Lunar Research Station

Station Design - Red Team

Antoine Prantzos, Kevin Azad, Kjell Gordon, Ragnheidur Tryggvadóttir, Sheng Yang & Thomas Gilet
MSc students, KTH, Royal Institute of Technology, Stockholm, Sweden.

***Abstract*—This paper presents a design proposal for a lunar research station that can support long-term human presence on the moon. The proposed design takes into account the unique environmental conditions of the moon, such as extreme temperature variations, radiation exposure, and the presence of vacuum. The station's design includes a modular habitat that can be expanded to accommodate additional crew members, but primarily consist of a few core modules dedicated to human needs and station requirements such as sleep and logistics as well as a laboratory module that can facilitate a range of scientific research activities. To address the energy requirements of the station, we propose the use of a combination of nuclear and hydrogen fuel cell power systems. The paper also outlines the challenges associated with constructing and operating a lunar research station, including the need for assumptions regarding advanced life support systems, reliable communication infrastructure, and autonomous robots for maintenance and repairs. Overall, the proposed design provides a framework for future research and development efforts towards establishing a sustainable human presence on the moon.**

***Index Terms*—Human Spaceflight, Lunar Base, Moon**

Supervisor: Christer Fuglesang

I. Introduction

IN the year 2037, the Artemis program has been successfully concluded, paving the way for a new era of lunar exploration. With the increasing recognition of the scientific potential of the Moon, plans are underway to build a large research station on its surface. This station, modeled after the Amundsen-Scott Station on Antarctica, will provide a base for up to 50 people to conduct cutting-edge research and exploration activities. The Station Design team has been tasked with designing this Lunar Research Station, named Celestial Heaven, to be operational by 2040. In this paper, the station type, layout design, and interior, as well as its construction and power sources will be analysed and discussed. The aim is to create a sustainable, functional, and safe environment for researchers to push the boundaries of science and discovery on the Moon.

A. Project Focus

The goal is to design a Lunar Research Station located on one of the Moon's potential habitable locations to be constructed and habitable by 2040. The station will need to house a crew size of 50 individuals and protect them from the hazards of space such as vacuum, radiation, temperature extremes, and potential micrometeorites.

The project as a whole is divided in to five major areas: overall coordination, station design, operations, logistics, and Human aspects. As the team is dedicated to station design, management, cost, research, short- and long-term upkeep, and life support system(s) details will not be covered in this paper and are instead analysed by the other teams.

B. Limitations and Assumptions

Some general assumptions regarding the project include:

- The Lunar Gateway (Space Station) is already in place.
- The Starship launcher with the Superheavy is operational.
- Crewed human habitat already exists on the Lunar South Pole.

The following assumptions were also made:

- The station has an internal, high functioning recycling system.
- Hydrogen and ice is available on location.
- Food growth is possible on the moon.
- Certain technologies mentioned throughout the paper, not yet fully proven, are working and readily available.

II. Methods

A. Station Type

The general layout of the base is one of the first problems to solve. There are important factors to consider in the design, such as safety against radiation or meteorites and ease of construction. To make a decision based on rational elements, different layout options are listed in two categories: *Design Options* and *Modifiers*. Elements from the two different categories can be associated to form a complete layout.

The *Design Options* are:

- Module Pods
- Cave Base
- Vertical Tower
- Singular Dome

Module Pods/Surface pods will be able to connect to each other through corridors. This allows for the possibility to seal each module off from the rest in dangerous situations. No Extravehicular Activities (EVA) would be needed to get between modules. Their approximately spherical shape is beneficial for load bearing capabilities. They can be relatively easy to build since adding more modules for future expansion would be a repeatable, iterative process.

A **Cave Base** is a base set up in a lunar cave. It will have a lot of natural shielding, however finding a site with a cave large enough to house the whole, or most of, the station may be difficult. Having the station inside a cave, would limit the view of Earth. There are lunar caves and tunnels that could be exploited, but it would require a lot of work to accommodate them for our purpose. These natural tunnels or caves provide protection from cosmic radiation, solar radiation, and also meteorites, micrometeorites, and ejecta from their impacts. A cave would insulate the station from the extreme temperature variations on the lunar surface and could provide a stable environment for inhabitants.

A **Vertical Tower** would be a tower, either built down into the ground or up on the surface. A tower would be particularly difficult to construct due to the natural difficulty of building vertically instead of horizontally outwards. With only one structure, containment of emergencies may be challenging. However, tower potentially requires less surface area, and could be beneficial if a challenging and rocky station site were to be chosen. If it is built underground it provides good shielding from the environment.

A **Singular Dome** is a big dome hosting everything beneath it. The main advantage is that this design will be space efficient. Additionally, with one structure, you will have easy access to every part of the station. However, this poses the same challenges with emergencies as the vertical tower, in that it might be difficult to contain hazards in emergency situations. The singular dome would also be disadvantageous if an expansion of the base is needed.

The *Modifiers* are:

- **Surface**: The station is built on the moon surface, with no need to excavate very deeply. This avoids having to dig a lot, and thus the need of big excavators. Radiations remain then the biggest problem.
- **Underground**: The whole station is built underground, with at least 3 m of lunar soil above the highest point of the base. Opposite to the *Surface* modifier, *Underground* provides an ”easy” radiation and micrometeoids shield, but requires more construction vehicles and facilities.
- **Split**: A split base would serve as two separate bases. They could each serve different purposes and be in different locations, with short travel in between. Having two separate bases could help with specialization, as each base could specialize in different things and set the whole base up for that specific purpose. It could also be a simple way to cover two different areas of the location. With a split base you also have the inherent safety of having a spare base if something happens to one. Additionally, the stations would have separate life support systems and power systems.
- **Duplicate**: The idea is to duplicate a base that is designed for hosting 25 members. This provides great safety since the two bases run independently. Indeed, if a base malfunctions in any capacity, the other base can continue to allow for permanent human residence on the moon and the utilization of the latter, can host the 25 other members until their repatriation.

We can then introduce rating categories that will help us to evaluate each option in a qualitative way :

- **Construction ease**: The base must be constructed within a reasonable amount of time (2 years) with a reasonable cost, and a realistic workload.
- **Natural shielding provided**: Radiation is one of the major concerns for human residence on the moon, and achieving shielding with today’s technology in a realistic way mostly relies on passive shielding with materials. Regolith can be used in that purpose, and an appropriate architecture for the base can thus provide a ”natural” shielding.
- **Ease of use**: The station should be easy to use for all the different missions it is assigned, such as Science experiments and EVAs while also hosting the crew in acceptable living conditions.
- **Management under emergency**: Emergency and life threatening conditions should be handled in a way that provides the higher probability of recovering the crew alive and not wounded. The layout of the base can enhance emergency management procedures and consequently needs to be designed from this point of view as well.

Each option goes through this rating scheme and an associated weighting of the grades, to conclude what is the best combination.

B. Station Layout Design

Once the type of station is selected, the design specifics begin with the layout of the station. Per the design of the Amundsen Scott Antarctic research station [1], a research station needs to have the following core functions and capabilities: sleeping, leisure, eating, and life support for the crew, a power station, a workshop or garage, communications, logistics and research areas. For the case of an emergency, a lifepod, or self-sufficient living area where crew can take shelter in and survive in should be present. All of these aspects and more are incorporated in to the design of the station layout. The layout with the most organic, logical, safe and easy-to-use structure is selected for the base.

C. Interior Module Design

With each module's purpose defined, details regarding the interior design are now planned. Each module is named after notable figures in space history which serve as an inspiration for the historic accomplishment of creating a lunar station. Each module will consist of 3 floors, roughly each with a radius of 6.6 m.

1) Logistics Module - Tereshkova: Having communication is key in a remote base whether it is on the Moon or on Earth. The logistics module has to be able to house computers and data systems that are on the base. There needs to be internet and WIFI going through the base as many systems depend on it constantly. Communication between modules is also necessary. Communication to and from earth will be done through KU-bands and S-bands.

Storage is also a big part of the base as food, water and oxygen tanks will need to be stored in a location closed off and preferably cold. The oxygen takes up a big part of the storage facility as they are required to be stored in big tanks around the base.

2) Garage Module - Lovell: Having vehicles such as rovers, robots and excavators is also important. Using the excavator we can dig on the surface of the Moon but they need to be able to be either housed inside or be connected to a module via outside. Big excavators can be stored outside. Having a workshop is also necessary as many tools and vehicles will need to be repaired and/or maintained.

3) Living Module - Armstrong: The living module houses every activity that is not work or sleep for every occupant of the station. To create a good environment for everyone, it has to be split into separate parts, to accommodate everyone. It also has to house the food hall and the kitchen. For practicality, the food should be prepared and eaten in the same general area. With most of the station following the same schedule, all occupants have to be able to enjoy the living area at the same time. There should not be a lot of excess room that is not being used, as real estate on the Moon is expensive and should not be wasted. The living area should also include some viewing area of the Moon's surface and the Earth. This could include windows or an addition to the module.

4) Sleeping Module - Gagarin: The sleeping module is where every member of the station sleeps. Privacy is very important, since people are living there for extended time, so some sort of sleeping modules or bedrooms should be considered. The sleeping module should only include the bedrooms and toilets.

5) Lab Module - Fuglesang: The lab module should include a farm for food production as well as labs to perform experiments. The lab module should also contain an airlcok to the outside, as some of the experiments might require easy access to the outside.

6) Life Support Module - Shepard: The life support module is a key component of the base as all power and required systems depend on it. It will consist of Air Cleaning, Water Recycling, Active Thermal Control System and Power System. The air cleaning will consist of the base removing CO_2 from the atmosphere while also having air filtration.

7) Life Pod Module - Grissom: As its name suggests, the Life Pod is designed to be the safe place if everything goes wrong. It thus needs to be able to function as an entire mini base if the main one has failed. The general requirements for this module are quite easy to express : Being able to host all the fifty members of the crew and keep them alive for twenty-eight days, the needed time to evacuate all crew members from the station.

D. Hull Design

The hull walls of the station primarily need to be able to hold the pressure inside the station. It has to prevent decompression of the station while also being able to shield the occupants of the station from radiation. For all pressure vessels, including this station, a form of container is needed. The thickness required of the material to adequately hold the pressure inside is calculated using Equation 1.

$$t = \frac{PR}{2SE - 0.2P} \tag{1}$$

Where t is the thickness, P is the pressure, R is the inner radius, S is the allowable stress and E is the joint efficiency. The allowable stress is a function of the selected material whilst the joint efficiency, which essentially determines the quality of the joining (usually welding) of the materials, is assumed to be a reasonable value of 0.75 [2].

The material used for the primary structure could either be sourced from the Moon or brought there from Earth. Being able to source the material from the Moon would be cheaper for transport, but would require a lengthy and extensive operation to be put in place first to extract the material from mining.

E. Pressure

When selecting the pressure for the station, a few factors need to be considered. The pressure and oxygen level can't have any negative health effects on the occupants of the station, as they will live in the environment for long periods at a time. The pressure levels of the EVA suits need to be considered too. EVA suits function at a pressure of around 0.3 atm, and 100% oxygen concentration. A large pressure difference between the suit operating pressure and the station pressure will result in a longer EVA preparation time to prevent diving sickness, which prolongs the overall required time for an EVA. It also limits reaction time for an urgent EVA to perform important, time-sensitive tasks such as hull repairs. Safety should also come into consideration, as a higher oxygen concentration can pose an increased fire risk. Other less important factors are convenience and comfort; lower pressure affects the boiling point of materials, which can affect cooking time and temperatures and other inconveniences.

F. Power

The power system for the station needs to provide continuous power to all necessary station processes. Station back-up power and the life pod's power system will also be included in the analysis. To design an appropriate power system, the power requirements of the station must be first defined.

The main power consumption of the station can be summarised in two parts: general station upkeep and Hydrogen production. Hydrogen production is considered separately as its power consumption is so large. General station upkeep includes powering life support, lighting, heating and cooling, etc. and its power consumption is approximated by studying the power requirements of comparable arctic stations, the ISS, and an average household.

The power requirements for Hydrogen production is determined by analysing the electrolyzer which processes water (gathered by mining lunar ice) and splitting it into both Oxygen and Hydrogen. The produced Hydrogen and Oxygen can be re-used as back-up power via hydrogen fuel cells and can be used for rocket propellant. The quantity of required Hydrogen is dictated by the Logistics team (for rocket fuel) and the sizing of the back-up power system. Once the power requirements are defined, an appropriate power source can be determined.

G. Construction

Once the general concept of the station is decided upon, the details for how to construct said base are developed. Existing technology engineered for lunar application and common place technologies are examined for possible station construction application. Basic designs are roughly sketched that represent devices that could potentially be created for the construction of the station. The timeline of the construction of the station is generally considered, but not examined in-depth as that is left to the Operations team.

H. Station Maintenance

To keep the station running, its components have to be monitored and repaired if necessary. To complete inspection protocols, out-of-bounds protocols (when the situation is not nominal but not harmful yet) and safety protocols will need to be created. To perform the inspections and if needed to repair components, the crew should always have some members qualified in the appropriate domain.

I. Safety & Off-Nominal

The moon's hostile environment for humans and their facilities forces us to consider off-nominal cases as well as safety counter measures to ensure the durability of this research base on the Moon and the survival of its crew.

Our concerns can be listed into two categories : the ones with natural origin and the ones from human activity.

Natural origin

- Natural radiation of all types (SPE, GCR)
- Meteorites
- Lunar dust and soil
- Vacuum

Human origin

- Vital system failure
- Depressurization
- Fire

The goal is to have a response for each hazardous situation that may be caused by the above mentioned.

III. Results

A. Station Type

A matrix of the different choices was made giving each module a grade depending on the function and safety of each type. Grades included variables such as *Construction*, *Shielding*, *Living* and *Safety*. A high priority was put on construction as it is a very important part of the base. To increase shielding of surface pods a hybrid setup was chosen.

The station type with the highest scores was **Module Pods** with both **Surface** and **Underground** modifiers. In order to have both a safe and practical base, module pods partially buried in to the lunar surface with additional regolith piled on top for protection connected by corridors are used. From each module, one can move easily between modules through corridors and, in the case of an emergency, multiple corridors will be available to different modules. The exception for this is the lifepod module and the power module. This station type offered the best combination of construction ease, shielding, ease of use and management under emergency. A rendering of what the surface/underground module pod station could look like is presented in figure 1.

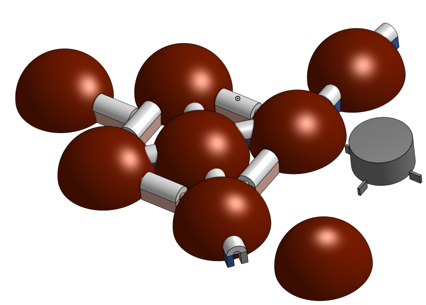

Fig. 1: 3D Rendering of Module Station Design

B. Station Layout Design

So that the station is easier to build and to traverse in between modules, the modules are placed close to each other. Exceptions are made for the power module, since it houses a nuclear reactor and is therefore located at a distance from the station.The position of the different modules in relation to one another is chosen following a logical use of the station and can be seen in figure 2.

The central module is the life support module, because of the fact that it is the most important one. The life support's outputs such as air and recycled water needs to be provided effectively to each part of the station, and it needs to be easily accessible in case of a breakdown or emergency. The lifepod module has only one access to the rest of the station because it needs to be able to be sealed easily and rapidly from the rest of the station. It is directly connected to the sleeping module and the living module, since the latter are the places where the crew spends most of their time, and thus where the crew will most likely be if a breakdown occurs.

Lab, Logistics and Garage are aligned in that order for transportation and operations purposes. The garage is where EVAs and transportation of material from the launch pads to the station occur. Cargo then passes through the logistics module before being distributed throughout the station (primarily to life support and the research lab modules). EVAs can also be performed from the lab for science purposes. Finally, the antenna is located close to the logistics module since the communication of the station is handled through the logistics module.

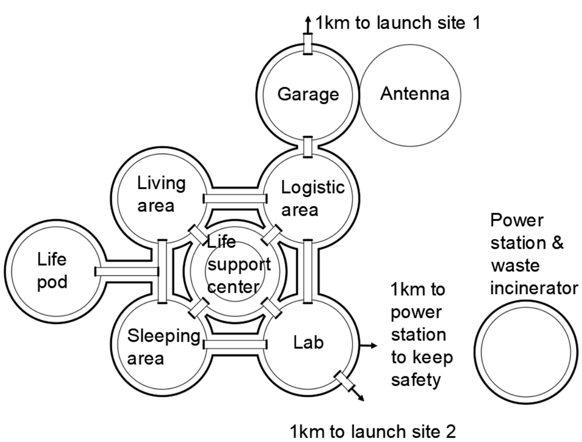

Fig. 2: Station Design Layout

C. Interior Module Design

1) Logistics Module - Tereshkova: The logistics module, named after Valentina Tereshkova, will be the main hub for the stations communication. As communication needs to be externally (to and from Earth) but also internally (to and from different modules) there are high requirements on the different systems inside this module. Computers will need to be up to date and connected to all systems to constantly be monitored by personnel and AI.

The main floor will be divided into Center Console, Data Handling and Communication. The center console monitors what is going on in the base as well as give updates on the different levels of subsystems for example the level of CO_2 in the air as well as current water availability. The main hub also monitors potential disasters such as micrometeorites and increase in radiation from the outside where the information is then relayed to the other modules via intercoms.

The top and bottom floor of Tereshkova will be used for storage and computer systems that are not in use. Food, water and oxygen tanks will be stored here as well as other equipment that someone might need quick access to. The main hub is also connected to the outside for launchpad transfers where there are incoming and outgoing shipments.

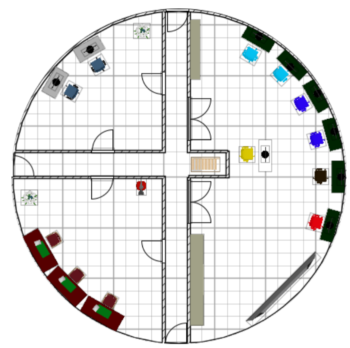

Fig. 3: Main floor of Logistics

2) Garage Module - Lovell: The garage module, named after Jim Lovell, will store vehicles and allow safe access to the outside though EVAs. This is also where crew members can perform maintenance and work using tools (in both chambers).

The main floor is comprised of a depressurized chamber which is first entered through Tereshkova. To use the vehicles or perform an EVA you have to enter the pressurized chamber first to gain access to the non pressurised section. In this area the vehicles are used and some are connected to the outside such as a rover or a truck. The top and bottom floor houses more storage that is available through an elevator for easier access.

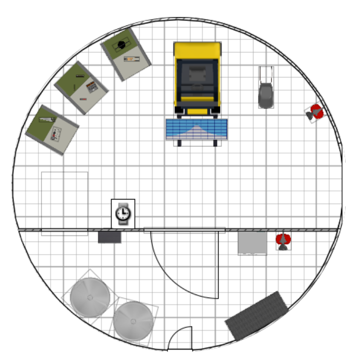

Fig. 4: Main floor of Garage

3) Living Module - Armstrong: The Living Module, named after Neil Armstrong, is the module designated to all activities outside of work and sleep. Armstrong, like the other modules has three floors. The first two floors are designated recreational areas, while the top floor is the food hall and the kitchen. On each floor there is an air shelter, positioned at the farthest point from the emergency exits.

The bottom floor, or Armstrong -1, is $108\,m^2$. It is split into four rooms, each room around $25\,m^2$. One room is designated as a bathroom room. It houses 6 bathroom stalls for all occupants of Armstrong, pictured in the top left corner on Figure 5. The other three rooms, are all designated to different activities. In the top right corner, there is an empty room. It contains two tables and chairs, and can be used for any activity the occupant desires. On the bottom right corner there is the art room. In it there is a couch on the middle of the floor and artwork covers the walls. In the bottom left corner there is the green room. This room is filled with plants and flowers, for the occupants of the station to enjoy a bit of nature. The art and green room are both quiet rooms to help with mental health and relaxation.

Fig. 5: Bottom floor of Living

The main floor, or Armstrong 1, is $136\,m^2$. It is also split into four rooms, each room around $32\,m^2$. On Armstrong 1 the top left room in Figure 6 is the quiet room. In the quiet room there are privacy booths. Two $2\,m^2$ sized booths where occupants can get some privacy to call home, or do other things that require privacy. The rest of the room has couches and chairs and quiet areas for occupants to relax in. This room would be perfect to sit and read a book, work on your computer or just scroll through your phone. In the top right corner is the gym. Although small, it can house 12 people at a time. It has four treadmills, four stationary bikes and four Advanced Resistive Exercise Devices. In the bottom right corner is the game room. This room has a multi game pool table, that can be turned into a foosball table, ping pong table and possibly some other games as well. There is also a table to play board games or just sit and talk. There is a couch and a television, for playing video games. In the bottom left corner, is the movie theatre. There is a projector, a screen and chairs, where regular screenings of movies are held. There is also a popcorn machine to get the authentic movie theatre experience. As well as a movie theatre, this room is also the music room, where occupants can create their own music. Some musical instruments can be found there, and the astronauts can put on musical shows in the room. Connected to Armstrong 1 is is the observation deck. It is an addition to the module made of lead glass. It will have some radiation shielding, but not enough to stay there for prolonged time. To mitigate the exposure some radiation protective clothes might be considered. The observation deck will be facing Earth, and has comfortable sofa beds, where it's comfortable to sit and watch the horizon and lie to watch the stars. The observation deck is important for mental health. Being able to see the Earth, as well as enjoying the view is important to the astronauts mental health. Due to its diminished radiation protection, it would be placed outside the outer regolith layer of the hull, and time spent on the observation deck might have to be monitored and limited.

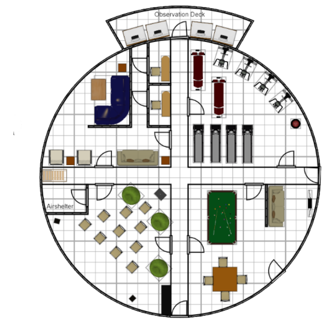

Fig. 6: Main floor of Living

The top floor, or Armstrong 2, is $108\,m^2$. It is split into two parts. One third of the floor is designated to the kitchen area, and two thirds are the food hall, as pictured in Figure 7. In the food hall there are 12 tables, or enough to sit all occupants of the station. The tables can be all separate or put together to create a bigger table. Between the kitchen and the food hall there is a wall with a window. On either side of the window are long tables, where the chefs, can put the food. This would work as a sort of buffet, where everyone gets their food from the long tables. In the kitchen there are either pressure cookers or some pressurized cabins for food that has to be cooked in 1 atmosphere.

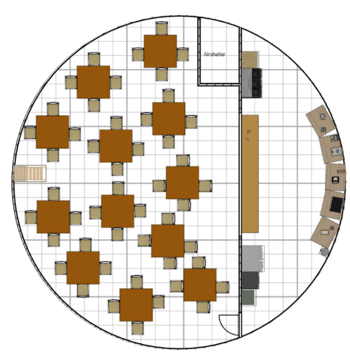

Fig. 7: Top floor of Living

4) Sleeping Module - Gagarin: The sleeping module, named after Yuri Gagarin, has all three floors designated to bedrooms. Each person on the station will be allotted a private bedroom of $6\,\mathrm{m}^2$. Although small, each room will have a bed, some storage for personal items and $4\,\mathrm{m}^2$ of floor area. The rooms will be soundproof and lockable, to ensure proper privacy. Each floor will have the same setup, of bedrooms and toilets. The showers in the station will be on Gagarin 1. The bedrooms will have a computer built into them, so the astronauts can both monitor the stations status from their bedroom as well as using it for recreational use. On each floor there is an air shelter, positioned at the furthest point from the emergency exits.

5) Lab Module - Fuglesang: The lab module, named after Christer Fuglesang, has two floors designated to labs and one floor designated to the farm. On the bottom floor, or Fuglesang -1, is the lab. Although only $108\,\mathrm{m}^2$, it has at least $175\,\mathrm{m}^2$ of farmable land. The farm will be in sort of towers, with at least two floors. With the $175\,\mathrm{m}^2$ of farmland the station can grow around 30% of the occupants caloric needs. The farm can be sealed off from the rest of the station, with a airtight door between Fuglesang -1 and 1. The farm also has it's own ventilation system separate from the rest of the station. On the top two floors of Fuglesang the labs of the station are. Each floor will have between 1 and 4 labs. The labs will be distributed between participating nations. There would also be a possibility of renting the labs out to private companies. The size of the lab could depend on the nation's or company's contribution to the station. The labs interior would be decided by the owner, with possibility of offices or other rooms. Emergency showers could also be installed as well as all necessary lab equipment. On Fuglesang 1 there is a airlock to the outside. Since the airlock can work as an air shelter, there would only be need for air shelters on Fuglesang -1 and 2. As labs can contain flammables and other dangerous equipment some extra security equipment might be needed depending on the labs function.

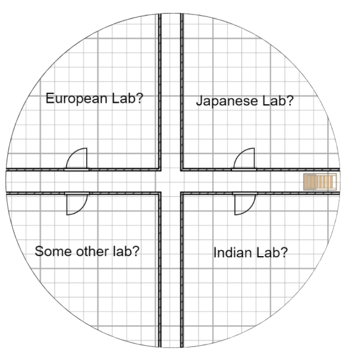

Fig. 8: Main floor of Lab

6) Life Support Module - Shepard: The life support module, named after Alan Shepard, will be the most critical module of the base as everything is connected to it and dependent on it (except lifepod). The outside of the module consists of a walkway that is connected to the four modules, Armstrong, Gagarin, Tereshkova and Fuglesang. Using this walkway the crew mates can traverse the base easily and effectively. This also makes Shepard accessible from every module.

The inner part of Shepard is comprised of all hardware needed for the base to function as it should (except for the Nuclear Reactor). It is has a water cleaning system, generators, and fuel cells. It is in there where two crew mates are constantly monitoring the levels of the module as well as relaying information to the main hub in case of an emergency or anomoly in the levels.

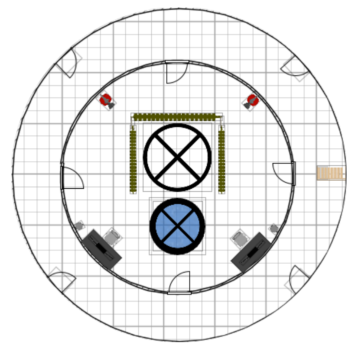

Fig. 9: Main floor of Life Support

7) Life Pod Module - Grissom: This module must be able to keep all fifty crew members alive. Thus, it is designed to host everything needed for that purpose. Some vital parameters were computed:

- Food Energy: $3.6 \cdot 10^6\,\mathrm{kcal}$
- Water: 3500 L
- Power: 400 kW
- Toilets: 7
- Beds: 50
- Showers: 3
- Reduced life support system

In addition to that, medical areas are needed with medical supplies, since it is highly probable that members of the crew will be hurt in such an extreme emergency case. An area of $30\,\mathrm{m}^2$ was chosen as an adequate medical area, and $3\,\mathrm{m}^3$ of medical supplies of all kinds, in addition to three medical beds and one scanner.

For food high caloric food rations were chosen to save space. Accordingly, $1\,\mathrm{m}^3$ is needed. Another cubic meter was added to have more diversity in food since twenty-eight days of survival rations is not the healthiest diet.

Finally a control room for communication with Earth and general rescue operations was added.

The bottom floor of the lifepod includes toilets, three superimposed beds, a storage area with a part of the reduced life support system. The medical area with medical stuff for first and basic aid is also on this floor.

The main floor has many beds, some toilets and the control room in which the coordination for the rescue will take place.

The top floor is basically a sleeping floor, with the amount of beds necessary to host the rest of the members. It is also where food and a part of the water are stored, in the center and between the beds. The junction between the floors is maid with stairs lying in the center of the floors. All around this module there are some desks with material for distraction for the crew, to try to keep its moral in a hard situation within a very densely populated space.

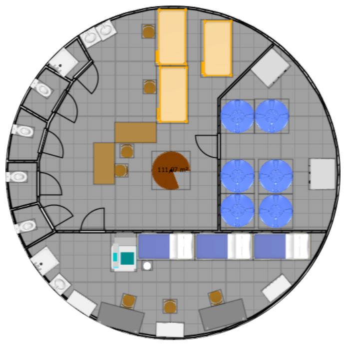

Fig. 10: Bottom floor of Lifepod

D. Hull Design

As a balance of cost, strength and proven technology, Aluminium was selected to be the primary structure material of the station. The design of the hull was decided to be a 4 layer hull. The inner most layer is a 6 cm thick layer of aluminum that holds the 0.5 atm of interior pressure in the station. The next layer of the hull is a 1 m layer of regolith. This pattern is repeated so that the third layer is another 6 cm layer of aluminum and on top of that there is the final layer or regolith which is 3 m thick. This design is illustrated in Figure 11. The thickness of the aluminum layer was calculated using Equation 1, based off of the decided interior pressure of the station.

Between the two aluminum walls, the pressure is a step lower at 0.25 atm. This pressure difference between the two aluminum hulls is to help detect the location of both a interior and exterior hull breach. A pressure sensor in between the walls can tell which wall has had a breach by detecting if the pressure in the hull drops or increases. If the inner hull is breached the inner air will flow from the inside to the space between the hulls due to the relatively lower pressure. If the outer hull is breached the air will flow from the space between the hulls to the outside vacuum, decreasing the pressure between the walls. This difference in pressure and measurement in flow used with the 2 hulls design allows for hull breaches to be determined quickly so that repairs can starts quicker. The regolith layers are primarily for radiation protection; a total of 4 m of regolith is enough to give proper radiation shielding for humans to live on the station for extended periods of time [3].

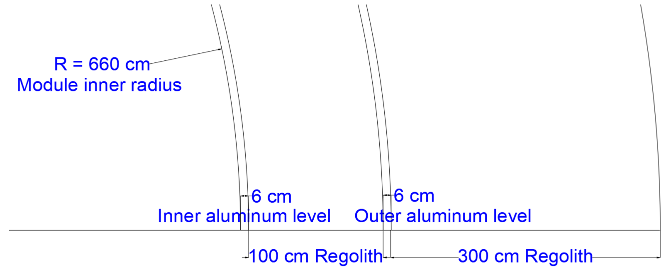

Fig. 11: Layout of the hull

In collaboration with the Logistics and Overall Management teams, it was determined that transporting the primary materials for the station, Aluminium, from Earth was worth the cost since it heavily reduced the station construction time.

E. Pressure

The pressure in the station was decided to be 0.5 atm with a 34 % oxygen concentration. This pressure was chosen for multiple reasons: it is the pressure chosen by NASA for upcoming missions [5], it is close enough to the suit pressure to not need an extensive pre-EVA preparation, and it poses no health risks for the occupants. The EVA suit pressure was the main deciding factor, as EVAs would need to be performed frequently and a pre-EVA preparation of 2-4 h was not deemed practical.

The largest concern with lowering the air pressure and increasing the oxygen concentration, is increased fire risk. With increased oxygen concentration, the delay in ignition decreases [5]. That results in a slightly higher fire risk, which can be mitigated with the use of non-flammable materials, proper fire detection and protection protocols. Another difficulty with lowering pressure is cooking. With lower air pressure, the boiling point of water lowers; for 0.5 atm it is lowered to 82 °C. This will increase the time needed for cooking with water since the temperature of the water, and therefore food, cannot reach as high temperatures. To avoid this, a pressure cooker will be available in the kitchen.

With the lower interior pressure on the station, the stress on the hull is decreased. With this decreased stress on the hull, the thickness can be reduced and the amount of aluminum needed to transport to the Moon will be decreased. The decreased pressure can be an exciting opportunity for some research, but as some experiments might require higher pressure, some pressure chambers or other pressure equipment would be available in the labs.

F. Power

The general station upkeep power requirement is determined to be approximately 302 kW. This is calculated by compiling a data set of maximum and minimum power requirements per person on the ISS [6], a typical US household [7], Halley Research Antarctic Station [8], McMurdo Antarctic Station [9], and Amundsen-Scott Antarctic Research Station [9]. The data set maximum and minimum are disregarded as they were extreme outliers. The resulting average is about 6.02 kW/person. When this is scaled up for the lunar base's population of 50 people, the station's total power requirement can be approximated to be 302 kW.

To refuel rockets upon arrival to the lunar base, a minimum of 150 kg of Hydrogen (and the respective amount of oxygen) needs to be produced per day so that the rockets can fully refuel upon arrival 11 times per year. Additionally, to have 4 days of available backup power per month via a Hydrogen fuel cell, a minimum production of 65 kg of Hydrogen more per day is needed. This results in a total Hydrogen production requirement of 215 kg per day.

This Hydrogen output requirement can be met with the use of currently available technology such as the Cummins HySTAT-100 Electrolyzer. It produces 215 kg of Hydrogen per day, but requires 500 kW of power to run [10]. This brings up the total power requirement of the base to approximately 800 kW. A high power density source is required to meet this large power demand.

An up-scaled version of NASA's Kilopower Reactor Using Stirling Technology was selected. A single prototype of this nuclear power source provides 10kW and has a mass of 134 kg [11]. Assuming a linear scaling of this technology, this power source could provide 800kW of electrical power and have a mass of 10.7 tons.

Ballard FCgen-HPS fuel cells were selected to provide back-up power and power for the life pod. These fuel cells provide 150 kW of power [12] when fueled with the required Hydrogen and oxygen as mentioned previously.

G. Construction

The construction of the station would begin with the landing and deployment of the equipment and robots needed. This would include, amongst other things, 10 regolith excavation rover robots, at least two module constructor robots, and at least one corridor construction robot and a solar panel array power source for the robots. The first significant step is to begin excavation; since the station's modules will be half buried in the ground, approximate hemisphere holes need to be dug out. The holes need to be large enough for the 6.6 m radius sphere modules so a total of at least 4,817 m^3 of regolith must be excavated for the modules.

Once the first hole is excavated, construction of the module itself can begin. The construction of spherical modules is difficult to accomplish. Therefore, the spheres were sectioned and split in to small identical pieces to later be put back together again. These small pieces would be stacked and transported to the Moon along with the other equipment. The pieces will be fed along a conveyor system and assembled piece by piece, with the module rotating via a system of rollers between each piece added until a layer of the module is complete. Once one layer is complete, the whole module will be rotated to begin construction of the next layer. This process, and details of the module construction robot are outlines in Figure 12. This construction would be completed on site, inside the dug holes so as to prevent the need of transporting the modules and once complete, the construction robot would be folded or disassembled so it can be removed from under the completed module.

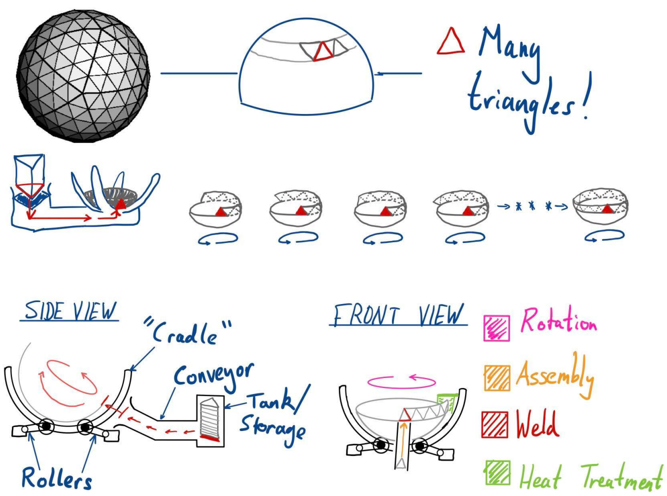

Fig. 12: Stages of Construction

The corridors connecting each module are also split in to identical smaller parts and are assembled, welded and heat treated in a similar system using a conveyor once a trench has been excavated for them. They are then installed to join two pods together. Finally, regolith is used to cover the base so that there is at least a total of 3 m thickness on top of all areas of the modules and corridors to adequately protect people from radiation [3]

Once the first of the modules and corridors are assembled, the interior work can begin. Floors, walls and structural pillars if needed will be created via a large 3D printer using regolith [13]. Since the structures have been created in an open environment and will be exposed to lunar dust, one of the tasks that the humans will have to complete before the station is habitable is removing said dust. Lunar dust is abrasive and can pose serious health issues if in contact with humans. The dust removal can be achieved by astronauts in EVA suits using handheld devices which applied static charge to dislodge the dust from objects [14]. Once the dust is dislodged, it can be gathered and removed. Then, individuals can begin finishing touches such as pressurization of the modules and corridors, wiring and lighting, plumbing, and assembly of furniture.

H. Station Maintenance

The maintenance of the base is one of the duties for the crew but some components require an expert to be maintained. This is true for the key elements of the base such as *Life support*, *Power production*, *Central computer* and *Habitat structure*. The goal is to rely on safety protocols first, as it is typically done inside a nuclear power plant, and in case of need use the expertise of a crew member to address the problem. To do so there should be among the crew (at each time on the base, this has to be taken into account for crew changes), at least two persons with the adequate knowledge.

- *Power production* (including the nuclear reactor), *Structure* and *Life support* : the experts could have others duties in the base, they could be researchers as well.
- *Central computer* : the expert would be the IT responsible of the base, which is already a main duty.

I. Safety & Off-Nominal

To mitigate the issues raised before, several solutions will be presented in order of their impact on the mission

- *Radiation*: Thanks to the hull design, there should be no risks for the crew inside the base.
- *Lunar Dust*: After each EVA some lunar dust may find its way in the airlocks. To get rid of it, the same technique as used during the construction could be used (electrostatic charges) [14].
- *Micro-Meteorites*: It should only affect the outer layer of the structure (regolith) which can be redone by rovers.
- *Fire*: Extinguishers will be present in the risky areas of the base (kitchen, labs, workshop) and thanks to the station design it is possible in extreme measure to seal off a module and depressurize it to stop the fire. Early detection of fire is one of the key components of fire protection. With decreased gravity and decreased delay in ignition, fire detection can be difficult, so detectors should be present in all air vents on the station and all high risk areas. In addition, an automatic fire extinguishing system close to those we have on Earth can improve the safety of the base.
- *Depressurization*: The impacted module can be sealed from the base if the amount of time necessary to find and repair the leak and loss of air is too great. The crew inside the damaged module can either escape to another one, or if impossible, flee in one the numerous air-shelters and wait for rescue.
- *Irreparable Life Support Damage or Unusable base*: Abandon of the station and confinement in the Life Pod until help comes from Earth.

IV. Discussion

A. Station Type

The chosen station type was, as described in section III-A, a modular station that is half buried and half underground. When comparing the results of this report to other concepts for a Lunar or Mars base, the same station setup of half buried to fully buried modules is the most popular one. Since other findings give the same results as this report, it can be argued that the station type chosen is probably an optimal station type.

For the layout of the base, this report details a layout of a few closely connected modules, and each modules serves a specific purpose. This layout can also be found in other research, but is not as common as the modular station type concept itself. As the layout of the base is dependant on the use of the base and personal design choices, the comparison to other bases is not as vital as with the station type. For the specific use of the station, the layout was considered to fulfill all the required needs and safety issues.

B. Power

Solar arrays, similar to those on the ISS, were initially considered to meet the station's power needs, but the large power requirement of Hydrogen production made it so that the mass of solar panels needed to be transported from the Earth would be unfeasible. Nuclear power was selected instead and an assumption must be made that a scaled-up version of what NASA is currently working on is available in 2037. The total nuclear system would have a mass of 10.7 tons, 3.5 tons of which would be the Uranium 235 isotope. This fuel should last 10 years and would need to be refilled. This isotope is highly radioactive and special care would need to be taken for transportation and radioactive waste management. Additionally, the nuclear power source would need to be placed far enough from the station or shielded to prevent additional radiation affecting the station's population.

Fuel cell back-up power was sized assuming the station could survive on 50% of the normal operating power requirement, entering in to a low power mode until main power could be brought back online. The Hydrogen required for this back-up power was calculated using the consumption rates of the fuel cell multiplied by the required duration of running.

C. Construction

Spherical modules were selected for the station because spheres are the most efficient pressure vessel based on natural geometry. A sphere can generally withstand the most amount of force per unit mass. This is especially relevant in a lunar base as the is the best shape to incorporate to stop a rupture in the station walls. The spheres were split in to small identical pieces for ease of assembly. Machines excel at completing repeatable processes which is exactly how a spherical module that has been split in to multiple, identical pieces that need to be put back together again could be built. Having the modules submerged into the ground will provide for higher protection as well as making the construction itself more stable.

V. Conclusion

In order to improve the base for future missions, research into optimizing the layout of the base and further research regarding the material that could be integrated in to the station available in the lunar environment instead of shipping from Earth should be performed. Future improved and more efficient solar power technology could also be investigated to see if there is a possibility in running the entire or partial station on solar power for power source diversity and redundancy and less reliance on nuclear power

Developing a lunar research station requires a high level of technological readiness, which is currently not feasible with our existing technologies. The technology readiness level (TRL) refers to the maturity of a particular technology and its readiness to be used in a specific application. While we have made significant progress in space technology, building a sustainable research station on the moon requires a range of advanced technologies that are not yet available. These include technologies for long-term life support systems, autonomous robotics and lunar additive manufacturing for construction and maintenance, advanced power systems, and lunar ice harvesting among others. Achieving the required level of TRL for these technologies will require significant research, development, and testing before they can be safely used for lunar exploration and research.

In conclusion, the construction of a Lunar Research Station marks a significant milestone in human space exploration. Our team has worked diligently to design a station that is not only functional and sustainable but also promotes the safety and well-being of its inhabitants. We have considered all aspects of the station, from its layout and interior design to its construction and power sources. The station's construction and operation will undoubtedly be a challenging endeavor, but it is also an opportunity to expand our understanding of the Moon and its potential for scientific discovery. We hope that our design will serve as a model for future space exploration projects and inspire new generations to continue pushing the boundaries of what is possible in space.

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