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Lunar Economy Village Initiative (LEVI)

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A Lunar Economic Village Initiative (LEVI) is proposed as the design basis for a lunar settlement aimed at enabling commercial mining of Lunar Minerals. LEVI is ultimately envisioned to positively benefit industry, promote economic growth, and make a meaningful impact to the present climate crisis on Earth. LEVI introduces technologies and operational concepts organized within a phased development plan that support and enable the successful return of lunar minerals to Earth. Currently, excessive CO_2 generated from terrestrial power production is one of the main culprits for greenhouse gas emissions on Earth. Promising alternative energy approaches such as nuclear fusion require rare Helium-3 isotopes that are almost non-existent on Earth. Future wide-spread adoption of nuclear fusion as a power resource therefore cannot rely on fission by-products. Lunar mining can be a promising solution for both, and hence, is the focus of LEVI—a concept of operation for infrastructure supporting Lunar mining as well as a human settlement conceived in two parts: a main settlement within the Polar Region as well as a mining outpost at a Mineral Rich Lunar Maria deposit site.

I. Nomenclature

ACCD	=	Art Center College of Design
AIAA	=	American Institute of Aeronautics and Astronautics
ISS	=	International Space Station
ISRU	=	In situ-resource utilization
LEVI	=	Lunar Economy Village Initiative
NASA	=	National Aeronautics and Space Administration
PSR	=	Permanently Shadowed Regions
SDG	=	Sustainable Development Goals
STEM	=	Science, Technology, Engineering, Mathematics
LEO	=	Low Earth Orbit
LLO	=	Low Lunar Orbit
LCROSS	=	Lunar Crater Observation and Sensing Satellite
LRO	=	Lunar Reconnaissance Orbiter
K	=	Kelvin
PV	=	Photovoltaic
KREEP	=	K-potassium, REE-rare earth elements, and P-phosphorus
PKT	=	Procellarum KREEP Terrane
^{3}He	=	Helium-3
EVA	=	Extravehicular Activity
CO_2	=	Carbon Dioxide

II. Introduction

Major mineral deposits on the Moon like ^{3}He (Helium-3) are generally at great distances from the polar regions. On the other hand, the polar regions are highly promising potential locations for sustaining a prolonged human presence, as evidence from the Lunar Crater Observation and Sensing Satellite (LCROSS) and other missions suggests that Permanently Shadowed Regions (PSRs) in the polar regions contain valuable water-ice deposits. The scope of the Lunar Economy Village Initiative (LEVI) is conceived in two parts: a main settlement

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within the Polar Region as well as a mining outpost at a Mineral Rich Lunar Maria deposit site. The outpost develops and expands on existing Earth-based mining technologies that can be developed and adapted in-vacuum and introduces zoning principles (land-use and master planning principles) for the outpost to achieve successful mining operations, including mineral comminution, beneficiation, extraction, and export of the minerals back to Earth. The settlement at LEVI focuses on the construction of multiple habitats via in-situ lunar regolith additive manufacturing (3D-printing) and proposes a method for outfitting the interior of the habitats over the course of a predominantly autonomous construction process. The main settlement will allow expedition teams to routinely visit mining outposts to support semi-autonomous mining operations and maintenance. The main settlement and mining outpost are proposed to be constructed in five distinct phases in parallel, with each successive phase further expanding the size of the settlement and its necessary components to enable additional capabilities and enhanced operations: culminating in cost-effective lunar mineral export back to Earth.

The infrastructural challenges of supporting a permanent human presence on the Moon and Mars parallel many large-scale human health and sustainability challenges on Earth. In 2015, the United Nations General Assembly adopted 17 Sustainable Development Goals (SDGs) aimed at steering institutions, economies, and policies towards sustainable objectives shared by all. Several of the United Nations' global sustainable development goals parallel the goals of sustainable development for a permanent human presence in space, including the creation of sustainable cities and communities, responsible consumption and production, clean water and sanitation, good health and well-being, and more. An aim of LEVI is therefore to help improve several United Nations Sustainable Development Goals (SDGs), including climate action, affordable/clean energy, decent work and economic growth, industry, innovation, and infrastructure.

The Climate Action SDG aims to reduce current energy production's pollution, with its excessive CO_2 (Carbon Dioxide) emissions being the major contributor to climate change. Global power generation currently accounts for around 40% of all CO_2 emissions [1, 2], primarily from the burning of fossil fuels like coal, natural gas, and oil. This contributes to a potential global average temperature increase of 5-8 degrees Celsius by the end of the 21st century [1], and will severely impact ecosystems and people's livelihoods. It is essential that renewable and alternative energy sources, like nuclear fusion, replace fossil fuel power generation sources to minimize CO_2 pollution. However, many renewable energy generation sources are geo-limited, with nuclear fusion being one of the few cleaner power sources that can plug into existing power grids anywhere. However, nuclear fusion fuels like tritium, deuterium, or ^{3}He are very scarce on Earth. Lunar mining can offer large quantities of ^{3}He fusion fuel, which is crucial for sustaining an affordable nuclear power source in the future. The industry SDG aims to develop sustainable and inclusive economic growth and development worldwide. Over 45% of the current global economy relies on minerals produced by mining-related industries. However, accessing the deeper mineral-rich mantle layer on Earth is challenging, due to pressure and temperature limitations in traditional mining methods. The scarcity of certain minerals in the crust may lead to economic challenges and unemployment in mineral-dependent industries with increasing demands. Establishing a lunar presence will open access to various lunar mineral resources, which can be exported to aid various industries on Earth. A lunar presence also requires international contributions from various private industries and will expand the workforce to create more jobs for people.

III. LEVI Site Selection

The main settlement will be constructed adjacent to a PSR with easy ingress/egress access, and water ice presence to provide a critical water supply to the settlement. The site should also have a relatively higher average temperature and flat terrain for future expansion of the settlement. The PSR temperature and crater topography provide great benchmarks for determining settlement support elements adjacent to the settlement site itself. According to Paige et al. (2010) and the LRO Diviner instrument [3], PSRs like the ones in Shackleton, Shoemaker, Haworth and Cabeus all have a low average temperature suitable for water-ice preservation. However, the maximum temperature in the Shackleton PSR would rise to around 100K, while other PSRs in the region have a colder average temperature of 70-80K. A smaller temperature fluctuation is optimal for water ice preservation. The area of the PSRs is relatively much larger on Shoemaker and Haworth compared to Shackleton and Cabeus, meaning a higher chance of larger water ice deposits. The topography is important to analyze the ingress/egress accessibility of each crater. Shackleton is a relatively younger crater than others, and has steeper slopes. Shoemaker and Haworth on the other hand, have gentler slopes than Shackleton due to their more eroded rims. Cabeus has the most eroded rim of the other three and has the most accessibility, due to being one of the oldest craters in the region. Another point of interest worth considering is that on Mons Malapert, a relay tower and a solar PV generation zone can be set up, which can allow direct communication with Earth and additional support for the power infrastructure. For the settlement site, the site temperature is benchmarked using the temperature the International Space Station (ISS) experiences: Between 153 K (Dark side) and 393 K (Sun side), with an average of 273 K [4]. The non-PSR regions at the South Pole in general have a lower average temperature compared to what the ISS experiences. The sun-facing slope of Mons Malapert has the highest average temperature of around 176-200K in the entire local region, but is not a suitable topography for construction. The flatter terrains near a PSR that have higher average temperatures, and easy access into a PSR are: rim of Shackleton crater, north-east of Haworth/east of the Mons Malapert region. Other hotter locations are either far from PSR, or do not have suitable topography for the accessibility of PSR/settlement expansion. Below is a chart scoring each of the site candidates around those four PSRs based on the PSR average temperature (water-ice deposit preservation chance), PSR topography (suggestive of accessibility), Crater Accessible Warm Flat Region Average Temperature (Settlement environment hostility), and Crater Accessible Warm Flat Region Topography (suggestive of settlement constructibility). Each site option is scored from 4 (highest) to 1 (lowest) for each category:

Site	Crater PSR Average Temperature (K)	Crater/PSR Topography	Crater Accessible Warm Flat Region Average Temperature (K)	Crater Accessible Warm Flat Region Topography	Site Candidate Score
Shackleton	51-60 (2)	Steep slope (>20°), smaller PSR (2)	151-175 (4)	Very close to PSR, rim terrain(0-5°) (4)	8
Shoemaker	31-40 (4 tie)	Medium/calm slope (10-15°), large PSR (3 tie)	126-150 (3 tie)	Far From PSR, flat terrain(0-5°) (2)	12
Haworth	31-40 (4 tie)	Medium/calm slope (10-15°), large PSR (3 tie)	126-150 (3 tie)	Closer to PSR, slope(5-10°) (3)	13
Cabeus	41-50 (3)	Slight slope/flat terrain (0-5°), smaller & scattered PSRs (4)	126-150 (3 tie)	Far from PSR, slope(5-10°) (1)	11

Table 1. LEVI Site Selection Candidates (Sites near Shackleton/shoemaker/Haworth/Cabeus)

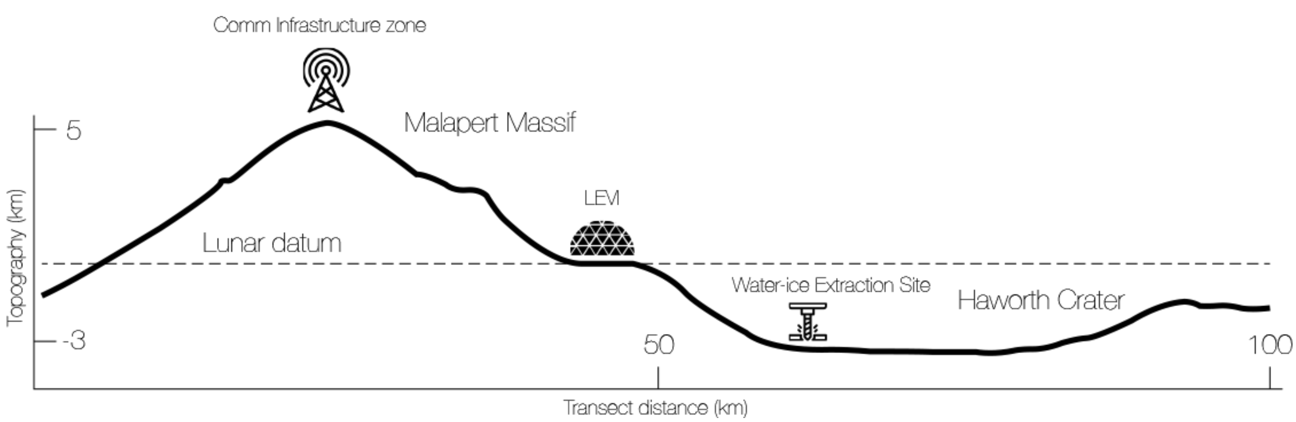

Figure 1. LEVI Site Overview relative to topography

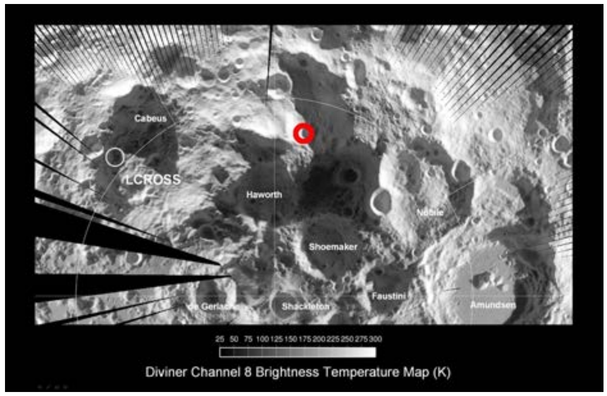

Figure 2. Lunar South Pole Imaged by LRO Diviner [5] with Main Settlement Site Selection circled in red

Based on this analysis, the site near north-east of Haworth/east of the Mons Malapert region scores the highest, it is marked with a red circle in Figure 2. This site also allows the main settlement to be constructed potentially adjacent to the future Artemis Base Camp landing site, with the ability to assist each other on various tasks within the region. The potential Artemis landing sites of Haworth and Malapert Massif (Figure 17) all have direct access to Haworth crater, potentially sharing water-ice deposits & communication infrastructure.

The Lunar Mining Outpost's main objective would be extracting ^{3}He for Earth bound nuclear energy production, while the secondary objective is to extract various metals for either In-Situ Resource Utilization (ISRU) or export purposes. The exact location of the outpost would be determined after a high mineral concentration is located through on-site prospecting using ground penetrating radars and robotic pilot drill prospect missions. ^{3}He concentrations are especially high in the high-Ti mare basalts, in regions like the Mare Tranquillitatis and Oceanus Procellarum (Figure 18). The concentration of helium 3 exceeds 20 ppb, and by Ian A. Crawford's measurement [6], those two regions consist of an estimated ^{3}He total mass of 2×10^{8} kg [6]. The ^{3}He is embedded in basalts that spread across the entire surface and require extraction. The concentration of the ^{3}He is low in the polar region, and current data lacks information about PSRs low temperature's effect on ^{3}He retention. Metals like iron and siderophile elements are predominantly present in silicate materials such as pyroxene, olivine [7], and ilmenite, both require mineral extraction to separate them from the ore. Figure 19 by Mark Robinson and Miriam Riner shows that the Oceanus Procellarum (right side of the figure) contains abundant olivine concentration. The South Pole–Aitken basin (SPA) near the south pole lacks olivine concentration but exhibits higher concentrations in other minerals like Aluminum. KREEP on the other hand, is found sandwiched between the lunar crust and mantle, with thorium and uranium serving as tracers for KREEP concentration detection. As shown in Figure 20, the thorium concentration is centered around Oceanus Procellarum. Current research indicates that the concentration of REE in urkreep at Apollo 14 and 15 landing sites is approximately 0.12 wt%[6], while Chang e 5's landing site (Oceanus Procellarum) shows a slightly higher concentration of REE lithophile elements [8, 9]. These findings suggest a lower-than-expected REE concentration on the surface. However, the Chang e's sample depth at 2 meters, and a similar sample depth for the Apollo 15 mission may not have penetrated beyond the local regolith, or the local deposit may not be as concentrated. More data would need to be gathered on future prospecting missions covering a larger land area/deeper depth. Based on the above data, Oceanus Procellarum is a strong site candidate for mining outpost construction.

IV. LEVI Settlement Design

Two operational bases are proposed; a main settlement northeast of the Haworth crater, and a mining outpost in Oceanus Procellarum region. The main objective of LEVI main settlement is to sustain long term human survival on the Lunar south pole.

A. Overall Zoning

The main settlement will be built in 5 stages, with each phase adding more infrastructure to increase settlement personnel capacity, operation capability, and living standards. The settlement's basic operation can be satisfied with three habitats, a living module, an entertainment module, and an operation module. Those three modules act as one branch section of the settlement, with each branch able to support 12 astronauts. Two branches of habitat make up one zone, and each zone is isolated from other zones to isolate hazard damage to the overall settlement. Between the zones, a Funifor cable car system allows crews to travel between zones without the need of EVA (Extravehicular Activity). In Phase I, only one branch will be constructed. This number will be increased to as many as 16 branches (8 zones) in the final phase, with a capacity of 192 astronauts. To benchmark an expanding construction timeline, the settlement will be constructed in a linear direction, around the expanding Funifor cable car system. The main settlement construction phases will happen in parallel with the construction phases of the mining outpost.

B. Modular Habitat Design

The Main Settlement comprises multiple modular habitats with different uses, such as a living module, entertainment module, and operation module. These identical modules are interconnected by inflatable and extendable hallways, forming the primary living spaces for astronauts. Each modular habitat is a hybrid class 3 structure [10], featuring an outer 3D-printed regolith shell, a foldable inner insulation structure, a soft bottom and top sealing structure layer, two connector shafts, and a top 3D-printed regolith roof. The design prioritizes using ISRU materials for the outer structure and foldable inflatables for easy packaging during transportation. The habitats can be stacked and connected via two connection modules on each side. Additionally, two side windows offer astronauts views outside for mental relief.

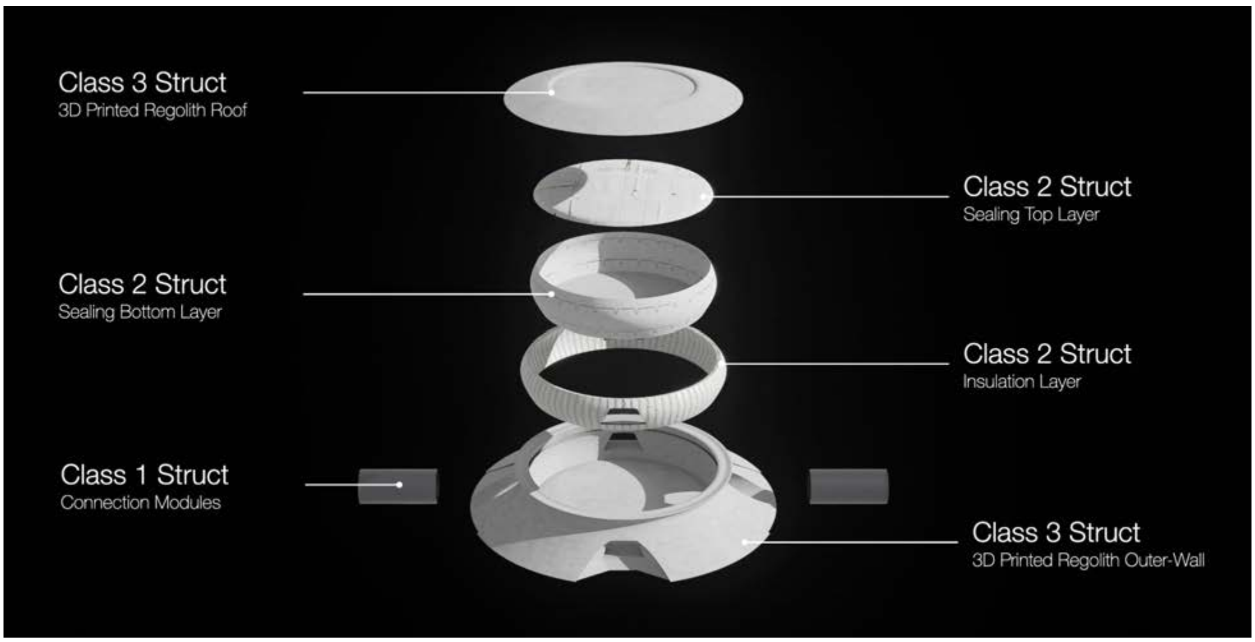

Figure 3. Modular Habitat Explosion View

The construction process of a single habitat is as follows: first, excavation will create a foundation pit, followed by reinforcing the pitwall by printing the regolith to the wall using construction feedstock from the excavation process. Next, the regolith outer-wall will be printed. Upon completion of the outer-wall printing, the connection module and insulation layer are installed. Subsequently, the bottom sealing layer will be installed inside the outer-wall, and its openings will be connected with the connector modules. With the bottom part of the sealing complete, the top opening will allow easy outfitting of larger equipment and also allow the printer to print interior non-structural walls using regolith. When outfitting is done, a top sealing layer will permanently seal the top of the bottom sealing layer, akin to closing a lid. Concurrently, the regolith roof is continuously printed from the top of the outer-wall towards and extending over the top.

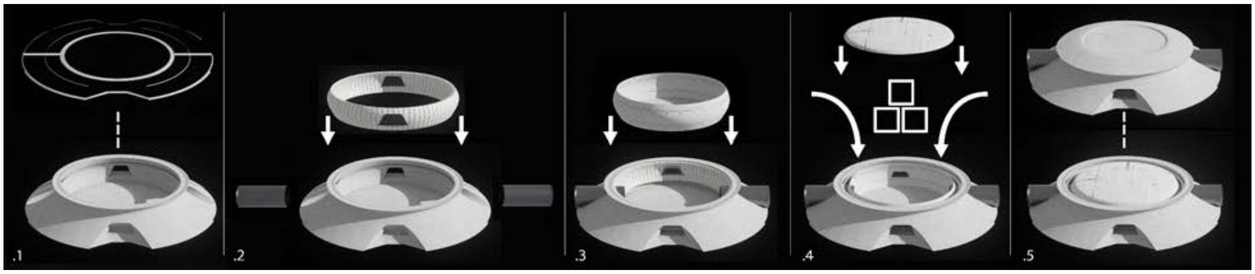

Figure 4. Modular Habitat Explosion View

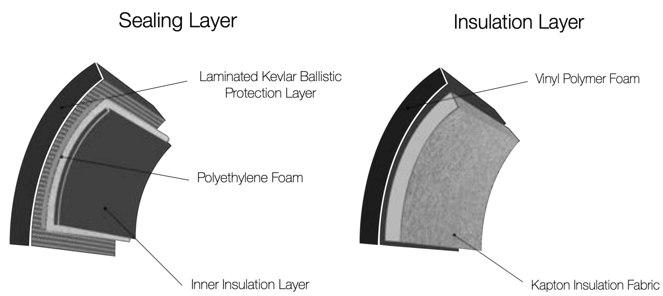

Figure 5. Modular Habitat Sealing/Insulation Materials

To deal with the low temperature at the pole, the insulation layer of the habitat serves dual purposes: enhancing temperature insulation while also providing some structural integrity to the regolith structure. Inside, the atmosphere-sealing layer assumes a critical role in holding the atmosphere in for life support. It consists of a laminated Kevlar ballistic layer, acting as the final line of defense against potential micrometeorites impacts. Additionally, there is a layer of polyethylene foam for further temperature retention and multiple fabric layers to effectively seal the atmosphere. Both the living module and the operation module will be semi-submerged from the lunar surface, using the natural terrain as a part of their natural defense against space radiation and micrometeorite impacts. The entertainment modules, however, will be built fully above ground level, allowing easier docking of the Funifor cable car system for in base transportation.

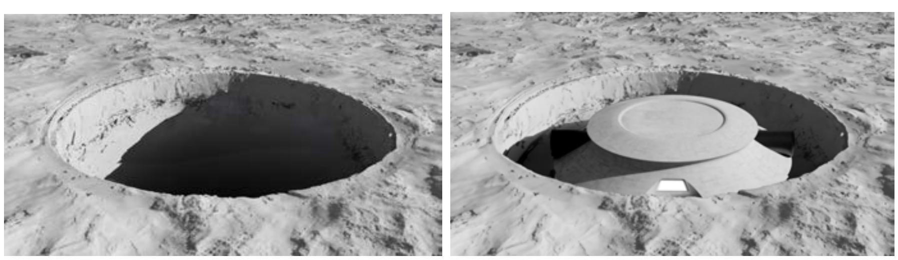

Figure 6. Modular Habitat Before/After Construction

Figure 7. A settlement branch with Funifor Cable Car on the right

C. Modular Habitat Interior Zoning

The zoning of the modular habitat interior is primarily built around the central hallway to facilitate an efficient flow of people and materials between multiple habitats. The cut through central hallway will allow uninterrupted foot traffic across multiple habitats, without the need to go through other room sections. The rest of the interior is divided into hallway left and right rooms, where different room layouts are designed for different habitat functions. Figure 8 shows the floor zoning of each module, with the brown lines representing the 3D printed interior regolith walls. The living module's interior layout has self-sustaining life support and essential survival supplies. With a capacity for up to 12 crew members, it features private crew quarters on one side of the habitat, atmosphere control systems, water storage, radiation shielding, and functions as an isolated shelter in case of emergency. Additionally, the module is always connected to an airlock module, which features a standard EVA airlock door and three EVA easy egress ports.

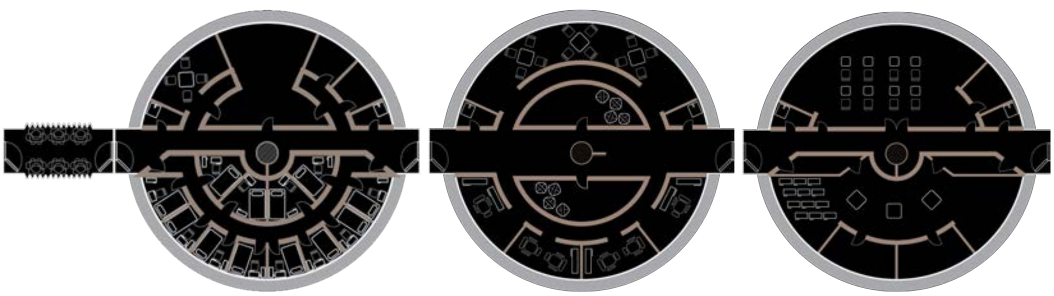

Figure 8. From Left to right, Living Module, Entertainment Module, and Operation Module Floorplans. (Brown indicates regolith printed interior walls)

The entertainment module's interior layout features customization upon construction. The printing construction of the interior walls along the two room areas will depend on the specialized usage of the specific rooms, such as cafeterias, VR rooms, gyms, medic bays, or storage rooms. The operation module interior layout is operation oriented, similar to entertainment module layout, each room can be tailored on construction for specialized operational roles. Both the entertainment modules and operation module’s customizable interiors are designed around the central hallway, with both module types sharing life support produced from the closest living module through air ducts and pipes.

D. Base Transportation System

The Funifor cable car is a proven mode of transportation on Earth, and, according to Peasrson [11], could work very well in a low gravity environment. A much longer span can be connected between the towers to clear very difficult terrain. It is a great system to transport people and goods between two fixed destinations, and would work well as the on-site transportation system in the main settlement. The entertainment modules of the settlement are constructed above ground to act as cable car docking stations. The flexible airlock docks on each side of the cable car will simultaneously dock with a maximum of two entertainment modules on both sides, creating a hallway between two neighboring zones for personnel and goods to move across. Traveling to zones further away will require staying on the cable car until it moves into the next station.

E. Main Settlement Construction Timeline

Phase I aims to construct an initial base infrastructure for the first human crews. Rover missions will explore the regolith's volatility, terrain, and on-site resources like water ice beforehand. Once the specific site location is picked, robots will construct landing pads. Major construction materials will arrive by landing pads, with initial construction utilizing remote VR control to aid in phase I construction. Essential infrastructure, including water ice extraction equipment, lunar mobility vehicles, and electric grid, will be constructed first. Then, with all the materials on-site, construction of the 3 habitats can begin. Phase I would conclude with the completion of habitat construction. Phase II aims to test initial settlement survivability with crew inside. Crew members will arrive on site for the first time and complete additional construction. Crew members will validate the settlement by living for a test period of time, focusing on base operations and prospecting water ice spots for potential extraction in Phase III. This phase will test all aspects of settlement operations crucial to the astronauts' survival. Phase III aims to expand the base capacity to 36 astronauts with expanded operation capabilities. Two additional branches of habitats will be built, with the construction of the funifor system connecting those two zones together. In this phase, on-site water extraction operations can begin to transport water ice from the PSR water site to the settlement. Operation modules will install additional equipment for electrolysis, thermodecomposition, and thermal chemical processes. The other operation module will focus on remote commanding of the mining operation in the mining outpost. There will be a dedicated gym to accommodate long term astronaut stays. At this stage, the settlement still largely relies on Earth imported resupply missions to sustain base operations.

Phase IV aims to establish a large settlement with basic self-sustaining capabilities, including on-site food and water production. The goal is to accommodate up to 96 astronauts, in 24 habitats in total. In this phase, the mining outpost will be able to provide valuable construction materials like metals for additional support of construction materials on projects within the settlement. Each zone can be specialized in general towards a specific operation, such as science-focused or mining focused. Additional landing pads will be constructed to house backup departure rockets and supply landers. A relay tower can be constructed on Mt Malapert massif [12], allowing direct communication with Earth. The mining operation in this stage will be providing oxidizer for the Lunar Gateway, so one of the objectives of the main settlement would also be focusing on the production of hydrogen to fuel the landers on the gateway. Phase V aims to establish a fully functioning lunar surface economy with complete self-sustaining capabilities. The settlement's capacity goal is to sustain a total of up to 192 people, made up of 48 habitats in total. In this phase, the settlement will act as a mining operation hub for different commercial operations to integrate with the base. By doubling the habitats, more spaces can be accommodated for additional personnel to support different commercial objectives on the lunar surface. Greenhouses and on-site water ice storage will reach a point where they can sustainably produce enough food for the astronauts in the settlement. Various modules will have fully expanded capabilities to command lunar surface, orbit operations to create a viable lunar economy.

V. LEVI Mining Outpost Design

The LEVI mining outpost's main objective is the export of ^3He and valuable minerals back to Earth and other parts of the lunar system. Oceanus Procellarum’s absence of water-ice means the location can not support a long term human presence without enormous amounts of surface resupply. Thus, a semi-autonomous mining outpost is needed with minimal human upkeep. There will be on-site maintenance missions from the main settlement maintenance team from time to time, and they will stay in a small habitat on-site for short term stays. The outpost will be expanded in phases to increase mining operation capabilities, mineral processing capabilities, and meet increasing export demand. Thus, the minefield bench geometry needed to take into consideration the future expansion.

A. Lunar Mining Process

The general mining process on Earth consists of six steps. First, prospecting, exploration, and delineation are the processes of locating and validating mineral deposits. Next is bench geometry, designing a minefield infrastructure for the mining and processing operations. Then, mining operations mine raw ores from the ground, and the raw ores undergo mineral processing operations to become purified materials. Further refinement of the purified material will turn it into industrial-grade materials. This end-product is then distributed to end-users for further productions [15]. In lunar mining, exported material weight vs. value is an important benchmark in determining the economic margin of exported minerals to Earth. It is best to process the natural ores into concentrated, purified materials, before they are exported to Earth. [13] Most of the current refining methods require an atmosphere and large, complex equipment, bringing those to the lunar surface are impractical at this stage. In conclusion, the lunar based operations at the mining outpost will consist of prospecting, exploration, delineation, bench geometry, mining operations, and mineral processing. The processed ore will be exported to Earth to undergo further refining processes before distribution. The mining outpost will operate within the parameters of all lunar-based operations mentioned above.

B. Lunar Mining Operation Types

Precision mining explosives are the primary way to efficiently remove earth in most mines nowadays, but this method is too dangerous for space mining at the moment and will not be the focus of this paper. Methods like bucket wheel excavators and dozers should be utilized for lunar scenarios. Lunar mining operations consist of three types: surface or near-surface mining, open-pit mining, and underground mining. [14] Strip mining is a type of surface mining that can cover a large area of shallow depth, and is ideal for ^3He mining. The disadvantage would be the waste ores each rover would have to carry back to the outpost, which likely means low mining efficiency. In an autonomous sense, strip mining can be largely automated through the use of autonomous strip mining rover swarms. To increase mining efficiency and quantity, open-pit mining can access deeper depths at a much larger quantity. Open-pit mining mines the pit in a circular pattern, layer by layer from the top to bottom. This mining method creates ramps that go from the surface towards the pit center for transport trucks. Open-pit mining has a higher mining efficiency than strip mining because it's usually fixed on a locally concentrated mineral deposit, and the open pit can be mined and extract a large quantity of minerals without outstanding transportation infrastructure. In a lunar mining scenario, large quantities of underground olivine and ^3He deposits could justify an open-pit minefield. Open-pit mining can utilize automated mobile bucket wheel excavators along pit walls for mining, and autonomous trucks for mineral transport to be fully autonomous. For much deeper deposits, underground mining can be utilized. Underground mining usually involves shaft style mining, and usually requires extensive infrastructure for shaft support. In a lunar mining scenario, if a much deeper, concentrated deposit of olivine, or rare earth metal is located, a manned underground mine should be justified. In an autonomous sense, long-wall type mining using a bucks wheel can be utilized if the deposit is located in a horizontal shape, this type of underground mining can be operated autonomously without staff.

C. Surface Mineral Transportation System

Different transportation systems will be employed based on the different types of mining operations. In strip mining, mining rovers will either carry minerals directly to the mining outpost site, or they can work alongside dedicated transport haulers that drive to a rally point for the rover swarm to unload onto. For open-pit mining, transport haulers and funifor carts will handle mineral transportation. Transport haulers will carry excavated minerals from the bucket wheel excavator to the top of the pit. Unloading onto the cart on a Funifor cable system, the cart will haul the minerals towards the mining outpost site. For underground mining, a mineral conveyor belt/elevator would be utilized to transport minerals to surface level. From there, either a Funifor cable system, or transport haulers will transport the ores to the mining outpost.

D. Mineral Processing

Mineral processing involves three main stages on the moon: mineral comminution, mineral beneficiation, and mineral extraction. Mineral Comminution refers to breaking big rocks into smaller rocks, two options for vacuum comminution are currently the most ideal. [16] The pressure crusher, which uses grinding gears to crush rocks, but may have lower efficiency in low gravity. The impact crusher, which uses a shaft to crush the ores. It is more versatile, can be used in closed circuit to eliminate dust spread, and requires minimal redesign for lunar use. Mineral beneficiation is the process of separating mineral ores from waste ores. Mineral beneficiation faces challenges in a vacuum environment due to the lack of access to liquid. However, some options remain viable, such as waterless magnetic separation [16], which uses magnetic force to separate metallic ores from waste ores, and the electrostatic separator, which uses static force. A mineral sorting machine could also be used with extensive redesign. Mineral extraction is the extraction of mineral materials from mineral ores. Many existing methods require an atmosphere or have a high power load. However, thermal decomposition stands out as a viable option [16]. It relies on sunlight to heat up either a hydrogen gas as a reducing agent, or the ores directly. This process would thermally extract the oxygen from the ore and leave the target mineral materials, concentrated sunlight is required as the main source of power, and the fact it comes from solar thermal means a minimal power load.

E. Mineral Export

Export efficiency is measured by the frequency of exports and per export quantity, it is more ideal to have the efficiency bottleneck on the production capability rather than on the transport capability. The most common export method is to transport minerals via rockets. This method is the most developed and doesn't require any additional infrastructure beyond the ones already there. However, each landing would require the lander to replenish its fuel at the gateway beforehand. The frequency largely depends on the availability of hydrogen and oxidizer synthesized from the south pole main settlement, or brought from Earth to the gateway. Additionally, for this method to be within a reasonable price range, both the lunar lander, interplanetary transport rocket, and LEO return vehicle need to be fully reusable. In the long run, the export efficiency will be bottlenecked when the processed pure materials each cycle outweigh the capacity of the lander, and by scaling up the operation, more landers and rockets will need to be constructed, adding to the prerequisite material cost. Having more vehicles also means the launch frequency will be further bottlenecked by the lunar fuel production capability, which takes time, cost, and infrastructure to scale up. Thus, this method is best served as an early-stage approach for Earth export, but not as a long-term solution.

A higher export efficiency method is needed for the long term, according to the Rotary Sling-Tethers section in Commercial Lunar Propellant Architecture [17], lunar mass drivers being a very promising solution. By utilizing a kinetic energy rotational launch structure like the one being developed by SpinLaunch [18], it can further lower the launch cost and increase the launch frequency. This structure converts rotational energy into kinetic energy to launch the payload, and is ideal for the low gravity, vacuum lunar environment. The launch structure needs to generate enough rotational energy to provide more than 2.38 km/s of delta V for the pods to escape lunar gravity well. If SpinLaunch can achieve their goal of generating over 5 km/s of delta V using their Earth launch system [18], then it will be well enough for a lunar launch system. Once launched, the pods themselves do not require propulsion systems as they are on a free return trajectory. They only need ablative heat shields, parachutes, and possibly reaction wheels for reentry, with everything except the heat shield being fully reusable. Upon landing on Earth, pods can be refurbished and be turned around for the flight back rather quickly. This method would allow an interplanetary rocket to carry multiple pods to increase export frequency by a huge margin, so the export efficiency will no longer be bottlenecked by the transport capability. In the long run, pods could be constructed on the lunar surface using lunar metals as well.

F. LEVI Mining Outpost Design

The Mining outpost will employ the impact crusher for mineral comminution, the magnetic separation belt for mineral beneficiation, a thermal decomposition thermostat array for mineral extraction, and both rocket and rotational kinetic launch mass driver for mineral exports. The outpost will be constructed in a circular expanse, centered around the circular thermal decomposition heliostat array, with the incoming minerals making their way through the infrastructure along the outpost circumferences towards the center. The mining outpost will also operate differently during the day/night cycle. The night operations will focus on mining minerals and raw ores for processing preparations. The day operation will focus on energy intensive mineral processing operations to produce purified materials for export.

1. Lunar Night Operation flow

Mining operations are the only operations that can be conducted at night, mineral processing operations that require massive amounts of energy will be idle. Strip mining will be happening during the night, with strip mining rovers dozing the regolith into their internal containers, and covering a large amount of surface areas by swarm. Autonomous haulers will rendezvous with rover teams at the nearest rally point. The rovers will then unload their materials and continue mining, while the haulers return to the outpost to unload. In open-pit mining, a wheeled bucket excavator or traditional excavators will remove regolith, which autonomous haulers will transport up the pit wall lanes. From the surface, the haulers will unload the minerals onto the Funifor conveyor cart system, bringing them to the outpost. For underground mining, minerals will be extracted using either long-wall type autonomous mining or traditional excavation. Both methods will transport minerals to the surface via elevators and conveyor belts. The minerals will then be unloaded onto haulers, which will either travel directly to the outpost or to the Funifor cart system, depending on the underground minefield location. All of the mining operations can also be extended into daytime to fulfill processing demand as well.

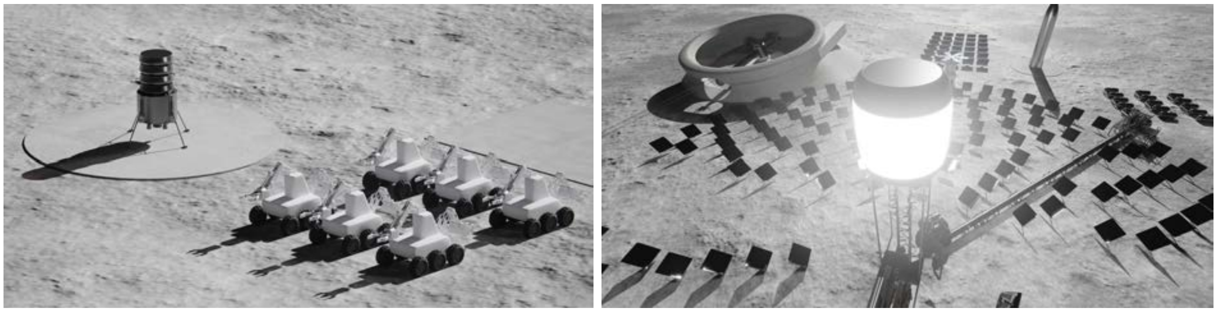

Figure 9. Strip Mining rovers, Lander carrying stacked return pods and Solar decomposition Tower

2. Lunar Day Operations flow

During lunar day operations, the minerals mined overnight will be prepared for processing. The impact crusher will reduce large rocks into finer ones, feeding them into the closed-loop conveyor belt system. After passing through the impact crusher, the minerals will undergo a magnetic separation beneficiation process to separate waste ore from valuable mineral ores. The waste ores will be sent to dumping grounds located on the outpost's outer edge, where they can be repurposed for further on-site regolith 3D-printing. To minimize dust dispersion across the outpost during operation, both the impact crusher and the magnetic separator will be constructed within a 3D-printed regolith cover structure to ensure closed-loop operation. The benefited mineral ores traveled within the enclosed conveyor belt will be conveyed to on-site 3D-printed regolith storages for pre-extraction holding. This semi-underground pit with regolith-printed outer walls provides temporary mineral storage.

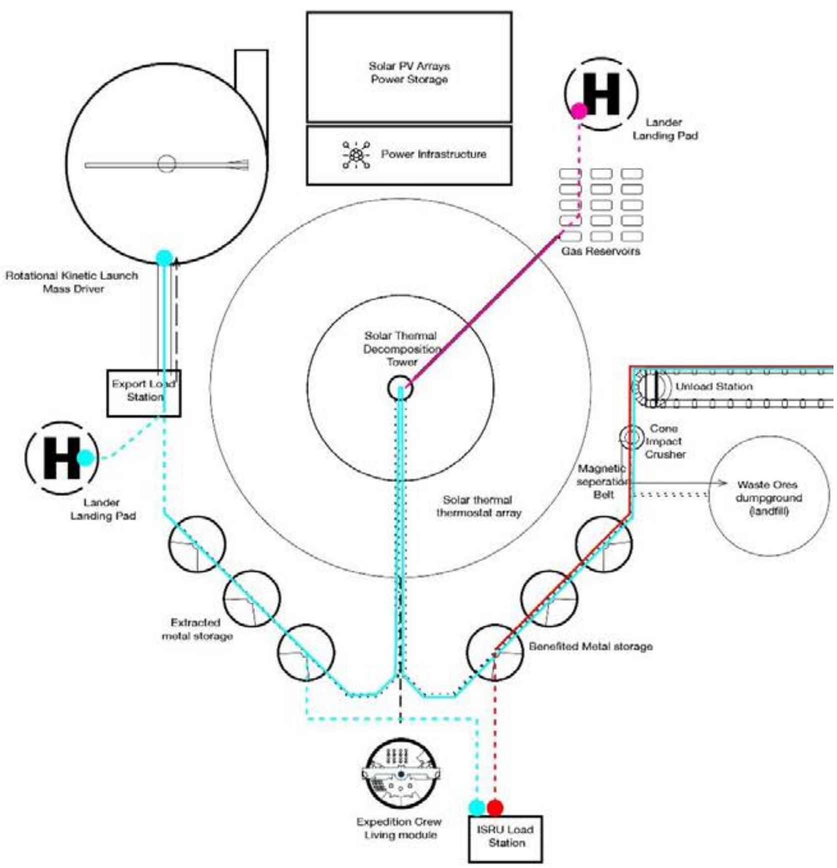

Figure 10. Mineral processing and export flow (Red represents ore outflow, Blue represents extracted pure material outflow, Pink represents extracted gas outflow)

Next, the minerals will be transported from the pre-extraction storage to the solar decomposition tower. The thermal decomposition process heats the regolith, releasing ^{3}He in a gaseous state. The ^{3}He gas will then be pumped to the gas reservoirs located at the outpost's edge, where it can be loaded for export. For metal extraction, the end products will be pure metal minerals and oxygen. The oxygen will be pumped to the gas reservoir, while the pure metals will head to the post-processing storage. From these storage areas, the metals can be used for ISRU construction or exported by lander or mass driver. ISRU metals can be transported to the main settlement for construction using lunar landers on short-distance suborbital flights or by constructing an access road for larger surface transport convoys to reach the settlement in the long term. The extracted gases will also be exported, either by lunar landers through the gateway, or by the rotational kinetic launch mass driver.

3. Rotational Kinetic Launch Mass driver

The Rotational Kinetic Launch Mass Driver makes the most use of ISRU materials by combining the SpinLaunch base rotational spindle launch structure with a 3D-printed regolith outer structure. The launch structure is first installed inside the lunar foundation, the regolith wall will then be printed around the structure to act as foundation support, with the walls protecting the launch space from accumulated dust from nearby processing operations. The launch platform is constructed at a slope angle and is fixed to ensure a launch angle suited for fixed free return trajectory to a landing zone on Earth each lunar cycle. The processed pure materials will be loaded onto the pods in the assembly zone, and a Funifor cable system will load the pods from the assembly zone to the mass driver.

G. LEVI Mining Outpost Zoning and Phase Construction Timeline

The expansion of the mining outpost zoning is designed using the evolution of the Bingham open-pit mine in Utah as a case study benchmark [19, 28]. The mining outpost is separated some distance from the mining fields to allow for larger future expansions. In Phase I, the lunar mining outpost's main objective is prospecting minefields and constructing essential supporting elements. Surface rovers will prospect different mining site candidates with pilot holes, targeting high-concentration locations of mineral deposits. Once suitable mining sites are identified, outpost construction will proceed. The construction of the landing site allows rockets to transport materials, and equipment to the outpost. Critical power infrastructure and living modules will be constructed to prepare housing for future maintenance teams. The construction robots will work on building the impact crusher, magnetic separator, and Funifor cable cart system. By Phase II, the basic power grid of the outpost will be online, and extensive landscape operations will flatten the surrounding areas. The outpost will possess basic abilities for mineral comminution and beneficiation processes. A Funifor cable system will connect potential mining sites with the outpost, and a pre-processing mineral storage facility will allow small-scale mineral storage for research purposes.

In Phase III, initial mining operations will commence. A fleet of transport haulers and strip mining rovers will be dispatched to the outpost for strip mining operations. Additionally, a mobile bucket wheel excavator will be assembled for open-pit mining. The beneficiated minerals can either be exported back to Earth at this stage using rockets, or utilized for on-site ISRU purposes. The outpost will also start to construct solar thermal decomposition towers and heliostats at the center of the outpost. The heliostats will be constructed in a circular pattern to maximize thermal exposure toward the tower. In Phase IV, the objective is to enable mineral extraction capabilities and underground mining operations. An increased flow of minerals from both open-pit and strip mining will reach the outpost, thus increasing processing demands. The completion of the thermal decomposition tower will allow it to extract minerals in large quantities to meet those demands, allowing a larger quantity of refined, pure materials to be packed for transport. Underground mining can happen with long-wall type bucket wheel mining being implemented at an underground deposit, which can be fully autonomous. The extracted gas can be exported, used as oxidizers outbound for a lunar gateway rocket refuel, or used for complex methods of mineral extraction/refinement that require an artificial atmosphere in the future.

In Phase V, the objective is to implement a more cost-effective mineral export method to Earth, enabling an effective lunar economy. The rotational kinetic launch mass driver will be constructed on the outskirts of the outpost, where outbound extracted minerals can be loaded into a landing pod, and loaded onto the launcher using a funifor cable. The same landing pods will be recycled on Earth, stacked, and redelivered to the outpost through rockets, bringing down the transport cost. To effectively scale the operation for future expansion of mining capacity, multiple outposts can be built alongside to compensate for the growing need for mineral processing, when the expanding mining operation yields more mineral output than single outpost processing power.

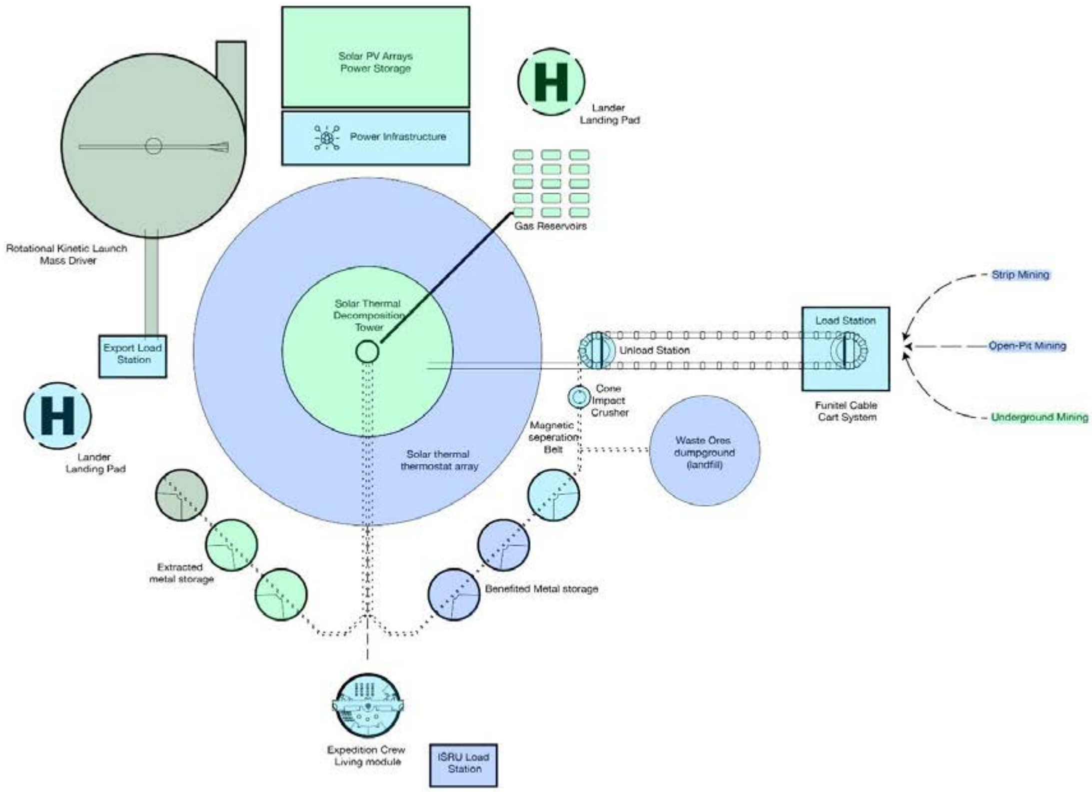

Figure 11. Mining Outpost Construction Phase Plan, Phase I & II (Light Blue), Phase III (Dark Blue), Phase IV (Light Green), Phase V (Dark Green)

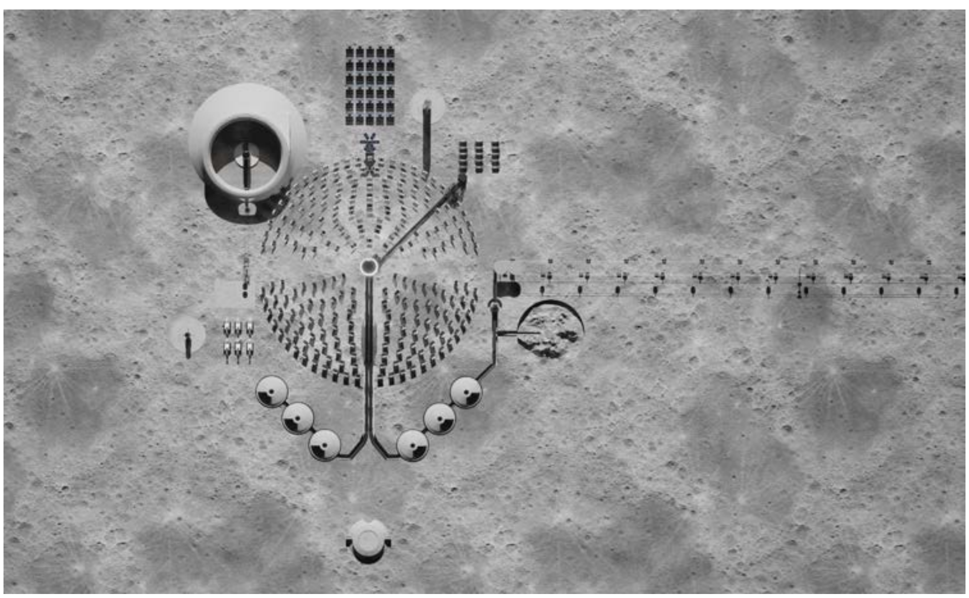

Figure 12. Mining Outpost Phase V

VI. Conclusion

In the near future, LEVI could facilitate widespread adoption of nuclear fusion reactors globally, addressing the ongoing energy crisis and reducing dependence on fossil fuel power generation. Additionally, the metal exports will significantly lower costs and enhance accessibility to crucial materials, promoting competition and decreasing the prices of industrial and consumer products. LEVI may play a vital role in establishing a sustainable lunar presence and economy in the near future.

Figure 13. Main Settlement Phase V & Mining Outpost Phase V

VII. Appendix

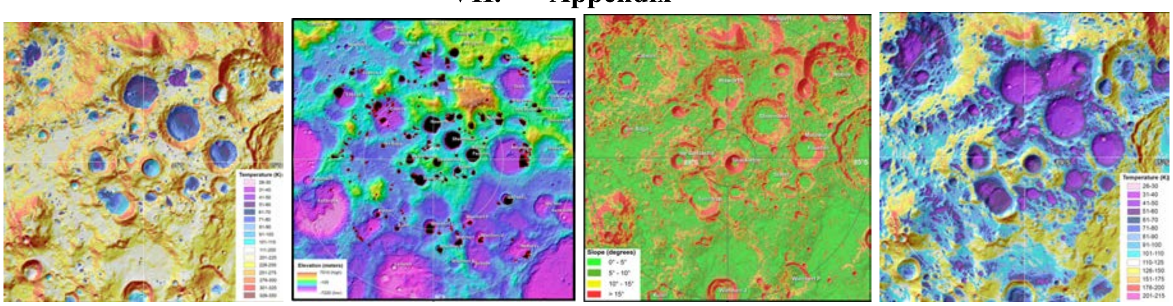

Figure 14. (Left To Right) a), Average Near-Surface Temperatures Modeled at the Moon's South Pole (85°S to Pole) [20]. b), Maximum Near-Surface Temperatures Modeled at the Moon's South Pole (85°S to Pole) [21]. c), Topography and Permanently Shaded Regions (PSRs) of the Moon's South Pole (80°S to Pole) [22]. d), Slope Map of the Moon's South Pole (85°S to Pole) [23]

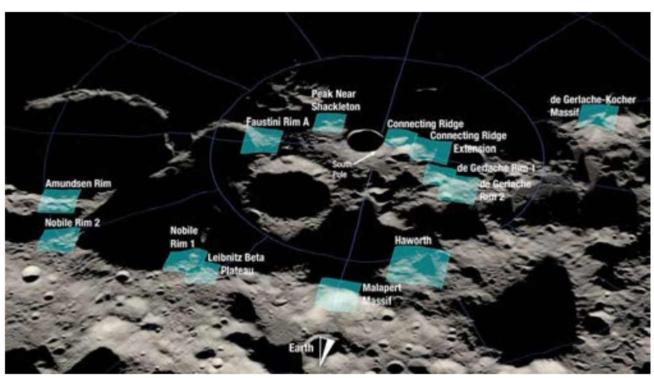

Figure 15. NASA Artemis Landing Site Candidates [24]

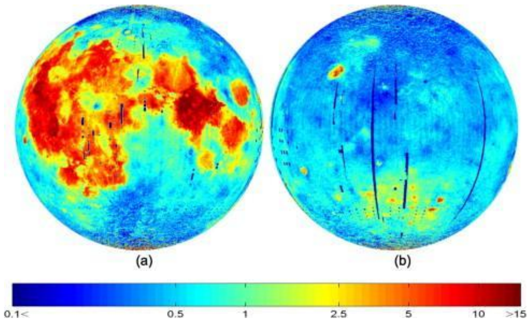

Figure 16. Estimated concentration of ^{3}He (parts per billion by mass) in the lunar regolith [25]

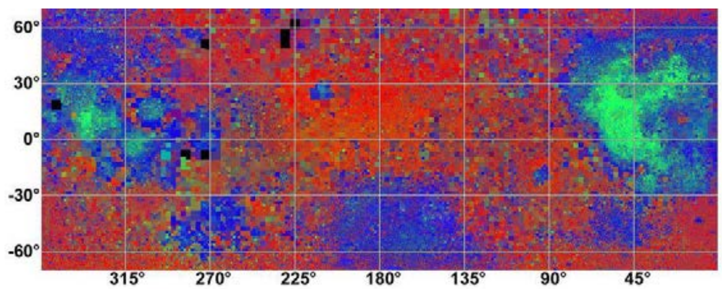

Figure 17. Generalized mineral map of the Moon; red indicates relative anorthite abundance, green represents olivine abundance, and blue shows total pyroxene abundance (clinopyroxene plus orthopyroxene). The map is centered on the farside of the Moon (180◦W longitude) [26]

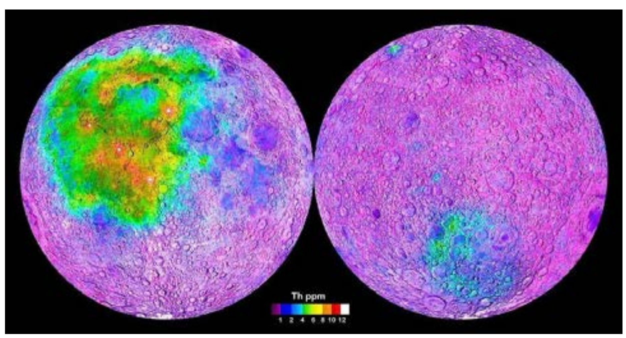

Figure 18. Map of lunar surficial Th concentrations on the nearside and farside [27]

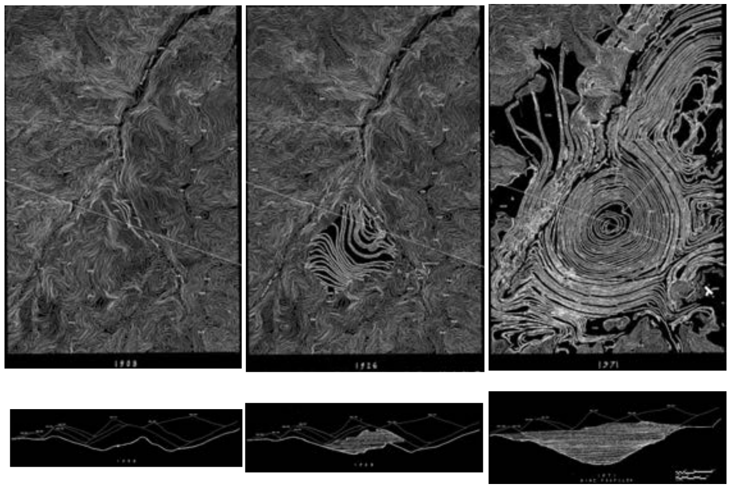

Figure 19. Bingham Mine Evolution (1908-1971) [28]

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