Human spaceflight
Manned Lunar Base: base construction and lay-out

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Abstract: The purpose of the following paper is to make an analysis of the base construction and layout for a manned lunar basis. First of all, a location needs to be chosen in order to establish the base. Then, the technology which will be used is going to be chosen. In order to protect the crew team of astronauts which will come, some radiation analysis has to be done to be sure they can live there. Finally, a power analysis will also be performed in order to bring enough power supply material to the Moon.

Introduction

This report presents a feasibility study on the construction point of view of a manned base on the moon to be used for scientific purposes by the end of ISS's operation and preparation for a human mission to Mars.

Under many possible aspects of view, the main concerns accessed here were on how to provide a breathable environment to the crew and provide shielding against radiation, micrometeorites and temperature meanwhile trying to minimize the mass and therefore the cost of the mission. The feasibility study was developed under three major points: Building technology, power supply and mass and volume estimations.

Therefore a set of five objectives were followed to fulfil a feasible construction of the base:

The first step is to define the location of the base since it impacts on different aspects of a manned moon base mission, such as launch operations, environment and exploration.

The second task was to define a design concept, taking into account mission duration, crew size, and environmental aspects (temperature, radiation and mechanical protection).

As defined in the design concept, building technology is further investigated, being the first critical point for feasibility.

Next step is to investigate a power supply design (how to generate and store power for continuous base operation), the second critical point for feasibility.

Finally, mass and volume estimation analysis takes place fulfilling the third critical point for feasibility in comparison with present cargo capsules available.

1. Location of the base

The location of the base was chosen to be on the South Pole's surface of the Moon. This decision was guided by different requirements. Temperature stability, sunlight incidence and mass reduction, along with exploration opportunities were the baselines to define the location of the base and are further described in the following sections.

1.1 Surface base

The choice of building the base on the Moon's surface and not underground was purely guided by its lower complexity. An underground base could have some benefits. It could provide reliable shielding against radiation and temperature, and mechanical protection. However, building a base underground would require heavy machinery, therefore increase in payload mass, and possibly consume a lot more time, which cannot be affordable by our scope.

1.2 Temperature stability

Since an underground base was not an option, the surface environment was taken into account. The choices were then, equatorial or polar regions. The following table describes the temperature in different regions of the moon [1]. Under a temperature point of view, a polar region sustains better stability, which can be translated as a more simple and reliable temperature regulation system.

	Shadowed polar craters	Other polar areas	Front equatorial	Back equatorial	Limb equatorial	Typical mid-latitudes
Average temperature	40 K	220 K	254 K	256 K	255 K	220 < T < 255 K
Monthly range	none	±10 K	± 140 K	± 140 K	± 140 K	± 110 K

Table 1: Estimated lunar temperatures

1.3 Exploration opportunities

In 2009, the NASA's LCROSS (Lunar CRater Observation and Sensing Satellite) mission blasted particles from a permanently shadowed crater on the Lunar South Pole. This resulted in finding water trapped inside these types of craters [2] [3]. Water is a valuable resource not only to supply the crew on the base, but also to produce fuel to propel rockets (hydrogen) and oxygen. Producing fuel on the Moon could be worth on future missions to Mars, for example. Thereby, placing the base near a crater on the South Pole is the right approach for this mission.

1.4 Sunlight incidence

To be able to supply power to the base, the best option is through solar arrays. Thus the location must be in a high sunlight incidence spot. NASA's Lunar Reconnaissance Orbiter's (LRO's) Lunar Orbiter Altimeter (LOLA) is used to gather elevation data that was used to accurately simulate sunlight conditions on the Lunar South Pole [4]. This simulation resulted in the image show on Figure 1.

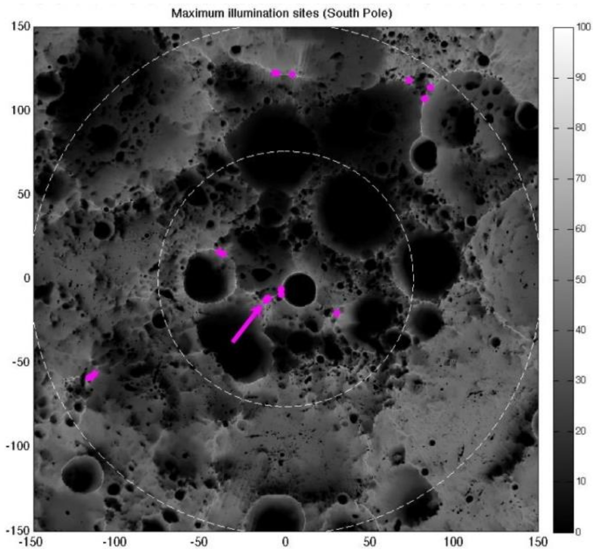

Figure 1: Average solar illumination of the South Pole region above 85°. Sites of maximum illumination are emphasized.

The pink arrow on the image point at the best illuminated site. With more than 92% of sunlight incidence, granting 243 days of continuous illumination over a year with no period of total darkness for more than 24 hours, that is the perfect spot for a Moon base.

The exact location is at 222.2° E, 89.45° S. This point is relatively near the Shackleton crater, at an estimated distance of 10km. The base could also be located closer to the crater's rim, also with high illumination. An illustrative layout for the base can be seen in Figure 2.

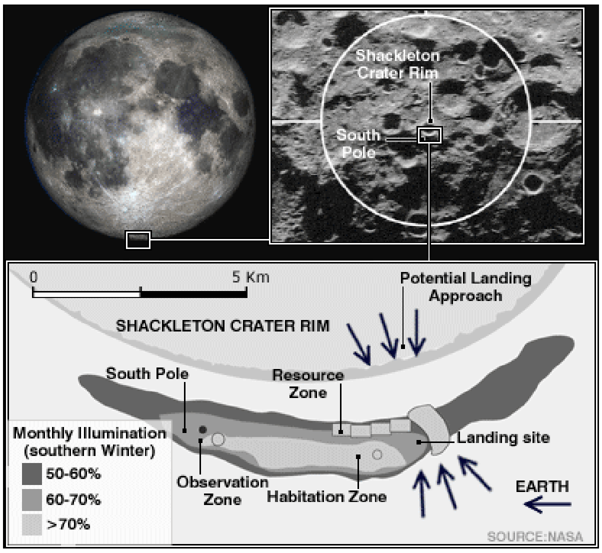

Figure 2: Illustrative layout of the lunar base.

2. Building Technology

For the construction of the lunar base a building technique can be used whose basics were already investigated by the *European Space Agency ESA* supported by the architecture company *Foster and Partners* as an industrial partner in course of a feasibility study. The fundamental principle of this new technique is based on a capsule system combined with a 3D printing technology that allows setting up a lunar base by using local materials and will be considered hereinafter in more detail.

2.1 Capsule System

The foundation stone of each section of the base is a capsule, a tubular module (figure 1), which can be easily transported by a spacecraft.

Figure 3: Capsule-Module with inflatable dome [6]

If the capsule is placed in a first step on the lunar surface, an inflatable dome is unfolded from one end of the capsule and extends to provide a support structure for the later construction phase in which a robot-operated 3D printer is used to build up layers of regolith over the dome to create a protective shell. For a more detailed explanation of the printing and robotic technique the reader should be referred to section 1.2.
Once the construction phase is completed, the original capsule functions as an airlock and a technical support module (figure 4).

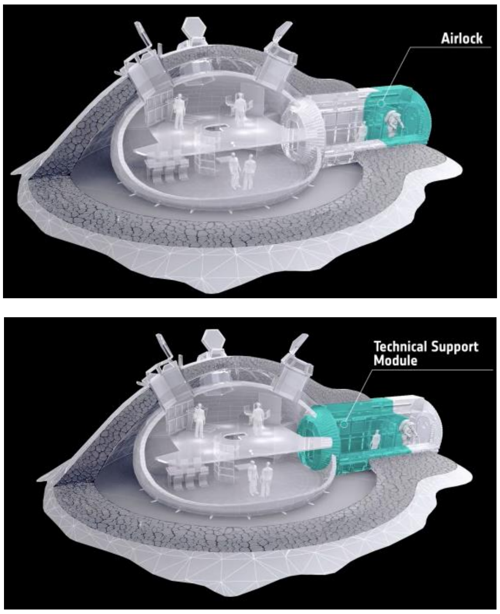

Figure 4: Capsule functions [6]

In addition, the integration of adapters enables a later connection of different capsules by additional inflatable structures which serve as connection corridors and are explained in more detail in section 1.3. Thus, the capsule, which is placed during the first mission on the moon surface and represents in combination with the first regolith dome the living area for the crew, serves as the main nodal point and with its airlock as the main exit point of the base. ([6], [7], [8])

2.2 Volume and mass for the inflatable structure

2.2.1 Inflated structure

As explained previously, the first part of the lunar base will be built without the help of any crew team, and that is why prefabricated structures will be sent on the Moon. The inflatable structure has been chosen since it can be assured the structure is finished and available for the crew before the astronauts come in. On the other hand, the related technological aspects have to be taken into consideration and even if the half sphere inflated structure seems like a good choice, one has to remember that the technology might not be enough developed in 2024 to be able to construct such a structure. For the lunar base study, it will be considered that the structure can be built and that it is actually possible to design it. One thing also important to remember in the design is the space which will be left for the life support material or the storage. This has been taken into account on the following characteristics:

Volume by astronaut (m^3)	Inside Pressure (bar)	% of O_2
120	2/3	28

Table 2: Living characteristics in the inflated structure

In order to facilitate the EVA (Extra Vehicular Activities), the percentage of oxygen has been increased compared to the percentage present in the Earth atmosphere. Moreover, the general pressure has been lowered compared to the one of the atmosphere. The structure will also have to support the internal pressure load and all the kinds of loads that it will endure during the transportation to the Moon. It will also have to resist abrasion even if it is protected by the regolith layer. The form of the inflatable structure chosen is a half sphere which means that since the necessary volume for the astronauts is known, one can determine the mass and volume of the non-yet inflated structure thanks to the figures found in [10]. Considering the crew will be a 6 astronauts crew, the total volume needed will be of 720m^3 which leads to a total mass of 2.1 tons and a volume of around 38.28m^3 for the inflated structure which is going to be put on the first shuttle.

Now, if a pressure of 2/3 bar is considered with 20°C of temperature, this means that according to the perfect gas law at least 19970 moles of air are needed. With 28% of O_2, the molar mass of air is 29.24 g/mol, so the total mass of air can be determined: 584 kg. Then, this is a current volume of 720m^3 which is way too important to be brought in space. To be able to bring this amount of air on the Moon, the air has to be compressed. Considering the perfect gas law for a given temperature and amount of molecule, it can be seen that the volume will decrease if the pressure rises. According to different research, the air can be compressed up to 300 bars. So, if the air brought to the Moon is compressed at 100 bars of pressure, this means the final volume is only of 4.8 m^3. Depending on the structure which will maintain the air compressed, the pumps which will be probably needed to inflate the structure, it can be estimated that the total mass for the "air system" will be around 1 ton.

2.2.2 Capsule

The mass of the capsule has to be considered too. It is difficult to imagine a good guess for the capsule as such a capsule hasn't been designed yet. On the other hand, it is possible to find some figures concerning the capsule currently used to supply the ISS. The table below shows different examples of such capsules:

Type of capsule	Diameter (m)	Height (m)	Mass (ton)
ATV	4.5	10.3	21
Dragon	3.7	6.1	12
Progress	2.72	7.2	7.3

Table 3: Dimension and volume for different capsules

According to this data and to the different needs of the capsule such as the airlock or the technical support module, a guess of 8 tons for the capsule can be made.

2.3 Printing Technology

The Monolith D-Shape printing technology used to build the basis is provided by the architecture company *Foster and Partners*. For a better explanation of this technology the two areas "Printing Process" and "Robot Technology" will be discussed in the following.

2.3.1 Printing Process

For the printing process, a method is used where the desired structure is built up layer by layer. The original printing process was developed to create sculptures and is working on artificial coral reefs to support preserve beaches from energetic sea waves. This old method was picked up and developed to enable a printing with lunar regolith instead of earthly sand.

As previously mentioned, the ‘ink’ required for the printing process consists mainly of lunar regolith which has to be mixed with magnesium oxide to turn it into ‘paper’ one can print with. In a last step a binding salt is added which converts the material to a stone-like solid. The two last-mentioned additives represent related to the mass of the entire building material only a very small percentage. This fact relativizes the disadvantage that both the magnesium oxide and the binding salt have to be carried along in tanks during the flight to the moon.

Furthermore, one had to rise to an additional challenge in the development of the printing procedure. The effect of working in a vacuum needed to be assessed since the whole process is based on applying liquids which, of course, would boil away if it is unprotected in vacuum. To encounter this problem the Italian space research firm *Alta SpA* developed a technique whereby the 3D printer nozzle beneath the regolith layer. They figured out that small 2 mm-scale droplets stay trapped by capillary forces in the soil, leading to the conclusion that the printing process can indeed work in vacuum.
These so developed printers are building at a rate of around 3.5 m per hour with a layer thickness of 5 - 10 mm, enabling to complete an entire module in a week. Furthermore, the use of this new printing technology makes it possible to minimize the required payload for the transportation of the equipment to the moon. The mass which has to be transported is only composed of the capsule material, the binding salt, the needed magnesium oxide and the robotics. Due to the utilization of local resources on the moon, the transport and construction is very cost-efficient. ([7], [8], [9])

2.3.2 Robot Technology

In the construction phase the lunar habitation is operated by a robot-operated 3D printer used to build up layers of regolith over the inflated dome to create a protective shell. On end it has a scoop to collect the regolith (figure 5) and transport it to the building site. Briefly after the arrival on the lunar surface it can be also used by the robot to straighten the ground at the spot where the inflatable dome should be raised. In this way it creates a suitable foundation for the construction. In the center of the robot, containers are mounted for the magnesium oxide and the binding salt which are transported through tubes to a robotic arm at the other end of the robot (figure 6). This robotic arm has six axes and an attached printing head at the end of it (figure 7) which can be optimally guided in order to print the desired structures. The robot is powered by solar cells and batteries. Due to the fact that the location of the planned moon base is almost always illuminated by the sun, the energy supply of the robot is mainly secured by the solar cell system. In the few hours during the year when there is no sun light present, energy collected in the batteries is used. However, the building of the various modules can be scheduled so that the sun is shining throughout the construction time and thus the robot is always well supplied with energy.

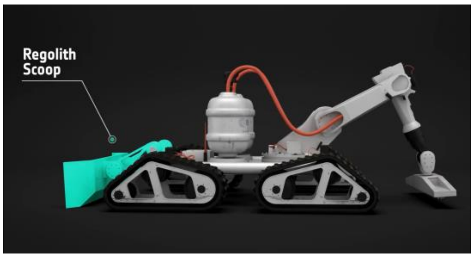

Figure 5: Regolith Scoop [6]

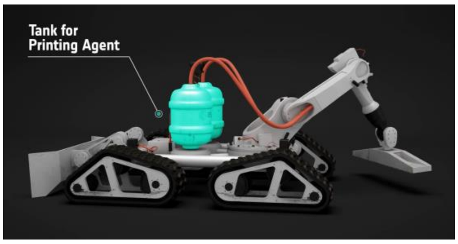

Figure 6: Tank for Printing Agent [6]

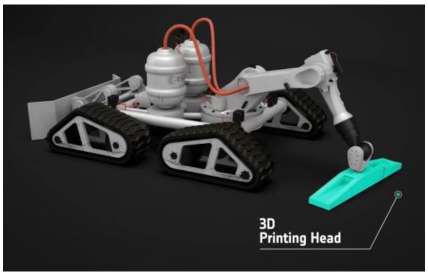

Figure 7: 3D Printing Head [6]

The total weight of the robot, which is mainly for the transportation of the robot via spacecraft of enormous significance, is about 350 kg. The estimation of the weight can be found in table 1. Here, the Mars rover MER, a robotic arm offered by the German company KUKA and a commercially available scoop are serving as the basis for this estimation. The data sheets can be found in the appendix. Furthermore, 800 x 800 x 500 mm are assumed for the dimensions of the robot in the *transport mode* in which the scoop and the robotic arm are fully pulled in.

During the building process the robot collects with its scoop regolith on the moon surface (figure 8) and transports it to the building site where it is unloaded on the uppermost printed layer. Now the regolith can be used to print the next layer by turning the robot and applying the printing head (figure 9). The printed pattern of the regolith shell corresponds to a honeycomb structure which is light and incredible strong at the same time. The time that is necessary to build the lunar habitation strongly depends on the number of used robots and the dimensions of the inflated structure. For the construction of the first module unit, that represents the living module, a construction period of less than one month is assessed on condition that just one robot is used. ([6], [7], [8], [9])

	Weight [kg]
MER Mars Rover	174
KUKA Robotic Arm	54
Binder container	unknown
Scoop	10
Total	300 - 350

Table 4: Robot weight estimation

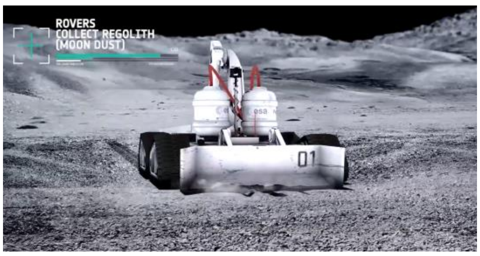

Figure 8: Rover Collects Regolith [6]

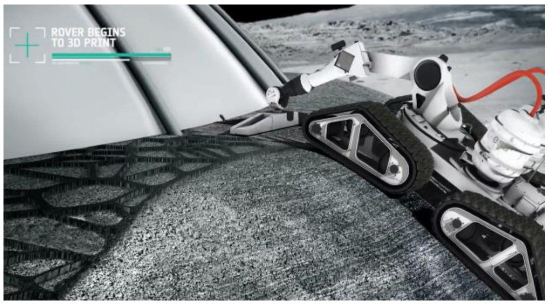

Figure 9: Printing Process [6]

2.4 Module System

Once the living module is built up together with the in the first capsule integrated main airlock as a result of the first mission, the lunar base can be extended step by step during subsequent missions. For this purpose, the already mentioned modular building system is introduced in which each module fulfills a specific task and has its individual functionality. With respect to the room layout, the inner space of the inflatable structure can be organized according to the particular function of the module. As an example, the reader is referred to the by NASA operated research station FMARS (Flashline Mars Arctic Research Station) whose room layout can be found in figure 10.

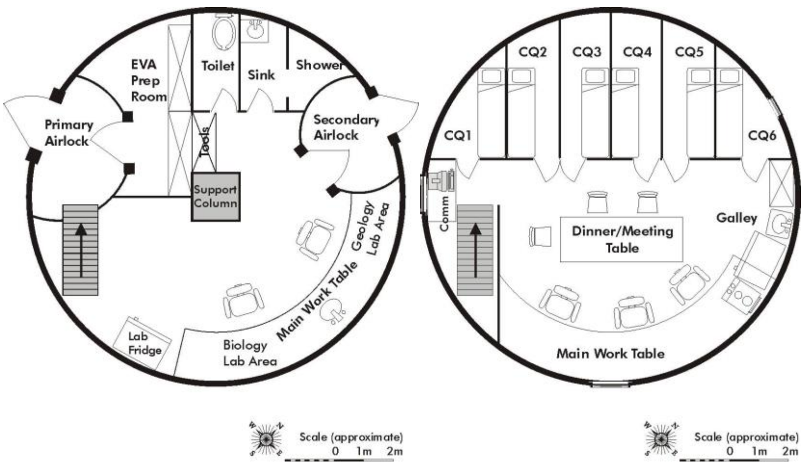

Figure 10: Room layout of FMARS [5]

During a second mission, the first crew and a further capsule are transported to the moon. The crew can now move into the already completed living module whereas the second capsule forms the foundation for the experimental module. The encasement of the second inflatable dome is now much faster since a second printing robot is delivered

together with the capsule that operates parallel to the first robot in the construction. While other following missions, additional modules can be delivered and built. This could be for example a green house.
An advantage of these additional capsules is that they do not necessarily include all their own air lock since the capsules are all connected to each other and thus the main air lock in the living module can be used. Additional air locks are only serving as an emergency exit whereby the necessary redundancy in essential systems is guaranteed. In this way the additional capsules can be designed much smaller which leads to a lower payload for the used launch and transportation system.
The connection of the individual modules or capsules takes place by adding additional flexible inflatable structures which are covered by layers of lunar regolith (figure 11). In order to connect the capsules and the gangways airtight, an adapter system is needed which consists of gates that seal off the not connected capsule or can be closed in an emergency case – for example in case of a fire in one module – in order to protect the other modules.

Figure 11: Module system [8]

3. Radiation shielding

3.1 Radiation exposure

The shielding provided by earth atmosphere is absolutely inexistent on the surface of the moon, due to its lack of atmosphere. Thus, shielding against space radiation is one of the main challenge to overcome when studying the feasibility of a lunar outpost.

3.2 Permissible exposure limits

Since nothing could replace the terrestrial atmosphere on the moon, permissible exposure limits have to be set in order to limit chronic risks to an acceptable level in terms of legal, ethical, moral and financial considerations. According to NASA's permissible exposure limit [12], several limits can be set.

-Cancer risk limit: Career exposure lead to a maximum of 3% risk of induced death by cancer. These dose limits have a large biological and physical uncertainty associated with them. New exposure limits also require that this risk should not be exceeded at a 95% confidence level, and this may decrease allowable astronaut exposure by a factor of 6.

Age	25	35	45	55
Male	0.7	1.0	1.5	3.0
Female	0.4	0.6	0.9	1.7

Table 5: examples of career dose limits for different ages at exposure (Source NCRP [13])

-Dose limit for non-Cancer effect: Short term dose limits are imposed to prevent non cancer health effect including performance degradation (vomiting, sickness or death). There are dose limits for

-Blood forming organs (BFO)
-Central nervous system (CNS)
-Skin
-Eyes
-Heart

3.2 Radiation types

Radiation exposure is one of our main concern regarding the feasibility of a lunar outpost. Knowing the exposure limits must come to pair with a good understanding of the different types of radiations to which the astronauts will be subject. Those radiations can be divided into two groups.

-GCR (Galactic cosmic rays)
These radiations consist mainly of protons and heavy nuclei coming from outside of the solar system at high velocities. The radiation level is low and steady since galactic cosmic rays constantly bombard the lunar surface, so that they represent a large fraction of the total dose equivalent. When dealing with long span missions, they represent the limiting factor in terms of radiation exposure. Also, it appears that the GCR flux decreases significantly during large solar particle events. Here the Badhwar-O'Neill model of the 1977 solar minimum environment was used as a worst case GCR environment.

-SPE (Solar particle events)
These radiations consist mainly of protons emitted during solar events. As opposed to GCR exposures, which are chronic and threaten the long term health of astronauts after their return to Earth, solar particle events (SPE) generate very high intensities of energetic protons, which can produce acute effects that could be disabling or even life threatening. The largest SPE ever observed was in February 1956. This will serve as a worst case scenario in the sizing of the radiation shield.
When dealing with these types of solar events, a warning time of 20 minute can be given to astronauts in order for them to take shelter in the base.

Another indirect type of radiation can occur when SPE are GCR particles come smashing through the lunar surface are even the radiation coating device. These secondary radiations consist mainly of protons and can be really harmful for the human body. Taking this into account will lead to an increase in the thickness of the radiation shield.

3.3 Regolith Shielding

3.3.1 Indoor life

Regolith is a layer of loose and heterogeneous material almost covering the entire surface of the moon. Studies have shown the possibility of using this regolith to design structures based on the terrestrial 3D printing technology [14]. Regolith will be mixed with a binding agent and sprayed over the inflated enclosure. Studies have shown that regolith turned out to be a good substitute for purposes of radiation protection, as it provides a high percent dose reduction per unit areal density (see figure 1 below) [15]. Thus, a 50 cm layer of protective regolith could be sufficient to provide adequate SPEs and GCR protections for at least a year of indoor life, assuming a density of 1.5 g/cm^3. Reducing the total dose equivalent by more than 80%.

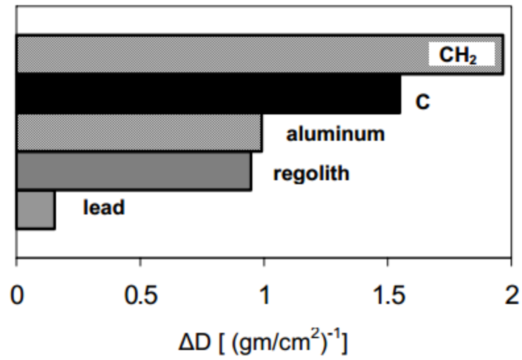

Figure 12: Average percent dose reduction per unit areal density (gm/cm^2) for regolith compared to polyethylene, graphite, aluminium and lead.

The doses during the transfer and during extra vehicular activities have not been taken into account. The thicker the layer the better the shielding. A 1.5 m could be a good solution to counteract the effect of secondary particles emitted. No actual studies have been made on this matter, and this should be further investigated before any long term mission.

3.3.2 Extra vehicular activities

Radiation exposure time for the astronauts can be divided into three categories: the Extravehicular Activities (EVA), the scientific and research activities, and the sleeping and personal time activities. Here the GCR exposure for the EVA portion of the astronaut activities is investigated, since that is the time the astronauts will be least protected, and since the shielding during research/personal time will be entirely provided by the regolith layer.

According to the HZETRN (model used by the NASA to help scientists and engineers study the effects of space radiation on shielding materials, electronics, and biological systems), the maximum admissible daily effective dose for an astronaut on the lunar surface is about 0.085 cSv under the 1977 GCR environment. Therefore, a 500 days lunar mission made up entirely of EVAs would lead to a global exposure of 0.425 Sv. The table 2 below show this as a percentage of career limits for LEO space missions.

Age	25	35	45	55
Male	61%	43%	29%	14%
Female	108%	72%	48%	25%

Table 6: 0.425 Sv Exposure as a Percentage of LEO Career Effective Dose Limits

Now, taking into account the biological uncertainties attached to these radiation level limits, more detailed model must be analysed. If exposure limits are decreased by a factor of 6, GCR radiation become the limiting factor for a long span mission. Further, EVA hours could should be limited to 90 days [16].

4. Structural analysis

The structure will have to resist to three different loading conditions:
-Inflatable structure pressurized, without regolith on top.
-Inflatable structure pressurized, with regolith on top.
-Inflatable structure depressurized, with regolith on top.
The two first conditions result from the construction sequence. The last one results from the case where a micrometeorite punches a hole in the structure, leading to air leaking out and progressively up to a total depressurization. In this case, the base will have to be rebuilt but it must not collapse so that astronauts can have time to get out of it.

4.1 Inflatable structure pressurized, without regolith on top

For the first loading condition, the requirements in terms of structural resistance will be carried by the inflatable structure itself.

4.2 Inflatable structure pressurized, with regolith on top

For the second case, when the regolith is in place on top of the pressurized enclosure, the regolith load has to be calculated to make sure the structure will hold. The pressurized enclosure is a hemisphere of radius 7 m. When considering the regolith layer, the total radius is up to 8.5 m. To calculate the structural load induced by this layer of regolith, a simple model consists of taking the overall weight of the regolith layer and dividing by the ground area of the structure. With an average density of 1.5 g/cm^3, the structural load is about 8.9 kPa. This is far lower than the pressurization level inside the inflatable structure. Also, part of the regolith will carry its own weight. Thus, the pressure inside the enclosure will be sufficient to hold the structure.

4.3 Inflatable structure depressurized, with regolith on top

For the last case, aluminium lattices will carry part of the structure's weight in case of depressurization. These lattices will be installed by the astronaut inside the inflated structure upon arrival. They can further be used to hang equipment because the upper part of the enclosed area will not be used by the astronauts.

5. Power supply

5.1 Which power supply on the lunar basis?

As expected, no power supply is directly available on the Moon. Different ways can be thought of to produce energy there. The two main ones could be to bring sort of a nuclear power plant on the Moon or to prefer solar panels related power. The nuclear supply could be interesting for a long trip mission in the deep space or potentially if the position of the lunar basis had been one close to the equator where solar power would have been difficult to design. As the location for the basis is close to the Shackleton Crater in the South Pole of the Moon, precisely in a so called "peak of eternal light", the solar power seems preferable to be used. With less than 20 Earth days of darkness a year, it looks like one of the best place to settle solar panels. Moreover, it seems, prima facie, that the nuclear power supply would be more complex to build, use and maintain there than the solar panels.

5.2 Which cells to choose?

A lot of data concerning the solar cells and solar panels can be found. It is interesting to think that the best performance for these types of cells haven't been achieved yet and that numbers of studies keep on being led by scientist always trying to improve their efficiencies. According to the Rocket propulsion course material of KTH (*reference*), which provides data concerning the different types of cells existing nowadays, the type of cells which should be preferred in order to build a solar array on the Moon can be evaluated.

In order to compare the efficiency of the different cells, a specific solar array has been taken into account. So, the values of efficiency, mass and power are given considering the cells are used on the Miranda X4 solar array. This array, with a surface of 2.976m² and an original mass of 6.25kg was first used in 1974.

Cell type	Cell efficiency	Mass (kg)	Watts (W)	Watts/kg
Original X4	7.7	6.25	310	49.6
High efficiency	16	6.85	644	94
GaAs/Ge	19	8.04	724	90
Triple junction	28	8.26	1127	136.4

Table 7: Performance of the X4 solar array with different types of cells

Even if the high efficiency cells and the GaAs/Ge cells seem quite similar given the power by mass, the use of new types of cells such as the triple junction cells appears to be preferable according to these values as they provide a better power by mass for a similar area. One of the disadvantages could be the related mass of the cells, so in order to check if they really are the best choice; a simple study can be made.

Let's imagine the Moon crew needs 1MW of power and let's consider the difference between the high efficiency cells and the triple junction cells as they are the ones with the more difference between mass and power by mass.

Cell type	Mass needed (kg)	Area needed (m²)
Triple junction	7329	2641
High efficiency	10637	4621

Table 8: Performance of two types of cells for a given wanted power

The triple junction technology, as a new technology, might be more expensive to produce and buy. But, considering the importance of the price to send mass in space, it can be assumed that even if the triple junction cells are more expensive on the ground, their related mass and power efficiency will be an advantage to use them on the lunar basis.

Previously, it has been mentioned that the field of solar power supply is in constant evolution. Some example of the recent outbreak can be mentioned, particularly considering the works done in the field of the triple junction cells. If some achievements in study labs are considered, research and tests have proven that triple junction cells have managed to reach a new record of 44.4% of efficiency and may be able to carry on improving up to 50% according to the articles [17] and [18].

Therefore, when the time of the launch of the mission comes, the triple junction cells may have reached an even better efficiency.

5.3 How to take into account the time and space environment?

As the type of cell has been chosen, some companies which provide this type of cells can be considered. Particularly, the company called Azurspace is really interesting. It corresponds to one of the companies which provide important firms and agencies involved in the space field such as ESA or Airbus ([19]). Azurspace proposes different types of triple junction cells, the ones designed for classical space solar panels and the ones which have been improved for space mission with a higher integration level. It is difficult to estimate which precise level of integration will be needed but one can expect it will be a higher one. The related efficiency of the cell doesn't change which comforts the idea of choosing the improved ones, as they may be easier to adapt on the lunar base if necessary. The triple junction cells available possess two types of efficiency: 28% and 30%. More particularly, one triple junction cell measures 30.18cm² and weights in average 3.5 grams. These are important values considering these cells will be assembled and sent to space. One other aspect concerns the power available for this typical cell.

Considering the abilities of the cells are given in a test environment with a temperature of 28°C, it can be supposed that the 30% efficiency cells will be better considering space's environment will induce a decrease in the real power provided as this one is linked to the temperature. According to the information stated on the specification sheet of the product, the acceptance value of voltage for one cell is 2350mV and the related average current is 500mA. These values evolve with the temperature when max power is considered, with a negative slope for the voltage ($\Delta V/\Delta T$=-6.1mV/°C) and a positive one for the intensity ($\Delta I/\Delta T$=0.28mA/°C). The two effects, even if they are contraries, don't compensate a loss of power on the Moon induced by the fact that the base so as the solar panels will be at a temperature between -75°C and -20°C. The final critical loss of power can be found on the table below.

Temperature	Voltage (mV)	Intensity (mA)	Power (mW)
28°C	2350	500	1175
-75°C	1721.7	528.84	910.5

Table 9: Loss of power of the cell due to temperature

So, considering the values given in the previous table, it can be assumed that the critical loss due to temperature for the 30% triple junction cells will be around 22.5%. This is important when the size of the solar panels have to be chosen, but it's important to remember that as this one, the others cells would also have suffered loss in efficiency due to temperature which means the choice of this particular cell remains valid.

However, other losses have to be taken into consideration and particularly losses due to time. Indeed, according to typical data for solar array design parameters, a loss equal to around 40.5% of efficiency after 15 years can be observed for GaAs cells (with ultra MJ). These cells can be considered to have an efficiency equals to 28%. Given the fact such a data haven't been found for the cell chosen, it has be assumed that its loss due to time is the same. This gives finally a theoretical final power available of 542.2mW by cell.

Finally, the transforming system has to be taken into consideration, but it will be considered its efficiency as equal to around 98%, which is not a bad assumption according to [20].

5.4 How power supply will be provided and how to store it?

Thanks to the location of the base and the solar panels, the necessary power will be produced. But as much as create the power is an important task, store the energy is also one. Indeed, it will be compulsory to have some storage system for different reasons. Firstly, even if the base is located in a so called peak of eternal light, there will be some moments during the year during which there won't be any sunlight shining on the base. Secondly, it can always be careful to have some storage system as a backup plan in case a solar array malfunctions. In order to do so, some batteries must be taken to space as well.

The classical battery which is used today and that can be thought to be sent to space is the Lithium-ion battery. Of course, the dimensions or the number of battery will depend on the need of storage, but one can imagine that during the dark periods fewer activities will be performed in order not to use too much energy. Another battery which can be considered is the Lithium-Titanate battery which has the advantage of possessing a better lifetime and which is nine times faster to recharge compared to the other Lithium batteries. One of the drawbacks is its autonomy which is smaller than the ones of the other batteries. Considering an eventual problem and the importance of redundancy in space, it could great to have the different types of batteries in the lunar base to possess a solution of storage for different events that can appear.

5.5 How to build the solar panels on the Moon?

The mass of the solar panels is sized considering the power supposed to be needed for the lunar base. The problem about bringing the given mass to space is actually the volume the panels could take. Moreover, one has to think about a structure to maintain the solar arrays oriented through the Sun. In order to do so, a similar structure as the one used by NASA to test the deployable solar arrays which are going to be sent to space can be used. Indeed, the principle of the support structure can be seen on the figure below.

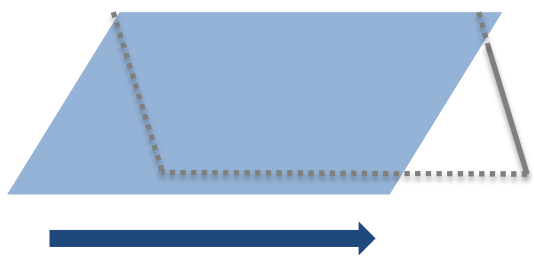

Figure 13: Deployable solar array and support structure

The principal idea is to be able to fold the solar arrays so some volume can be earned on the space shuttle. Once arrived on the Moon, the crew team will have to assemble the support structure and deploy the arrays on it. Considering that it is possible to separate the arrays and given the gravity on the Moon, it won't be too difficult for the crew to build the power supply system which in addition has already been tested on Earth.

5.6 Mass of the power supply system

It is quite difficult to estimate the power consumption of each astronaut on the lunar base. However, in order to have an idea of the mass of the solar panels which will be necessary to bring on the Moon, the power consumption of an average habitant of the USA (12000W/year) has been taken into account since it is the most important consumption in the world. In order to be sure to have enough power, this value has been multiplied by 1.5 and the available power which can be produced by the cells is the one of 542.2mW by cell. Thanks to that, one can estimate that enough power will be produced at the beginning of the mission as the cells will be new. By taking the transforming system efficiency into account, this gives a mass of around 711kg and an area of 601m² for the 6 member's crew. Finally, by taking the support structure into account and to have a little margin, a total mass of 1 ton is considered for the power supply system.

6. Total mass: 1st mission

One can find bellow a summary table of the different masses for the first mission.

Part of the base	Related mass (ton)
Capsule	8
Inflatable structure	2.1
Air system	1
Robots	0.7
Power supply system	1
Total	**12.8**

Table 10: Masses of the different parts of the first lunar base module

7. Second mission

The second mission corresponds to the manned mission. Not so much details will be provided considering this mission. It is though important to remember that the available mass for the base is only of 7 tons. This on the other hand won't be such a problem since the principal base module will have already been constructed. These 7 tons will be used to bring an experimental module which will be linked to the first module. The inflatable technology can be used again as the 3D printing robots will already be present on the Moon, but the size of this second module will be less important to the one of the first one. It can be considered that no more than 2 astronauts will perform experiments at the same time which decrease the mass and volume of the structure and the air necessary. Moreover, the experimental related capsule, as it will be linked to the first part of the base, won't need an airlock and less volume for technical support, which also means a possible decrease of mass.

Conclusion

This report aimed to assess the feasibility and set the scene for a human-rated lunar outpost. The overall objective for the base design was to provide a breathable environment to the crew and provide shielding against radiation, micrometeorites and temperature meanwhile trying to minimize the mass and therefore the cost of the mission. Prior to the design phase, a reflexion guided by several requirements (ground foundations, temperature stability, exploration opportunities and sunlight incidence) led us to establish the outpost geographic location near Shackleton crater on the lunar South Pole. The very concept of the outpost is based on dome-shaped inflatable and pressurized enclosures covered with a layer of regolith of approximately 1.5 meters, which ensures temperature insulation and radiation shielding for a year of indoor life. The entire base will most likely consist of several of these sheltered enclosures, which renders possible an incremental approach in the building process. The building technology makes use of the terrestrial additive manufacturing process, which will be executed by 3D-printing robots using a mixture of regolith and a binding agent. When it comes to power supply, triple junction cells appear to show promising results and could well be used in deployable solar arrays to supply the base with electrical power. The overall study led us to believe in the feasibility of such a base design, as it would result in an approximate payload mass of less than 13 tons.

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