Development of a Permanent Manned Base on the Lunar Surface: A Comprehensive Study

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Abstract-

The goals of the lunar base are to sustain permanent human habitation of the moon, while also being open to expansions in the future, especially if the base grows into a colony. A base designed to sustain permanent manned habitation on the lunar surface will be situated near the lunar poles, ensuring sunlight for most of the year, which grants lighting without exposing the base to extreme temperatures. These locations also grant access to lunar water-ice in the surrounding craters.

The base will be supported by already existing or in-development systems developed by private companies to save time and money. In addition, the base will be launched in separate modules and connected on the surface, similar to the assembly of the International Space Station (ISS). In the testing, lunar regolith based concrete failed to withstand vacuum exposure and high thermal exposure. ISS-esque and regolith-covered designs were better performing, however when combined with the fact that regolith-covered modules would warrant sending an excavation vehicle to the base site, a station module design is the optimal method for initial base construction.

The base will be staffed by a series of rotating crews, ensuring a constant operation of the base. These missions will overlap so that the station always has two or more crews actively at the station at a time. Water-ice extraction will be handled by private companies, and as such was not covered in this study.

I: INTRODUCTION

Since the Apollo Program conducted by NASA began in the 1960s, a permanent human presence on the surface of the Moon, or a "Moon Base", has been a long-term goal of American, Russian, and Chinese space programs. With NASA's Artemis program slated to return man to the Moon within the coming years, the idea of a permanent human base has been brought back into the public's consciousness. This study will review several of the most common ideas for development of a crewed lunar surface base, as well as evaluating the advantages and disadvantages of each method. Then, the method for construction, assembly, habitation, and operation of a lunar base will be explored. These methods for the development of a permanent settlement on the lunar surface have been found to be cost-effective and timely, and can all be constructed using current technological capabilities.

II: RATIONALE

A. Habitation

The base will be able to permanently sustain a dozen people on the lunar surface year round, albeit requiring resupply missions from Earth. This base needs to provide not only mission space such as command & science, but living quarters such as beds and a kitchen. To fit the most utility into a limited space, the base's interior will be geometrically laid out similar to that of a submarine [2]. The base modules also need to include multiple points of entry and exit, ensuring that the crew can still leave in case an adjacent module depressurizes. To ensure the crew still has enough room to work and live, there must be at minimum $80m^3$ per person, with the exception of during a crew transfer, in which case the crew count may temporarily increase while the station is handed over to the new arrivals. The exact specifications of the habitation of the base will be elucidated upon in V and VIII.

B. Scientific

The scientific components of the base will be divided into two separate categories. First, geology, which will study the composition and history of the Moon, along with how the lunar resources can be used [10]. Second, biology, which will study how lifeforms can grow and adapt while living on the Moon, mostly in fields such as botany and medicine. On the base crews, each of which has six people, three of the crew members must have a postgraduate degree in a science field such as biology, chemistry, physics, or medicine.

C. In Situation Resource Utilization (ISRU)

The base will not initially sustain itself via ISRU, but the ability to extract, refine, and utilize the lunar resources needs to be a possibility in the future. Notably, the base needs to be able to supply power to ISRU systems. The resources available on the lunar surface are metals and water-ice [10]. Water-ice will be the focus of most manned lunar settlements, and any metal extraction facilities will likely be unmanned. As such, the base will also need to be situated somewhere with access to water-ice.

III: LOCATION

A. Region

Based on the analysis of multiple lunar maps and models from orbiters, the best location for the lunar base to be situated has been determined to be a ridge situated near the lunar south pole [1], at 88°43'12"S, 132°28'12W. Specifically, a three-way ridge, situated between Shackleton crater, Henson crater, and de Gerlache crater, which is only a few kilometers from water-ice sources, and which receives sunlight 93.97% of the year [13], preventing excessive nighttime operations on the lunar surface. As a consequence of this high latitude, the sun will remain low in the sky, which means that solar power will be inefficient compared to at the lunar equator.

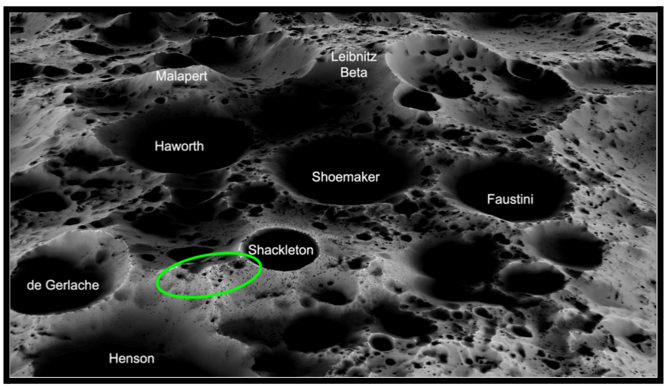

Figure 1 - LPI data-based CGI of the lunar south pole, with Octantis ridge circled in green.

B. Terrain

The terrain of the base location, which will be referred to as Octantis Ridge, is only available to us in low quality photographs. As such, a lunar orbiter, of which there are several, will scan the terrain ahead of time [3]. Given it is a ridge, and based on currently observed geology on the moon, Octantis will likely have a flat top with sloped sides, running between the three craters, with the centerpoint of the ridge being closest to Shackleton. This junction of the ridge will be roughly where the base is situated, but ahead of any base modules being landed, a preliminary scouting mission will occur. A pressurized lunar rover and manned lunar lander will touch down at the site, and then a crew will drive around the region looking for a spot clear of any notable obstructions. This excursion mission could be delegated to upcoming manned lunar missions such as Artemis V. Once this location is determined, the construction of the base can begin.

C. Resources

The main resource available for the base from Octantis ridge is water-ice at the bottom of nearby craters. These craters, due to their location at the lunar south pole, have permanently shaded interiors, enabling water to remain on the surface in its solid state rather than sublimating. [5] The Moon's surface is also covered in helium-3, an isotope of helium deposited by the solar winds that bombard the Moon. However, fusion electricity generators have not been developed to an efficiency or reliability that they can be deployed on the lunar surface, but in the far future the base may be powered by fusion energy using helium-3.

IV: BASE CONSTRUCTION MATERIALS TESTING

A. Station Modules

Based on the design of the ISS, this base design calls for the modules to be made in a similar fashion to the ISS, which results in a highly effective module at the expense of increased mass and cost. [9] The exact specifications of the design are that the module walls will be made of, inside layer to outside layer, are 0.25cm Titanium Plating , 20cm Polyurethane Foam , 2.25cm Whipple Shielding, and 0.25cm Titanium Plating. This will provide four times as much radiation protection for the crew as on the ISS, which is crucial because the lunar surface receives nearly four times as much radiation as the ISS does.

B. Regolith Covered

This design calls for unshielded station-like modules to be assembled, then covered in a half-meter of lunar regolith. This coverage will provide shielding while also reducing launch mass. [13] The exact specifications of the design are that the module walls will be made of, inside layer to outside layer, are 0.25cm Titanium Plating, 2.5cm Polyurethane Foam, 0.25cm Titanium Plating, 50cm Lunar Regolith, 0.5cm Thermal Fabric. This design will be the most effective relative to its mass and cost.

C. 3D-Printed Lunarcrete

An innovative design, this base consists of an inflatable habitat that is then shielded by a 3D-printed layer of lunar regolith aggregate concrete [5]. This is the most cost-effective and enables rapid expansion of the base, but it is highly experimental and the technology to 3D print the lunarcrete is still in development [3]. The exact specifications of the design are that the module walls will be made of, inside layer to outside layer, are 0.125cm Pressure Fabric + 18cm Lunar Aggregate Concrete. This will need to be validated by testing to prove that it is viable as a construction material for pressurized vessels.

D. Study Guidelines

The three listed designs will have test segments made for their validation. The primary research of this study will be to analyze the optimal method to construct and assemble a lunar base. Below are the three material combinations for the base construction being tested, inside layer to outside layer.

First, the station-module design. 0.25cm Titanium Plating + 10cm Polyurethane Foam + 2.25cm Whipple Shielding + 0.25cm Titanium Plating

Second, the regolith-covered design. 0.25cm Titanium Plating + 2.5cm Polyurethane Foam + 0.25cm Titanium Plating + 50cm Lunar Regolith + 0.5cm Thermal Fabric

Third, the 3D-printed lunarcrete design. (0.125cm Pressure Fabric + 18cm Lunar Aggregate Concrete

Each testing segment will be mounted with the "outside" facing up, and the "inside" facing into a 10cm*10cm*10cm lead-lined container. The test segment will then be held to the test bed by twelve steel clamps, and the space between the clamps will be sealed with flue tape, ensuring the point of failure will be the test segment. This assembly will then be subjected to a battery of experiments.

Vacuum: Assembly will be placed in a vacuum chamber, have 95% of the atmosphere removed, then be left inside for 5 minutes. The internal container will still be at 100% pressure. The assembly will then be removed and inspected for damage.

High Thermal: Assembly will be placed in an oven at 130C for four hours. The assembly will then be removed and inspected for damage.

Low Thermal: Assembly will be submerged in -80C dry ice for 30 minutes before being placed in a freezer at -20C for twelve hours. The assembly will then be removed and inspected for damage.

Microwaves: Assembly will have a microwave detector placed inside of it, then the assembly will be exposed to microwaves for 10 minutes, and the amount of microwaves that weren't blocked will be measured.

Radiowaves: Assembly will have a radio receiver placed inside of it, the radio receiver will then be contacted by a radio transmitter, and the quality of transmission will be measured.

Upon completion of these trials, the performance of each test segment will be compared, and, along with supplementary data on radiation from secondary sources, the optimal method was determined.

V: MATERIALS TESTING ASSESSMENT

A. Results

Each material will receive a score out of four for each of the five batteries based on their results against the batteries., with one being the worst and four being the best. The scores will then be combined to create a total score out of twenty.

Firstly, the station-module design. The segment withstood the vacuum exposure without incurring any damage or deformation, however, rapid re-exposure to pressure resulted in minor depressive deformations on the exposed side of the test segment. The segment withstood the high thermal exposure without incurring any damage or deformation, and cooled quickly after being removed. The segment withstood the low thermal exposure without incurring any damage or deformation, and warmed quickly after being removed. The microwave dosimeter recorded that only 30% of microwaves penetrated the segment. The radio receiver's audio was barely legible, data collection on the receiver implies that more than 72.5% of radio waves were blocked. In total, the station-module design received a score of 3/4, 4/4, 4/4, 3/4, and 3/4, for a total score of 18/20.

Secondarily, the regolith covered design. The segment withstood the vacuum exposure without incurring any damage, regolith simulant appeared to deform by shrinking in volume as the air between the regolith simulant particles was removed, rapid re-exposure to pressure resulted in the regolith simulant particles being launched into the air in a cloud of dust. The segment withstood the high thermal exposure without incurring any damage or deformation, and cooled quickly after being removed. The segment withstood the low thermal exposure without incurring any damage or deformation, and warmed quickly after being removed. The microwave dosimeter recorded that only 30% of microwaves penetrated the segment. The radio receiver's audio was barely legible, data collection on the receiver implies that more than 72.5% of radio waves were blocked. In total, the regolith covered design received a score of 3/4, 4/4, 4/4, 2/4, and 2/4, for a total score of 16/20.

Tertiarily, the 3D-printed lunarcrete design. Vacuum exposure resulted in minor cracks and chipping to the test segment, likely caused by tiny air pockets within the lunarcrete. Re-exposure to pressure did not result in any damage to the lunarcrete. High thermal exposure resulted in severe cracking and chipping of the concrete, potentially due to structural deformities inherent to the concrete due to its usage of regolith simulant as aggregate. The segment withstood the low thermal exposure without incurring any damage or deformation, and warmed quickly after being removed. Before high thermal testing, the dosimeter recorded that only 28% of microwaves penetrated the segment. However, after high thermal testing resulted in damage, 54% of microwaves penetrated the segment. Before high thermal testing, the receiver's audio was entirely blocked. However, after high thermal testing resulted in damage, only 60% or more of radio waves were blocked. In total, the 3D-printed lunarcrete design received a score of 2/4, 1/4, 4/4, 2/4, and 2/4, for a total score of 11/20.

Figure 2 - Photograph of Mr David Roberts mixing a test segment of lunarcrete.

B. Comparison

Before determining the ideal base method, first the methods that are unviable must be ruled out. In this case, the lunarcrete design. Studies conducted by other researchers found lunarcrete to be a viable construction material using on-site lunar resources [5], however in the testing for this research paper, the lunarcrete failed to withstand vacuum exposure and high thermal exposure. Sulfur-based lunarcrete may also be viable [7], however for the time being, lunarcrete will be ruled out for initial base construction. Station-module and regolith-covered were neck-and-neck in their results, however, station-module received the highest score, and along with the fact that regolith-covered modules would warrant sending an excavation vehicle to the base site, it will not be selected for the base construction. As such, the study recommends the station-module design be used for the development of a permanent manned base on the lunar surface.

VI: SECONDARY SPACECRAFT

A. Crew Arrival/Return Orbiter

For the Crew Arrival/Return Orbiter, Lockheed Martin's *Orion* capsule can carry up to six astronauts, and NASA is already using it for the Artemis Program. It will be launched on a New Glenn, then rendezvous with a Falcon Heavy transfer stage. The spacecraft will transport the crew from Earth to lunar orbit.

B. Moon Orbiting Space Station

For the Moon Orbiting Space Station, NASA's *Gateway* space station already meets the program's needs, and is currently in development, with launches planned for several years from now. It will be launched by various government-contracted private companies and assembled in lunar orbit.

C. Lunar Surface Access Module

For the Lunar Surface Access Module, Blue Origin's *Blue Moon* lander already meets the program's needs, and is currently in development, with test flights planned just a few years from now. It will be docked at Gateway until a landing, at which point it will go down to the surface with the crew. It will need to be modified to carry six crew rather than four, however Blue Origin has stated that it's capacity can be upgraded if needed, and since it will only act as the lander and not as a temporary base, less space per crew member is acceptable.

D. Pressurized Lunar Roving Vehicle

For the Pressurized Lunar Roving Vehicle, Toyota's *Lunar Cruiser* rover already meets the program's needs, and is currently in development in conjunction with JAXA, and deployments are being planned for several years from now. It will be landed by at the base site before other modules to pinpoint the base location.

VII: MANUFACTURING & COST

A. Contractors

Each system and module's contracting is best done by analysing both government partners such as other nations and by past experience that various companies have working in the respective field. [1]

The launch vehicles for the base will be contracted to Blue Origin and SpaceX, specifically Blue Origin's New Glenn and SpaceX's Falcon Heavy, as both are proven heavy-lift launch vehicles with a relatively low price point.

Node 1, the command center, and Node 7, the nuclear reactor, will be contracted to Lockheed Martin, as they have experience in designing both command control centers and nuclear reactors for space flight [13].

Node 2, the laboratory, and Node 3, the greenhouse, will be contracted to Thales Alenia Space in conjunction with the European Space Agency. They have experience building lab modules for the International Space Station, and which are contracted to help construct Gateway. In addition, this will help to tie in the European side of the project, creating incentive for them to help fund the program.

Nodes 4, 5, and 6, all of which are kinds of living quarters, will be contracted to General Dynamics, who have experience building both aerospace components as well as living quarters on US Navy vessels such as submarines, which is crucial given the habitation modules are based on submarine interiors [6].

Nodes 8-13, all of which are airlock/docking port combinations, will be contracted to Nanoracks, who built the airlock for the Space Shuttle and the International Space Station.

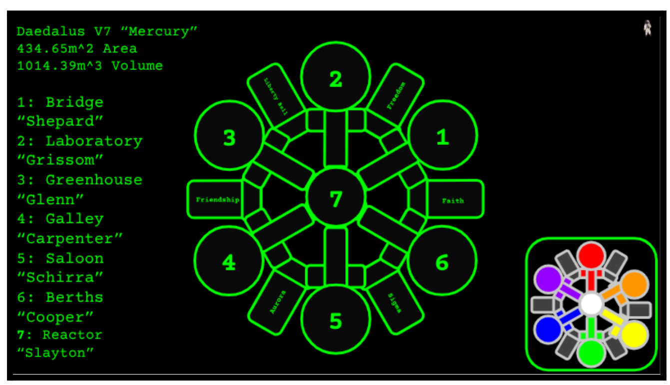

Figure 3 - Top-down sketch of a lunar base design based on this paper, with a key for base nodes.

B. Construction Cost

To calculate the cost of the base, the cost of both the modules and the launch vehicles must be calculated, along with the cost of testing. A lump sum of $2,000,000,000 for testing, integration, and pre-launch transportation will be included. All launches for the base's assembly will utilize either Blue Origin's New Glenn or SpaceX's Falcon Heavy, depending on the launch. New Glenn is ~$100,000,000 per launch, and Falcon Heavy is ~$150,000,000 per launch.

For base construction, Nodes 1, 3, 7, 8-10, and 11-13 will launch on Falcon Heavy, and Nodes 2, 4, 5, and 6 will launch on New Glenn. An additional Falcon Heavy launch will be required to launch the initial setup supplies and equipment. The initial cost of Orion, Gateway, four Blue Moons (three primary and one backup), and two Cruisers will not be factored into this as they are already going to be required for the Artemis Program. This brings the total launch cost for the base's construction to $1,600,000,000. As for the pricing of the modules, Node 1 will cost $20,500,000,000, based on the cost of prior Lockheed command systems. Nodes 2 and 3 will cost $10,000,000,000 each, based on the cost of Skylab and Spacelab. Node 4, 5, and 6 will cost$ 5,400,000,000 each, based on costs for General Dynamics sub systems. Node 7 will cost approximately $14,400,000,000, based on the cost of the NERVA and DARPA nuclear programs. Nodes 8-13 will cost $250,000,000 each, based on the cost of the Quest Airlock. This brings the total module cost to $67,200,000,000. Adding these values together, the total cost of building, testing, and launching the base is ~$70,000,000,000. Given that the ISS cost NASA ~$96,000,000,000 to build, this is more cost efficient, in large part due to the launch systems being far more economical.

B. Sustainability Cost

For sustaining the base, nine New Glenn launches will be required, and three Falcon Heavy launches will be required. Three New Glenns for Orions, six New Glenns for resupply missions, and three Falcon Heavys for the Orion transfer stages. In addition, Orion costs $1,000,000,000 per launch. Each resupply craft and transfer stage will cost $35,000,000. As such, a cost of $1,315,000,000 for all the craft per year and $1,350,000,000 for all the launches per year brings the operational cost of the base to $2,665,000,000, bring to $3,000,000,000 to account for crew training and testing of spacecraft. Given NASA spends $3,000,000,000 on the ISS each year, this is approximately the same cost, and as such is within current budget margins. As a final tally, the base will cost $70,000,000,000 to construct and $3,000,000,000 per year to maintain and operate, similar to the amount that NASA spent on the ISS.

C. Time Cost

For the time pricing of the base's construction, it must be consider how the base will be constructed. Notably, the base is not designed to work as one module and slowly expand, rather it needs all modules to function properly. As such, all modules will be developed simultaneously so that they can be launched at similar times. Assuming that the base is made an official program in 2026, and assuming that Gateway is fully operational by 2030, the scouting mission to find the base's exact landing site can occur the year after. Another two years will likely need to pass before the modules have been finely tuned for their location. Once this is done, up to two modules can be launched per month.

New Glenn is projected to be capable of launching ten times per year, and Falcon Heavy is projected to be capable of launching six times per year. Accounting for this, Nodes 6 and 7 will launch first, one requiring a New Glenn and one requiring a Falcon Heavy. Next, Nodes 1 and 2 are launched the following month, one requiring a Falcon Heavy and one requiring a New Glenn. Next, Nodes 8-10 and Node 3 will launch the following month, one requiring a Falcon Heavy and one requiring a New Glenn. Next, Nodes 11-13 and Node 4 will launch the following month, one requiring a Falcon Heavy and one Requiring a New Glenn. Finally, Node 5 will launch the following month requiring a New Glenn. As such, once the launches begin, the base could be fully launched in 7 months, more accurately 9 so that assembly difficulties can be accounted for.

Following the completion of these launches, landings, and dockings, the first crew can be sent to the base to fully setup the base and all it's systems. Accounting for this schedule, the base can be fully operational by 2034. If the base's development begins later, slide the end date down accordingly. In short, eight years from program start to base completion. This, however, does not account for private industry setups on the Moon such as those for water-ice extraction. Given the ISS took twelve years to build, this schedule is accelerated in comparison to that program.

VIII: PROCESS OF ASSEMBLY

A. Autonomous Assembly

Both the docking ports and each airlock acts as a docking port, both being based off of a scaled up version of the IDS. When the modules are landed, they will have wheels mounted on their side, enabling them to traverse the lunar surface, albeit at very low speeds. Once all modules are docked, the wheels are retracted up, and then removed by the crew upon their arrival.

B. Manned Setup

Upon arrival, the base's equipment and life support systems will be outside in the resupply craft. The crew will have to bring these in and set them up before the base can be utilized. While they set up the base, they will stay in the Blue Moon lander for habitation. The setup will take no more than three days, at which time operations can begin.

IX: CREW ROLES, SCHEDULING, AND ROTATION

A. Roles

A lunar base crew will consist of six astronauts [9]. At least two of the crew must have pilot qualifications in accordance to NASA regulations. One of these astronauts with pilot qualifications will be mission commander, and another will be mission pilot. At least two of the astronauts must have engineer qualifications in accordance to NASA regulations. One of these astronauts with engineer qualifications will be the flight engineer. At least two of the astronauts must have scientist qualifications in accordance to NASA regulations. Preferably the fields in which they are trained are chemistry for the ISRU lab, or botany for the greenhouse experiments, however these are not requirements. At Least one astronaut must possess medical qualifications in accordance to NASA regulations. This astronaut will serve as mission surgeon. If all crew requirements are filled and there are still available slots, they may be filled by other mission specialists or private astronauts. Another requirement is that two of the astronauts on each mission must be from foreign space agencies, such as CSA, ESA, or JAXA. These crew do still need to meet the NASA qualifications for their respective fields, however. Roscosmos and CNSA astronauts are specifically prohibited from being assigned to base crews or visiting the base in accordance with Public Law 112-10 Section 1340, also known as the 2011 Wolf Amendment.

B. Scheduling

Each crew will spend 250 days at the lunar base [13], with at least two crews at the base at a time. Ten days before a mission leaves the base, another one arrives and begins the transfer process. To ensure continuous base rotation, there will be a new crew approximately every four months. The base commander is the mission commander of the crew with seniority on the base.

C. Rotation

Two launches will be required per crew launch, one for a transfer stage, and another for Orion. In this case, a Falcon Heavy will launch as the transfer stage, and a New Glenn will launch Orion. The two will rendezvous in low Earth orbit, perform their trans-lunar injection burn, and undock from the transfer stage. Afterwards, Orion will perform lunar orbit insertion and dock with Gateway. The crew will then transfer into a Blue Moon lander and land on the surface near the base. Once the crew enters the base, the ten day overlap period is used to adjust the new crew to the base. Following this, the crew that has just completed their 250 day shift will depart the base in the Blue Moon lander that they arrived in.

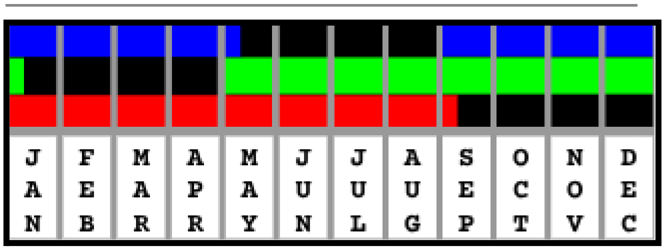

Figure 4 - A graphic of the schedules of the three base crews, illustrating how they overlap for crew transfer and base command turnover.

During their stay on the surface, the astronauts will receive ~100mSv of radiation. The NASA radiation limit for NASA astronauts over their entire career is 600mSv [2], meaning that an astronaut can be assigned to a maximum of 6 crews to the base. Given time spent on LEO missions and on surface EVAs, the more accurate amount of base crews an astronaut could be assigned to is 4-5. Given that the highest amount of days spent in space by one person in total is 1110, which would be approximately 4.5 stays on the lunar base, this limit will be relatively reasonable.

X: EMERGENCY PROCEDURES

A. Health Emergency

Incase of a physical medical emergency on the base, such as a fever or other illness, the afflicted crewmember is to abstain from their mission duties until they are well again to ensure a swift recovery. Incase of injuries such as cuts or punctures, onsite medical equipment can be utilized, preferably by the crew surgeon, to treat them. If an illness or injury is too severe to treat on-base, the crew on which that member is assigned will be split, and the mission pilot, along with the afflicted crew member, will return home early. If the mission pilot or mission commander of a crew must return home early, the mission pilot of the other crew on the base will return home with them. This early return will leave the rest of the crew temporarily without a lander, but the backup lander can be autonomously sent down to the surface to remedy this absence.

B. Mental Breakdown

Incase of a mental breakdown such as a panic attack or fit of rage, the base commander will determine if the crew member is fit to complete their duties. If not, they are to be relieved of duty until such time as they are considered fit to complete their duties again. If severe enough, they may be sent home in a similar manner to that incase of severe medical emergency.

C. Life Support Failure

Incase life support systems such as the water reclaimer, CO_2 filters, or temperature control fail, backup systems are in storage and can be installed by the flight engineer. If these also fail, the base is to be temporarily abandoned and the crew will proceed to the Lunar Cruiser rovers, which can support crews for up to 30 days. If the system failure cannot be remedied in this time, the crew is to return to their landers and return to Gateway, where they will spend the rest of their mission duration.

D. Reactor Failure

Incase the base's nuclear reactor goes near critical, or otherwise has significant issues, the system will automatically shutdown [11]. In this scenario, the solar panels present on the individual modules for their autonomous operation will be utilized for backup power, but power to external systems such as the rovers or ISRU equipment will be turned off. Once power to the reactor is restored, base operations will return to normal.

E. Atmospheric Depressurization

Incase of depressurization, the connecting modules will be shut off but the adjacent airlocks will still be accessible, enabling any crew in the depressurizing module to escape. The entire crew will don their spacesuits and the source of the depressurization will be identified. It will then be sealed, pressurization will be tested, and if successful, the crew can take off their spacesuits. If a full seal cannot be obtained, the crew will perform the same contingency as incase of life support system failures.

F. Geomagnetic Storm

In the event that a coronal mass ejection is projected to hit the base, all base crew will proceed to the reactor module and seal all connecting doors. This is the most radioactively protected module in the entire base, being in the center of all other modules and covered on top by the reactor. Once the storm is over, the crew can return to their normal activities.

XI: THE NEAR FUTURE

A. Operating Costs

As the base expands further, costs to supply the base with new crews, supplies, and repair costs to pre-existing equipment, the cost of the base may double within the first 20 years of operation. Additionally, Falcon Heavy, one of the two launch vehicles contracted to support the base, will cease operation, as it's parent company SpaceX transitions to using their Starship launch system. As such, a new heavy-lift launch vehicle will be needed to fill in the gap in flights. Based on current launch vehicles in development, Relativity Space's Terran R launch vehicle will act as a low-cost replacement for the Falcon Heavy's missions. Another launch vehicle that could fill the Falcon Heavy's slot is a proposed "Vulcan Heavy", a derivative of the Vulcan-Centaur with the SRB's replaced with two Vulcan core stages.

B. Base Expansion

The base design accounts for potential future expansion to the base to enable growth, which in turn enables a longer lifespan for the base's utility. Potential expansions are larger habitation modules, newer laboratories, ISRU modules, or storage units. These modules, in turn, will also include docking ports and airlocks to enable further expansion of the base. In addition, the option to begin utilizing other construction methods not used in the original base's construction, such as lunarcrete, will be considered to reduce cost. However, this will require more infrastructure. Non-connected expansions to the base are those of mining equipment, additional rovers and 3D printers.

C. Civilian Habitation

The fact that crews will be staying on the base for longer and longer periods of time, especially as radiation shielding improves, means that there may be an incentive for people to move to the base full time. In this scenario, some are likely to bring family members with them, in which case the base must account for the fact that there may be people on the base who are not working, rather living. As such, large habitation modules similar to a hotel or apartment complex will need to be developed in conjunction with the exportation of resources and the development of greenhouse projects. The base must be able to adapt to these new demands.

XII: THE FAR FUTURE

A. Resource Exportation

The base will not be capable of being funded solely by tax funding forever. One potential avenue of generating incentive to continue the development of the lunar base is that of exporting resources, namely hydrogen, oxygen, chromium, scandium, and yttrium, back to earth for profit. This profit would then be put back into funding the base, similar to how colonies in the Americas were supported by exporting raw resources to their home countries. This will require far more advance equipment than planned for the initial base, but that can be developed and sent when the base grows enough to warrant it.

B. Self Sustainability

The greenhouse module of the initial base will serve as a tech demonstration of a more advanced greenhouse module that could be sent to the base.This larger greenhouse could grow food for the crew to eat reducing the need to resupply missions. Additional forms of on-site food production, such as hydroponic fish farms, may be viable sources of food for the crew. However, these technologies are still in development, and the feasibility of such technology is not yet fully known.

XIII: CONCLUSION:

As mankind expands his domain out into the cosmos, the methods in which a foothold is established must be carefully considered, so that programs such as Artemis do not backslide and abandon the Moon like the Apollo program. At the same time, the Artemis program must be set up in a manner than can both reuse existing architecture while also innovating. This proposed lunar base, with a permanent crew of a dozen, space station derived modules, and potential for exploration, research, and exploration, is what the Artemis program needs to succeed. Additionally, the lunar base proposed here can be built for less than the International Space Station, so this base proposal is more likely to get approved by U.S. congressional committees. The time to begin the colonization of space is right now, and the development of a permanent manned base on the lunar surface is critical to such an effort.

XIV: REFERENCES

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