Prosperity Lunar Station - Potential Design Criterions and Constraints for Lunar Settlement in 10+ Years' Time

The Moon Society: Moon Base Design Contest

Submission: Nexus Aurora, and Space Medicine and Life Science (SMLS) of SGAC

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Introduction

Living on the Moon may very well be a reality closer than we think. Although mass human migration won't be experienced by the general public until the 22nd century. Nonetheless, the very start of that journey begins in this century, in this decade for that matter. At this current time, viruses such as the Coronavirus, spread rapidly across the planet which are further induced by overpopulation. Rising temperatures and sea-levels due to drastic changes in the environment cause even further concern for the future of our planet, amongst others. As humans, it is in our nature to never stray away from life-threatening challenges and to forever be relentless in the pursuit of a solution, especially for problems we have caused ourselves. But whilst this noble fight continues, the unrestrained vision of a new "home away from home" on our neighboring Moon grows stronger and stronger. A home that is safe, clean, and unique. One we can start anew.

Aside from the growing evidence that humanity is consuming the slowly depleting natural resources of our planet, for many decades researchers have been relishing the idea of the Moon as a potential alternative habitat that can actually be obtained. For decades there has been interest in the Moon being an "experimental playground" to conduct studies and test lunar technologies as a stepping stone towards the colonization of Mars (1). While the International Space Station (ISS) has been an essential laboratory to study the effects of microgravity on biological systems, etc., the Moon will be a different laboratory that will be more essential for science as a 'natural laboratory' to study planetary processes and evolution. Not only will this open up the opportunity for the environment to be a training ground to learn how to conduct scientific exploration from a planetary surface, but it will also be an opportunity to use infrastructure and resources associated with human exploration to leverage support for autonomous scientific investigations. By acting as a refueling station, it would also allow a drastic drop in space travel expenses through the economies of scale. Our proposed plan for the design of the Prosperity Lunar Station is as follows.

Timeline

The Prosperity Lunar Station is composed of two lunar bases, Lunar Habitat 1 (HAB1) and Lunar Habitat 2 (HAB2), with initial construction plans to focus on the primary base, HAB1. The design plan follows the scheduled timeline shown below in Figure 2 in which Phases 1-3 will initiate. Phase 4 follows through once the main elements of the lunar base have been constructed and maintained (~2040). These are planned missions, mostly consisting of the NASA Artemis programs, that will be critical in constructing the initial habitat designs and studies on the lunar surface. In the next 5 years the Artemis programs plan to return astronauts back to the Moon, and in 10-15 years' time they hope to establish a human presence on the Moon. Our proposed designs will be integrated with the Artemis missions to expand on their construction of the Artemis Base Camp. This will help build the foundations of a settlement or base for an initially small community, rather than a lunar village or city.

- Phase 1 - Research: Imaging, utilizing CLIPS and CUBESATS
- Phase 2 - Gathering: Human crew members collect data, harvest regolith, materials, etc.
- Phase 3 - Construction: Begin establishing first platforms of the base, autonomous robots
- Phase 4 - Expansion: Maintain base, increase capacity, follow-up lunar studies

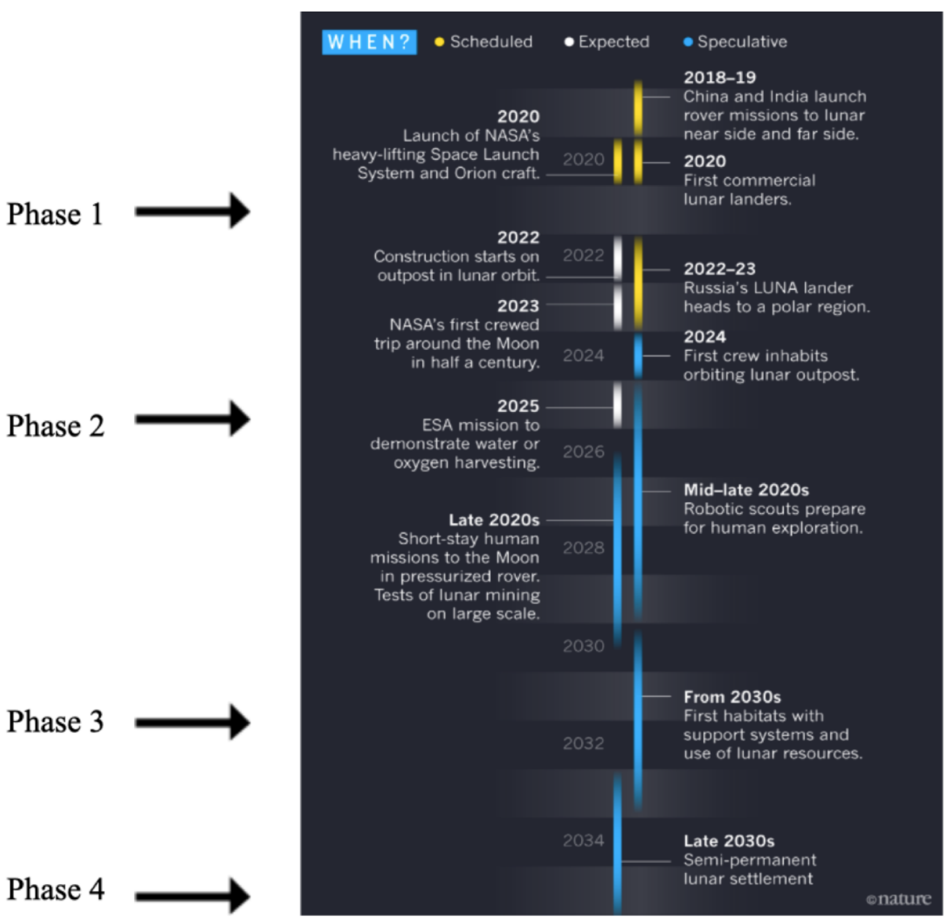

Figure 1: Scheduled, expected, and speculative timelines for Moon exploration (1)

Earth vs Moon

In designing the lunar settlement, it was very important to define the differences between the Moon and Earth and challenge in order to brainstorm solutions. The Moon has many key differences to our planet regarding the living capabilities, but it also has many key similarities which makes it a suitable testing ground for further exploration class missions (ECM). The main differences are listed below:

- Gravity - 1/6th gravity of Earth
- Radiation - more exposure to galactic cosmic rays and solar flares
- Atmosphere - different atmosphere and environment (lunar dust)
- Communication - fast local communication, 2-3 day return
- Travel - small volumes, 2-30 day return to surface (~14 day)

Architecture

Architectures on the Moon must consider a habitat that can sustain itself in an extreme environment, as well as one that has resources that will be helpful for maintenance and urban development at growing scales, so the planning at the initial stages will generate a favorable expansion in a distant future. Currently the International Space Station (ISS) is established as our settlement in space, which contains a small population of inhabitants and a small habitable volume (maximum 13). Aside from the ISS, we have yet to create any environment that can sustain life in the long-term, one that is specifically not in orbit. It is critical to ensure that the structural integrity of the lunar base is durable and maintained over a long period of time. The gravity on the Moon is weaker than that on Earth, being about one-sixth of its strength. While this weaker gravity makes it more difficult to dig underground due to the stronger opposing reaction forces, it also allows for long-span structures.

Two Bases

The structure of our design for the lunar base will consist of two separate bases, each critical for the survival of the crew and for the establishment of a long-term colony on the Moon. The purpose of having two bases utilizes the key advantages of their respective locations, which overweigh the disadvantages of constructing more than one base. As the Artemis Base Camp establishes itself, Lunar Habitat 1 will be the first construction site as the primary base. For every 4 astronauts, they would require 93 square meters, and therefore, HAB2 would require roughly 200 square meters, and HAB1 would require approximately 250 square meters.

- Lunar Habitat 1 (HAB1) - Equator (Oceanus Procellarum)
    - Primary base, settlement headquarters
    - Proposed to be inhabited by 8 astronauts and 4 tourists.
    - Modules:
        - Ground level (Major Module): astronaut reception space, dormitory (12 individual cabins), restrooms, recreational room, and gym. Greenhouse module connected externally (x2).
        - Underground level (Minor Modules): laboratory, operations center, medical bay, kitchen, Prosperity Room (activities for tourists, mini-museum, video streaming, etc.)
- Lunar Habitat 2 (HAB2) - South Pole (Shackleton's Crater)
    - Secondary base, research center
    - Proposed to be inhabited by 8 astronauts.

- Modules:
  - Ground level (Major Module): dormitory (8 individual cabins), restrooms, recreational room, and gym. Greenhouse module connected externally (x2).
  - Underground level (Minor Modules): laboratory (x2), operations center, medical bay, and kitchen.

Site Selection

Equator

HAB1 will be located along the equator of the Moon, specifically in a region within the Oceanus Procellarum (the largest maria on the Moon). In this location constant satellite communication can be reached and maintained, ensuring the best communication between the primary base of the lunar settlement and Earth. On the equator, it is also the easiest for incoming spacecrafts to land and outgoing spacecrafts to launch, hence why the launch pad is located closer to HAB1. This further reinforces that HAB1 will be an ideal location as the main point of contact as the lunar base's main headquarters. While power will be difficult to sustain during lunar nights, our photovoltaic arrays counteract this hurdle (1). Also, the region is rich in Helium-3, a rare element on Earth and a key material for nuclear fission, making it a useful resource to mine (2). The main three factors used in selecting the base sites includes; scientific objectives, resource utilization, and operational considerations.

South Pole

HAB2 will be located in the southern region on the Moon, specifically at Shackleton's Crater, near the South Pole-Aitken basin. In this location the sun is almost permanently generating natural light on the horizon, except for brief and predictable lunar eclipses (lit 70-80% of the time), making it suitable to rely on photovoltaic arrays as an energy source and self-sustainable (2) The interior of the crater is permanently shaded, offering opportunities for sample analysis, harnessing energy and establishing the necessary life support systems, as well as on-site resource utilization experiments. Mining the regolith here makes it an essential resource for the building materials needed for the base's construction, also generating useful items. The permanently shadowed craters in the south pole of the Moon are estimated to contain water in concentrations of 100 to 412 parts per million (3); thus, deposits of water ice could accumulate to produce breathable air and rocket propellant for transportation and industrial activities. A main disadvantage for lunar habitability is the need to survive the lunar night consisting of 354 hours, hence why we are suggesting HAB2 to select a high terrain location at one of the Moon's poles. Despite ensuring high terrain in the lunar pole, it is still nonetheless on the dark side of the Moon, and thus will be susceptible to intermittent communication, and landing will be difficult during dark periods.

Lava Tubes

The first consideration were lunar lava tube skylights. These are essentially underground tunnels, once filled with ancient lava, usually located in pits inside impacted lunar craters such as Philolaus Crater. There are several key advantages regarding the habitation of lava tubes. They tackle the critical challenges crewmembers will be faced with on a daily basis; harmful cosmic radiation, sporadic micrometeorites, temperature swings, and launch and landing sandblasting. With no protective magnetic field or atmosphere, the lunar surface is a very volatile environment to live in, but a lava tube may provide the perfect protection against these risks. Through further studies, they may also provide the base with an underground network of tunnels, potentially supplying a safe underground pathway between the lunar bases (4) . The difficulty with moving forward with this concept is that far more research is needed to verify lava tube skylights as a potential site for a human habitat. Despite only being able to physically study Earth's lava tubes at this current time, the use of 3D mapping and simulation analysis is still attainable to better understand the size, strength and structural stability of lunar lava tubes. But until that vital data is collected during Phase 1, we can't move further with it. There is also the risk of seismic activity and thus, discovering methodologies to reinforce the structure of the lava tubes will be critical (5). By Phase 2, if lava tube skylights can be scientifically proven to be a safe and secure environment, then future expansion (Phase 4) will consider the construction of future lunar bases in such locations.

Materials

The design of the base will be smooth, clean, durable, robust, minimalist and self-sustainable. Materiality was a key design criterion that was considered. It was decided that the most viable and lowest cost whilst maintaining function is to 3D print with local materials i.e. from the lunar soil (regolith). Fortunately, the lunar surface is rich in construction material that in the presence of the right equipment could be extracted and transformed into raw materials and goods. In fact, crucial elements that can be converted into metal alloys are abundant on the Moon, such as Iron, Titanium and Aluminum. The Silicone that is necessary for the production of glass, mirrors, electronics and solar panels is also highly present. Lunar Calcium and Magnesium will play an important role by intervening both in the production of inorganic material and biomass (6).
In addition to physicochemical extraction methods, it may also be possible to take advantage from microorganisms such as *S. desiccabilis* as a long-term and low energy consuming process for biomining and leaching elements from the lunar soil. Results of related experiments on basalt performed in microgravity are encouraging and after required optimizations, we envisage the possibility of having a facility where such organisms are continuously fed with a "lunar mud" in order to break it to its elementary composition that we can later collect, separate and use (7)(8).

	A 11	A 12	A 14	A 15	A 16	A 17
SiO_2	42.2	46.3	48.1	46.8	45.0	43.2
TiO_2	7.8	3.0	1.7	1.4	0.54	4.2
Al_2O_3	13.6	12.9	17.4	14.6	27.3	17.1
Cr_2O_3	0.3	0.34	0.23	0.36	0.33	0.33
FeO	15.3	15.1	10.4	14.3	5.1	12.2
MnO	0.2	0.22	0.14	0.19	0.3	0.17
MgO	7.8	9.3	9.4	11.5	5.7	10.4
CaO	11.9	10.7	10.7	10.8	15.7	11.8
Na_2O	0.47	0.54	0.70	0.39	0.46	0.40
K_2O	0.16	0.31	0.55	0.21	0.17	0.13
P_2O_5	0.05	0.40	0.51	0.18	0.11	0.12
S	0.12			0.06	0.07	0.09
Total	99.9	99.1	99.8	100.8	100.8	100.1

Table 1: Average chemical composition of lunar soils at Apollo Landing Sites
(https://ui.adsabs.harvard.edu/abs/1998nvmi.conf...20B/abstract)

Lunar soil as an abundant resource will play a crucial role for shielding manned habitats, not only against micrometeorites and temperature variations but also from space radiations. However large amount of regolith may be needed in order to effectively protect from radiations. In fact, for a circular module size e.g. 8m diameter and

8m in length, roughly 40 metric tons of regolith material could be required to reduce the incident radiation (usually 32) by at least a factor of 2.
On the other hand, many studies suggest that a thick layer of ice or pure solid/liquid hydrogen can be also used as a radiation shielding for extra-terrestrial colonies. In addition the strength and plasticity of ice can be tuned to answer the engineering requirements (atmospheric stress) by adding elements like salts, this concept allows the shielding to also play the role of a storage space for hydrogen/water (9). Consequently, we estimate that the combination of different solutions is necessary to offer an efficient radiation protection strategy, this will be discussed further in the “Radiation protection” sub-section (10).

Modular Design

The habitat must be protected against solar radiation, temperature swings, and the constant bombardment of micrometeorites that the lunar surface experiences. It will also be necessary to combat the internal atmospheric pressure, materials used for the construction of the base will have to withstand dramatic amounts of expansion and contraction in addition to previously cited stressors (1). The structure will need multiple anchor points due to weaker gravity (⅙ of Earth’s gravity). Having several anchors allows to have wider spaces, the type of soil must be considered if deep excavation is feasible or not in order to intervene and identify the number of anchors so as not to raise the cost, the structure and shell must be able to be extracted and expand due to the extreme temperature because we will need to incorporate heating and cooling in different environments.

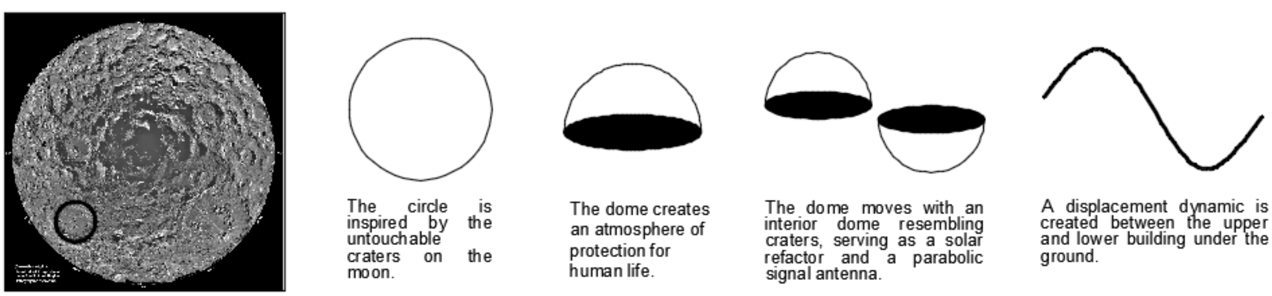

Figure 2: Concept design - project inspiration (own elaboration)

The architecture of the base will be built by the generation of self-assembled modules which will be critical in the gradual colonization of the Moon with different human activities. The adopted shape is a hemisphere forming a geodesic dome. The base at the ground level (Major Module) on the lunar surface is connected with three smaller service modules (Minor Modules) that can be used by other nearby modules, and a module of the same magnitude in the subsoil (Fig. 3). This shape will be replicated containing 8 astronauts per base, occupying an approximate area of 200 square meters. The proposed design will maintain an atmosphere similar to Earth, with two containers, one upper and one lower, which will withstand the pressure conditions and reduce structural stresses (Fig. 2). It is proposed to take the multiple lunar craters as inspiration and attach to the ground. The proposed color is from the lunar regolith and dust material that will be 3D printed
The upper and lower dynamics allow us to carry out the activities proposed for habitability, as well as to have climate control by level, to be able to move clean air from top to bottom, as well as water.

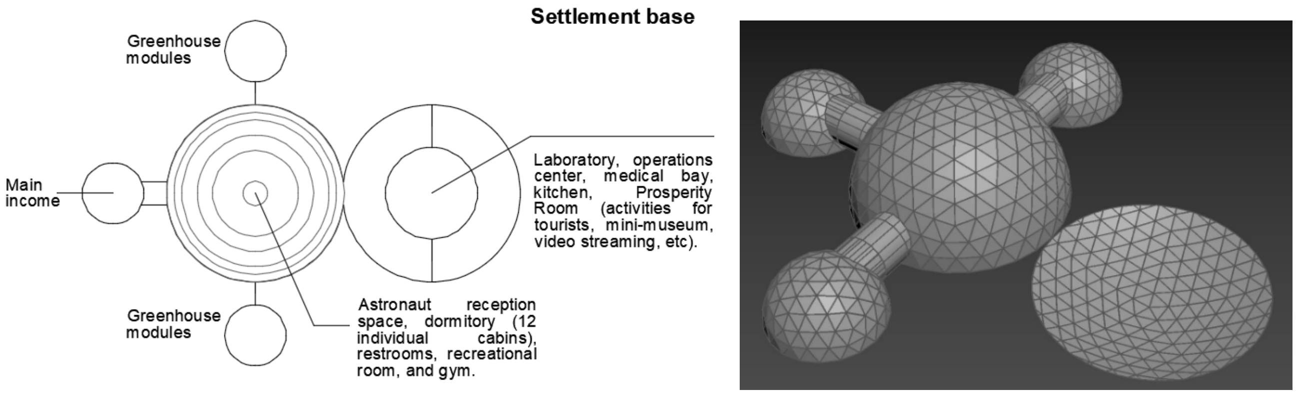

Figure 3: Concept design - distribution of environments and 3D render of HAB1 (own elaboration)

In the surface geodesic dome we will have two layers, the first layer of ice and the second layer of regolith bricks built in 3D, this double layer allows us to protect from radiation and due to this attachment, a superficial shell is created that when anchored to the ground support and provide independence of the interior space, this characteristic allows the building to contract and expand independently (Fig. 4).

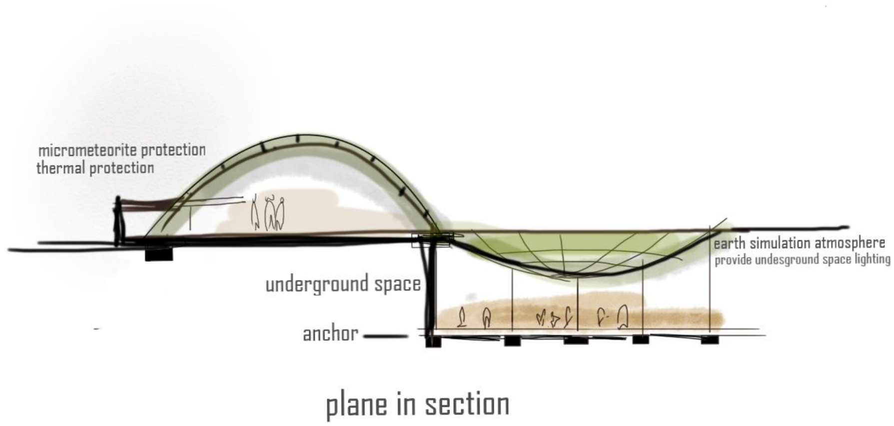

Figure 4: Concept design - plane in section of Major Module connected to one Minor Module (own elaboration)

In the larger module, the airlock adapter is connected on the left side at the main entrance (astronaut reception), that defines the geometry in the form of a tube when entering, then it is passed to the support laboratory, on the second level it contains the individual cabins of the astronauts, the toilets and the recreation area; approximately the occupation area for hygiene of each astronaut consists of 3 cubic meters, 4.5 cubic meters of work and 2.5 cubic meters of free space, for a total of approximately 10 cubic meters per astronaut. In the lower underground module, also on two levels, it contains the dry laboratory on the left side and the main operations center, on the right side the main exploration laboratory, medical bay and prosperity room under the artificial atmosphere (Fig. 5). The anchors of the building (Fig. 4), the columns hold the upper part to the lower part, reaching the lowest level of the building, the beams are concentric in nature because it gives us the greatest opportunity to house various equipment and furniture within the floor level (Fig. 3).

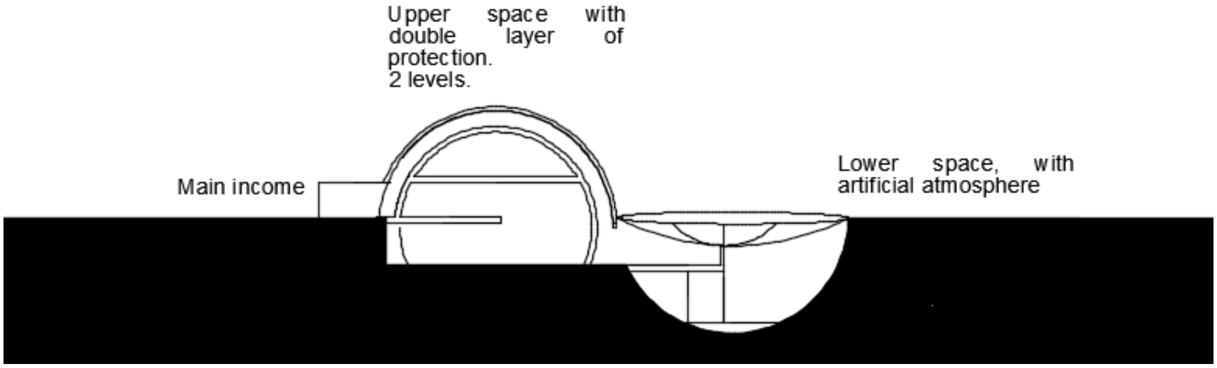

Figure 5: Cross-sectional area of Major Module connected to one Minor Module (own elaboration)

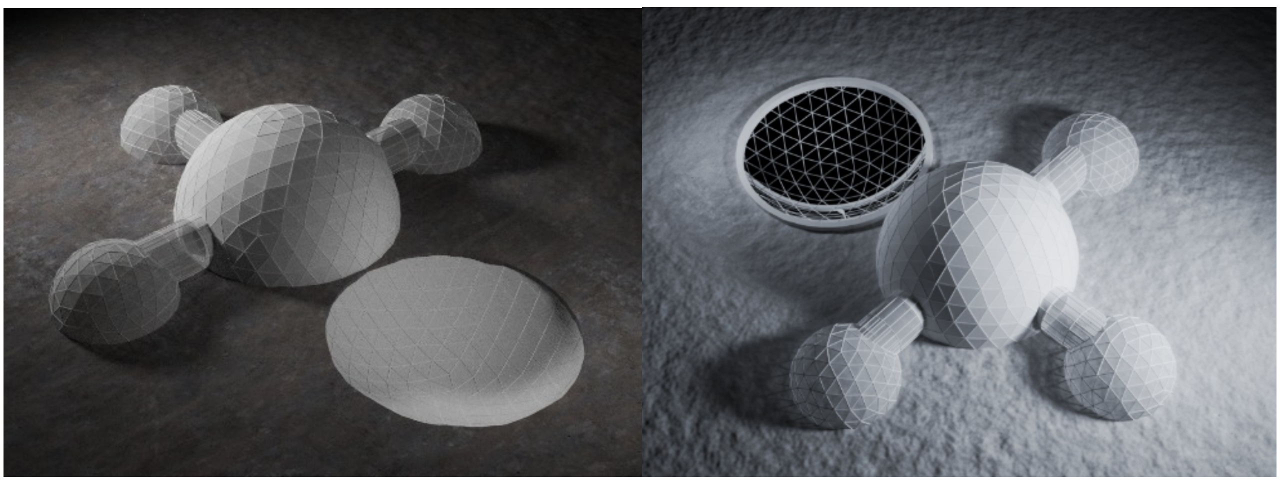

Figure 6: 3D render of architectural volume (own elaboration)

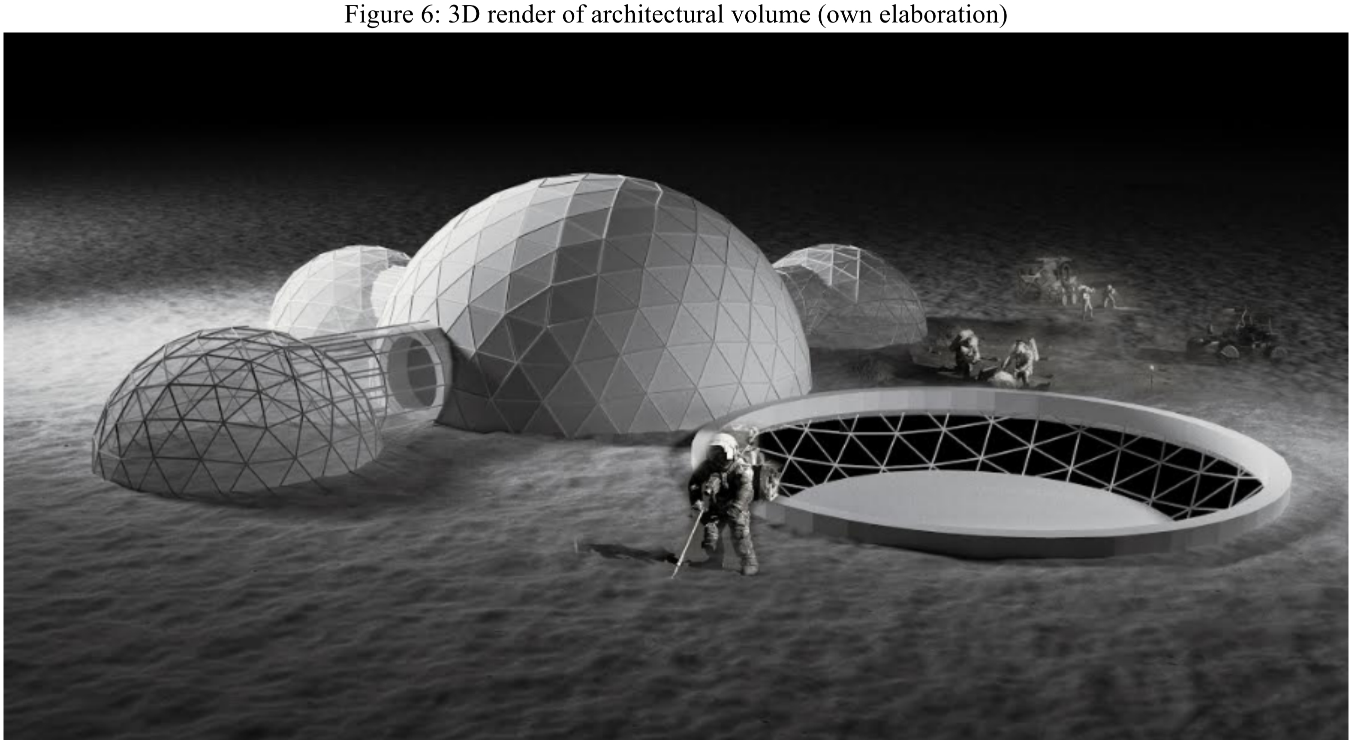

Figure 7: Simulated 3D representation of architectural volume on the Moon (own elaboration)

Safety and Radiation Protection

The lunar surface is directly exposed to galactic cosmic ray particles (GCR) and solar energetic particles (SEP) because it has an extremely thin atmosphere and a weak magnetic field that allows these charged particles to interact with the matter on its surface generating secondary radiation. The effective equivalent dose of GCR particles on the lunar surface reaches 416.0 mSv year −1 and in the case of solar energetic particles it reaches 2190 mSv / event (11).

In general our radiation protection policy is based on the principle of keeping radiation exposure always to the unavoidable minimum. Lunar tourists are informed early in their application process of the risks related to the radiation dose they will inevitably absorb during their space flight and stay on the Moon, tourists wishing to experience EVA must acknowledge their responsibility for the additional deliberate exposure. The technical crew assisting in this kind of touristic activities are also aware of the risks and apply intentionally for such a position. Operations that can be performed by rovers and robots (either autonomous or remotely piloted) are privileged in the decision making process and in the planning of maintenance, mining or exploration activities.

From a more technical perspective, two relatively accessible lunar resources will be used as primary material for shielding the base and its inhabitants from space radiations, we suggest that sensitive sections of the habitats should be positioned under a layer of ice or water consisting itself in a storage or backup tanks for such resources. The second layer of the radiation shield is in contact with the external environment, it is composed of 3D printed interlocking bricks and sheets as suggested by LIQUIFER Systems Group(12). These building materials are produced by a team of robots feeding the lunar soil to a 3D printing machine equipped with solar powered furnaces, a technique that is already at level 5 of technology readiness. We estimate that producing a stock of such bricks and sheets before the establishment of the base will allow a rapid assembly of the outer shell and therefore a quicker shielding of the naked modules once it is delivered. In fact some of the current studies suggest to directly construct this outer shell by progressively sintering regolith straightly on the construction site. However, from our point of view this transition phase will expose the unprotected modules and sensitive equipment they may contain to additional damaging radiations until protective layers are fully deposited over them, as an important quantity of regolith is needed in order to efficiently protect the habitat (from 0,46 to 5 meters thickness)(13)(14).
Therefore for our design, a robotic team previously delivered on the establishment site should stockpile interlocking building blocks for the regolith-based shell. Once our modules are delivered and water (or ice) tanks placed over as planned, the outer shell should be quickly and easily assembled by the robotic team. The outer shell's components are finally sealed together thanks to the same sintering technology(15)(16)

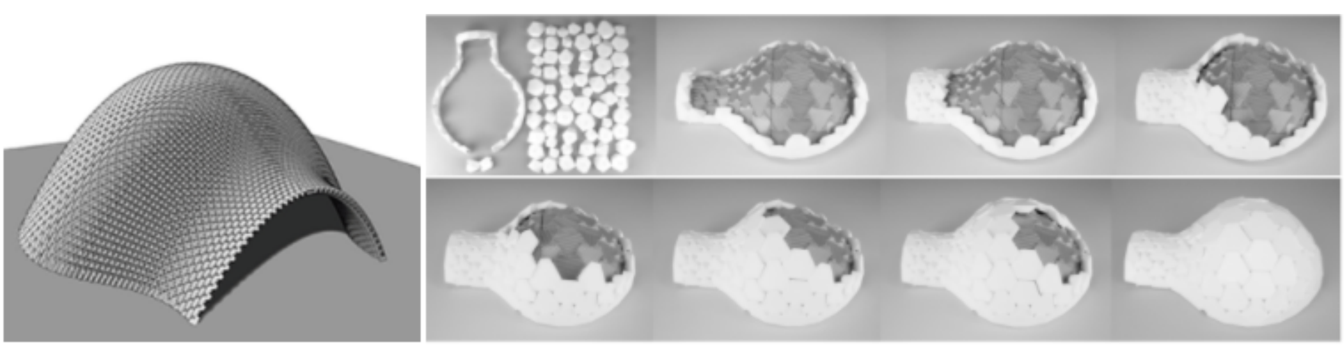

Figure 8: Concept of interlocking bricks construction
https://doi.org/10.1145/3355089.3356489

The design approach we have taken prioritizes in the safety and security of the lunar base's crew. Design specifications, compared to other isolated space-related environments e.g. ISS and analog mission sites, include; faster emergency evacuation procedures, at least two exit/entry points from any one room/module across the base, backup generators closer to the base, quicker access to medical bay/clinic from any room/module across the base, and significant reduction of dangers and risk factors e.g. micrometeorites, radiation, etc. By designing the base to have at least two possible escape routes at any one location at the base during an emergency evacuation due to a gas leakage or fire, it'll allow us to isolate the damaged or breached zone.

Engineering

Space Medicine and 3D Printing

There are some options for robots that can assist with medical emergencies such as teleoperated surgical robots, which have the potential to offer medical assistance both on the earth and in space. In long-distance telementorship, time, cost and effectiveness along with a higher level of medical care provided are several benefits that this medium can provide, while in extreme telemedicine such as space exploration it is one of the few options available for adequate medical help. Telemedicine can be online (in real time) or offline and this will vary depending on the technical quality of the link communication. We are going to see that telesurgery allows doctors to treat patients geologically separated from themselves in an invasive way. Provides instant and unlimited remote access to the medical site which means that the doctor is truly capable of performing operations through robots and others teleoperated devices (17)

Currently, logistics operations operating within the Low Earth Orbit (LEO) system such as the ISS depend on refueling missions from the Earth. In a space mission to the moon, the baseline logistics design requires that the necessary materials be Store in advance at the beginning of the space exploration mission, but as it is a long-duration mission, a large amount of materials will be required to be transported, which could pose some limitations, due to this, manufacturing materials to order during the space mission It would reduce costs, payload and also reduce risks as well as allow greater capacity to carry material for unforeseen needs on board. The medical materials to be produced at the lunar base must be differentiated into emergency materials and for non-emergency events considering that the limitation is in the response time of the 3D printing system (18).

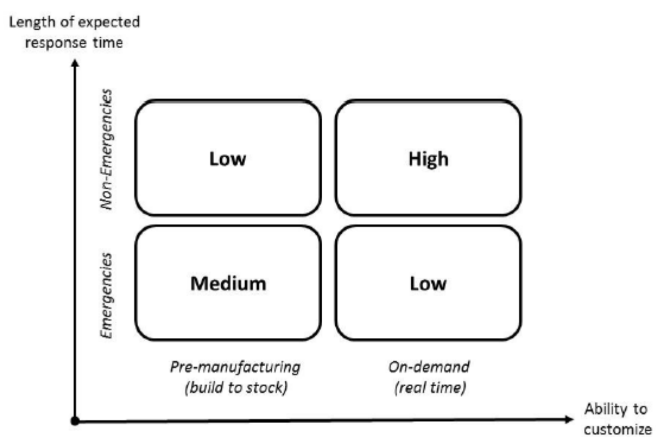

Figure 9: Potential impact of a 3D-printing supported response to in-flight medical events

Carrano AL. Selected On - Demand Medical Applications of 3D - Printing for Long - Duration Manned Space Missions. 2017

Non-emergency Events:

- There is little information on non-emergency events during space flights due to the rigorous selection of astronauts with a careful medical evaluation, but being under the effects of microgravity for a long time can condition several physiological alterations generating potential risks for the preservation of health (18).

Applications	Examples
• Dental	Crowns, abutments, bridges, drill guides, aligners, bite guards.
• Orthotics and prosthetics	Flexible splints, calipers, braces, custom casts, foot inserts.
• Ear	Specula, custom hearing aid shells.
• Pharmaceutical drugs	Custom compounded, quick dissolving tablets.
• Medical instruments and utensils	Tissue forceps, clamps.
• Vision	Contact lenses.

Table 2: Potential applications of 3D printing for non-emergency medical events

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Emergency Events:

- Over the years there have been 17 non-fatal emergencies in the general areas of trauma, cardiopulmonary, internal medicine and genitourinary in manned space flights. With an emergency incidence rate of 0.06 event per person / year, but due to strict medical evaluation, this rate is unrealistically high. There are medical risks and conditions associated with the microgravity environment including radiation and toxic gas exposure, increased risk of fractures and dislocations due to bone demineralization and confined spaces, muscle and ligament injuries due to muscle atrophy, possible blunt injuries and penetrating during EVAS, infectious diseases due to confinement, among others (18).
- 3D printing technologies can support the following:

Orthopedics for trauma	Aluminized flexible splints (capable of adapting well to the astronaut's anatomy and specific to the type of injury) For invasive procedures, orthopedic implants are considered as hip replacement cups or cranio-maxillofacial plates with designed porosity(18).
Advanced cardiac and trauma life support	For medical resuscitation events, one of the most common advanced life support procedures involves inserting a chest tube. Devices that support such an advanced feature as a laryngeal mask could potentially be manufactured (and even customized) in anticipation of these events with 3D printing technologies(18).
Surgical instruments	Scalpels, clamps, and hemostats, among others(18).

Table 3: 3D printing technologies supporting emergency events

Environmental Control and Life Support Systems

The Environmental Control and Life Support System (ECLSS) is a technology that allows a living being to survive outside the environment it is physically adapted to. It is what offers humans the possibility to wander in deep oceans or far into space, away from the familiar surface of our home planet. It is therefore one of the most important aspects of all manned space missions. These systems are required to adjust temperature and pressure, to protect from radiations, to produce oxygen, and to recycle CO_2 and moist, in addition to filtering waste and contaminants.

Oxygen and Water Production

At the design stage of any inhabited space endeavor, NASA Ames Research Center advises to follow this general rule: "*The longer the mission, the more the life support system should use recycling and regenerable technologies*". In our case, we assume that in the permanent lunar base, a crewmember is assigned for a minimum of a six months shift. Consequently oxygen consumption will represent no less than 150 kg/person. When minimal requirements for hydration are added to the equation, essential resources increase to 788 kg/person and based on ISS estimations: one crewmember's hygiene and cleaning routine will consume around 1600kg of a total mission's water stock. It is clear therefore, that to be integrated in our lunar design, the technology for supporting the life of a 20 persons' team must be capable of producing and processing in a safe, reliable but sustainable way at least 48 tons of basic resources for every six month mission (19).

Standard crewmember needs	kg
Oxygen	0.84
Food solids	0.62
Water in food	1.15
Food preparation water	0.76
Drinking water	1.62
Total oxygen, food, and water mass	4.99

Table 4: Standard crewmember oxygen, food, and water needs.
https://ntrs.nasa.gov/citations/20040012725

It is assumed that a system (be it on an extra-terrestrial surface or on a spaceship) capable of growing half of its food requirements through photosynthetic plants (or algae) will also be able to offer enough oxygen for sustaining the life of the crew and this is where innovative designs such as Controlled Ecological Life Support System (CELSS) or Bioregenerative Life Support Systems (BLSS) find their application.

For the lunar permanent base, we estimate that a system combining the bioregenerative technology to physicochemical processes such as Zvezda coupled to Elektron or OGS/Sabatier represents both a reliable and sustainable solution (20).

BLSS technology has been continuously improved during the last twenty years, the MELiSSA project for example has currently a 10 years operational pilot plant composed of a closed loop able to produce the required oxygen for one person and to recycle organic waste into edible biomass that covers 20% of its needs (21).

Therefore, in our lunar settlement advanced BLSS are implemented progressively in the main base (HAB1, the primary base) for all sectors of secondary importance (such as corridors, halls, recreational spaces, kitchen, labs, workshops, offices, storage areas, etc.) while critical areas (such as command and communication office, sickbay, dormitories, etc.) are connected to regenerative physicochemical ECLSS. From the perspective we have taken, in the case of a disaster, sensitive areas such as aforementioned should always be able to function at full capacity and thus be equipped with a technology capable of immediate recovery following repairs. This way crew safety specifications are met and at the same time, at least 20% of the lunar base's food needs can also be produced (22).

The base is also equipped with back-up reservoirs where oxygen and hydrogen are stored for emergencies in addition to backpacks tanks of breathable air placed for example at regular intervals within corridors' walls and airlocks.

Resupply

In order to compensate for eventual losses or base expansion and new arrivals, resupplies in water and oxygen are considered. This should occur primarily through the transformation of lunar ice and secondarily through incoming commercial or governmental landers. For almost the same reasons, a resupply in nitrogen (essential for the ECLSS to produce an air breathable for Humans) must also be planned in collaboration with the incoming traffic. In fact, the recycling process may be unable to meet the lunar base's needs and we cannot mine this element on the lunar soil due to its very poor nitrogen content.

As we progress from Phase 2 into Phase 3, more valuable data is being gathered before the onset of the lunar base construction. At this stage, autonomous rovers and robots will be vital providing key information regarding the lunar ice caps and their sustainability. There's strong evidence that permanently shadowed regions of lunar craters such as Shackleton's Crater contain water ice from comets that have previously impacted the Moon. This water will be good for drinking, cooking food, bathing, making concrete, and splitting into oxygen and hydrogen for rocket propellant (8). In our proposed design, located within the permanently shadowed craters are the readiest source of hydrogen and oxygen. Rovers with specially-designed mirrors, inspired by the technique used by the Norway town, Rjuken, will channel sunlight into the craters at the correct angles depending on the crater's topography and ice cap location, and heat the ice. This methodology is a proven technique that will be highly effective for this function. With the focus of the sunlight onto the ice surface, an overhead dome would capture water vapor. Harvested condensed water from ice caps or ice-filled regolith would be processed further by first being shuttled to a processing plant to split the water into hydrogen and oxygen by solar electricity. The gases produced could then be used for three purposes - either stored and used as propellant, be used to supply energy to fuel cells, or used as water. For water, rovers would use wirelessly-powered internal ovens to heat up ice regolith by training high-power lasers onto photovoltaic cells on the rover, and as a result release water (1).

Power Supply

The power supply in our design proposal takes inspiration from the Apollo studies and Artemis strategy, as well as the current energy systems in the ISS. In terms of power consumption, the ISS requires 75 to 90 kilowatts to function, but it generates more than it needs - up to 120 kilowatts, for a maximum crew capacity of 13 persons. For a crew of 20 persons on the lunar base we have planned for a system that can provide something from 140 to 200 kilowatts at a minimum. Depending on the design approach of the station, we considered whether or not we will be minimalist like the ISS or more comfortable meaning more pressurized space and more accessories, etc. In addition, also transport vehicles can potentially be relying on the station for charging their batteries either for locomotion or for their own ECLSS. The ISS uses lithium ion batteries for every 30mins (23).

Next-door to each base, along the equator (HAB1) and at the sunlit poles (HAB2) of the lunar surface, we will have a set of photovoltaic arrays to supply the base with electricity. They are lightweight and modular, but the disadvantage is that there is no sunlight on the Moon for 14 days at a time. Hydrogen fuels cells will be critical here to counteract this during the nights, but they in turn require energy storage systems which can generate unwanted mass. Considering this, photovoltaic arrays is still the most optimal solution to power the lunar base against other options. In future studies towards construction (Phase 1-2), minimizing nighttime power usage will be the main objective as this will significantly reduce mass. As a reserve power supply, initiated following the construction of the base (Phase 4), HAB2 would be powered by a nuclear fission reactor during the lunar nights. Due to its location, HAB2 is prone to Space Nuclear Power and Propulsion (SNPP) systems are safe, reliable, and efficient. This is due to being able to continuously power and have low mass at high power (24).

Resources

Local Production

The design proposed through the research facility, Yuegong-1, a Chinese lunar analogue-astronaut base, successfully allowed the crew of 3 persons to rely on half of their food needs on a vegetation area of $58m^2$. They grew 5 types of cereals, 15 different vegetables in addition to mealworms as their primary source of proteins (25) .Consequently, a $386m^2$ underground or sheltered surface could be considered for an optimized vegetation area in our lunar base. It will be expected to not only produce a significant part of the crew's nutritional needs, but will also contribute to improve the quality of life inside the station by providing rare fresh and crunchy produce in addition to green spaces. Green areas have proven numerous beneficial effects on our mental health, reinstating itself an essential feature for long-term space missions where astronauts will experience extreme isolation, routine and discomfort (26).

In the near term, plants such as lettuce and spinach are one of the best candidates for our vegetation area due to their relatively short growth duration (28 days) and high harvest index (nearly 90%). Radish, chard and red beet are also potential considerations(27). Considering the specificity of our lunar base, which has a relatively small crew capacity, the cultivation of plants such as potatoes, wheat, beans, etc. (needed for their rich content of protein and carbohydrate) for daily consumption is not a priority as it will be easier to obtain these ingredients in dehydrated powder format more adapted for long-term storage, gradually reducing to the essential the food processing steps and related technical requirements.
Both lunar bases (HAB1 and HAB2) are equipped with a sheltered greenhouse known as the Food Production Facility (FPF) which will be used to grow and study vital crops. This will include a variety of rooms each with a specific function. One is the Vegetation Room holding our aeroponic platforms that sustain the plants arranged in multi-racks or vertical towers systems. This allows easy access during maintenance or harvest and also maximizes the use of resources and available surface (28). This vegetation area is semi-automatic and requires low human supervision, in addition it is assisted by AI that is capable of adapting in real time the environment and nutrition to the plant's stage of development. It notifies the crew on unsolved issues, stocks and time for harvest or maintenance.

Figure 10: Aeroponic platform
https://www.tandfonline.com/doi/full/10.1080/17429145.2018.1472308

Sharing the lunar greenhouse spaces will also be the Mycelia Factory room. Here, specific food products such as mushrooms and yeast which are excellent versatile nutritional resources will be given a dedicated space. Growing relatively quickly and easily, and occupying low surfaces they have also shown to perform even better in low gravity, reinforcing thus their suitability for our base (29). These organisms produce 100% edible biomass providing all essential amino acids in addition to many vitamins and even lipids (ex: *Yarrowia* and *Lipomyces*) (30). Therefore, to grow mushrooms we plan to set up a platform closely similar to the one used for our plantation produce, based on facilitation equipment to optimize their growth called Mushroom Walls, as seen in Figure 4. As for yeast, Figure 5 showcases what a group of 10 liter-bioreactors will look like as they will be needed to enable the fermentation process. They are expected to produce in 24 hours 60-100g of dry yeast each. Both the Mushroom Walls and the bioreactors will be based in the Mycelia Factory room (31)(32). In addition, we assume that in the near future meat-like (sulfurous and carbonyl-containing volatile compounds) or fish-like flavors and smells (trimethylamine oxides, hydroperoxides, carbon volatile compounds) (33) could be produced locally by enzymatic reactions or through genetically modified plants and microorganisms. This will help in diversifying and enriching the menu of the crew.

Figure 11: Mushroom Wall prototype design

Figure 12: Yeast bioreactor production unit

https://groundcondition.wordpress.com/2012/06/26/urban-vertical-mushroom-farms-at-arcam-food-and-architecture-fair/

Resupply

The transportation of dry food is by far easier and cheaper than frozen or liquid forms and this is especially valid also in space. In addition, dry food can be stored for longer periods and due to its dehydrated nature, it is less affected by radiation damage. Consequently, our food system is largely based on dehydrated and powdered nutritional material partially produced in the base (yeast, micro algae, etc.), to which resupply from Earth is also expected but kept to the minimum (such as powders of cereals, sugar, nuts, freeze-dried juice, fruits, coffee, etc.). Locally grown fresh elements such as vegetables and mushrooms complete the nutritional needs of our crew.

Food Processing

Astronauts are highly qualified staff expected to operate in remote and hard conditions for the sake of cutting edge science or highly important business projects. Their time is valuable and should be optimized and focused on the main technical tasks. Therefore, the food processing system is designed to operate with minimal human supervision, utilizing autonomous technological systems. Lunar base kitchens will be equipped with a set of 3D food printers that use powdered elements such those cited previously as bioink, this will help lunar settlers enjoy a variety of meals in addition to tuning it to their nutritional needs (correct deficiencies or excess, required calories, etc.). These programmable machines can autonomously print then cook items such as pasta, pizzas, cakes, burgers etc. This 3D food printing facility will be located in the kitchen of both bases, HAB1 and HAB2 (34)(35).

As the lunar base evolves from Phase 3 to Phase 4, the range of food produce will increase and diversify. This is very important for the crew's mental health, especially because the crew is there for a long period of time. Today, on the ISS, almost any basic food option can be provided for an astronaut and be maintained in microgravity, so these will be similar capabilities in the lunar greenhouses, but in lower gravity conditions. The growing diversity of the menu will also specifically appeal to the demand of space tourists visiting the site.

Vessels

Prosperity Lunar Station will have one landing bay which will act as the settlement's traffic control facility close by to HAB1 at the equator of the Moon. Whilst having a landing bay for each base would be convenient, it'll be unnecessarily costly beyond budget to build two at the initial stages of the Prosperity Lunar Station. Assuming future expansion (Phase 4), a secondary landing bay will be developed directly at HAB2 at the south pole. Following the construction of HAB1, HAB1 will be the point of contact to supply resources and equipment for HAB2, with a fabricated lunar roadway between them for ease of travel.

ISS

The year 2020 marks the 20th anniversary for the ISS. The station is set to retire around the mid-2020s as it completes its scheduled function, but will be crucial in its future function as a highly utilized lunar orbiter platform. Here, this transition will be very important as the ISS outpost and staging post to transport rovers, etc. to the lunar surface, through the support of NASA, ESA, and JAXA, amongst others, including private companies(1). A key rover, in particular, is NASA's Volatiles Investigating Polar Exploration Rover (VIPER) which will be very important to reconfirm the H2O molecules found on a sunlit region of the lunar surface by NASA's Stratospheric Observatory for Infrared Astronomy (SOFIA). Following further observational flights, VIPER's role is to create the first water resource maps of the Moon for future human space exploration (36).

Gateway

Gateway will be very important in contributing to the developmental process to build the lunar base and beyond. Even crewless, it will still be maintained and operate remotely. Early Gateway science payloads will include using ESA's ERSA and NASA's space weather instrument suite, HERMES, to monitor fundamental data on solar wind and solar particles. Both systems will help us learn how to keep crew members safe on the lunar surface by providing a better understanding on the risks of solar flares and radiation exposure in Gateway's orbit (37)(38) .

Surface Vessels

In terms of local transportation on the lunar surface, we investigated the idea of hyperloop technology, but found this to be unnecessary and highly expensive to install, despite the reduction in travel time between bases and landing sites. Lunar Rover Vehicles will be effective and sufficient for transportation between sites. Aside from this function, specialized lunar rovers will be vital for astronauts to study the lunar atmosphere and surface, amongst other research investigations, including the Moon's geological history in order to learn more about the early conditions of the Solar System (39).

CUBESATS are very useful miniature systems used for over a decade, originally for remote sensing and communication activities in LEO. Microbial growth and crop systems can be made on the Moon but not without some challenges. They suitably abide by the goal to obtain a small self-contained environment, also known as a Lunar Plant Growth Experiment (LPX), and CUBESATS are great examples of these. The key objectives for local production on the Moon includes; germination, phototropism, and circumnutation. In the next 5-10 years, currently two small lunar landers, Commerical Lunar Payload Service (CLPS) as part of Artemis program, have been chosen to be transported (Astrobotic and Intuitive Machines). These landers will carry LPXs and will be critical to introduce the first set of lunar astrobiology studies for crop growth, aside from those already executed on the ISS, but the disadvantages of the lunar landers need to be considered. They are small, low powered, and are susceptible to the very hot temperatures of the Moon, and thus, the location where these CLPS land on the lunar surface will be critical towards the longevity of these experiments (40)

Economic Considerations

Financial Feasibility

There is a steady growth in demand to build a lunar market from a variety of different industries. Medical researchers, for instance, seek to better understand how the human body responds to extended stays in low gravity. Planetary scientists want to study the Moon's composition and topography to learn about Earth's origins. Astronomers desire to build radio telescopes on the far side of the Moon. Explorers want to test equipment or produce propellants for journeys to destinations beyond the Moon(1) . With the onset of SpaceX's development of their Falcon 9, they have successfully been able to reduce the cost per kg and per launch more than their competitors due to its efficiency and reliability as a reusable rocket. Innovative methodologies to get payloads into space at a cheaper price such as this will be encouraged and utilized in order to lower the overall cost of commercial spaceflight. Previous estimates carried out by NASA for their Moon base project calculated the investment will cost \$20-\$30bn. CSIS 2009 estimated the cost of the development of the lunar base at \$17bn for a four person crew plus the cost of transporting the required cargo and return(41).
Using these precedent calculations, our top-down assumptions for the cost of constructing the two lunar bases are of the same order of magnitude. Note, we have not included a bottom-up BOM or other estimates as we will not achieve sufficient accuracy at this early scoping stage.

Our crew is required to be 7 times larger than the CSIS conceived base. However, CSIS estimates are based on bringing all of the required materials from earth to construct the base. Whereas our plan is to partially 3D print the structure using lunar regolith and to use the lunar lava tubes. The first point will reduce the amount of material required from Earth and the second will reduce the requirement to build structures from scratch. Our assumption is therefore that we will require a similar investment level to the CSIS project.

Sustainable Cost with Earth Supplies

Hofstetter et al have estimated 4.4 metric tons (mt) of supplies per crew member per annum on a lunar base (41). We have a crew capacity of 20 (max 30), including lunar tourists, but on average if the crew is 25 members, this is approximately 110mt (110,000kg). We have assumed that in the first 5 years of the base, the transportation of cargo, although the most costly, will be trips to and from Earth rather than a LEO or Lagrange point handoff. With this approach, for every kilogram of cargo, ~3.7kg of fuel is required. The total weight (cargo + fuel) for the resupply missions would be ~500mt.

With a current ~$4500/kg to LEO cargo cost (Falcon 9) (42) and $5,620 to GTO (Falcon Heavy)(43) , we will take an optimistic estimate of the per kilo cost using the Falcon 9 LEO per kilo cost, on the assumption that in the coming ten years the per kilo cost will from Earth to the Moon will drop. Under these assumptions, the cost per annum of supplying the lunar crews would be $2,250,000,000 to transport the required supplies to the crew. SpaceX Falcon Heavy can carry 26,700 kg to GTO (geostationary transfer orbit) and 16,800 kg to Mars(43) . Our assumption, based on the carry capacity to GTO, is that ~19 trips will be required to and from Earth. The return capacity from the Moon back to Earth will be less depending on the return vehicle design, but the fuel requirements can be satisfied by the resources mined on the Moon.

Tourism Opportunity

How can space tourism be a valuable resource to sustain lunar travel? Based on the above calculations, the cost to sustain one crew member position for the year is $90M. With the ~19 trips per year to the lunar bases from Earth to resupply the crew, there is an opportunity to subsidize each trip with tourists. A 30 day trip to the ISS has been priced at ~52M USD - the journey to the Moon is significantly further than to LEO, but aside from the initial launch and return costs, the cost of the trip is keeping the tourist alive and comfortable (44). We would estimate that the price of a 30 day trip to the Moon would cost a similar price, or at least at a similar order of magnitude within the next 10 to 15 years.

With a Moon tourist to crew ratio of no greater than 6 trained astronauts to 1 tourist, the Moon base system would support at most 5 tourists. However, as a majority proportion of the astronauts will be located at the South Pole base, it is likely the greatest number of tourists at any point in time is two in the equatorial "Earth View" base. On this basis, operating at 100% capacity (2 tourists at any one point), the annual income from Moon tourism is ~$1.25B per year. The cost of sustaining these tourists is approximately $180M, and so there would be ~$1B surplus from tourism. There would also be supplemental tourist income from the required training and other related tourism opportunities such as lunar base simulacra on Earth which could be operated to cater to the mass market.

Generating Income through Lunar Resources

Lunar mining promises to be a fruitful vein of opportunity. Much research and speculative calculations about the possibility of mining rare metals and Helium 3 to send back to Earth and on to subsequent outposts in the solar system(2) .We have not included such economic forecasts in this report, though as expressed above, we recognize the need and the opportunity to mine the lunar ice for fuel. According to Sowers (1) a profit could be returned by mining around 1,000 tons of ice and electrolyzing it into oxygen and hydrogen. The cost of sending lunar mined materials back to Earth or to outposts beyond is markedly cheaper – approximately $1/50^{th}$ of the price sending the return fuel from Earth (1).

The ISS National Lab (ISS NL) commercial research model provides a helpful precedent for the viability of commercializing access to a unique laboratory. Since opening commercial research opportunities to the US economy, the research conducted on ISS NL has contributed to an incremental $900M to the US economy alone and "open[ed] up more than $110 billion in addressable markets" (45). With a larger crew and a more diverse set of research opportunities, we estimate research contracts will contribute a surplus, although not as significant as the premium tourist experiences. In addition to mining and research, there is an opportunity to utilize the Moon's microgravity environment for the manufacturing of exotic materials to be brought back to Earth.

Unique Content

The lunar surface will provide the most dramatic scenes mankind has ever seen. With the rise in camera technology in the 50 years since humankind last stepped foot on the lunar surface, the opportunities to create an untold amount of "mind-blowing" content is unimaginable. In this way, our lunar base design will leverage access to the most unique content in our Solar Systems. We anticipate that there will be unprecedented demand for access to TV and film content with the purchase of certain rights, such as fly-on-the-wall content and documentary content will be able to conservatively generate towards $500M per year. For reference, the TV rights to broadcast a live Premier League match in the UK is ~£10M per game to the rights holder and per year is worth over $5BN (46). Tottenham Hotspur were paid by Amazon Prime Video a reported ~£10M for the rights to record a fly-on-the-wall documentary series for a whole season (47). There will also be other opportunities for unique content in the gaming industry for the mass market as well as at the premium end, such as remotely controlling rovers and drones on the lunar surface.

Society and Culture

Building a lunar base represents a great challenge. Conditions on the lunar surface are extreme with a rotation period of 28 weeks, which would imply two weeks of light and two weeks of darkness. The Moon lacks a significant atmosphere to be able to distribute the heat from the sun which ranges from -180 degrees Celsius at night to 214 degrees Celsius during the day, except at the poles where the temperature is constant. The problem of temperature and of the extensive diurnal and night cycles imply a great problem to locate a lunar base dependent on solar energy or cryogenic storage. Therefore, a place where these great problems could be avoided is by locating the lunar base at the lunar poles where the temperature is constant. Therefore, the location of a lunar base in an area polar could obtain energy in a continuous way by using mirrors or collectors that rotate slowly to follow the sun. These are some important aspects before considering taking humans to the Moon and forming a society. What needs to be considered is that the duration of day and nights are different to those on Earth, as well as the temperature conditions. Adding to this, the individuals travelling to the new colonized site will no longer be on their home planet which can play a very important role in the psyche.

An important part of being able to take humans to the Moon and be able to form a society in this environment, is to ensure that their life is not monotonous. Considering that they will also carry out periods in isolation this could lead them to states in which they can feel lonely, anxious and sad, culminating in a potential depressive disorder. Due to this, it is important to develop activities that boost the crew's creativity such as painting, music, poetry, and singing. Other useful activities aimed at maintaining a balanced mental and spiritual state include meditation and consistent sleep patterns. The crew's life must be entertaining enough to be able to weigh the long periods of confined isolation to which they will be exposed, away from the developed Earth they once would have lived on. Consistent satellite communication with Earth will also vitally contribute to this effort. This strategy will take place from Phase 4 onwards, and will allow the lunar base to prioritize function alongside form, ensuring a suitable habitat for humanity.

The lunar base will be a habitat destined to sustain human life in extreme conditions. The architectural design will have a great impact on the health of the inhabitants. Coexistence spaces should be created that allow breaking the bubbles of loneliness and isolation that future inhabitants of the Moon may face and if it is possible to introduce or decorate spaces that emulate nature within the lunar base. Likewise, colors and light can be used and correctly used as therapeutic tools to promote mental well-being and at the same time create a warm place. The relationship that the environment may have with the human being through visual stimuli will play an important role in the astronaut's physiological reactions. The best case scenario, this would generate a positive reaction, low stress levels, and a balanced psychological mood(48).

Astronaut analog missions such as HI-SEAS and the Antarctic Research Station will be critical to simulating planetary investigations and studies, but will be even more critical in the next decade as they'll be used as a test bed for space tourists who plan to stay at the lunar base for longer periods of time. It'll also ensure strict screening and training for tourists embarking on these journeys. There are key lessons that can be learnt from these functioning remote bases on Earth prior to Phase 3, testing mental health, confinement, isolation, limited luxury, day-to-day base maintenance, and scientific experiments, etc. (49)(50).

In terms of size of the crew, the designated figure was between 10 and 30 persons, and our design proposal suggests the initial team to set up and maintain the base will be a size of 20. There needs to be sufficient crewmembers to maintain the safety of the base and crew whilst still executing the scientific or commercial duties. From 2001, on the Mir Space Station, which held the first commercial space flight, the first tourist traveled with a supervising astronaut. The first set of space tourists aboard a spacecraft was successful. We plan to extrapolate this by ensuring the tourist is trained thoroughly, assisting in the maintenance of the lunar base, but also will be able to rely on the expertise and experience of astronauts who will supervise them as they carry out their designated duties. The ratio of astronauts to tourists will be 4:1. Therefore, for a 20-person crew, 16 will be astronauts and 4 will be tourists. Half of the team of astronauts will go to each base; 8 astronauts settled in HAB2, and the remaining 8 astronauts with the 4 tourists in HAB1(51)(52).

Management and Politics

At Prosperity Lunar Station, how the lunar settlement will be governed, is a key consideration to explore for future missions to the lunar surface and beyond. The development of the Prosperity Lunar Station will create a human settlement that will be an international commercial center of exploration excellence. It will represent the innovation of Earth. In this way, whilst the distance between Earth and the Moon is large, the connection will remain strong. For all astronauts, tourists and inhabitants on the Moon will have to go through several checkpoints on Earth before embarking on their journey. Passengers must have a Lunar Passport which entitles legal eligibility to travel to the Moon. Gateway or future lunar orbiters will act as another form of station-border control. Policies and Law on the Moon shall continue to run under the United Nation's Committee on the Peaceful Uses of Outer Space (COPUOUS), following the (1976) Outer Space Treaty. A General Assembly by the UN will be conducted every 5 years to review & follow-up on its rules and whether to expand or not. All nations (governmental bodies) that would want to share access upon the Prosperity Lunar Station will therefore be required to sign in agreement with the terms & conditions of The Outer Space Treaty. It states that: Space is free for all nations to explore, and sovereign, individual and business claims cannot be made. All space exploration & activities must be for the benefit and interests of all nations and humans (so nobody can own the Moon nor have any military base there). It is not subject to national appropriation, including that no nation or organization can claim to 'own' the natural resources available on the Moon. Nuclear weapons and other weapons of mass destruction are not allowed on celestial bodies or in outer-space (peace is the only acceptable use of outer-space locations). Individual nations are responsible for any damage their space objects cause and all governmental & non-governmental activities conducted by their citizens. These nations must also "avoid harmful contamination" due to space/lunar activities. The Rescue Agreement gives astronauts assistance during an Unintended Landing or emergency, in which then all nations shall immediately take all possible steps to assist in this case (54).

Conclusion

The design plan we have proposed for the lunar base relies on and complements the trajectory of current commercial and governmental missions planned for the Moon. We have considered the technical constraints and expected design outcomes. This particular design format will allow many scientific accomplishments to unfold. It'll be the first opportunity to perform fundamental research in both unique radiation and partial gravity environments outside of LEO. The locations cited, will be critical to evaluate both short and long-term radiation effects on seed viability plant performance, nutrition and palatability. Since our lunar base design prioritizes microbial studies, prior to its construction and during its early years of operation, it'll enable the demonstration and development of dependable, advanced crop production systems needed for a Mars habitat. It'll also allow the evaluation of regolith compared to hydroponics and soil-less approaches, demonstrating automated crop production technologies in similar environments .

Moving forward, there will still nonetheless be numerous persistent technical challenges that we will need to tackle such as estimating the market shift of the space industry in 20-30 years' time. This is difficult to predict, but it will be consequential without the support of the public and private sector. Other "gray" areas in our design includes the lunar water source and lava tubes which we still have insufficient data on. With the gradual rise in business opportunities that have great promise in the industry, it will unequivocally continue to drive the private sector to stride forwards towards space, but key hurdles will be faced at the expense of this rise. These challenges include the critical regulation of federal governments on space debris, governmental collaborations, and safety.

Further analysis and follow-up studies will continue to be carried out as preparation to colonize the Moon takes place, which will slowly but surely transition into a Mars Integrated Analog mission (56). Through the execution of the Prosperity Lunar Station, the first lunar settlement will be built and expanded further to reach the future goals of humanity. Our thirsty endeavor to travel back to the Moon awaits us. We hope this design will set us accordingly on the path to prosper on the Moon, the cornerstone for Solar System science and exoplanet studies.

References

1. Gibney E. How to build a Moon base. Vol. 562, Nature. NLM (Medline); 2018. p. 474–8.
2. NASA. Developing a site selection strategy for a lunar outpost: science criteria for a site selection. 1990.
3. Honniball CI, Lucey PG, Li S, Shenoy S, Orlando TM, Hibbitts CA, et al. Molecular water detected on the sunlit Moon by SOFIA. Nat Astron [Internet]. 2020 Oct 26 [cited 2021 Jan 31];1–7. Available from: https://www.nature.com/articles/s41550-020-01222-x
4. Meghan Bartels. Are Moon Caves Safe for Astronauts? Earth's Lava Tubes Can Help Us Find Out | Space [Internet]. [cited 2021 Jan 31]. Available from: https://www.space.com/41921-exploring-lava-tubes-for-moon-landings.html
5. Cruikshank DP, Wood CA. Lunar rilles and Hawaiian volcanic features: Possible analogues. Moon [Internet]. 1972 Mar [cited 2021 Jan 31];3(4):412–47. Available from: https://ui.adsabs.harvard.edu/abs/1972Moon....3..412C/abstract
6. Lunar resources - Wikipedia [Internet]. [cited 2021 Jan 31]. Available from: https://en.wikipedia.org/wiki/Lunar_resources
7. Byloos B, Maan H, Van Houdt R, Boon N, Leys N. The Ability of Basalt to Leach Nutrients and Support Growth of Cupriavidus metallidurans CH34 Depends on Basalt Composition and Element Release. Geomicrobiol J [Internet]. 2018 May 28 [cited 2021 Jan 31];35(5):438–46. Available from: https://www.tandfonline.com/doi/abs/10.1080/01490451.2017.1392650

8. Charles.Cockell. BioRock rare earth element leaching data. Univ Edinburgh [Internet]. 2020 [cited 2021 Jan 31]; Available from: https://datashare.ed.ac.uk/handle/10283/3740
9. Van Ellen LA, Peck DP. Use of in situ ice to build a sustainable radiation shielding habitat on Mars. Proc Int Astronaut Congr IAC. 2018;2018-Octob(October 2018).
10. Adams JH, Hathaway DH, Grugel RN, Watts JW, Parnell T a., Gregory JC, et al. Revolutionary Concepts of Radiation Shielding for Human Exploration of Space. Nasa [Internet]. 2005;(March):1–110. Available from: http://hdl.handle.net/2060/20050180620
11. Naito M, Hasebe N, Shikishima M, Amano Y, Haruyama J, Matias-Lopes JA, et al. Radiation dose and its protection in the Moon from galactic cosmic rays and solar energetic particles: At the lunar surface and in a lava tube. J Radiol Prot [Internet]. 2020 Dec 1 [cited 2021 Jan 31];40(4):947–61. Available from: https://doi.org/10.1088/1361-6498/abb120
12. Design of interlocking building elements | regolight [Internet]. [cited 2021 Jan 31]. Available from: https://regolight.eu/2018/04/10/design-of-interlocking-building-elements/
13. Miller J, Taylor L, Zeitlin C, Heilbronn L, Guetersloh S, DiGiuseppe M, et al. Lunar soil as shielding against space radiation. Radiat Meas. 2009 Feb 1;44(2):163–7.
14. Lunar Station Protection: Lunar Regolith Shielding (AAS 03-720) - NASA/ADS [Internet]. [cited 2021 Jan 31]. Available from: https://ui.adsabs.harvard.edu/abs/2004ilc..conf..143L/abstract
15. Meurisse A, Makaya A, Willsch C, Sperl M. Solar 3D printing of lunar regolith. Acta Astronaut. 2018 Nov 1;152:800–10.
16. Urbina DA, Madakashira HK, Salini J, Govindaraj S, Bjoerstad R, Gancet J, et al. Robotic prototypes for the solar sintering of regolith on the lunar surface developed within the Regolight project. Proc Int Astronaut Congr IAC. 2017;4(November):2632–41.
17. Haidegger T, Sándor J, Benyó Z. Surgery in space: The future of robotic telesurgery. Surg Endosc [Internet]. 2011 Jul 22 [cited 2021 Jan 30];25(3):681–90. Available from: https://link.springer.com/article/10.1007/s00464-010-1243-3
18. Carrano AL. Selected On - Demand Medical Applications of 3D - Printing for Long - Duration Manned Space Missions. 2017;(August 2016).
19. Jones H. NASA Technical Reports Server (NTRS) [Internet]. 2002 [cited 2021 Jan 30]. p. 15. Available from: https://ntrs.nasa.gov/citations/20040012725
20. ISS ECLSS - Wikipedia [Internet]. [cited 2021 Jan 30]. Available from: https://en.wikipedia.org/wiki/ISS_ECLSS
21. Alemany L, Peiro E, Arnau C, Garcia D, Poughon L, Cornet JF, et al. Continuous controlled long-term operation and modeling of a closed loop connecting an air-lift photobioreactor and an animal compartment for the development of a life support system. Biochem Eng J. 2019 Nov 15;151:107323.
22. Giacomelli GA, Furfaro R, Kacira M, Patterson L, Story D, Boscheri G, et al. Bio-regenerative life support system development for Lunar/Mars habitats. In: 42nd International Conference on Environmental Systems 2012, ICES 2012 [Internet]. American Institute of Aeronautics and Astronautics Inc.; 2012 [cited 2021 Jan 30]. Available from: https://arc.aiaa.org/doi/abs/10.2514/6.2012-3463
23. About the Space Station Solar Arrays | NASA [Internet]. [cited 2021 Jan 30]. Available from: https://www.nasa.gov/mission_pages/station/structure/elements/solar_arrays-about.html
24. Hickman JM, Curtis HB, Landis GA. Design considerations for lunar base photovoltaic power systems. In: Design considerations for lunar base photovoltaic power systems [Internet]. NASA Technical Reports Server (NTRS); 1990 [cited 2021 Jan 31]. p. 10. Available from: https://ntrs.nasa.gov/citations/19910004946
25. Yuegong-1 - Wikipedia [Internet]. [cited 2021 Jan 30]. Available from: https://en.wikipedia.org/wiki/Yuegong-1
26. Urban green space interventions and health: A review of impacts and effectiveness. Full report (2017). 2017 May 5 [cited 2021 Jan 30]; Available from: https://www.euro.who.int/en/health-topics/environment-and-health/urban-health/publications/2017/urban-green-space-interventions-and-health-a-review-of-impacts-and-effectiveness.-full-report-2017
27. NASA Technical Reports Server (NTRS) [Internet]. [cited 2021 Jan 30]. Available from: https://ntrs.nasa.gov/citations/20030032422
28. Lakhiar IA, Gao J, Syed TN, Chandio FA, Buttar NA. Modern plant cultivation technologies in agriculture under controlled environment: a review on aeroponics. J Plant Interact [Internet]. 2018 Jan 1 [cited 2021 Jan 31];13(1):338–52. Available from: https://www.tandfonline.com/doi/full/10.1080/17429145.2018.1472308
29. Wang Y, Cheng Z, Song W, Liu Z, Shi Y. [Biological effect of space flight on edible fungi onboard recoverable scientific satellite]. Space Med Med Eng (Beijing) [Internet]. 1998 Aug [cited 2021 Jan 31];11(4):249–53. Available from: https://pubmed.ncbi.nlm.nih.gov/11543241/
30. Ageitos JM, Vallejo JA, Veiga-Crespo P, Villa TG. Oily yeasts as oleaginous cell factories [Internet]. Vol. 90, Applied Microbiology and Biotechnology. Springer; 2011 [cited 2021 Jan 31]. p. 1219–27. Available from: https://link.springer.com/article/10.1007/s00253-011-3200-z
31. Gellenbeck S, Pryor B, Giacomelli G, Rd R. Mushrooms on Mars: A Subsystem for Human Life Support [Internet]. 49th International Conference on Environmental Systems; 2019 Jul [cited 2021 Jan 31]. Available from: https://ttu-ir.tdl.org/handle/2346/84470
32. Vieira ÉD, Da Graça Stupiello Andrietta M, Andrietta SR. Yeast biomass production: A new approach in glucose-limited feeding strategy. Brazilian J Microbiol [Internet]. 2013 [cited 2021 Jan 31];44(2):551–8. Available from: www.sbmicrobiologia.org.br
33. Van H, Hwang I, Jeong D, Touseef A. Principle of Meat Aroma Flavors and Future Prospect. In: Latest Research into Quality Control [Internet]. InTech; 2012 [cited 2021 Jan 31]. Available from: http://dx.doi.org/10.5772/51110
34. Terfansky ML, Thangavelu M. 3D Printing of Food for Space Missions. 2013 Sep 10 [cited 2021 Jan 31]; Available from: https://arc.aiaa.org/doi/abs/10.2514/6.2013-5346
35. 3D Printing: Food in Space | NASA [Internet]. [cited 2021 Jan 31]. Available from:

https://www.nasa.gov/directorates/spacetech/home/feature_3d_food.html
36. Potter S. NASA's SOFIA Discovers Water on Sunlit Surface of Moon. NASA [Internet]. 2020 [cited 2021 Jan 31]; Available from: http://www.nasa.gov/press-release/nasa-s-sofia-discovers-water-on-sunlit-surface-of-moon
37. The Scientific Context for Exploration of the Moon. The Scientific Context for Exploration of the Moon. National Academies Press; 2007.
38. Hatfield M. Lunar Gateway Instruments to Improve Weather Forecasting for Artemis [Internet]. 2020 [cited 2021 Jan 31]. Available from: http://www.nasa.gov/feature/goddard/2020/mini-weather-stations-on-lunar-gateway-to-study-deep-space-environment
39. Work and live on Mars: Inside a new base developed for future missions | Science| In-depth reporting on science and technology | DW | 20.12.2019 [Internet]. [cited 2021 Jan 31]. Available from: https://www.dw.com/en/work-and-live-on-mars-inside-a-new-base-developed-for-future-missions/a-51738228?fbclid=IwAR0NspMLZNv547yjOgA1Y9Whp63P5jXfJkqn1cmbeR1heteitQBfghQAIKo
40. NASA. Artemis III science definition report. 2020.
41. Costs of an International Lunar Base | Center for Strategic and International Studies [Internet]. [cited 2021 Jan 31]. Available from: https://www.csis.org/analysis/costs-international-lunar-base#_ftn8
42. SpaceX - Falcon 9 [Internet]. [cited 2021 Jan 31]. Available from: https://www.spacex.com/vehicles/falcon-9/
43. SpaceX - Falcon Heavy [Internet]. [cited 2021 Jan 31]. Available from: https://www.spacex.com/vehicles/falcon-heavy/
44. Tourist cost to visit International Space Station with SpaceX is $52M [Internet]. [cited 2021 Jan 31]. Available from: https://www.cnbc.com/2019/06/11/tourist-cost-to-visit-international-space-station-with-spacex-is-52m.html
45. Investment Perspectives: Opportunity and Economics of ISS National Lab Research [Internet]. [cited 2021 Jan 31]. Available from: https://www.issnationallab.org/blog/investment-perspectives-opportunity-and-economics-of-iss-national-lab-research/
46. TV Rights in Football - Premier League Analysis | Sports Business institute [Internet]. [cited 2021 Jan 31]. Available from: https://www.sbibarcelona.com/newsdetails/index/403
47. All or Nothing? Filling in the blanks in Amazon's Tottenham series – The Athletic [Internet]. [cited 2021 Jan 31]. Available from: https://theathletic.co.uk/2065130/2020/09/15/tottenham-amazon-mourinho-all-or-nothing-pochettino/
48. Schlacht IL, Birke H. Space design: Visual interface of space habitats. Pers Ubiquitous Comput [Internet]. 2011 Jun 28 [cited 2021 Jan 31];15(5):497–509. Available from: https://link.springer.com/article/10.1007/s00779-010-0326-4
49. Isolation at the extreme: What life is like spending winter in Earth's most inaccessible research stations | National Geographic [Internet]. [cited 2021 Jan 31]. Available from: https://www.nationalgeographic.co.uk/science-and-technology/2020/04/isolation-extreme-what-life-spending-winter-earths-most-inaccessible
50. Architects HB. Halley VI British Antarctic Research Station | Hugh Broughton Architects [Internet]. [cited 2021 Jan 31]. Available from: http://hbarchitects.co.uk/halley-vi-british-antarctic-research-station/
51. All About The First Space Tourist - Space Legal Issues [Internet]. [cited 2021 Jan 31]. Available from: https://www.spacelegalissues.com/all-about-the-first-space-tourist/
52. Book Review: Dragonfly, NASA and the Crisis Aboard Mir|National Space Society [Internet]. [cited 2021 Jan 31]. Available from: https://space.nss.org/book-review-dragonfly-nasa-and-the-crisis-aboard-mir/
53. Sucharitkul S. Liability and responsibility of the state of registration or the flag state in respect of sea-going vessels, aircraft and spacecraft registered by national registration authorities. Am J Comp Law. 2006;54(SUPPL.):409–42.
54. Who owns the Moon? Space law and the Outer Space Treaty [Internet]. [cited 2021 Jan 31]. Available from: https://www.rmg.co.uk/discover/explore/the-moon/who-owns-the-moon
55. Who Owns the Moon? Law & Outer Space Treaties | Space [Internet]. [cited 2021 Jan 31]. Available from: https://www.space.com/33440-space-law.html?fbclid=IwAR3Y1crX3anNYayRIOeasKAR4-5U0AaMA7RahmZmpCV9tjuxAzAX2Aq6xyU
56. Exploration SL. NASA ' s Plan for Sustained Lunar Exploration and Development.