Base Lunar Installation for Scientific Studies (BLISS) Station Design

Team Blue

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***Abstract*—The long-term objective of the Artemis program which returns mankind to the moon is to establish a permanent lunar base. Assuming that Artemis was concluded successfully by 2037, this report presents a conceptual station design of the Base Lunar Installation for Scientific Studies (BLISS) to be operational by 2040. Similar to the Amundsen-Scott station on Earth's south pole, BLISS is supposed to host up to 50 astronauts permanently. Its location is chosen on the connecting ridge of the Shackleton crater near the lunar south pole due to high solar illumination, resource availability and low slopes to conduct extra-vehicular activities (EVAs). In order to transport and build the station on the moon, a modular design consisting of inflatable, half-cylindrical tubes of 4.5 m diameter is chosen. The tubes are oriented in a compact rectangular layout and divided into living areas, working areas such as laboratories and workshops as well as a greenhouse for plantation growth. Additionally, a cupola for astronomical observation, a life-support module and emergency modules for safety are added. Once installed, the modules are protected from radiation using a 4 m thick layer of solar sintered regolith. The cargo rover ATHLETE as well as the excavation rover RASSOR 2 are employed to accomplish the manufacturing of the base shielding which is sufficiently protected against radiation to allow astronauts to stay on the station for up to 7 months. BLISS is primarily supplied by the Roll-Out Solar Arrays (ROSA) that were also used on the International Space Station (ISS) and which are placed in a circle around it. As a back-up system, the nuclear Fission Surface Power (FSP) plant is transported to the moon, which also serves as a testbed for Mars missions where less solar power can be harvested. Energy storage and conversion are accomplished by making use of hydrogen fuel cells, which are also advantageous in terms of life-support synergies and propellant manufacturing.**

***Index Terms*—Lunar Base, Shackleton Crater, Modular Design, Sintered Regolith, Regolith Shielding, ATHLETE Rover, RASSOR2 Rover, Roll-Out Solar Arrays, Fission Surface Power, Regenerative Fuel Cell System, Depressurization**

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I. INTRODUCTION

THE big scientific potential of the Moon has become more and more apparent over the years and it was recently decided to build a large research station on the Moon. The aim of this project is to design a permanent Lunar Research Station to be operational by the year 2040. The station is required to host up to 50 people at a time and is based on the design of the Amundsen-Scott Station in the Antarctica. It was assumed that the Artemis program was concluded successfully with all goals met, albeit some years delayed by 2037. There is a Lunar Gateway in place and launchers such as Starship with the Superheavy are operational since several years. A small temporarily crewed human habitat on the lunar south pole already exists. Although most of the technologies mentioned in this report are still currently in development, it was assumed that by 2037, many of the technologies and rovers have been developed and tested on the lunar surface.

Key environmental factors affecting lunar structural design and construction include: one-sixth g, the need for internal air pressurization of habitation-rated structures, the requirement for shielding against radiation and micrometeorites, the hard vacuum and its effects on some exotic materials, a significant dust mitigation problem for machines and airlocks, severe temperatures and temperature gradients, and numerous anticipated and accidental loading conditions. The structure on the moon must be maintainable, functional, compatible, easily constructed, and made of as much local materials as possible.

This report describes the location of the base on the moon, the general architecture of the base, the building technology and materials used to build the base as well as radiation protection of the base. Additionally, the power and thermal supply are introduced and two off-nominal scenarios are presented. A table of the abbreviations used throughout this report can be found in Appendix 8.

II. LOCATION OF THE BASE

The choice of the base location is a fundamental consideration for the mission. It is the result of reflection between the different parts and teams of the mission. Extensive discussion allowed a set of constraints to be defined to determine the optimal location of the base.

A. The importance of temperature

First of all, it is required that the environment is bearable for human beings. For this reason, temperatures should remain within a reasonable range and not fluctuate too much. As can be seen in Figure 1, the lunar equator faces temperature fluctuations of the order of magnitude of 300°C over a month, i.e. on a lunar day/night cycle (compared to 24 hours on Earth). It is not feasible to plan a long-term human mission with such fluctuating temperatures. Thus, the possibility of locating the base near the Equator was eliminated, despite the advantages such as permanent communication with the Earth and relatively flat areas. On the other hand, we observe that the fluctuations at the poles are about 100°C throughout the year. This is why the base location analysis was oriented towards the poles.

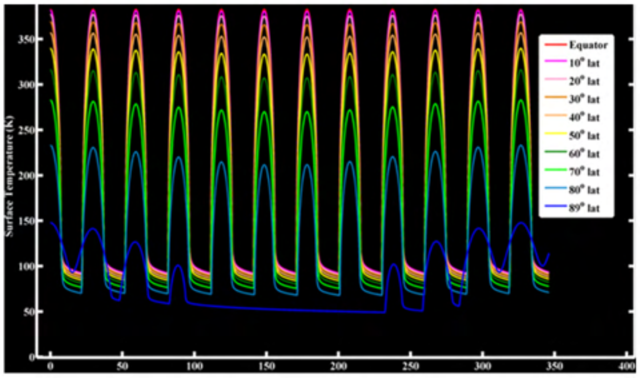

Figure 1: Annual temperatures of different latitudes of the Moon [1].

B. Access to solar energy

The polar regions of the moon are the most exposed to sunlight, with areas that are illuminated up to 90% of the year. The regions with the highest average solar illumination are at the South Pole. NASA has identified the sites with the highest illumination rates for its Artemis mission [2]. Out of these, the two sites with the highest annual illumination are shown in Figure 2. Their official names are Site 001 and Site 004 and they are located around the Shackleton Crater. Table I shows that Site 001 has the highest average solar illumination of 89.01%, and Site 004 is in fourth place with an average solar illumination of 86.71%. High solar radiation is valuable as it will generate energy to power the base, as depicted in Chapter V.

Longitude	Latitude	Rank	Average solar illum. (%)
222.69	-89.45	1	89.01
222.73	-89.43	2	88.60
223.28	-89.44	3	87.13
204.27	-89.78	4	86.71

Table I: List of most illuminated spots at the south pole [3].

C. Proximity to Permanently Shadowed Regions (PSRs)

Permanently shadowed regions (PSRs) are areas near the north and south poles of the moon that never receive direct sunlight and thus have stable and very low surface temperatures. These temperatures allow the accumulation of ice and other volatiles, which are of interest due to several reasons. Firstly, astronauts could melt this ice to produce water and use it for life-support. Likewise, it could be used to produce oxygen for breathing. It can be obtained by the electrolysis reaction which separates a water molecule (H_2O) into oxygen and hydrogen gas. And lastly, the hydrogen molecules that can be extracted could be a source of propellant for rockets.

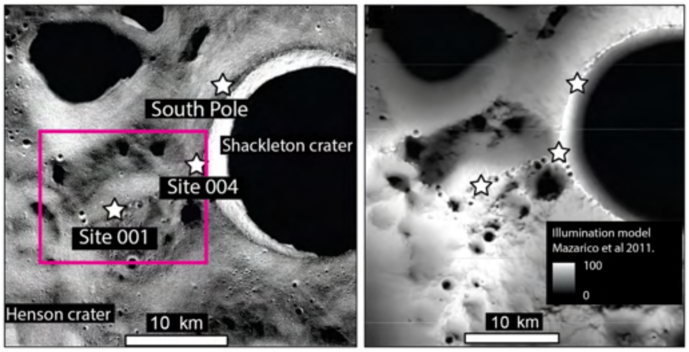

Figure 2: Aerial view showing Sites 001 and 004 in the vicinity of Shackleton Crater [4].

It can be seen in Figure 3 that Site 004 is relatively close to one of the largest PSRs which is located in the Shackleton crater. Site 001 is surrounded by numerous smaller PSRs whose diameter can range from a few hundred metres to a kilometre. Figure 3 shows the same area as Figure 2 and specifies where water ice may be stable at the surface (gray) to depths of 2.5 meters (deepest blue). Within the Shackleton crater, the ice appears to be stable at the surface and around Site 001 there are three main areas where the ice is stable at the surface (yellow circle on the right-hand side of Figure 3).

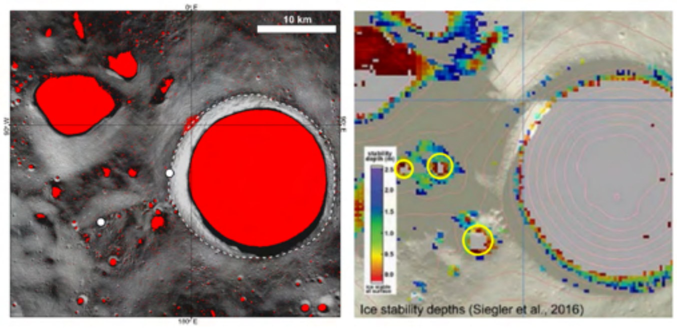

Figure 3: Maps showing PSRs near the south pole [5] [6].

D. Geological constraints

Geological constraints are important when choosing a base for several reasons. Firstly, it is important that the terrain is relatively flat so that the base and launch pad can be located nearby. Secondly, geological aspects will affect EVAs. An astronaut can move on a slope of up to 15° and walk up to 2 km from the base. If a pressurised rover is used, this can be extended to 10 km and 25° [5]. The interior of the Shackleton crater has a slope of 35 to 40°, which makes it impossible for rovers and EVAs to explore the crater. Therefore, Site 004 on the rim of the Shackleton Crater does not seem to be an optimal position for research missions and EVAs. On the other hand, Site 001 is located on the same plateau at a similar altitude while the nearby PSRs have slopes of the order of 10-20° (see Appendix 4). These can therefore be explored by rovers or during EVAs.

E. Selected location

The discussed criteria led to the decision of the most suitable site, which is located at the south pole of the Moon: Site 001 (222.69°,-89.45°). It offers the possibility of having two extremes in one location: The highest solar illumination and PSRs nearby that are permanently dark. This area also has many metal resources thanks to the lunar regolith (H, O, S, Fe, Mg, Ca, Al, Mn, etc.). The oxygen content is estimated at 45% of its weight. Another important point is that the Earth remains visible every day from Site 001, which is important for the mental health of the astronauts.

F. Launch and landing pad

The choice of the landing site and the construction of the launch pad are important for the success of the mission. The dust on the Moon's surface is the source of many problems, which are compounded by the fact that it is electrically charged which increases its adhesive properties. These problems include adhesion to clothing and equipment, reduced external visibility during landings and difficulty in breathing and seeing clearly [7]. To address this, the landing pad is built 1 km from the base as recommended by NASA and will look like Appendix 10.

III. ARCHITECTURE OF THE BASE

In this section, the design choices regarding the architecture and the layout of the base, as well as a comparison between different concepts, will be covered.

A. Modularity

A large number of papers reviewing lunar base concepts have been published by different scientists, and many of them agree on one point: The base needs to be modular, i.e. different modules with their own function are connected together to form the entire base [8], [9]. This makes the transportation via the launcher much easier, as each module has a reduced volume and mass, and can then be assembled on site. It is also a matter of safety, since they can be closed off individually in case of an emergency such as a depressurization hazard.

Several module designs have been reviewed as per [9], the main ones being pre-fabricated and inflatable.

1) Pre-fabricated: Rigid pre-fabricated structures are known to be extremely resistant to pressure loads and hard to puncture. The shell can be assembled with little effort, but still requires the supervision of astronauts through EVAs. However, the penalty is a generally higher mass and transportation volume.

2) Inflatable: Inflatable modules are fabricated with high-resisting fabric, and are meant to expand using internal pressure once on site. They are efficient in multiple ways. Firstly, they can be transported when folded, thus reducing the volume by up to 80% compared to the inflated volume. The materials used are also very light. On top of that, the installation on-site can be done remotely without the need of EVAs. However, they are known to be more fragile than pre-fabricated modules regarding the risk of punctures.

Between these two options, the inflatable design was selected. This choice was motivated by the fact that many studies have been directed towards the search for new materials that make inflatable modules as sturdy as pre-fabricated ones. In particular, Kevlar will be used on several layers since it provides high strength and tear resistance. On the interior, Nomex will give thermal and electrical protection. Both of these fabrics are relatively light, and have been used on the ISS, proving their reliability. Moreover, NASA has conducted experiments on several types of resins to show that, when mixed with these fabrics, it can be rigidized using different methods such as UV-Setting or Thermosetting [8]. That way, in case of a puncture in the shell of the module, the structure will not collapse on itself if the interior depressurizes. Between the Kevlar and Nomex layers, a compact foam will provide thermal insulation to the base, as shown in Figure 4.

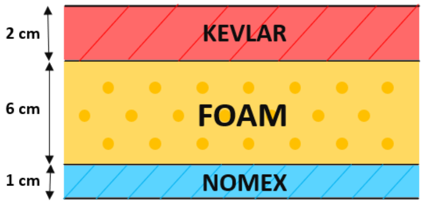

Figure 4: Composition of a module's shell

Regarding the shape of the modules, the literature shows various concepts including a dome, cylindrical, or cubic shape [9], [10]. However, the cylinder-shaped module offers the best compromise between structural integrity (since a round ceiling hardly bends under pressure loads) and space optimization. In fact, a dome allows for a highly resistant structure, but is very wasteful in terms of space. On the contrary, the cube-shaped module manages space very well, but the edges can concentrate high loads and rupture more easily.

Being on the moon with only one-sixth of the earth's gravity, one needs more space to move around. Thus, a radius of 4.5 m for the modules has been chosen to accommodate for this criteria. This will leave space on the ceiling for cables and storage, which will take around 0.8 m in height, and for a leveled floor to tackle the ground irregularities which should take 20 cm of the space. A representation of the allocation of space in the module can be seen in Figure 5. In the end, 3.5 m height will be available for the future inhabitants. Furthermore, NASA [11] recommended a minimum habitable volume at which performance can be maintained for long missions of about 20 m^3. Despite this recommendation, a design volume of 120 m^3 per person (i.e. 6000 m^3 in total) for a lunar habitat has been chosen, based on research of long-term habitation and confined spaces.

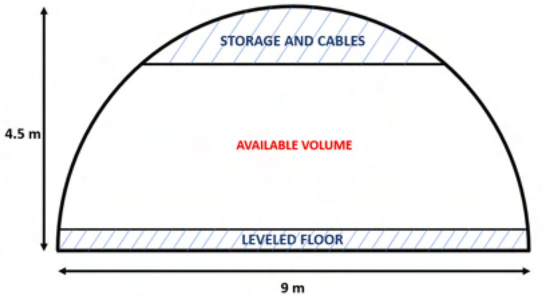

Figure 5: Cross-section of a module

B. Space allocation

The main purpose of having multiple modules is to conveniently separate different activities.

Firstly, to fulfill the purpose of the lunar base and ensure its proper functioning, ”living areas” should be composed of bedrooms, bathrooms, galley, several lounges across the base for entertainment and relaxation, and a gym. Furthermore, the second main function of the base is research. Taking that into account, the ”working areas” should include laboratories and workshops, as well as offices and a communication room required for operations as agreed with the team. As for support, two emergency modules which are able to house the 50 inhabitants of the station in case of a life-threatening danger were added. In conjunction with the Human Aspects team, a life-support module is added which contains life-support systems such as a treatment plant and ventilation system. These modules are obviously reinforced because they are crucial to the proper functioning of the station. It is also worth to mention that a greenhouse as well as a small cupola are part of the layout. The latter has restricted access since it is not as heavily protected against radiation as the rest of the base, but it was deemed important to have one to keep a window on the exterior for the crew.

The allocation of space for each of these areas has been studied to optimize efficiency of the activities. Table II shows the proportions that were applied for the layout of the lunar base. It should be noted that emergency modules as well as the life-support module do not appear in the table because they are considered ”bonus” modules which are not counted in the 6000 m^3 volume required for 50 astronauts.

Area	Proportion of the total surface
Living areas	50%
Working areas	35%
Greenhouse	15 %

Table II: Space allocation in the station

On top of that, an additional module which will act as a storage area for rovers and materials was designed which is separated from the main base since it hosts dangerous equipment.

Different ways to commute the base have been reviewed, considering both the interior as well as the exterior of the base, such as the airlock and the suitport. The latter has the advantage of keeping the suits in an enclosed area to avoid bringing lunar dust indoors. However, it was found that the airlock is still the most reliable solution and the most practical for the purpose of the lunar station, since space is needed to transport equipment through. This being said, the number and placement of airlocks is crucial because they are the most exposed part of the base. Thus, it was decided to place one on the main module because as the starting point of the base. A second one is needed in the laboratory module since equipment necessary to the experiments conducted inside will need to be brought from outdoors. This one is bigger to allow larger equipment transports such as high piles of regolith. The last two airlocks are placed on both emergency modules, as an exit is required for evacuation if the entire crew is confined in them.

C. Layout of the base

Several criterion have been taken into account when deciding on the layout of the base with the following parameters being the most important ones. The final layout is visible in Appendix 5 and Appendix 13.

1) Safety of habitation and laboratories: Safety inside the base is crucial. Even though the layout choices are not fully decisive in terms of security, the arrangement of modules should still be optimized for preventative purposes. For example, it is necessary to place the laboratories the furthest from the habitation areas in order to prevent an accident in the laboratories from propagating to the living spaces. Habitation and laboratory modules will be where the crew will spend most of their time. Consequently, emergency modules should directly be accessible from these places. Furthermore, each module should include at least two exits for quicker crew evacuation, with the exception of the cupola which will have limited access.

2) Compact layout: Wide expansion of the base should be avoided to limit the length of cables or pipes, and the mass of equipment needed in general. It is also of matter of reducing commute time between different areas of the station.

3) Convenience of activities in the base: Related spaces would benefit from being close to each other, like offices and laboratories, or habitation and galley. The main module which contains the galley, the gym and other common spaces should be in the center of the station and connected to every other module to facilitate circulation.

4) Modularity: The modules need to be placed in a manner to allow future extensions of the base, if an increase of the crew size is desired. In this case, the main module in the center can still be attached to another one at one of its ends. The inside of the station will also be modular with easily removable walls. For example, the walls between the bedrooms will be retractable so that they can be extended if not all of them are occupied, thereby increasing living space for the crew. The removable walls are depicted with dotted lines in Appendix 5.

IV. BUILDING TECHNOLOGY AND MATERIALS

According to Johnson et al. (2017), it is estimated to cost around \$ 20,000 to transport 1 kg of building materials to the moon [12]. The concept of In-Situ Resource Utilization (ISRU) was investigated in this section with the aim of maximizing building efficiency and reducing environmental and monetary cost. The main challenges involved in the processing of lunar raw materials include the presence of microgravity, vacuum and extreme temperatures on the Moon's surface. When building on the Moon, construction elements are required to demonstrate properties such as high strength, low leakage, ductility, durability, stiffness, puncture and tear resistance along with low thermal expansion [9].

A. Lunar Regolith

In order for long term habitation on the Moon to be achievable, regolith shields, roads and launch pads must be constructed. Lunar regolith can be found at a depth of $3-20m$ on the moon's surface. On average, the regolith layer has a depth of $6-8m$ in the so-called 'terrae' regions and $2-4m$ in the 'mare' regions at an average density of 1.6 $\mathrm{g/cm^3}$ [13]. Due to the low thermal conductivity properties of regolith, the inner temperatures of a shelter can fluctuate by just ± 2.8 °C for a regolith shield of about 2.5 m [14].

B. Cast Regolith

Cast lunar regolith (or lunar basalt) is predicted to have near identical properties to terrestrial cast basalt [10]. Cast regolith should be manufacturable on the moon since the casting process only requires a furnace, molds and a ladle, based on the extensive terrestrial experience producing the material. The manufacturing process consists of melting regolith and cooling it slowly in a vacuum, allowing the melted material to gradually crystallize.

Advantages of using cast regolith include that it has ultimate tensile and compressive strenghts of about 10 times that of concrete and it has high abrasion resistance to combat the effect of lunar dust. Once a basalt shell has been produced, it can also be pressurized internally [15]. Disadvantages associated with the use of cast regolith as a building material include that it is brittle, hard to cut, drill or machine and it consumes approximately 360kWh/MT of energy to reach melting point [15]. Some of the elementary structural properties of cast regolith can be found in Appendix 11.

This type of material would be ideal for making lunar roads, launchpads and launchpad shielding. Once disturbed, electrostatically charged regolith may remain suspended above the lunar surface for long periods of time. In fact, a particle displaced by a rocket launch can travel up to halfway around the Moon [16]. Cast regolith was not chosen as the construction method of the shield since the manufacturing process was considered too energy intensive for the amount of volume required. Moreover, large pressurized spaces would be needed in order to melt and mould the cast regolith.

C. Lunar Concrete

In this section, the production of concrete from regolith found on the surface of the moon is investigated. There are several advantages associated with producing concrete on the moon such as the fact that all raw materials required for the production of concrete are abundant on the moon's surface. The exposure of concrete to vacuum conditions and the influence of low gravity were reviewed. It was discovered that the compressive strength of concrete would be altered if it is exposed to vacuum conditions before a certain setting point is reached [17]. Moreover, the presence of the vacuum may lower the quality of the concrete as it alters its composition during the hardening phase. The production of cement consumes approximately 2,200 kWh/MT [9].

The minimum volume required to shield the base from radiation using a lunar concrete density of 1.98 $\mathrm{g/cm^3}$ was approximated as $V = 46{,}260\ \mathrm{m^3}$. This implies that in order to manufacture the required amount of lunar concrete, one would need approximately 650 tons of water. This would constrain the construction process to be heavily dependent on the retrieval of water on the lunar surface, which is the reason why this method was not deemed feasible for this project. Polymer concrete and sulfur concrete were also investigated, but both were deemed unfeasible in the long-term.

1) Polymer concrete: It was discovered that to manufacture $V = 46{,}260\ \mathrm{m^3}$ of polymer concrete with just 2 % polymer mix, one would need to transport around 46 tons of polymer from Earth. This rendered the polymer concrete construction method unfeasible due to the high logistical costs.

2) Sulfur Concrete: Toutanji et al. (2012) discovered that a 7 cm thick layer of sulfur concrete is sufficient to minimally shield against short term exposure to radiation [18]. Sulfur concrete could be considered as a solution to the radiation shielding problem since: (i) no water is required in the manufacturing process, (ii) sulfur is an element which is abundantly present on the moon and (iii) it can be produced in cold temperatures. However, sulfur concrete has a tendency to sublime significantly after two months under vacuum [18]. Moreover, large-scale facilities are required for the mining of sulfur. Based on this analysis, it was concluded that, while Sulfur concrete could be a viable building alternative in the future, its low TRL renders it inadequate for this mission.

D. Sintering - Solar vs Microwave

In this project, the use of the sintering process was investigated as the main method used for processing the regolith. Both solar sintering and microwave sintering were studied and it was concluded that both methods should be used in tandem. By applying both methods, one would not only speed up the construction process, but should one of the two methods fail to operate successfully, there will exist an alternative. Laser sintering was not considered because of the large temporal and energy costs [19]. The pros and cons of both methods are listed in Table III.

Type	**Advantages**	**Disadvantages**
Solar	Free energy use TRL 4-5 Low weight	Maintenance & shielding Change in positioning No power 10 % of year
Microwave	Low temporal cost Suitable for pressure levels Heat and Depth Penetration	Low conversion efficiency Energy intensive Highland heating

Table III: Solar vs Microwave sintering

Solar sintering utilizes direct sunlight to generate a concentrated solar beam which fuses the regolith by means of mirrors and Fresnel lenses. During the process, the regolith must reach temperatures of up to 1000 - 1100 °C in order to sinter, which can be achieved by using a solar concentrator of $1 m^2$ which can reach 1800 - 2000 °C [20]. A solar concentrator is predicted to sinter a 100 m^2 area of 25 mm depth in approximately one month [21]. Something to note with the latter sintering method is that performance can decrease by 10% should the solar collector be covered in dust [22]. During Project RegoLight, the solar sintering process is being tested in a vacuum environment which can potentially raise its TRL from 3 to 5 [23]. The next step would be to test the technology in the space environment.

Microwave sintering is more energy intensive since the conversion from electric to microwave energy is capped at an efficiency of 60 %. From this energy, only 50 % will be absorbed by the regolith due to its low conductive properties [24]. As a result, it was concluded that to sinter 1 m^3 of regolith, one will need an excess of 70 GJ of total electric energy. Although this is quite costly from an energy point of view, the heat penetration depth is better than that observed from solar sintering [25]. One should also note that lunar highlands contain regolith with higher albedo (due to more constant light exposure), so the regolith in those areas may need more energy to be sintered than in darker mare areas [21].

In conclusion, both methods should be used to manufacture the regolith shield on the moon. The construction of a regolith shield plays a crucial role in the long-term survival of a manned base on the moon. If one method were to fail, then a second method would be readily available for construction use. Moreover, the solar sintering process is quite slow and the sun will not always be available as a free energy source. In these times, the energy intensive microwave sintering process may be used to help speed up production rates.

E. Construction of a Regolith Shield

The maximum annual dose of radiation which is considered the limit for radiation workers is 5 rem (Roentgen equivalent man). This value can be exceeded in a month even with a regolith cover of 2.5 m surrounding the habitation [26]. A regolith shield of 120 g/cm^2 is sufficient to maintain the worker radiation dose in the shelter below the aforementioned limits [27]. The minimum amount of radiation shielding performed by the Earth's atmosphere can be achieved on the lunar surface by using 1000 g/cm^2 or 6 m of regolith [28].

In this project, sintered regolith with a density of 2.5 g/cm^3 s iimplemented for the regolith shield. Since the density of the sintered regolith is higher than that of regular regolith (1.6 g/cm^3), the thickness of the regolith shield can be reduced from 6 to 4 m. A 50 cm gap was introduced between the inflatable layer and the regolith shield to ensure that no part of the regolith shield touches the inflatable structure, reducing the risk of puncture or damage in case of a moon-quake. The cross-section of the proposed regolith shield is displayed in Figure 6.

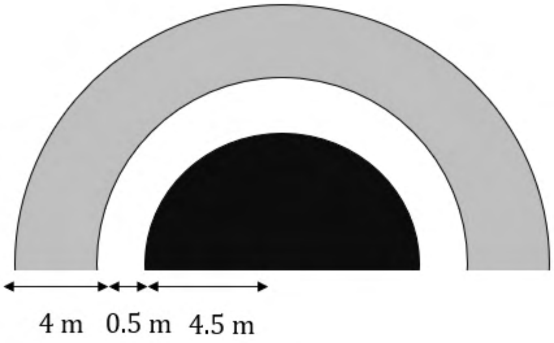

Figure 6: Shield cross-section (light grey) and module (black)

F. Construction Rovers

1) ATHLETE: All-Terrain, Hex-Limbed, Extra-Terrestrial Explorer is a 2340 kg rover designed by NASA for the transportation and handling of cargo on the moon. It has six limbs which can be used as legs, each containing a wheel. The wheels can also lock and be used as feet to 'walk' over more difficult terrain. ATHLETE will mainly be used for transporting regolith and placing the newly manufactured sintered blocks around the base. By using one of the legs as an arm, it has a maximum reach of 15.5 meters [29] which is more than enough to place the sintered blocks at the maximum height of 9 meters. Moreover, it exhibits a 14.5 tons payload mass, so it can also be used to transport any sintering devices or astronauts [29]. Human transport pods can be mounted onto it, as seen in Figure 7. It has a rolling mobility of 28 °and a walking mobility of 35 ° [29], meaning that it can traverse most of the terrain surrounding the Shackleton crater. In total, it was estimated that at least 5 ATHLETE rovers will be required for construction purposes.

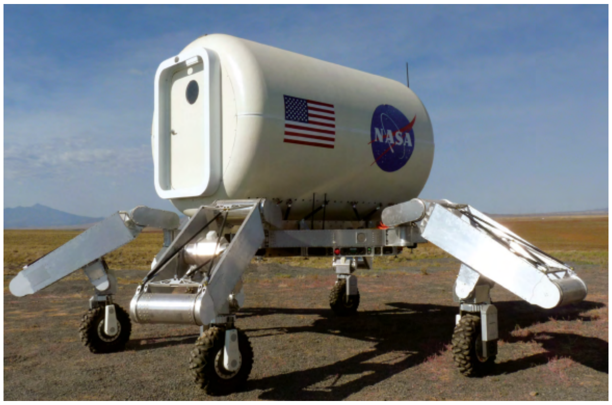

Figure 7: ATHLETE rover with human transportation pod [29].

2) RASSOR 2: The Regolith Advanced Surface Systems Operations Robot is a 66kg rover designed by NASA for planetary excavation. It functions by using an autonomous system which controls two counteracting bucket drums and is currently rated at a TRL 4. It has a power usage of 4 $\frac{W}{kg}$ of excavated regolith and it can excavate a minimum of 2.7 tons of regolith per day [30]. This value is more than enough to supply the daily manufacturing rate set out by the sintering devices which stands at 222 hours/m^3. In total, 35 RASSOR 2's were chosen for use in this project.

Figure 8: RASSOR 2 prototype [30].

G. Feasibility study

A total shield volume of V = 49,260 m^3 is required to be sintered on the lunar surface. A feasibility study was conducted based on a sintering rate of 222 m^3/hour [31]. The number of sintering devices was varied and the total associated construction time and payload mass of the sintering devices were calculated accordingly. The results are shown in Table IV and are also reflected in Appendix 6.

Sintering Devices	Construction time [years]	Payload mass [tons]
100	12.5	5
550	2.27	27.5
1000	1.25	46

Table IV: Construction Feasibility Study

By using 35 RASSOR 2 mining rovers, one would be able to excavate all the required regolith in 2.14 years. To meet the 3 year construction deadline of this project, it was decided to use 550 sintering devices. This would result in a total construction time of 2.27 years which leaves some margin for delays.

H. Radiation Protection

The two main sources of radiation from which astronauts must be protected are Galactic Cosmic Rays (GCR) and Solar Particle Events (SPE). The effects of GCR and SPE in terms of the appropriate thickness of lunar regolith are discussed in this section.

1) Galactic Cosmic Rays: While on the moon, humans are exposed to higher levels of radiation due to poor atmospheric and magnetic shielding compared to the surface of the earth. Humans on the lunar surface will be exposed to about 1.369 μSv per day, which is 200 times higher than what people experience on earth's surface [32]. Chronic exposure to GCR, the most energetic component of the space radiation environment, can cause cancer, cataracts, and sterility. The most abundant GCR particles are protons, making up about 90 % of GCR radiation.

2) Solar Particle Events: The products of solar flares also cause intense radiation on the moon. SPE are a stream of high-energy protons caused by a solar flare. SPE particles consist of various types of subatomic particles, including protons as well as electrons and heavier atomic nuclei such as helium, carbon, and oxygen. The majority of SPE has too small an effect to calculate its lunar radioactivity. There have been several extreme SPE that could have caused significant radiation exposure. Solar flares are much more likely during the solar maximum, which refers to the regular period of greatest solar activity during the Sun's 11-year solar cycle. The probability of a major solar flare type, such as the September 1989 or February 1956 benchmarks, occurring during a 6-month lunar mission is 1-10% depending on its SPE energy in a solar maximum scenario [33].

3) Regolith Shield: As mentioned previously, lunar regolith is the most feasible material for lunar shelters. Figure 9 shows the radiation exposure from GCR in a semi-cylindrical lunar regolith shelter on the surface of the moon [34]. The X-axis represents the thickness of lunar regolith, while the Y-axis represents the effective dose of radiation per year. Effective dose is a measure of radiation exposure specifically for radiological protection purposes. According to the International Commission On Radiological Protection (ICRP), 20 mSv is the limit of the annual effective dose at which humans can live safely for the rest of their lives. As illustrated in Figure 9, 6 m

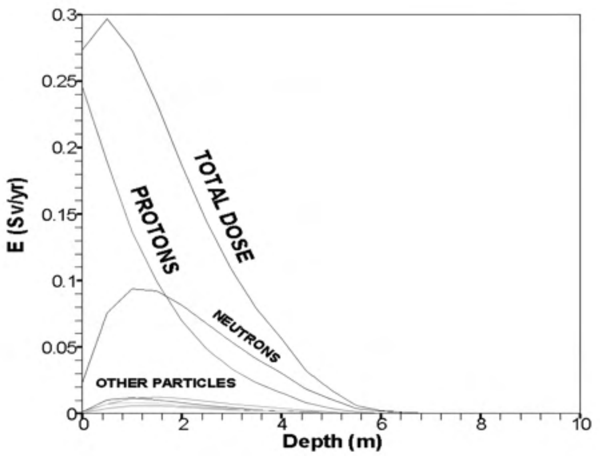

Figure 9: Effective Dose in a Lunar Regolith Tube [34]

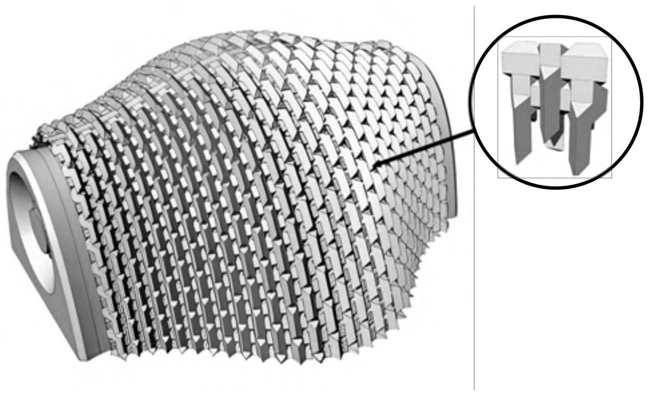

Figure 10: Shelter Made of Tetrahedron Elements [38]

thickness of regular lunar regolith meets the safety of radiation exposure, with less than 20 mSv per year. Far fewer effects of GCR are observable around 6 m, and almost no effects of SPE particles are observable after 1 m. Given that lunar regolith has a density of 1.6 $\mathrm{g/cm^3}$, the shielding thickness can be reduced by identifying a material that is similar to lunar regolith but has a larger density. However, the areal density must reach 1,000 $\mathrm{g/cm^2}$ ($\approx 6\ \mathrm{m} \times 1.6\ \mathrm{g/cm^3}$).

I. Selection of Shielding Materials and Methods

1) Shielding Materials: As a shielding material, solar sintered regolith was selected. It brings several merits to the feasibility of shelter construction. One is that the solar sintering process only needs the on-site material, lunar regolith. In contrast, polymer concrete requires additional ingredients such as water and polymer, which would have to be transported from Earth. A minimum shielding thickness of 50 cm for radiation requires over 120 tons of polymer [19]. This indicates that one Starship rocket would have to be used just to carry polymer since its payload has a capacity of 100 tons [35]. Therefore, polymer concrete is not feasible in terms of costs and logistics.

In addition, the solar sintering method has a 3D printing machine, making the technology more feasible. Appendix 7 shows a 3D printer utilizing solar energy to sinter lunar regolith developed by the project RegoLight [36]. Solar sintering 3D printing of lunar regolith has a TRL of 4. It was already tested in a vacuum and successfully created sintered lunar regolith bricks [37]. The bricks made in a vacuum demonstrate a similar composition to regular lunar regolith, giving the same shielding effect. Furthermore, the sintered regolith has a density of 2.54 $\mathrm{g/cm^3}$, which is larger than the normal lunar regolith density of 1.6 $\mathrm{g/cm^3}$. This suggests a possible shield thickness of 3.93 m, meaning this is thinner than 6 m but gives the same areal density of approximately 1,000 $\mathrm{g/cm^2}$ which is sufficient radioactive shielding for permanent habitation.

2) Construction Methods: The solar sintering 3D printer does not have a proper size to print whole shelters directly. It can only print brick-sized elements, which would be assembled to construct the shielding. The project RegoLight suggests a feasible method to 3D print tetrahedron-shaped elements and assemble them to create the shield shown in Figure 10 [38]. The shelter composed of tight-fitting tetrahedron elements allows the construction of a completely sealed and pressurized habitat. The center of mass of each element and the entire structure during assembly is self-supporting so that the construction would not require any external building support.

V. POWER AND THERMAL SUPPLY

In order to build, operate and maintain a lunar base, significant amounts of energy are required. A power and thermal system that is to be used on the lunar surface needs to be compact, reliable, low-weight and operate continuously independent of weather, available sunlight and other natural resources [39]. Power supply is required for life-support systems, subsystems such as communications, payload power as well as all auxiliary units necessary to run the base. The following paragraphs describe the power requirements for a permanent lunar habitat (V-A), introduce and discuss different types of power systems (V-B) and analyse how energy can be stored (V-C). Based on these design considerations, the set-up of the power and thermal system on the lunar habitat is presented (V-D).

A. Power Requirements

In order to estimate the power requirements for the lunar base, the operation of the Amundsen-Scott station in Antarctica was considered, which requires 467 kW in the summer when it hosts about 150 people at an average temperature of -12°C, while it consumes 510 kW in the winter to accommodate up to 100 people at average temperatures of -83°C [40]. While this is a terrestrial estimation, the International Space Station consumes 75-90 kW of power to host a crew of 3-7 astronauts [41], which means that a conservative estimation would be 13 kW per crew member, including all life-support systems, research energy requirements and so on. With this energy requirement per capita, and bearing in mind that the lunar base is supposed to host up to 50 astronauts permanently, the estimated conservative peak energy requirement for the lunar base would be 650 kW. It should be mentioned that this figure is a conservative overestimation for the power need, since the amount of energy required per astronaut will decrease when increasing the amounts of astronauts on the base. Most power estimates for a lunar base found in the literature were significantly lower than 650 kW, but a comparison between e.g. the estimates of the power needs of the ISS in the early 1990's and the actual power need of the ISS prove significant underestimation. This is because power needs strongly increase when energy-intensive research is conducted, as can be seen on the Amundsen-Scott Station, and also because most studies investigated a potential temporary base instead of a permanent research station. Hence, 650 kW should be taken as the power estimation for this conceptual study.

The initial power estimates for a lunar base in [42] distinguishes between three modes: Firstly, the baseline power estimates that 65% is consumed by life-support, 20% is consumed by housekeeping such as food preparation and washing, 8% is consumed by scientific instrumentation, 4% by communications and the remaining about 3% by habitat lighting. The waste heat is assumed sufficient to provide the station with heat, such that no extra power demand is added. Based on [42], one can assume that the baseline power is about 75% of the peak power of 650 kW, thus 500 kW. The remaining 150 kW would be available for ISRU, manufacturing, rover charging and EVAs. All the power estimates of BLISS are summarized in Appendix 9.

B. *Types of Power Systems*

Different types of power systems are space-rated and suitable for a lunar base, the most important of which will be discussed in the following paragraphs.

1) Solar Power: Most space missions have relied on solar energy as their primary source of power. Solar power is renewable, was previously tested in space and has a high specific weight, but also relatively low efficiency and is not a good testbed for power supply on Mars where less solar power can be harvested. Nevertheless, different kinds of solar cell types were investigated and it was found that highly efficient triple junction cells would be the most suitable option, as they are currently at efficiency levels of 28 - 32 % and could reach up to 40 % within the next few years [43], which makes them significantly more efficient than traditional X4 or GaAS/GE cells. Three highly efficient triple junction array types are listed and compared in Appendix 1.

Assuming that the high fluence solar cell from SpectroLab will increase its efficiency to 40% by 2037, it could produce roughly 546 $\frac{W}{m^2}$ since space-graded solar panels have a rough solar illumination of 1365 $\frac{W}{m^2}$ on the lunar surface [44]. Given the power requirement of 650 kW, this would translate into 11,900 m^2 of panel area. This matches relatively well with the values from the ISS, where peak power [45], both values of which are about a fifth of the requirement for the lunar base. $11,900m^2$ would result in exactly 10 tons of mass for only the solar cells at 0.84 kg/m^2 (see Appendix 1), which does not yet include structural mass, array orientation motors or the deployment and packaging mass [42]. In particular, the transport technology has to be taken into consideration since the arrays have to fit in the Starship payload fairing. The panels are supposed to be transported on a blanket to fold them like an accordion, similar to how arrays were transported to the ISS. The arrays of the ISS ROSA project that were taken as reference had a size of 6 x 13.7 = 82.2 m^2 and a weight of 325 kg per panel [46]. At 11.900 m^2 panel area, this would translate into 145 arrays and a total weight of 46.8 t (see Appendix 6).

2) Nuclear Power: The most commonly discussed alternative to solar is nuclear power supply such as radioisotope thermoelectric generators. Nuclear power is a well-established technology which, besides its widespread terrestrial use, was also employed on Mars Curiosity Rover, Cassiny and on other spacecraft to ensure continuous power supply, in particular for missions where sunlight is not constantly available [47]. One can generally distinguish between nuclear fission and nuclear fusion: While the first has been in global use since the midst of the twentieth century, the nuclear fusion technology is still being developed and not in wide commercial use yet. While it could revolutionize space power systems and has experienced recent breakthroughs, it was disregarded for the scope of this project due to its low TRL since it is not even established in terrestrial applications. Hence, only nuclear fission projects were further investigated.

In this context, NASA has plans to build a nuclear power station on the moon fueled by low enriched Uranium and coupled with a Stirling engine that could supply at least 40 kW at 120 Volts DC [48], more commonly known as the "Fission Surface Power" (FSP) project as displayed in Appendix 2. This power plant is targeted to be operational by 2029 for a minimum lifetime of 10 years in a lunar environment, so despite its currently low TRL of 3-4, one can assume this technology to be developed by 2037. It is supposed to weigh about 6 t and should fit within a 4 m diameter cylinder at 6 m length, which makes it suitable for transport with Starship [49]. Despite these advantages, nuclear power has a significantly lower specific power than solar power (i.e. 650/47 = 14 kW/t for ROSA compared to 40/6 = 7 kW/t for FSP) and also costs significantly more per Watt [42]. Additionally, it would be very challenging in terms of safety to transport the amount of uranium required to use such a reactor as the primary energy source. Given these constraints, solar energy was chosen as the primary energy source.

Nevertheless, the FSP plant proposed by NASA could serve three major purposes on a lunar station: Firstly, it could supply an additional 6% to the 650 kW conservative energy demand and therefore serve as a secondary, continuous power supply that makes up for the down-times of solar power. Given the long daily lunar cycle of 28 Earth days, solar radiation will not always be available, even when building the station in the area near the Shackleton crater. Secondly, it could provide energy in an emergency situation in case the solar panels are malfunctioning or larger maintenance needs to be conducted on some of the panels. And thirdly, a nuclear reactor could serve as a testbed for power systems for future Mars missions where less solar power can be harvested. It was thus decided to use the FSP as the secondary power supply to the lunar base.

Other power systems, such as the Jet-fuelled generators used on the Amundsen-Scott Station, were briefly investigated but discarded due to low maturity, low efficiency and lack of sustainability.

C. *Energy Storage*

Even if secondary power systems such as nuclear reactors can ensure quasi-continuous power supply, energy storage is required to balance peaking power demands and to recharge the units. Two major technologies were investigated that could provide such storage, namely rechargeable batteries and regenerative fuel cells [50].

As per Table 20-10 in [42], lithium-ion batteries are the highest performing in terms of specific energy and energy density. However, their operating temperature is relatively limited, which would be a major issue considering the stark temperature variations on the lunar surface. Their self-discharge rate is usually low at 0.167% per month at 20 °C, but the low temperatures during the lunar night would adversely impact self-discharge and thus reduce efficiency. Lithium-titanate batteries might be a suitable alternative as they provide a higher lifetime and recharge faster, but face similar performance issues at low temperatures.

As an alternative to rechargeable batteries, regenerative hydrogen fuel cells that make use of cryogenic storage of hydrogen and oxygen could be employed [42]. Hydrogen fuel cells operate by feeding hydrogen to their anode and oxygen to their cathode in order to generate electricity, heat and water. Next to their high efficiency and temperature resistance, hydrogen fuel cells would be a very suitable technology for other applications as well, most notably since the hydrogen could also be used as a propellant for deep space missions. Since water is a major lunar resource that is of interest for various fields of research, hydrogen fuel cells could provide synergies to develop multiple technologies required for long-term lunar habitation. Given these advantages, fuel cells are considered to be the most suitable option and thus chosen for BLISS.

The HERACLES moon mission that is planned for the late 2020's by the European Space Agency intends to make use of a Regenerative Fuel Cell System (RFCS) that is developed by Prototech, The RFCS is supposed to be a closed-loop system consisting of a solar-powered electrolyser unit to split water into hydrogen and oxygen, tanks to store both propellants and a fuel cell that uses the propellants to generate power and heat. This regenerative function increases the energy density in comparison with conventional batteries [51]. The largest version of the RFCS is supposed to weigh around 1300 kilograms [52], but considering TRL 5 and that the system for a lunar base will most likely be larger than the one required for HERACLES, a margin of 100% was assumed for a mass estimate of 2600 kilograms. According to the design study conducted in [42], a fuel cell system like this should be able to provide sufficient storage for 40 hours to survive the lunar night, and could potentially even make up for emergencies in case of power system failure if enough water is available. Providing enough battery capacity to store energy for weeks or even month is technically possible, but would require significant payload. Instead, the combination of two energy systems, where the secondary nuclear power system can serve as a back-up system, in combination with hydrogen fuel cells for energy storage can provide sufficient safety to the operation of the power system.

D. *Layout of Power System*

Based on the chosen energy and storage systems, the power system is implemented as shown in Figure 11.

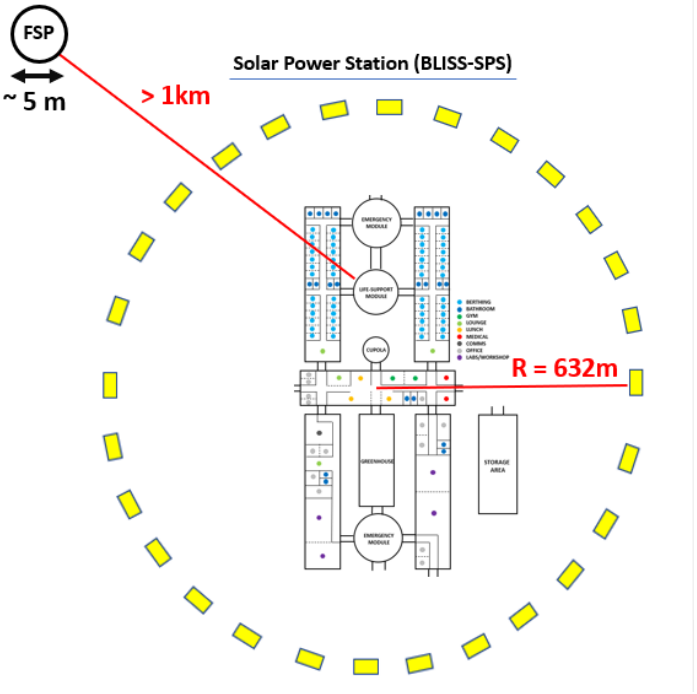

Figure 11: Layout of the BLISS-SPS and Power System

The solar power station (BLISS-SPS) is arranged in a circular shape around the station. The initial idea was to built a solar park of square shape as in Appendix 3, but the low azimuth of solar radiation at the Shackleton crater would have caused the panels to shadow each other if there were to be arranged in a closely packed square. Instead, the panels are arranged in a circle of 632 m radius, which yields a circumference of 3.97 km. Placing 145 arrays which are 13.7

m wide in a circle would require 1.99 km of circumference, but doubling this distance makes sure that the panels are more than double their height of 6 meters apart from one another as recommended to avoid shadows. Also, the distance of more than 500 meters to the base ensures that the panels are not shadowed by the base and mitigates the adverse impact from exhaust plume of landers near the base. Additional shadow protection is implemented by adding vertical lifting rods and sun angle rotation mechanisms to the panels. The nuclear FSP is supposed to be stored 1 km away for safety reasons, while the RCFS would be stored inside the life-support module.

VI. OFF-NOMINAL SCENARIO: DEPRESSURIZATION

The moon is a harsh environment where off-nominal scenarios have to be taken into account. Two of them are discussed in the following paragraph, namely meteorites hitting the lunar station and depressurization of one of the modules.

A. Meteorites

Due to the absence of a lunar atmosphere, meteorites cannot be burnt up or slowed down as on earth. They travel at 3-70 km/s speed [53] and their impacts can pose a potential risk to the safety of BLISS. On average, about 100 ping-pong-ball-sized meteoroids hit the Moon every day. In order to prevent damage to the station, the sintered regolith shield, which has been decided for the BLISS station design plays a vital role. The 4 m solar sintered regolith with a density of 2.5 g/cm^3 should be capable of shielding against meteoroids with a mass of 37 kg up to 52 cm diameter [54]. Continuous maintenance of the outer shell also ensures that the sandblasting effect of micrometeorites is counteracted to maintain 4 m thickness.

B. Depressurization

Possible damages to an inflatable module during its service life could lead to a catastrophic failure of depressurization. The pressure of the modules should be kept constant at 101.3 kPa of air, at least 26 kPA of pure Oxygen, which is similar to earth's atmosphere at sea-level to maintain human habitable conditions [19]. In case of having punctures in the shell, an intrinsic self-healing supramolecular polymer could be included in the compact foam shown in Figure 4 [55]. Once the layer ruptures, the polymer substance leaks into the hole and ultimately fills it up. Until the pressure returns to 1 atm, astronauts would temporarily stay in the emergency modules which are pressurized by closing off the access ways.

VII. DISCUSSION & CONCLUSION

A full three-dimensional design of BLISS using BLENDER can be found in Appendix 13. To conclude this report, some final remarks regarding the TRL of the technologies employed are presented and improvements as well as future work is discussed.

1) Technology Readiness Level: The location near the Shackleton crater has been researched extensively and probes have been sent there before, rendering it very suitable for a permanent base. Additionally, the modules presented in the architecture section have already been tested by several companies at a TRL of 8-9. Regarding the materials, the resin used to stiffen the modules has been researched but never tested at a TRL is 3, such that more tests must be carried out before the mission begins. Regarding solar sintering technologies, these have never been tested in space, but tests have been carried out in a vacuum. The associated TRL is of the order of 3-5 as these will probably still have to be improved. Furthermore, sintered regolith will be used to make a radiation shield, which is a conceptual idea that has never been realized. Thus, further studies are required to make optimal use of this shield before the base is built. In terms of power supply, the ROSA technology used on the ISS is ready for usage at a TRL 9 and can be further improved in efficiency until 2037, while the Nuclear FSP has a low TRL 3-4 on major subsystems such as stirling converters [49] which requires further development to be ready by 2037. Likewise, the Regenerative Fuel Cell System has a TRL 5 and also faces major development challenges in terms of efficiency.

Thus, the overall technology readiness level is rather high, in particular with respect to major subsystems such as the modular tubes and solar arrays. Nevertheless, major development work needs to be completed by 2037 to successfully build the station, in particular in the areas of manufacturing technology, nuclear reactors and fuel cells.

2) Improvements and Future Work: At this conceptual level of the station design, several areas of improvement have been identified which should be followed-up with future work. Generally speaking, the allocation of the individual modules can be further detailed, e.g. by specifying what kind of research is supposed to be conducted at which part of the workshops. Design engineers of BLISS should also better understand how to protect against GCRs, as this cannot be done using regolith shielding only and might require some sort of underground shelter near the base. To further specify the power and thermal supply, a more detailed analysis of the power requirements of every individual hardware should be conducted to give a more accurate estimate of power needs. Likewise, the exact circumferential layout of solar panels and the additional hardware required for shadow protection (lifting rods, sun angle rotation mechanism, etc.) will need to be investigated by extensive calculation of the azimuth angles of solar radiation on the lunar south pole.

Note: A table showing the division of work between the team members can be found in Appendix 12.

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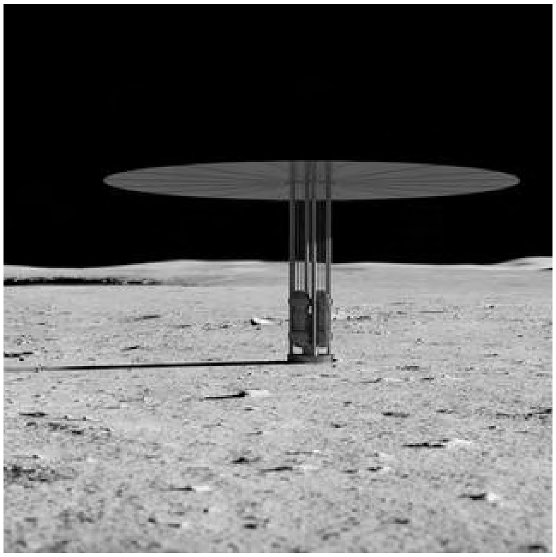
APPENDIX

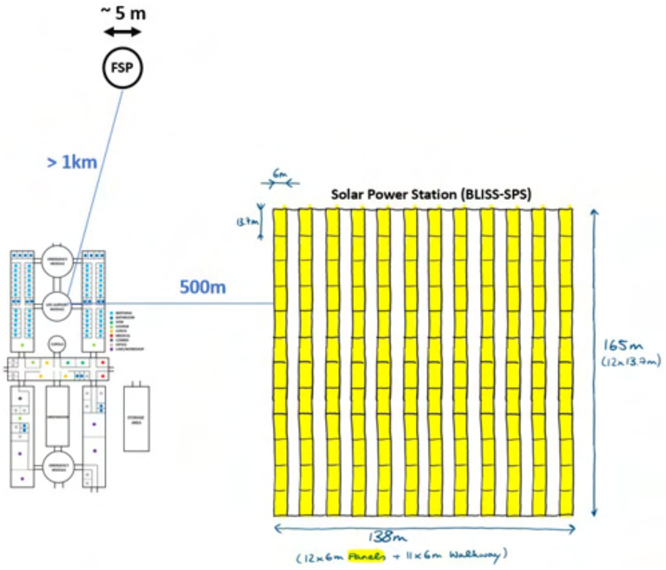
Appendix 1: Solar Cell Comparison [56], [57], [58]

Company	Array Type	Mass/Area [kg/m^2]	Efficiency [%]
AZUR Space	TJ 3G28C	0.86 ([56])	28
SolAero	ZTJ Omega	0.84 ([57])	30.2
SpectroLab	XTE-HF	0.84 ([58])	32.1

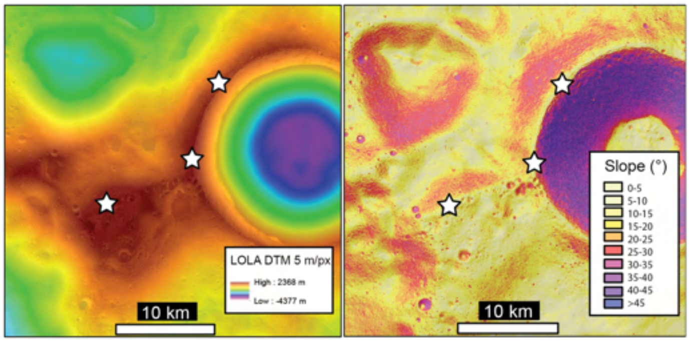
Appendix 2: NASA "Fission Surface Power" Plant [39]



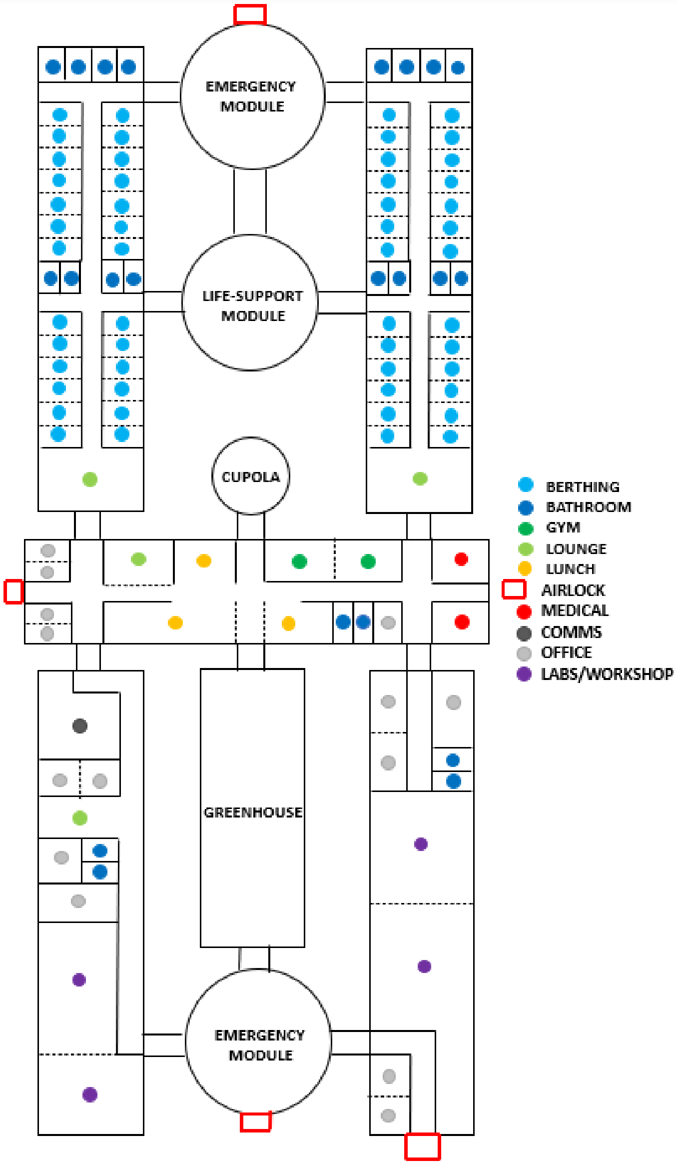
Appendix 3: Initial Layout of BLISS Solar Power Station



Appendix 4: Maps showing the geology in the South Polar Region [6]



Appendix 5: Layout of the base



Appendix 6: Mass Analysis

Mass Item	Weight [tons]	Margin [%]
Main Tube	44	5
Habitats (2x)	84	5
Emergency Modules (2x)	76	5
Airlocks (4x)	32	5
Greenhouse	21	5
Lab	40	5
Workshop	40	5
Life-Support Module	28	5
Storage	20	5
ATHLETE Rovers (5)	12	5
RASSOR 2 Rovers (35)	2	5
Solar Panels	46.8	20
Nuclear Reactor FSP	7.2	20
Hydrogen Fuel Cell	2.6	100
3D Sintering Equipment (550)	27.5	10
Airlocks	32	10
Total	480.1	8.3

Appendix 7: Solar Sintering 3D Printer [36]

Appendix 8: Table of Abbreviations

Symbol	Explanation
BLISS	Base Lunar Installation for Scientific Studies
EVA	Extra-Vehicular Activity
FSP	Fission Surface Power
GCR	Galactic Cosmic Rays
ICRP	International Commission On Radiological Protection
ISRU	In-Situ Resource Utilization
ISS	International Space Station
PSR	Permanently Shadowed Region
REM	Roetgen Equivalent Man
RFCS	Regenerative Fuel Cell System
ROSA	Roll-Out Solar Arrays
SPE	Solar Particle Events
TRL	Technology Readiness Level

Appendix 9: Power Estimate for BLISS [42], [50]

Parameter	Power Requirement [kW]	Baseline [%]
Life Support	325	65
Housekeeping	100	20
Scientific Instrumentation	40	8
Communications	20	4
Habitat Lighting	15	3
Habitat Heat	0	0
Baseline Power	500	100
ISRU Mining and Testing	100	20
Rovers Charging	30	6
EVA Floodlights	20	4
Peak Power	650	130

Appendix 10: Future Launch Pad Layout [59]

Appendix 11: Properties of cast regolith [15]

Property	Value	Unit
Tensional Strength	34.5	$\mathrm{N/mm^2}$
Compressive Strength	538	$\mathrm{N/mm^2}$
Young's Modulus	100	$\mathrm{kN/mm^2}$
Density	3	$\mathrm{g/cm^3}$
Temperature coefficient	7.5-8.5	$10^{-6}/\mathrm{K}$

Appendix 12: Division of Work

The workload of the subsections was distributed between the team members Anthony Drain (A), Jordan Boutoux (J), Keith Bajada (K), Sören Mohrdieck (S) and Tomoyasu Nakano (T) as described in following table.

Chapter	Team Members
Abstract	S
Introduction	K
Location	J
Architecture	A
Building Technology: Regolith, Sintering	K
Building Technology: Rovers, Mass	K
Building Technology: Radiation, Shielding	T
Power and Thermal Supply	S
Off-nominal Scenario	T, S
Discussion, Conclusion	J, S

Appendix 13: Final Design of BLISS in BLENDER