Project Shackleton

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January 31st, 2021

Introduction

It seems almost strange to think that people will again step foot on the Moon within the next ten years. With projects like Artemis well underway, one can not help but think about all the different opportunities that may arise. The prospect is almost overwhelming, but not impossible. Many people would express doubts about whether they feel it's worth it to attempt setting up shop on the Moon. According to a study from 2010, by the National Opinion Research Center's General Social Survey, only 23% of Americans believe that the government is not allocating enough funds to space exploration, versus a 2011 study done by PewResearch which suggests that 58% of Americans are "supportive" of continuing space travel[1]. The studies suggest that the interest is there, and the only challenge is making it worth the higher financial investment. So why do it?

Besides the famous quote by George Mallory, "because it's there," the Moon is also going to be a key foothold for humanity on the path to becoming an interplanetary species[2]. Moreover, the Moon is a very convenient location for many new developments. To begin, due to its low surface gravity and lack of atmosphere, spacecraft require far less energy to go into orbit or to escape the Earth's gravity well[3]. Furthermore, the abundance of metal makes manufacturing on the Moon simpler in terms of transportation of materials to the surface. Since its surface is mostly barren, humanity can move most, if not all, of its polluting industries there because there is no environment there for them to destroy. The Moon can play a huge role in mitigating climate change effects. Not to mention, from a research standpoint, since the Moon is directly exposed to the Sun and space, it becomes a perfect testing ground for experiments that require exposure to solar radiation or cosmic rays. With this information, researchers can develop radiation shields for future interplanetary ships. Finally, the Moon is the only place to find Helium-3—a very promising fuel for low-radiation nuclear fusion[4].

Moreover, at locations where Earth is out of sight, radio telescopes can not only operate without the electromagnetic interference of human activities on Earth. Adding such a telescope to the network of Very Long Baseline Array can theoretically boost the current system's angular resolution by 30 times. Logistically, with our current technology, the travel time to anywhere other than the lunar surface takes months. Essentially, the Moon truly is the stepping stone to deep space exploration.

In this paper, we present the challenges of building a long-term (at least 10 years) human settlement on the lunar surface for a crew of 20-30 people. Then, we present solutions to each of these corresponding challenges while making our design not only engineeringly and architecturally, but also financially feasible.

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[1] B. Kennedy, "5 facts about Americans' views on space exploration," Pew Research Center, Jul. 2015. https://www.pewresearch.org/fact-tank/2015/07/14/5-facts-about-americans-views-on-space-exploration/ (accessed Jan. 31, 2021).

[2] Sean, "'Because It's There' The Quotable George Mallory," *The Clymb*, Mar. 07, 2013. https://blog.theclymb.com/out-there/because-its-there-the-quotable-george-mallory/ (accessed Jan. 28, 2021).

[3] The delta-V needed to enter Low Earth Orbit (LEO) is 9.3 - 10 km/s. This means that a ship not only needs to have enough thrust power, it also needs to persist that power until it reaches that speed in order to enter LEO from Earth's surface. Delta-V is also used to describe a ship's capability to change its speed. In space, a ship with higher delta-V can travel further and faster.

[4] [1]esa, "Helium-3 mining on the lunar surface," *European Space Agency*, 2012. https://www.esa.int/Enabling_Support/Preparing_for_the_Future/Space_for_Earth/Energy/Helium-3_mining_on_the_lunar_surface.

Location

The ideal location for a lunar base needs to meet the following criterion: be in the line-of-sight with the Earth and close to an area with natural ice deposits. Being in line-of-sight with Earth enables direct radio or laser communication. It removes the need to establish relay satellites and have its communication bandwidth limited by its capacity. Being close to natural ice deposits is because ice is a handy resource in outer space. It provides drinking water for the crew and hydrogen fuel for spacecraft. Water is also a critical resource for industrial operations that will be mentioned later in this document.

We have selected the Shackleton Crater as our base's location because it is one of the most prominent craters at the polar areas of the Moons, where NASA has discovered the presence of ice[5]. Also, since the Moon has a very low obliquity ($\pm 1.6\ ^{o}$)[6], the sunlight is almost parallel to the ground. Parts of the crater's top are under permanent sunlight, and parts of it are covered by permanent shadow. Operators at the base can easily mine ice from the shadows and bring it across the shadow line to melt it. The side of the crater also provides the base protection against micrometeorite and solar radiation.

Architecture

One of the main goals is to make the lunar base self-sustainable, which means fewer supply ships from Earth. This has been shown in the materials being used to build the moon base structure and in the waste and water processing systems. Another critical aspect of the architectural design pertains to the challenges and risks of living on the Moon. For example, it is crucial to have emergency and backup systems in place, such as the sectioning of areas, emergency shelters with temporary oxygen supplies, enhanced evacuation routes and many sensors monitoring radiation, pressure, oxygen and carbon dioxide levels.

The envisioned lunar base is inspired by modern architecture and open concept. To add life and dimension to the majorly grey shaded building, most of the underground open area section (Levels B1&2) interior wall consists of green walls. In addition to the abundance of floor to ceiling glass walls facing the base's open core. Below are the floor plans and concept drawings of our proposed lunar base, presented from the top level to the lowest level.

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[5] "Ice Confirmed at the Moon's Poles," *NASA*, Aug. 20, 2018. https://www.nasa.gov/feature/ames/ice-confirmed-at-the-moon-s-poles (accessed Jan. 28, 2021).

[6] Wikipedia Contributors, "Orbit of the Moon," *Wikipedia*, Oct. 14, 2019. https://en.wikipedia.org/wiki/Orbit_of_the_Moon.

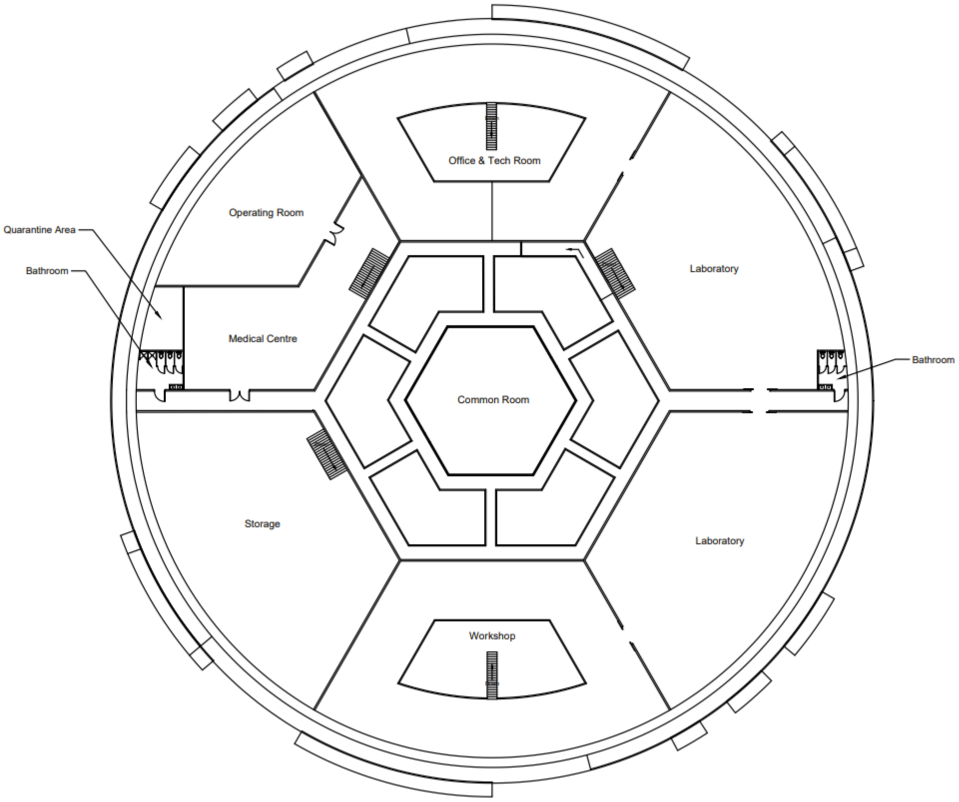

Figure 1. Floor plan of the L2 level of the lunar base (above ground)..

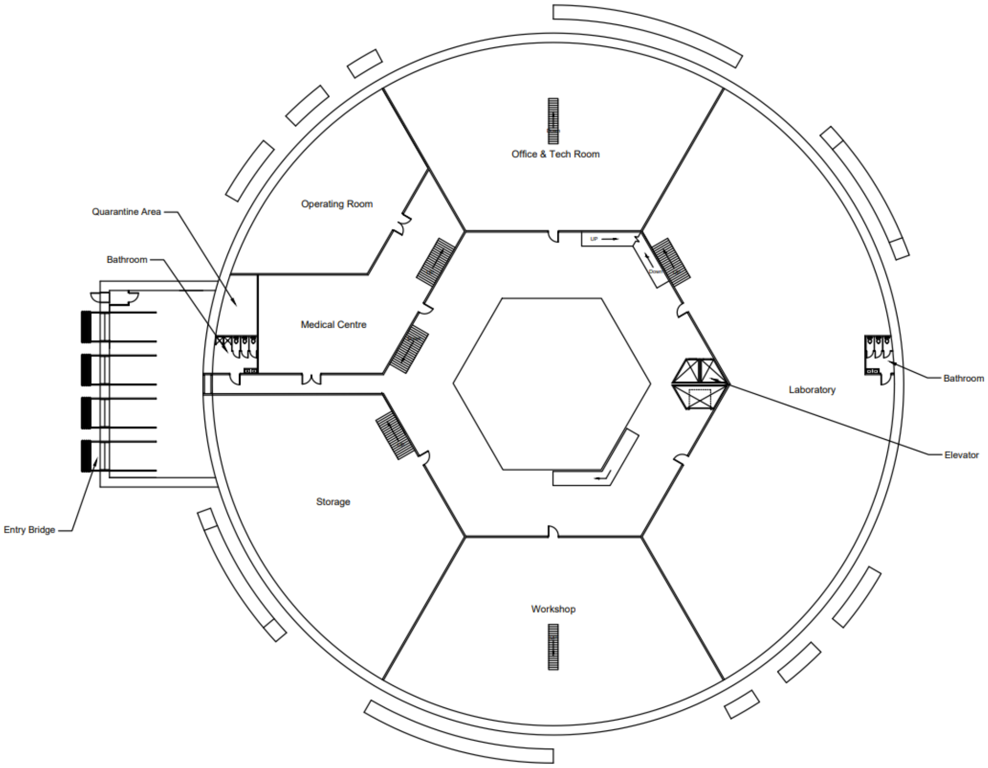

Figure 2. Floor plan of the L1 of the lunar base (above ground.)

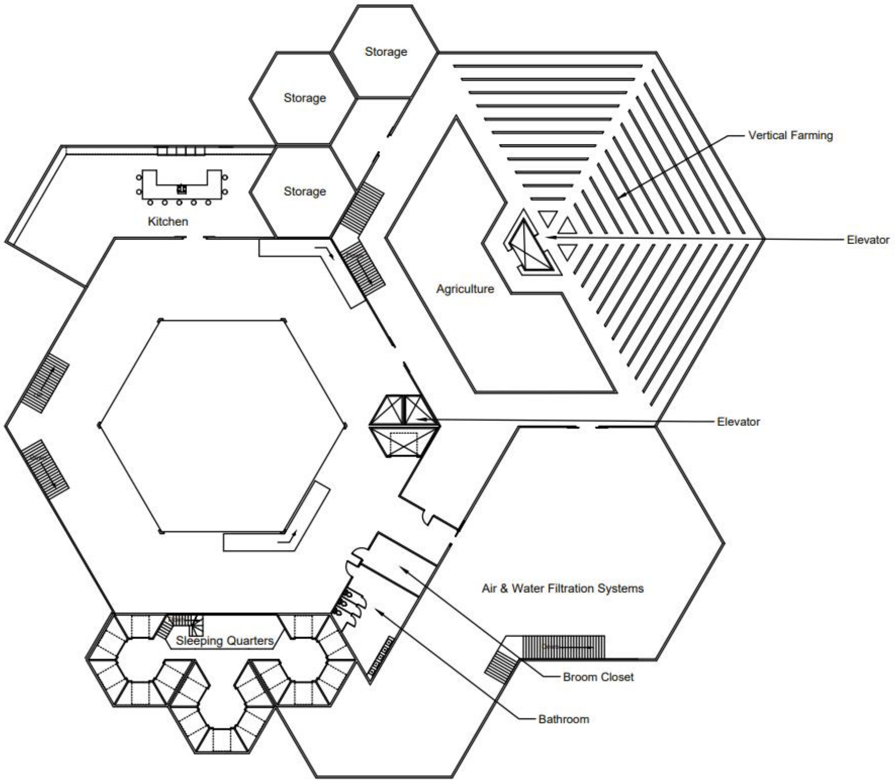

Figure 3. Floor plan of the B1 level of the lunar base (underground).

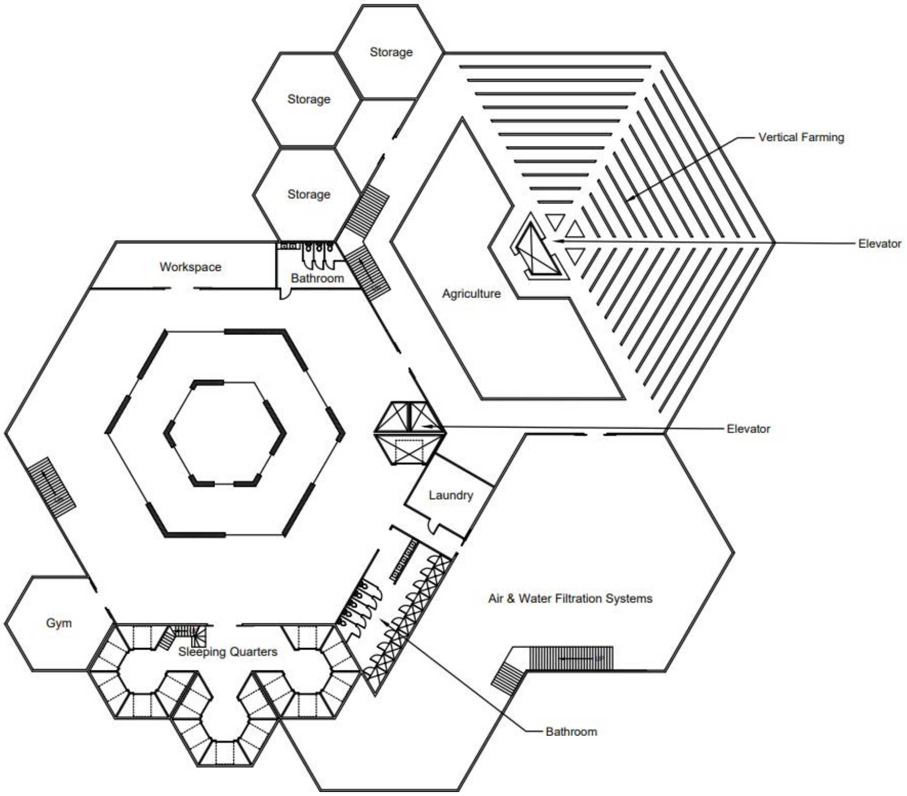

Figure 4. Floor plan of the B2 level of the lunar base (underground).

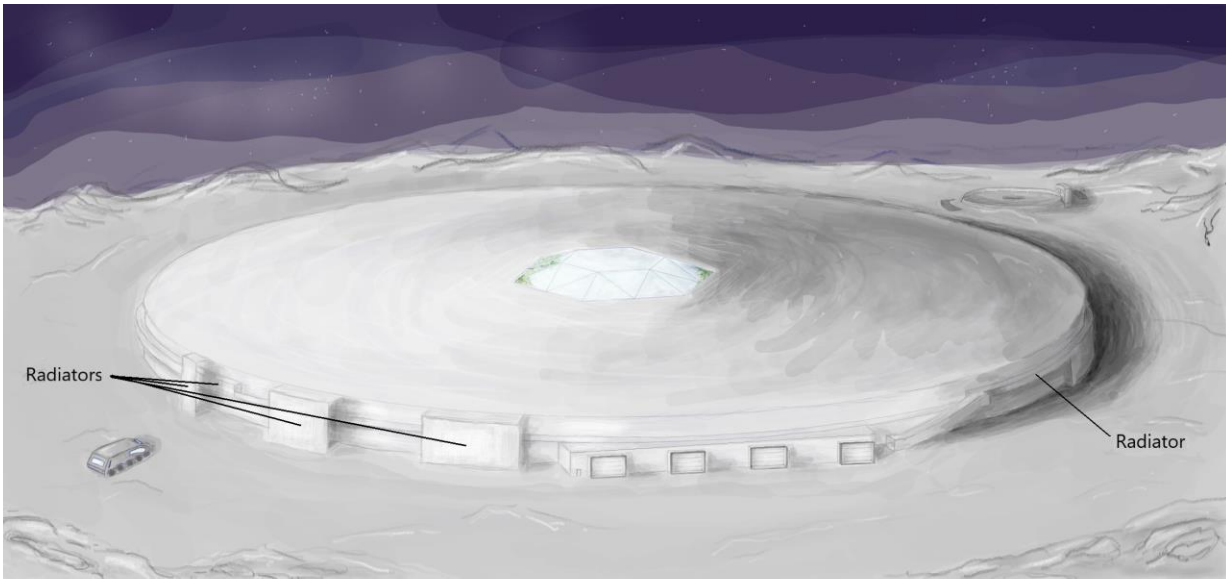

Figure 5. Exterior concept drawing of the lunar base.

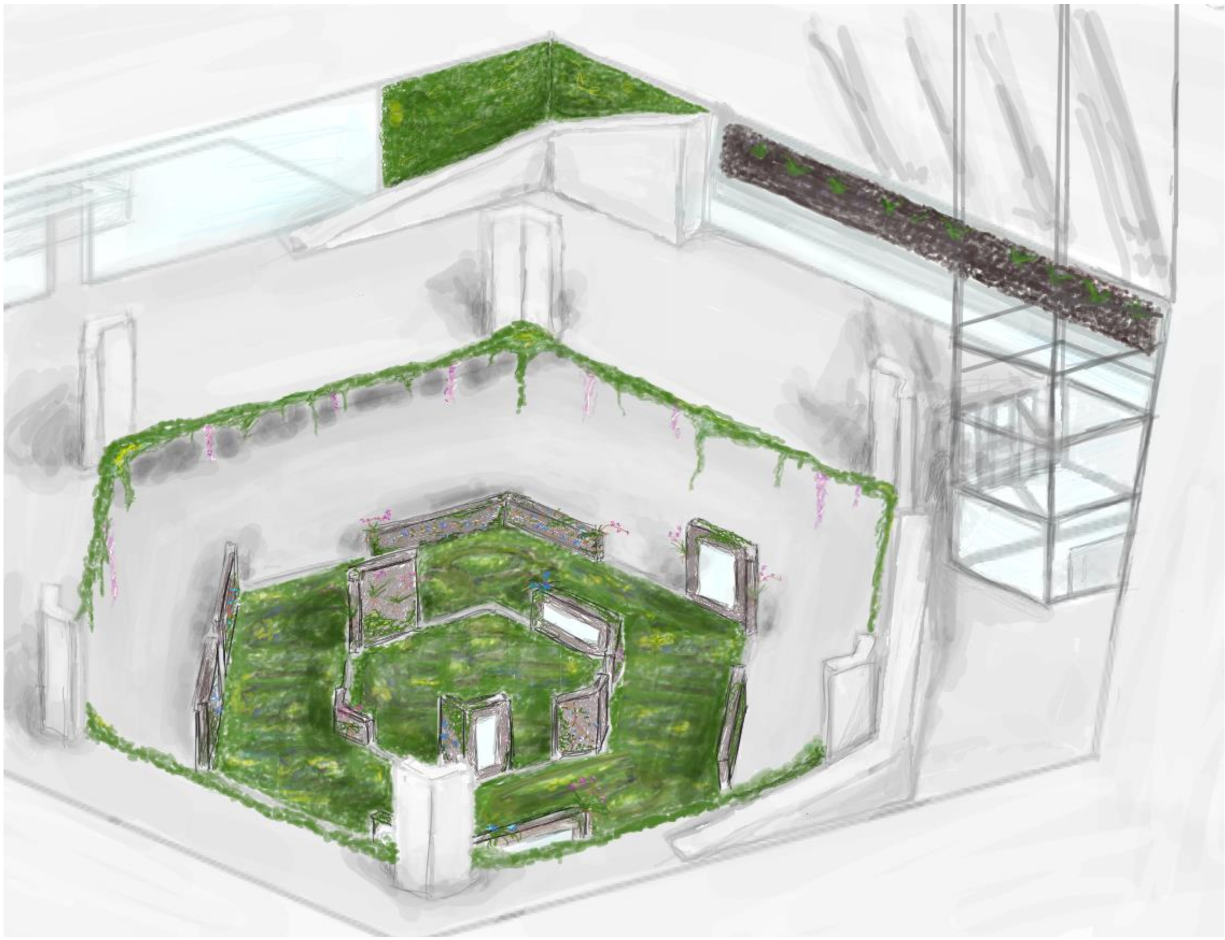

Figure.6 Concept perspective drawing of the interior of the underground section of the lunar base.

Radiation Shielding

In addition to the common knowledge that long-term and high-level radiation exposure can cause serious health issues to human bodies, electromagnetic and ionizing radiation can damage sensitive electronics as well. Therefore, it is only instrumental in protecting the inhabitants of the base from solar and cosmic radiation.

According to a study published by the Chang'e-4 mission team[7], the lunar surface radiation level is roughly 200~1000 times higher than that we experience every day on Earth (around 500 mSv/year, 500 times higher than the 1mSv/year dosage recommended by the United States Environmental Protection Agency for the general public), which is . Since the charged particles can be stopped relatively much easier, we used X-Ray photons at 2.0MeV in our model for the worst-case scenario. We calculated the thickness of different materials needed to reduce that radiation down to the recommended level. Since radiation dosage is defined by the amount of energy absorbed by mass, the radiation intensity ratio before and after absorption is the same as the radiation dosage outside and inside the structure. Hence the equation:

$$x = \frac{ln(R)}{\mu}$$

R is the dosage ratio (outside / inside),$\mu$is the attenuation coefficient unique to different materials exposed to different radiation intensities. For ordinary concrete, μ= 0.041209/cm; for lead, μ=0.704381/cm. We calculated that a concrete wall of about 1.67m thickness or a lead wall of 9.8cm would reduce incoming radiation to an ideal level. However, a dome of 10m in diameter needs almost 3000 metric tons of lead to fully shield the radiation down to the level acceptable for long term habitation. The transportation cost alone will cost more than the astronomical amount of the budget. Therefore, it is essential for any long term lunar base of 30 people to be constructed using as much of the lunar materials and as little of the materials from Earth as possible. An excellent example is the city *Artemis* in Andy Weir's novel *Artemis*. It consists of several double layer aluminum domes filled with lunar regolith, which is loose dirt found on the Moon's surface[8]. However, since we do not know much about the Moon's surface composition, we can not assume that there is enough alumina available to construct a base, not to mention that alumina electrolysis is a very power-consuming process.

Our alternative for aluminum, concrete, or lead is lunar regolith. The walls that come directly in contact with the lunar vacuum employ a sandwich-like structure, where a thick layer of loose lunar regolith fills the gap between two moon-concrete walls. According to the same study by ESA earlier in this paper, the best-performing moon-concrete comprises 3% mass of urea and 35% mass of 12M (480g/L) NaOH aquatic solution combined with the regular lunar regolith. The advantage of this configuration is that the only materials that need to be transported from Earth are urea, water, and NaOH pellets. The rest is entirely lunar regolith, which can be directly harvested on-site and requires minimum in-situ resource processing. We estimated the lunar regolith's attenuation coefficient based on the measurements by Moreira et al. [9], then calculated that the minimal effective thickness for a moon-

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[7] S. Zhang *et al.*, "First measurements of the radiation dose on the lunar surface," *Science Advances*, vol. 6, no. 39, p. eaaz1334, Sep. 2020, doi: 10.1126/sciadv.aaz1334.

[8] "Regolith," *Wikipedia*, Jan. 25, 2021. https://en.wikipedia.org/wiki/Regolith (accessed Jan. 15, 2021).

[9] A. Camargo Moreira and C. Roberto Appoloni, "Mass attenuation coefficient of the Earth, Moon and Mars samples over 1keV–100GeV energy range," *Applied Radiation and Isotopes*, vol. 64, no. 9, pp. 1065–1073, Sep. 2006, doi: 10.1016/j.apradiso.2006.04.002.

concrete wall needs to be about 0.7276m to reduce the inhabitants' radiation dose to a safe level for long-term habitation.

In the world of radiation shielding, two kinds exist: passive and active. Active shields operate as an artificial magnetic field that reflects or absorbs radiation, just like the Earth. On the other hand, passive shields are meant to reduce radiation flux, i.e., the amount of radiation penetrating a surface[10]. Passive shields are physical barriers, and their performance depends mostly on the barrier's material and thickness. Passive shields are the preferred choice since they do not require energy to run and leave room for expansion of the lunar base.

The shield's primary function is to protect the inhabitants from the ionizing and electromagnetic radiation from cosmic rays and the sun. Generally speaking, it is possible to create an idealized configuration of rays that represent radiation flux. From there, derive a shield shape that outlines a distinct area inside the base where the radiation levels allow long term habitation. In figure 7, a diagram demonstrates this principle with flux 'φ' (phi) and its angle of penetration 'θ' (theta)[11]. This diagram suggests that a cylindrical outer shield is a way to go.

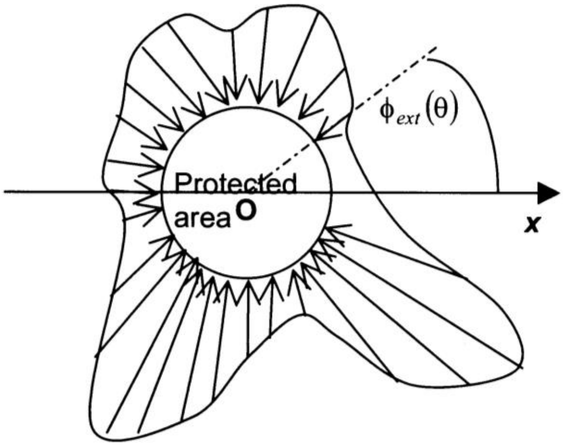

Figure 7. Diagram showing the protected area given radiation's angle of penetration.[12]

In reality, the angle with which the rays hit the moon base is nearly parallel to the ground[13]. As such, the cylindrical-shaped shields need only be taller than the tallest person it needs to protect. The idea behind this is very similar to standing behind a wall on a sunny day. If a person is shorter than the wall, then they benefit from the shade. On the moon, the same thing is true when a person stands in the shade of a wall. The sun can not reach the person, and therefore, neither the radiation.

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[10] H. M. Teodorescu and A. Globus, "Radiation Passive Shield Analysis and Design for Space Applications," *www.sae.org*, Jul. 11, 2005. https://www.sae.org/publications/technical-papers/content/2005-01-2835/#:~:text=We%20analyze%20passive%20radiation%20shield%20designs%20and%20techniques (accessed Jan. 2, 2021).

[11] *Idem 8.*

[12] *Idem 8.*

[13] *Idem 6.*

The Walls

Building materials count among one of the heaviest loads to transport from Earth. For the moon base to be sustainable and easily expandable, most of the moon base structure is made of lunar concrete, formed from lunar regolith and aggregate and lunar regolith[14]. Modifications need to be made to the lunar materials, namely with Urea and NaOH[15]. These substances are brought from Earth and make the concrete more ductile and, thus, more resilient to pressure and temperature changes.

The innermost layer is covered in electric pressure sensors penetrating through the wall. That way, in the event of any leaks, the crew can locate the panel and repair the damages. After that, two layers of concrete reinforced with steel grids. Sandwiched between these two layers is a gap filled with lunar regolith. The layer of lunar regolith acts as an insulator and a shock absorber as well. Over the outermost layer of concrete are white reflective paint, insulation purposes, and an anti-spalling coating. The entire wall's thickness has to exceed 1m to prevent a dangerous amount of radiation from penetrating it. The floor of the base is also made from reinforced lunar concrete. The above-ground portion of the moon base's overall height is 3.5 m in total, making any harmful sun rays well out of reach of any crew.

The center of the base holds a diamond-shaped glass dome. The dome is made from layering laminated lead glass plates together to fit into a steel cage. Lead glass is the best option since it's very dense and so provides ample radiation protection as well as a view to the outside[16]. This idea was inspired by the design of observation windows in hot cells, shielded chambers with robotic manipulators for handling highly radioactive materials[17]. Laminated glass is also handy since the glass does not shatter upon contact with any falling debris[18]. There is no filling between each glass panel, and the windows are equipped with thermal and pressure control sensors, just like the one found in the Cupola on the ISS[19]. This way, the crew can monitor the thermal expansion and detect any leaks among the glasses. These sensors are connected through the metal frames. On the glass, holes are drilled at twice the thickness of the glass pane from its edge[20]. The diameter of these holes respects a depth to diameter ratio of 3:1 to maintain precision in the drilling process. The purpose of these holes is to equalize pressure during a breach without putting too much instant pressure on a single pane of glass, providing time for evacuation and repairs.

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[14] "Lunarcrete," *Wikipedia*, Jan. 13, 2021. https://en.wikipedia.org/wiki/Lunarcrete (accessed Jan. 25, 2021).

[15] S. Pilehvar, M. Arnhof, R. Pamies, L. Valentini, and A.-L. Kjøniksen, "Utilization of urea as an accessible superplasticizer on the moon for lunar geopolymer mixtures," *Journal of Cleaner Production*, vol. 247, p. 119177, Feb. 2020, doi: 10.1016/j.jclepro.2019.119177.

[16] "Lead glass," *Wikipedia*, Jan. 06, 2021. https://en.wikipedia.org/wiki/Lead_glass#Properties (accessed Jan. 31, 2021).

[17] K. V. Kasiviswanathan, "Hot Cells, Glove Boxes, and Shielded Facilities," *ScienceDirect*, Jan. 01, 2001. https://www.sciencedirect.com/science/article/pii/B0080431526006811.

[18] "Laminated glass," *Wikipedia*, Jan. 10, 2021. https://en.wikipedia.org/wiki/Laminated_glass#Manufacture (accessed Jan. 12, 2021).

[19] "Cupola (ISS module)," *Wikipedia*, Jan. 14, 2021. https://en.wikipedia.org/wiki/Cupola_(ISS_module)#:~:text=The%20Cupola%20is%20an%20ESA%20-built%20observatory%20module (accessed Jan. 12, 2021).

[20] "tempered glass drilling holes, holes in tempered glass, laminated glass with holes for fixing, tempered glass manufacturers china," *www.sggglassmanufacturer.com*. https://www.sggglassmanufacturer.com/news/Process-of-drilling-holes-in-glass-tempered-glass-laminated-glass.html (accessed Jan. 9, 2021).

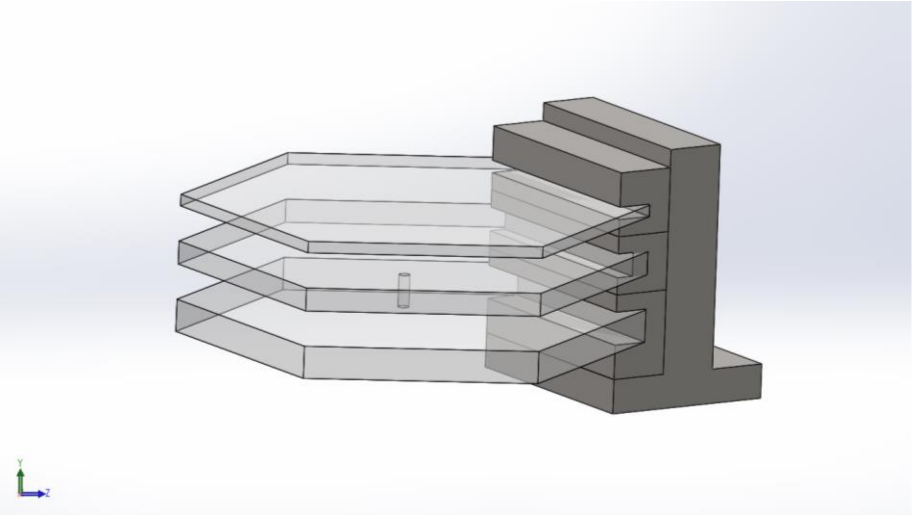

Figure 8. Cross section of the lead glass panels. Their steel support slots and the steel T-beam that serve as the skeleton for the entire dome.

As seen in figure 8, the glass panels are inserted as slots into the main holding structure. In this way, they can easily be removed or replaced if damaged. Each panel is thicker than the last, the top layer being the thinnest, acting as more of a crash layer, and the last being the thickest, acting as the radiation shield. The ratio of glass to lead is about 0.635cm for 0.015cm of sheet lead and, given that a 9.8cm sheet lead is being used as a reference dimension, the effective thickness, which is the minimal thickness the glass needs to be to stop dangerous levels of irradiation, should be 4.14 m[21]. However, irradiation levels vary depending on where the piece of glass is located. For example, a glass pane's effective thickness lying parallel to the rays is in its length rather than its thickness. As such, the following formula determines the thickness of the glass required.

$$t = effective\ thickness * \sin\theta$$

t is the thickness of the lead glass wall, θ is the angle made between the glass wall and the angle of radiation flux. This formula helps minimize the thickness of glass needed for the same amount of radiation protection. Knowing θ is between 90° and 180° excluded, a range of glass thickness can be anywhere between 4.14 to 0.072 m. The image above depicts the thickest portion of the glass to be 0.14m for an angle of roughly 178° created with the angle of penetrating radiation, simulating roughly what a glass plane nearly parallel to the flux angle looks like. The dome's overall structure is heavier at the base than the top, making it a more stable design.

Phases of Construction

Phase 1

After selecting a precise location to construct the base using the newest topography data, the first phase involves a batch of five robots sent to the said location, including two regolith gatherers, a material processor, and two material dispensers. The regolith gatherers work like snowblowers, except it collects

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[21] "A guide to the use of lead for radiation shielding,." [Online]. Available: http://www.canadametal.com/wp-content/uploads/2016/08/radiation-shielding.pdf#:~:text=It%20is%20produced%201%2F4%20inch%20thickness%20which%20is.

and stores the regolith on itself. At the beginning of the construction, they are responsible for flattening the ground and start excavating the room for the subsurface levels. They can transport the regolith to the mixer, to fill the gaps between walls or dump it at an empty spot at the edge of the construction yard. Once the subsurface levels are dug out, the mixer produces moon-concrete with regolith and the materials it had brought along. Then, the moon-concrete is deposited into the dispensers for further distribution. The production of moon-concrete poses one main challenge: concrete does not set in a vacuum. A possible solution to this problem has already been proposed that involves "premixing the aggregate and the cement and then using a steam injection process to add the water." [22][23] This process produces the necessary pressure required by the concrete to harden. Note that since the mixer requires no movement, may as well be the same original lander. Finally, equipped with visual sensors, LIDAR, and a robotic arm, the material dispenser lays the moon-concrete onto the designated spots by comparing the terrain and wth the 3D model of the base stored in its hard drive.

These robots' whole operation can be overseen by the ground control or astronauts aboard the Lunar Gateway Station[24]. The Gateway Station is important to this operation because it orbits the Earth-Moon L1[25], it is much closer to the lunar surface than Earth, therefore less communication delay. The Gateway Station also serves as a rest stop for human astronauts.

Once the base's framework is complete, a team of astronauts land on the site and spray down the base's outer wall with white reflective coatings and the inner wall with anti-spalling coatings. While the machines from earlier continue to produce moon-concrete, the astronauts lay down moulds and rebars, onto which the robots pour the concrete to make structural segments. One by one, these astronauts install the structural segments while living in the same spacecraft that has landed them on the moon. The structural elements become the floors and rooms of the base.

Phase 2

The third wave of arrival consists of a fleet of spacecraft, including crew transport, several freighters to transport the parts for airlocks and other essential machines, plus a tanker that carries enough resources to make the base livable. First, the workers install the airlock and life support system into the slots integrated into the external wall's original design and cryogenic oxygen tanks in a permanent shadow near the site. With a rover's help, a team of two workers can lay down the wires and solar panels to establish a functional electric grid, then connect everything into the said grid. Once a more efficient life support system is up and running, it will prolong human astronauts' stay and enable them to complete more sophisticated tasks, including the construction of a glass dome at the top of the base. Phase 2 is also the time for the crew to calibrate all equipment, check for leaks, and prepare for the official start of long-term human settlement on the Moon.

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[22] *Idem 11.*

[23] H. Cullingford, C. Xe, and M. Keller, "LUNAR CONCRETE FOR CONSTRUCTION Lunar and Mars Exploration Program Office,." Accessed: Jan. 31, 2021. [Online]. Available: https://space.nss.org/wp-content/uploads/Lunar-Bases-conference-2-518-Lunar-Concrete-For-Construction.p.

[24] K. Mars, "Gateway," *NASA*, Aug. 17, 2016. https://www.nasa.gov/gateway.

[25] Earth-Moon L1 is one of the five Lagrange points between orbiting bodies. The gravitational force of the two orbiting bodies balance out at these arbitrary locations, therefore spacecrafts can orbit them like they do around solid bodies.

Life Support

Power

The most reliable sources of energy in space are solar and nuclear. Although the Moon does have an interior made of molten magma during the very early stages of its history, most of it has already cooled down and solidified. Tidal heating is not possible because the Moon is tidally locked to the Earth, and tidal heating requires it to rotate with respect to the Earth.

Solar power can be harvested by both semiconductor solar panels and solar thermal plants. Both facilities must be built on the highest parts of the Shackleton Crater's rim to have a solar influx at all times because the sunray always comes in a shallow angle from all directions at the polar regions of the Moon[26]. Therefore, to deal with the low surface solar flux, solar panels must erect vertically and articulate to track the Sun for maximum energy. The mirrors of solar thermal plants are designed to focus the incoming sunray with half of its mirrors at all times.

On the other hand, nuclear power plants are not restricted by the shallow sun rays but by international concerns over its radiation hazard during a launch failure. According to the US Department of Energy Office of Nuclear Energy, small modular reactors (SMRs) are a class of small nuclear reactors that can fit in a cargo container and have a power output that ranges between hundreds of megawatts to thousands of megawatts[27]. One of these reactors can be placed inside an individual structure outside of the main base accessible by tunnels or corridors, or it can stand erect in an area outside the base like a standalone ship. The reactor's waste heat can either be directed to an individual radiator system or provide the settlers heating by connecting the secondary or tertiary cooling loop to the base's climate control system.

Atmosphere

Maintaining a breathable atmosphere is the baseline of any successful mission that involves human crew members. Therefore, this base is designed to have multiple redundant systems to ensure that the inhabitants breathe freely and safely during their stay on our base.

The first and most important part of maintaining an atmosphere is O2 generation. An average adult consumes 3.5ml of oxygen per minute per kilogram of their body weight at one atmospheric pressure[28] or 302.4 litres per day for an average adult. According to the data collected first-hand in 1965 from NASA's Surveyor missions, the moon's surface contains about 62% oxygen that is locked in chemical compounds, and a few of these compounds are metal oxides[29]. With the reduction of metal

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[26] *Idem 6*

[27] "Advanced Small Modular Reactors (SMRs)," *Energy.gov*, 2012. https://www.energy.gov/ne/nuclear-reactor-technologies/small-modular-nuclear-reactors.

[28] M. Kwan, J. Woo, and T. Kwok, "The standard oxygen consumption value equivalent to one metabolic equivalent (3.5 ml/min/kg) is not appropriate for elderly people," *International Journal of Food Sciences and Nutrition*, vol. 55, no. 3, pp. 179–182, May 2004, doi: 10.1080/09637480410001725201.

[29] J. H. Patterson *et al.*, "Alpha-Scattering Experiment on Surveyor 7: Comparison with Surveyors 5 and 6," *Journal of Geophysical Research*, vol. 74, no. 25, pp. 6120–6148, Nov. 1969, doi: 10.1029/jb074i025p06120.

oxides using hydrogen instead of carbon[30], the base can produce raw metal while replenishing its oxygen supply. Figure 9 illustrates a simple device based on the process mentioned above: as the hydrogen (either harvested locally or transported from Earth) is heated with the metal oxides, the hydrogen reduces the oxides into elemental metals and produces water vapour as a by-product; then, a condenser turns the water vapour into its liquid form and feeds it to the electrolyzer, where the liquid water undergoes electrolysis to produce oxygen and hydrogen. In the end, the hydrogen goes back to the metal smelter to repeat the whole cycle. Any hydrogen loss can be compensated by electrolyzing water or direct shipments from Earth. The above process can integrate with either a solar thermal power plant or a nuclear reactor involving a molten reactor core (e.g., a Molten Salt Reactor or a liquid metal fast reactor) that a focused solar beam or a nuclear reactor core directly heats the smelter . The hydrogen-water vapour mixture becomes a working medium for the thermal generator. To reduce cost, the same regolith gatherers used to construct the base at the beginning can also be used to harvest local rocks for this procedure.

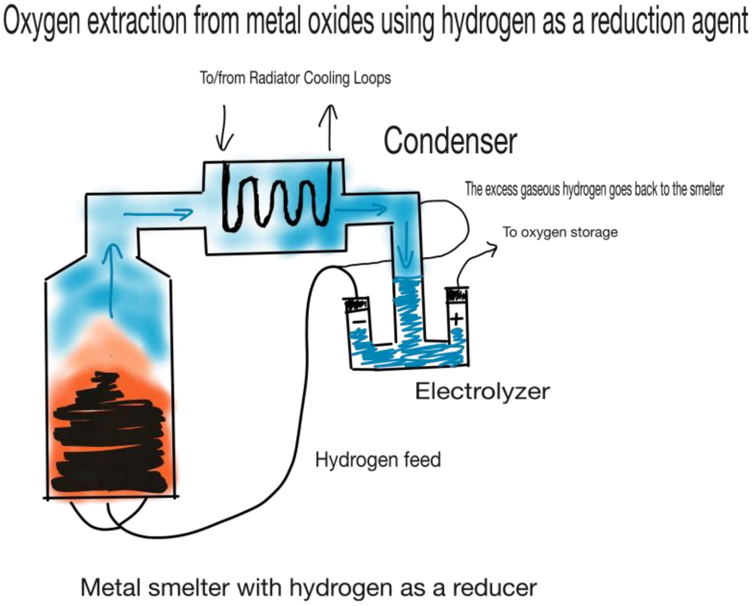

Figure 9

Water electrolysis is another way to produce oxygen reliably. Since a rocket engine's exhaust velocity is inversely proportional to the exhaust gas's molecular weight[31].Most hydrogen engines use a hydrogen-rich mixture to increase its specific impulse, increasing its fuel efficiency. Therefore, electrolyzing water to produce rocket fuel creates a surplus of oxygen for the crew to breathe. For every kilogram of hydrogen-oxygen rocket fuel (assume 6-1 mixture ratio like the Space Shuttle), there is about 0.429 kilogram of by-product oxygen. In an atmosphere of 21% oxygen, that equates to 328.16 litres of oxygen per kilogram of rocket fuel. Suppose the Apollo lander (~70% of it is fuel) had used hydrogen fuel. In that case, just refuelling 10 Apollo landers for 20 settlers can result in enough oxygen surplus for everyone to survive for eight days!

The other part of maintaining an atmosphere is to remove carbon dioxide. Intuitively, most people think about using plants to remove CO2 and produce oxygen, like the way it is in nature. However, during

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[30] D. Spreitzer and J. Schenk, "Reduction of Iron Oxides with Hydrogen—A Review," *steel research international*, vol. 90, no. 10, p. 1900108, Aug. 2019, doi: 10.1002/srin.201900108.

[31] "The Nuclear Thermal Rocket," *large.stanford.edu*. http://large.stanford.edu/courses/2011/ph241/hamerly1/.

the famous experiment Biosphere II the experimenters saw an explosion in the number of pests and "oxygen-gulping bacteria", which lead to the deprivation of food and breathable air[32]. Biosphere II's failure proved that nature is a complex system that achieves its function via an immeasurable amount of different paths. At that level of complexity, nature can restore its function by rerouting the biological substances from the damaged pathways to those that still work without overstraining them.

In comparison, artificial biospheres lack such capacity because they are much simpler and contain far fewer routes. Therefore, they are much more prone to a cascade of failures; yet, they involve so many species that such failures become almost impossible to predict. The failure of Biosphere II proves that artificial intervention is necessary for attempts of a similar scale.

There are currently three ways to separate carbon dioxide from the air: chemical absorption, membrane filtering, and cryogenic distillation. Cryogenic distillation is the most suitable for circumstances like on a lunar base. It involves gradually cooling the incoming air down and removing the air components depending on their boiling point, which is a physical property. The benefit of a cryogenic distillation system is that it can distill the air components by cooling them down in multiple stages. For example, most of the moisture in the air turns into the water at close to 0°C (32°F), and carbon dioxide turns into dry ice at -78.5°C(-109.5°F), a gradual reduction in temperature condenses water before carbon dioxide, hence to separate the two. The same process can separate harmful gases from the atmosphere, as well (although at one point, it might be easier to flush the gas outside into space and refill the cabin with fresh air from reserve). This system can also integrate with the base's climate control system. By running a coolant loop through the air outlet, the cryogenic distillation system can pre-moderate the outgoing air temperature by adjusting the amount of coolant going through the reheating loop instead of the external radiators. All the methods above have been widely used in industries and carbon dioxide removal projects. They can serve as each other's backups in the lunar base.

To reduce the air recyclers' load and micro-adjust the air quality, "green walls" can replace some of the base's internal walls. Each "green wall" is a modularized hydroponic system for selected species of plants. The plant species are selected to optimize the whole unit's oxygen output while releasing humidity and chemicals to the air for the inhabitant's well-being. There is also a dedicated greenhouse for growing food. The greenhouse has its carbon dioxide-rich atmosphere to boost crop yield. By feeding the air recycling system's carbon dioxide exhaust into the greenhouse, the base can achieve a full carbon cycle to conserve its resources. The separation of the greenhouse from the rest of the base reduces stress from other systems during an emergency. During a power failure, separating the greenhouse's atmosphere from the rest of the base conserves oxygen for the crew. The power for lumination in the greenhouse can be rerouted for more vital systems.

Meanwhile, since the hallways still need lighting for evacuation purposes, emergency lighting can sustain the plants' photosynthesis in the hallways, providing an alternate pathway for oxygen regeneration. The base also has indoor greenspaces with ample open space and real soil-grown grass, including one under the glass dome. These green spaces serve as relaxation areas, emergency rendezvous points, and redundant air and water processors.

During an accidental release of poisonous gas, the protocol isolates the affected area and flushes out the gas with air reserves.

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[32] C. Zimmer, "The Lost History of One of the World's Strangest Science Experiments (Published 2019)," *The New York Times*, Mar. 29, 2019.

Water Recycling

Much like on the ISS, any water, whether it comes from moisture in the air, urine, shower water[33], is vital for the astronauts as this can be purified into drinking water[34]. The Water Recovery System, or WRS, has a 93% recovery rate, which is great, but assuming that an adult needs three litres of recycled water per day, the system's loss rate is 0.2258 litres of water per adult per day[35]. For a base of 30 people, water supply alone takes up 203 kilograms of supply ship capacity per month, only to compensate for the loss of water due to the recovery process. It is paramount to improve on other water recycling methods and moisture maintenance in the base.

The ISS does not have an outlet for that extra 7%, but the moon base does. As mentioned in figure 10, the five-step treatment process for water indicates the possible uses for the urine concentrates as fertilizers[36]. This means that the water within the urine concentrate eventually returns to the atmosphere by the plants' transpiration. Some hydroponic units are designated to process wastewater with genetically-engineered plants.

As mentioned in the atmosphere section, a condenser recovers all the air's humidity from evaporated sweat, human activities, and plant transpirations. We estimate that recovering wastewater concentrates can increase the water recovery rate to up to 99%, translating to 29 kilograms per month per 30 adults.

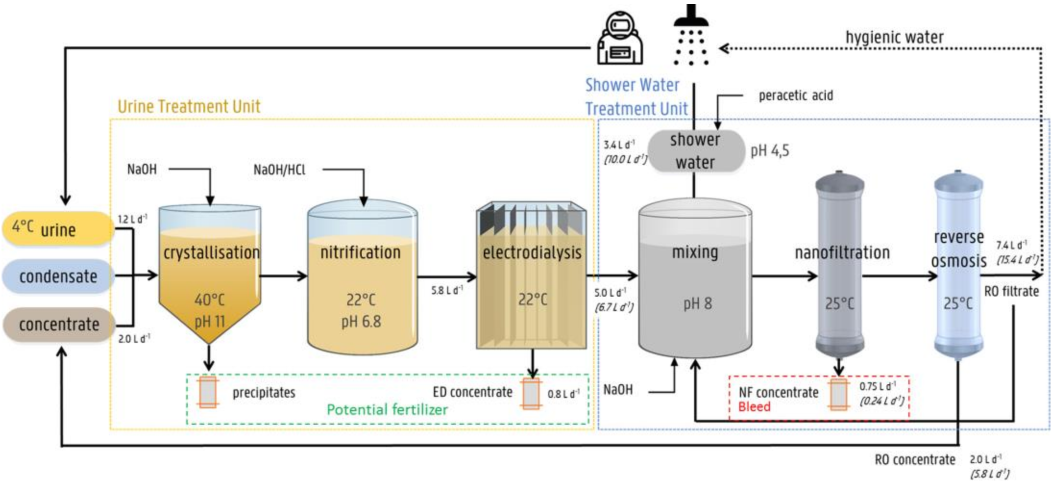

Figure 10. Image depicting the "5-stage treatment train for water recovery" which demonstrates how the remaining water waste can be used as fertilizer. [37]

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[33] "Water Recycling," *NASA*, 2014. https://www.nasa.gov/content/water-recycling/.

[34] "A five-stage treatment train for water recovery from urine and shower water for long-term human Space missions," *Desalination*, vol. 495, p. 114634, Dec. 2020, doi: 10.1016/j.desal.2020.114634.

[35] "A Novel Water Recovery System for Use in Space," *AZoM.com*, Feb. 28, 2019. https://www.azom.com/article.aspx?ArticleID=17704.

[36] *Idem 28.*

[37] *Idem 28.*

Food

Ultimately, the main challenge faced by producing food on the moon base is maintaining the optimal environment to maximize the crop yield while negotiating with some circumstances related to the lunar environment. Crews also need to balance their nutrient intakes using whatever is available.

To save space in the underground portion of the moon base, it utilizes vertical agriculture. Vertical agriculture is beneficial because it requires "70% to 95% less water than required for normal cultivation". Compared to traditional growing methods, vertical agriculture also produces more product while taking less space[38]. Such hydroponic systems grow crops in the greenhouse, plants in general throughout all parts of the base. The crops are sustained with hydroponic and aeroponic systems since they also alleviate the space taken up by all the plants. Hydroponics does not need soil to grow and therefore get faster access to water and nutrients, making it easier for the plants to grow[39]. They also contribute to water collection for the rest of the crops[40].

On the other hand, aeroponics grows crops by creating a mist of nutritious water around their roots, which would be very convenient since the base's atmospheric conditions are highly tailored[41]. NASA has even developed an Inflatable Aeroponic System (IAS), making it very easy to transport and uses even less water than the hydroponic system[42]. These systems are generally very resistant to pests and have incredible growth rates[43].

The best way to optimize nutrient intake naturally is by growing superfoods such as berries, leafy greens, nuts, whole grains, tomatoes and cruciferous vegetables[44]. These items are rich in vitamins, protein and fibre, which are essential for the settlers. By introducing multiple crop variants, Any other superfoods that can not be grown on the base like eggs and fish are replaced by substitutes.

Miscellaneous

Finances

The feasibility of a moon base requires consideration of the technology and whether or not cost is reasonable. For example, why develop a moon base now when the cost may be much cheaper a few decades from now? Or maybe, the cost of developing a moon base would be unfavourable to the general public due to the desire for government spending to be allocated elsewhere (i.e., health or education). By

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[38] https://www.facebook.com/thebalancecom, "What You Should Know About Vertical Farming," *The Balance Small Business*, 2017. https://www.thebalancesmb.com/what-you-should-know-about-vertical-farming-4144786.

[39] " Hydroponic Systems," *Epic Gardening*, Oct. 05, 2018. https://www.epicgardening.com/hydroponic-systems/.

[40] *Idem 38.*

[41] "Aeroponics," *Wikipedia*, Dec. 10, 2020. https://en.wikipedia.org/wiki/Aeroponics#:~:text=Aeroponic%20system%20refers%20to%20hardware%20and%20system%20components (accessed Jan. 30, 2021).

[42] "NASA - Inflatable Aeroponic System," *www.nasa.gov*. https://www.nasa.gov/offices/ipp/centers/kennedy/success_stories/Inflatable_Aeroponic_System_BBlinds.html (accessed Jan. 30, 2021).

[43] *Idem 35.*

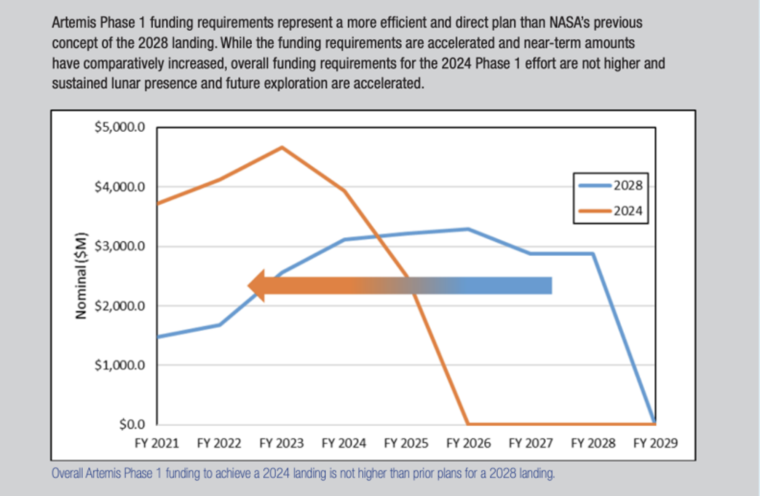
[44] K. D, "10 superfoods to boost a healthy diet - Harvard Health Blog," *Harvard Health Blog*, Aug. 16, 2018. https://www.health.harvard.edu/blog/10-superfoods-to-boost-a-healthy-diet-2018082914463.

exploring "financial feasibility," we can prove that the development of a lunar base is not only possible in the near future but economically sound.

The table below expresses the allocation of funding, considering the cost of the material goods required during all points of operation for the moon base. Although further funding may be necessary, the table represents a summary of cost. Later sections will provide insight into how these funding conclusions were made, and why margins may vary.

	Cost in Millions $ (USD)	**Single or Routine Purchase**
Program/Operational	$ 25 000 - 35 000	Single
Transportation	$ 6 000 - 12 000	Single
Energy & Water	$ 5 000 - 9 000	Single
Moon Base	$ 200 - 300	Single
SpaceSuits	$ 800	Single ($ 27 / space suit)
Amenities	$ 10	Routine
Total	$ 37 010 - 57 110	

Program and operational costs were developed through understanding the finances of the Artemis Program[45]. Through cost analysis of the program, we could deduce the cost of operating a moon base program would be in the range of $ 25 000 - 35 000 million, with the majority of this cost occurring in the first years of the program. We can assume that our program will cost relatively more than Artemis as it will be twice the length and require increased staffing. The allocation of cost distribution is represented similarly in the Artemis Program, presented below in the following graph[41].



Artemis Phase 1 funding requirements represent a more efficient and direct plan than NASA's previous concept of the 2028 landing. While the funding requirements are accelerated and near-term amounts have comparatively increased, overall funding requirements for the 2024 Phase 1 effort are not higher and sustained lunar presence and future exploration are accelerated.

Overall Artemis Phase 1 funding to achieve a 2024 landing is not higher than prior plans for a 2028 landing.

Figure 11[42]

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[45] [1]"NASA's Lunar Exploration Program Overview," 2020. [Online]. Available: https://www.nasa.gov/sites/default/files/atoms/files/artemis_plan-20200921.pdf.

Transportation cost, which includes necessary LVs[46] and transportation of goods, is estimated to be $ 6 000 - 12 000 million. The average cost of transportation is expected to decrease as new technologies arise over the upcoming decade. Continued research into X-series technology, and continued development of new LVs through NASA and SpaceX (notably) will decrease space transportation costs from $25 000/lb to several grand[47]. The most cost is assumed to come through the high amount of LVs required for space transportation. This includes several Falcon Heavy, which can be reused for further transportation, and Falcon-9. The high cost comes with maintaining at most 8-12 of these rockets and the logistics necessary to launch said rockets. Additionally, a custom rocket will be necessary that can be deconstructed for the moon base's usage. It will also include several construction tools, such as concrete pumps and robots.

Energy and water are vital to sustaining our moon base and can be considered a highly variable cost. This is due to both resources' routine necessity, and whether it needs to be transported via LVs or domestically sourced. Although the cost of developing a nuclear fission generator and mini-water plant may be costly in the short-term, these technologies are essential in allowing sustainable and long-term programs to occur on the lunar surface. Known ice deposits on the moon conceptually allow "ice mining," which may be a possible water source[48].

The moon base will cost between $ 200 - 300 million. While relatively expensive, costs were cut down through the usage of lunar material, such as regolith. Using these materials as a cement mixture for the moon base's walls and skeleton help cut down costs as fewer materials need to be transported to the moon base. Other materials such as metals and glass will be transported through LVs.

The cost of spacesuits came through understanding the cost of spacesuits for the Artemis Program. $ 500 million is the expected cost of the spacesuits necessary for the program. As we have more astronauts in our project, we expect the cost to be marginally higher; around $ 800 million.

The cost of amenities, including food, oxygen, medical resources, bedding, hydroponics, et cetera, is expected to be around $10 million a year. This cost is expected to be higher in the first few years of the program as more resources will need to be transported, and food will not continue to grow sustainably. Furthermore, items such as "oxygen" will be necessary to transport for the first few years. Still, it is assumed that oxygen will be plentiful over the years of integrating hydroponics and other oxygen-enabling technologies. Another technology that will allow for oxygen production is the "Oxygen extraction from metal oxides using hydrogen as a reduction agent" (see Figure 9). It is expected that most food can be produced on the moon base via hydroponics. Waste reclamation will allow further resource efficiency.

Stakeholders expected in funding the moon base are those who have funded Artemis and other space programs. This includes, but is not limited to, Boeing, Lockheed Martin, SpaceX, Blue Origin, et cetera. It can be assumed that these are willing investors as they designate themselves as pioneers in space travel and exploration. Although the desirability of funding new, major space projects currently is questionable due to the current pandemic, the accolade of developing the first near-term moon base may be considered desirable to investors. Private investors are also expected, although the majority of funding

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[46] Launch Vehicles.

[47] "NASA - Advanced Space Transportation Program fact sheet," *Nasa.gov*, 2010. https://www.nasa.gov/centers/marshall/news/background/facts/astp.html.

[48] S. Potter, "NASA's SOFIA Discovers Water on Sunlit Surface of Moon," *NASA*, Oct. 26, 2020. https://www.nasa.gov/press-release/nasa-s-sofia-discovers-water-on-sunlit-surface-of-moon.

will come through enterprises.In the later stages of our program, when we move towards industry and specialization, relying on private investors will become more valuable.

In conclusion, financing a moon base program is highly feasible in the upcoming decade. This is not only due to the abundance of new technologies in the space sector but also due to observing the desirability of investment in other programs similar in size and scope. Developing and managing the moon base program is only marginally higher than the Artemis Program's cost, as Artemis will cost around $ 28 000 million. In contrast, the moon base program will range between $ 37 010 - 57 110 million. With the cost being relatively similar (Artemis - 5 years, Moon Base - 10 years), and the general populaces appeal for space travel and exploration[49], the development of a moon base is highly feasible in the near future.

Governance

According to the Outer Space Treaty[50], no country can legally claim the land on which it builds any structure if the structure is on any non-Earth celestial body. Still, the structure can be legally treated as an extension of the country's territories. Suppose the Shackleton Base has been a joint effort by entities of different countries. In that case, the member countries are responsible for each of the elements (personnel, equipment, structures, etc.) they contributed, just like the way it has been on the ISS[51]. Disputes are to be settled by trials on the International Court of Justice[52].

Conclusion

In conclusion, the development of Project Shackleton is feasible over the next decade. This paper gives a rough estimation of challenges for setting up a long-term human settlement on the Moon and has demonstrated that all of the said challenges can be dealt with using current technologies. With the development of new technologies both in and out of the space sector, and the decreasing financial cost of space travel and exploration, the construction and development of a Moon base are feasible in the near future.

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[49] "Majority of Americans Believe It Is Essential That the U.S. Remain a Global Leader in Space," *Pew Research Center Science & Society*, Jun. 06, 2018. https://www.pewresearch.org/science/2018/06/06/majority-of-americans-believe-it-is-essential-that-the-u-s-remain-a-global-leader-in-space/.

[50] robert.wickramatunga, "The Outer Space Treaty," *Unoosa.org*, 2018. http://www.unoosa.org/oosa/en/ourwork/spacelaw/treaties/introouterspacetreaty.html.

[51] "International Space Station legal framework," *Esa.int*, 2019. https://www.esa.int/Science_Exploration/Human_and_Robotic_Exploration/International_Space_Station/International_Space_Station_legal_framework.

[52] "Jurisdiction | International Court of Justice," *Icj-cij.org*, 2019. https://www.icj-cij.org/en/jurisdiction.