus increasing the safety level of the crew. Also due to the general attachments on each module, it is possible and easy to increase the size by adding new modules.

Schedule

Priorities

The purpose of a time schedule is to carefully decide what should be brought to the surface of the moon in what order. The importance of this step can easily be underestimated when prior to this task the “hard part” can seem to been done. Sending mass to space is well known to be expensive and the consequences of doing it inefficiently could, in the worst case, lead to catastrophe. The benefits of today’s technology and the lessons learned from history enable great planning, which lead to improved financial possibilities. There are a lot of routines on prior missions that are taken into account in the logistics. The International Space Station is the most relatable source due to the fact that crew quantity will be identical on the lunar base. For example, food-, water- and air consumption data will not differ on ISS to the lunar base.

The time it takes for research and inventions to be applicable are often impossible to foresee. Therefore the first lander to touch down on the moon should be equipped with mainly life support systems and other necessities to survive on the moon. Consequently, science applications and experiments such as the greenhouse will be of lower priority in the building phase of lunar base.

When prioritizing the necessary material, bases, and research/science arrivals on location, dilemmas will most likely occur. Under the construction part, robots and other mobile machines were considered. If human lives could be guaranteed by trusting a robot to build the lunar base to be ready by human arrival a big step has been taken in the field of artificial intelligence. The problem with this proposal is that robots yet don't have the ability to assure the same building quality as the human sense for touch. Furthermore, such strategies have never been used which decreases the certainty of success.

On the other hand, the benefit of human presence is ensuring that the printers do their job. Consequently, the emergency module will be equipped with all the necessities for human survival such as food, water, and air. But something to do while the 3D printers are working on the dome inflatable module for power, as mentioned earlier, will be sent as a start. Additionally, the printing rovers will have to start as soon as possible, which is why they are included in the first arrival with the emergency and the inflatable module.

The Schedule

The project is, as mentioned earlier, based on a lunar base crew that will be switched out every sixth months. To be as efficient with time and money as possible, the supply to the base, with the survival kit, will be delivered in every crew shift. What also has to be considered is that the lunar base is going to expand and with that comes increased power requirements. So to begin with, there will be a lot of material transportation until the modules are settled. Until then, science and the potential to be able to produce food in a close loop system will be investigated on earth until it can be sent to space.

Figure 9 is an outline of what the transportation schedule to the moon could look like. The 3D printers may not be reliable in creating the structures and the sharp lines dividing tasks within different months may be blurred. 3D printers that work slower than expected or an event that slows down the process are taken into account, and there will be no problem if the first period's tasks overlap those of the second period.

During the second period, 2.25 tons of human survival supply are delivered. As mentioned previously, problems could unfortunately occur. With that in mind, the astronauts cannot be left on site with, for example, food for just the period they are staying. If something were to happen during the resupply and crew phase out mission so that the operation would have to be postponed, no proper supply for survival would be present. To ensure that such an event will never occur, there will always be food, water, and air to stay a whole period of six additional months.

Through the first year of building a lunar base, there is a lot of material scheduled to land on-site. The ability to carry this amount of cargo in terms of mass and volume can surely be questioned since just one module weighs around 10.2 tons. Discussion concerning reliability in the timeframe are left out since it only aims to explain what is needed to achieve the mission.

Figure 9: Lunar Base Time Schedule

Astronauts	3	6	6	6	6
Survival kit	Food, water and air	Food, water and air	Food, water and air	Food, water and air	Food, water and air
Arrivals	Emergency Capsule Inflatable Module 3D printing hoovers and material	inflatable module 3D printing material Power supply	Things needed for science Power supply	Greenhouse	
Tasks	Build first module - place to live set up everything	build second module - Science - Storage - suitsroom			

Conclusion

Throughout this project, several aspects of the specifications had to be discussed and taken into account, the most important being the scientific purpose of the Moon base and the related requirements, in order to make decisions about the construction and layout of the lunar base. The different criteria came from an overall coordination point of view, the human aspect, on-site mobility perspective and, as expressed above, the scientific purpose. Furthermore, the complexity of this project requires thoroughly analyzing the possible risks that could occur, preventing them from happening, but also thinking about an alternative solution in case things go wrong.

The conclusion of this study is a modular lunar base, in order to respect the delays but also to easily extend the initial facilities if needed. This base would be located on the Moon's southern pole, which presents ideal lighting conditions to power the base. The south pole is also very interesting in a scientific sense since it has not been explored yet. To protect the astronauts from the harsh lunar environment, a prefabricated module will be sent at day 1, to allow the astronauts to supervise the on-going work of 3D printed shelters above an inflatable inner structure. This combination of 3D printed dome with an inflatable structure is to be the long-term solution to provide enough work and living volume, at the most reasonable cost.

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