PROPOSAL FOR THE DEVELOPMENT OF AN ECONOMICALLY VIABLE LUNAR BASE

An Interactive Qualifying Project Proposal submitted to the faculty of
Worcester Polytechnic Institute as a requirement for a Degree of Bachelor of Science

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Abstract

The prospect of an economically viable lunar base holds much promise for the future of mankind. A lunar base that is self-sufficient both functionally and economically could bring unprecedented scientific developments for mankind. A base of this type would provide abundant resources for future space missions, making them less expensive. Lunar regolith is rich in many metals including iron, titanium, magnesium, and aluminum. These metals could be used to further expand a lunar base. Helium-3, found in the regolith that covers the moon, is present in much greater quantities than on earth. Helium-3 can power fusion reactors, and its rarity has been a major impediment to fusion reactor development on earth. A lunar mining colony will require an initial investment, but it will more than pay for itself when it is sufficiently developed. An economically viable lunar base promises to extend mankind's reach well into the solar system.

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1: INTRODUCTION

One of the National Aeronautics and Space Administration (NASA)'s goals for this century is to visit Mars, in much the same way that they did in the 60's on the moon. As a stepping stone for this, NASA aims to build a semi-self sufficient lunar base. This involves sending a reusable lunar spacecraft to the moon with a small crew in six month shifts. The base itself would be small and prefabricated, not largely relying on the moon as a resource. The goal of NASA's First Lunar Outpost (FLO) is to simply survive on the moon (Lindroos, 2007). This plan is a short-sighted result of NASA's budget cuts and resulting conservatism. They refuse to commit to the moon as a permanent base because they believe that only a temporary base is necessary in the development of a Martian base. A six month venture of this type would be costly and would not yield much in the way of resources or scientific development.

A more permanent lunar base that contrasts with NASA's smaller and less useful concept, while more expensive at the outset, would be far more beneficial for humanity. NASA does not have clear goals for the base, as it is does not want to commit to the moon. However, if a substantial, permanent base is designed and built with clear and tangible goals, that has the ability to return the initial investment, the case for colonizing the moon becomes much more convincing. A permanent lunar base would have great benefit for humanity not only in scientific progress, but it could become both functionally and economically self-sufficient.

This project will show that such a base is a realistic possibility. The economical case for the colony will be made. It will be shown that a forty year, six phase program can be implemented that will allow for the base to house forty-eight inhabitants. The base will consist

The moon is extremely rich in oxygen in the form of oxides present in the regolith and rocks that covers the lunar surface. In fact, lunar soil and rocks are about 45% oxygen, and the metals to which it is bonded could be extracted, with varying degrees of difficulty, as a usable resource (Eckart, 2006). Thus the lunar soil will provide an enormous amount of oxygen that is more than sufficient for supporting the life systems of a lunar base. The rest of the available oxygen could be used for the production of rocket fuel, both for use on the lunar base and for sale to support the lunar base financially.

There are several options available for extracting oxygen from the regolith and rocks on the moon's surface. The most straight-forward and likely category of oxygen extraction is called ilmenite reduction, as can be seen in Figure 2. This involved mixing ilmenite (iron titanium oxide, FeTiO3) with a reducing agent (such as hydrogen), resulting in the production of iron, titanium dioxide, and water. The water can then be reduced to hydrogen and oxygen. This is only one type of ilmenite reduction, and a different reducing agent would produce different products. This method would probably become widely used if large quantities of hydrogen became available from low earth orbit, which seems likely (Sadeh, 1992, pg. 754).

Figure 2: Ilmenite Reduction (Knudsen, 1992)

2: OVERVIEW OF THE DEVELOPMENT OF A LUNAR BASE

The proposal for a sustainable lunar base is comprised of six phases that will last approximately forty years. This program will cover everything from the first delivery and robotic assembly of initial structures to the point at which the base is fully self-sufficient and ready for free expansion. Phase 1 involves the initial payloads sent to the moon along with the robots and autonomous vehicles that will lay out the first structures to be built and assembled. The use of autonomous vehicles is important because of dangerous lunar radiation: the delivery and assembly of structures and equipment will occur before proper shielding can be implemented, so it can not safely be performed by humans. This phase will cover the first five years. Phase 2 involves robots digging trenches and gathering regolith with which to cover the living quarters. The first stage of crew arrivals, with assistance from robots and tools, will assemble the prefabricated living quarters and bury them under regolith so as to provide protection against harmful radiation and meteorites. The solar power grid will also need to be assembled to provide power for the living quarters. The nuclear power plant will not be needed yet, as the mining facility will require the majority of the power produced on the base. This phase will require ten years for completion. Phase 3 will encompass much of the construction of the agricultural, mining and processing, and research facilities. The nuclear power plant will need to be integrated into the base so as to provide the massive amount of power needed by the mining and processing facilities. Also, the expansion of the crew will be necessary to provide the additional manpower needed to sustain the multiple stages of the base being introduced in this phase. A network of roads will need to be constructed in Phase 3 to accommodate the movement of regolith between the mining and production facilities. Regolith

It is also important to consider power requirements for the base. At the final stages of the base, the power required will be more than one megawatt. This includes 965 kW for mining and production of raw materials such as oxygen, titanium, and Helium-3 (Sadeh, 1992, pg. 1178), as well as about 3 kW per person for life support and general power requirements (Sadeh, 1992, pg. 1178). This will be handled by a hybrid power system comprising a solar cell array and nuclear power plant. The power requirements at each stage of the base's development are shown in Table 2.

Phase	Living Quarters	Agriculture	Mining/Production	Total
1	N/A	N/A	N/A	0
2	30	0	N/A	30
3	30	100	965	1095
4	60	200	965	1225
5	60	200	965	1225
6	120	400	965	1485

Table 2: Power Requirements in kW for Phases 1-6

2.2: Functional Requirements

An important step towards developing a lunar base is to define how the different elements of the base support and rely on each other. The base can be broken into three primary functions: the living quarters, production, and research. Each of these functions will rely on other inputs and supporting functions. The inputs will include materials such as oxygen, water, and robots. There will be five supporting functions: power, mining, agriculture, logistical networks, and shielding. Each of these supporting functions will rely on some or all of the others. In Figure 5, each primary function will require the support of the functions listed below it. The hashed lines help indicate which supporting functions are needed by each of the primary functions. The living quarters will be supported by the agricultural unit, the generated

6 shows the evolution of the functional requirements as the base grows during the forty year program. The first phase of the base will consist of only the living quarters and robots. Since there will be no crew members during this phase, the only requirement for the base is power in the form of batteries. The second phase will include the addition of the crew and a solar power plant. The power plant will now be able to provide the power for the robots and the living quarters. However, at this point the supplies needed to keep the crew alive, such as food and oxygen, will be provided by earth. At the end of the third phase the functional requirements will be the same as those of the final base, but on a smaller scale. All of the components of the base will be present and the final three phases all involve the expansion and duplication of these elements.

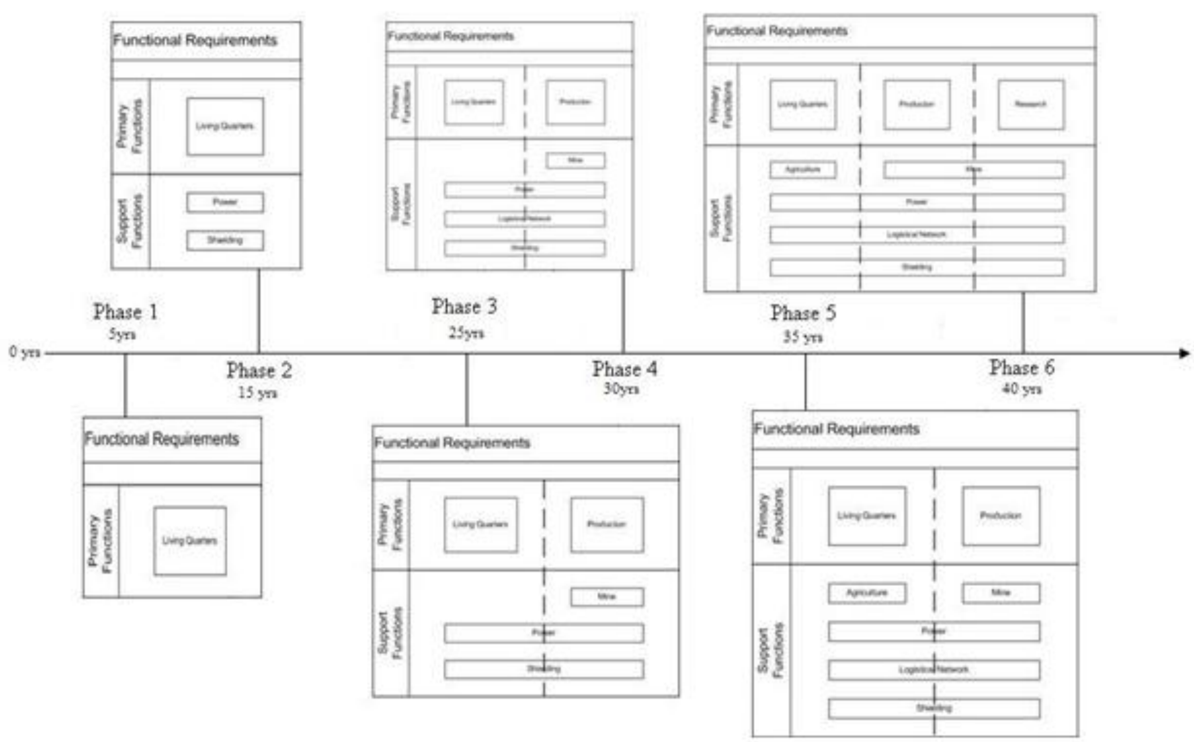

Figure 6: Functional Requirements Timeline

composites should be investigated. These materials are expensive, but they are extremely strong, and extremely lightweight. Additionally, unlike metal structures, they can be patched and repaired with a simple carbon fiber or fiberglass patch and epoxy. This can be completed without tools, and the impact on the structural integrity of the module, while not necessarily negligible, will not be an issue, as the stresses of moving and assembling the module will no longer occur.

There should be two main structures considered: a habitat module, and a module connector. The module will have an opening to which a connector can be attached, allowing a tree-like layout to develop. However, as building and transporting these modules is expensive, they should only be used where necessary. When possible, new buildings should be constructed on the moon, by the crew in place. The modular structures will only be used when it is not possible to construct the required buildings. With the modular base structures constructed on the earth and delivered to the moon via an unmanned spacecraft, the construction and assembly of the initial lunar base can begin.

It is also important to consider the size and power requirements (or lack thereof) of the base at this point. At this time, the base will have no power requirements for running. The only structure present will be the habitat, which is constructed by autonomous or remotely-operated robots. This habitat will cover about 240 square meters.

2.5: Phase II

With the modules for the base on the moon, the next step is to assemble and prepare them for use. A number of robots, along with any additional necessary construction materials

must be expanded, and three new facilities must be established. These new elements of the base are an economically productive facility, a logistical facility, and an agricultural facility. Upon completing these facilities the base will be nearing self-sustainability.

Until this time the living quarters is a small area consisting of space for a crew of twelve. New modules need to be added so that the facility can support an additional twelve crew members. However, it should be noted that this is actually a low priority project during this phase because the additional personnel will not arrive until the beginning of the fourth phase.

In addition to the living quarters, additional power will be needed for the base, not only for when new personnel arrive, but also for the new facilities that will be established. At this time all of the base's power is available in either the form of batteries, which have been brought from earth, or solar energy. Additionally, a nuclear fusion power plant will need to be constructed. This expansion is a high priority because the extra power will be required for the new facilities that will also be built during this phase.

The economic facilities, which consist of a mining facility, a processing plant, and a production plant, must be a priority during this phase. The mine will be almost entirely automated, and only two of the current crew members will be needed to work in the mine. In reality these two will be overseeing the process and maintaining the robots. Many of the robots involved in the mining process will be the same robots that were used to construct the living facilities. The rest will have specific functions and will need to be sent from earth. The mine itself is a strip mine and will need to be a good distance from the rest of the base. As the mining

The last new facility to be built at this time will be the agricultural facility, which will be the main source of food for the base. Various vegetables will be grown within the structure. The selection of these vegetables will be based upon dietary needs and ease of production. Among the produce grown will be vegetables and soy beans. Vitamin and fiber requirements will be provided by the vegetables, and protein can be provided by soy beans. All produce will be grown in a single structure. Unfortunately, it will be some time before the agricultural unit is productive due to the time necessary to cultivate the crops. (Conerly, 2008).

At this stage in the base development, the base will cover 4,214 square meters and require just over a megawatt of power. This is also the phase during which the nuclear power facility is introduced.

2.7: Phase IV

At this stage, the initial stages of the base have been successfully completed. The mining and refining of regolith have been implemented, and a reliable source of oxygen, helium-3, and various metals is now able to be stored and used. The ability to use metals, such as titanium, aluminum, iron, and magnesium, means that the base can be expanded using materials already found on the moon. The need for raw materials or even prefabricated materials from earth is now a thing of the past since the lunar base has access to new in-situ building materials. Rather than simply saving money, these efforts have lead to the base turning a profit by exporting excess oxygen to low earth orbit (LEO) for use as rocket fuel and helium-3 to earth for use in fusion reactors. Should fusion reactors become popular on earth, the lunar mining colony will be the primary source of helium-3.

The ultimate goal of this lunar base is to be completely self-sufficient to the point that very little to no dependence on earth is needed. A base of this nature would have very deep implications. Should an apocalyptic disaster such as asteroid impact, nuclear war, disease, or famine destroy mankind on earth, the self-sufficient lunar base and its inhabitants would be able to carry on the legacy of the human race. The chances of such occurrences happening are slim indeed, but the benefits of having such a base on the moon would serve only to benefit mankind.

Several commercial uses for the lunar base have been thought of over and over by many visionaries. The ability to send large objects to low earth orbit (LEO) relatively cheaply from the moon gives the possibility of hotels in orbit, large scale orbital landing pads, and other such large structures orbiting around the earth. Such structures would surely serve as a transition to a more advanced period in human history.

2.9: Phase VI

An important part of the base will be the duplication and extension of the base as more and more personnel arrive for duty from earth. The extent to which the base can be expanded upon depends largely on available resources such as oxygen, energy, space, and the raw materials required to construct additional components to the base as well as other separate modules. The bulk of the energy consumed by the lunar base will be by the mining and processing segments of the base, where nearly a megawatt of nuclear power is consumed. Assuming an adequate supply of oxygen to supply any new members of the base, and enough raw materials to construct the new structures, the only limit to the expansion to the base will

3: DETAILS OF PHASES 1, 2, AND 3

The primary focus of this project is to address the first three phases of the lunar base program. The description focuses on everything from the time that the initial materials are sent to the moon until the base is self-sufficient. At the end of the third phase the size of the crew on the moon will have doubled and most of the different facilities will be assembled and functional.

3.1: Unmanned Assembly

The first construction phase will include all of the activities on the site from the moment the first shipment of materials lands on the moon until the time that the initial crew of twelve arrives. The activities that need to be completed before the arrival of the crew are site selection, delivery of materials, and pre-construction, which will be completed by robots.

3.1.1: Site Selection

The first step for establishing the base is its site selection. It is important to note that the location was chosen based on numerous criteria, not all of which could be met by any single site on the moon. One must consider the probability of lunar impacts, radiation, the presence of water ice, concentrations of easily mined materials, ease of communication with earth, ease of landing and launching, and the ability to gather solar energy. This last consideration comes from the fact that in the initial stages (and to a lesser extent, later stages), the base will need to use solar power until a nuclear power plant can be constructed. The possible locations for the lunar base were the south pole, the equator, or the north pole. It also had to be decided if the base should be on the near or far side of the moon.

much of these materials as possible needs to be shipped ahead of time. Only non-perishable foods should be sent in this initial shipment because the crew will not arrive until all of the pre-construction is complete.

3.2: Arrival of Crew

Phase 1 will be complete when the robots have finished the assembly of the living modules. This means that modules will be set up in a trench. They will be evenly spaced on either side of the connecting unit. The crew will enter and exit via the airlock built into the connecting unit. They also need to be covered in regolith before the crew may inhabit them. This regolith will be the same soil that was originally removed from the trenches. With this completed, the crew may now arrive and begin their operations. Phase 2 encompasses all of the activities within the base from the time that the initial crew arrives to the time at which the materials for the production plant are received.

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The crew will arrive in a Lunar Lander that will follow the design of NASA's First Lunar Outpost plan. These landers are used for both transportation and shelter. After landing on the moon's surface, they are designed to house six crew members for approximately six months (Lindroos, 2007). The crew will be sent up in two of these landers, accompanied by as much food, water, oxygen, and additional batteries as possible. The landers are designed so that if the assembly of the modules undergoes a setback and, for some reason, the crew cannot move into the modules when they arrive, they will be able to live within the landers until the problem can fixed.

are sent, then they do not need to be re-supplied. Once the mining and production facilities are running, these necessities can be produced on the base.

3.3: Base Becomes Sustainable

The third phase of the establishment of a moon base will involve the activities that make the base self-sustainable until the time when additional crew members will arrive. The materials that arrived to mark the end of the second phase will now be used to build the remaining critical structures; the agricultural building, the mine, the processing and production facility, and the launch pads. In order for the mining, processing, and production facilities to be functional, a nuclear power plant must be constructed in order to provide the power required for them.

3.3.1: Mining Facility

The mining facility carries the highest priority of these four facilities. The food received with the building materials makes the agricultural unit temporarily non-essential, and the production plant is not needed until after the mines are operational. All operations and labor within the mining facility will be performed by numerous autonomous or remotely operated robots. The robots that will move the regolith to the processing plant will run on motor driven tracks. The regolith will be stored in a hopper on the back of the vehicle while it is being transported.

Next, the processing plant and the production facility will be constructed. They will share the same building. Once the regolith is deposited in the production facility by the transporting vehicles, it will be processed by another set of autonomous robots. The regolith

4: HABITAT DESIGN

At the outset of the lunar base endeavor, the main focus of the base effort is to simply survive. Thus, the living quarters must be given careful thought. In order to allow for easy expansion, the habitat should be modular.

4.1: Possible Construction Methods and Layouts

There have been several proposed module designs that can be broken into two major categories: rigid and inflatable. Rigid buildings are designed to make the assembly of the base as a whole simple. Once a piece of the base is obtained it simply needs to be dragged into place. These buildings can either be shipped to the moon in pieces to be assembled by astronauts there, or they can be shipped already in one piece. These buildings will be stable and depending on the thickness of the walls and what they are made out of, they may provide some degree of radiation protection. The problem with the rigid buildings is that they will be heavy and therefore expensive to transport. The weight will also make assembly of the modules on-site difficult.

The case for inflatable structures is that they will be easy to transport. They will be shipped while deflated, and therefore can be folded into a rather small bundle. The cost and difficulty of moving and assembling inflatable structures can be significantly reduced if the gas or liquid used for inflation is obtained from low earth orbit. If the structures are inflated with a gas or liquid with a low atomic number (such as hydrogen), an effective shield against radiation would result (Johnson, 1964). The downside is that these buildings will have to be designed in such a way that they cannot be punctured by non-earth objects. Also, they will have to be

hexagonal modules in a growing "honeycomb" layout (Matsumoto, 1998, pg. 2). However, this design does not allow individual modules to be quickly sealed off in the event of an emergency. If there were connectors or airlocks between the modules, the design would be safer. The design also does not facilitate easy movement from one module to the next; a common hallway connecting all modules is not present. A proposed inflatable module consists of rigid arches that hold together membrane walls (Sadeh, 1992, pg. 78). The design states that regolith should be used to shield these modules. However, it is difficult to properly cover these with enough regolith to avoid damage from impacts. Another design involves an inflatable structure supported with beams and arches which are filled with regolith (Sadeh, 1992, pg. 127). This is referred to as a Cylindrical Fabric-Covered Soil Structure, or CFCS. This design is unique and lightweight, but it is much larger than needed. Another proposed design is the Double Airlock design (Sadeh 1992 pg. 127). This design is intended to reduce gases lost during entrance and exit of the base. However, it does not use space efficiently, and is not modular or easily expandable. The different designs are compared in Table 3.

Construction Type	Rigid Honeycomb	Inflatable	Rigid Cone	CFCS
Ease of Transport	Low	High	High	High
Ease of Assembly	High	Low	Very High (prebuilt)	Low
Durability	High	Low	Medium	Low
Shielding	High (use regolith)	Low	Low	Low
Efficiency of Space Use	Medium	High	Low	Low
Ease of Movement through layout	Low	High	Low	High

Table 3: Comparison of Various Design Layouts and Construction Techniques

material, that is, it is composed of a matt of material with very high tensile strength (in this case, carbon filaments) bound in a plastic, such as epoxy (Ruess, 2006, pg. 5). Although carbon fiber is expensive, it is easily repairable, and the costs of transporting the material are much greater than the costs of actually constructing the buildings on earth. At this stage of the lunar base mission, large scale construction and assembly on the moon should be avoided, so the modules should be as prefabricated as possible.

Before the base can be assembled, a suitable area of regolith must be prepared for use as a foundation for the modules. This will be achieved by superheating the regolith with lasers in the area in order to create a glass-like surface (Mendell, 1985, pg. 402). Regolith in its natural form is unstable, and uneven loading in the base combined with non-uniform soil properties could result in uneven settlement, leading to undue stresses on the modules and connectors, possibly leading to failure. Also, fusing the regolith will reduce the likelihood of dust causing problems with machinery.

Research has shown that the minimum required living space per person is eight square meters of floor space and twenty cubic meters of total volume (Koelle, 2003, pg. 35). However, these dimensions constitute the minimum required living space, and will not support other activities such as recreation or research. Facilities for these will be added later when the base is more fully developed, or as needed. Additionally, more space will be needed for storage and devices capable of supporting life within the habitat.

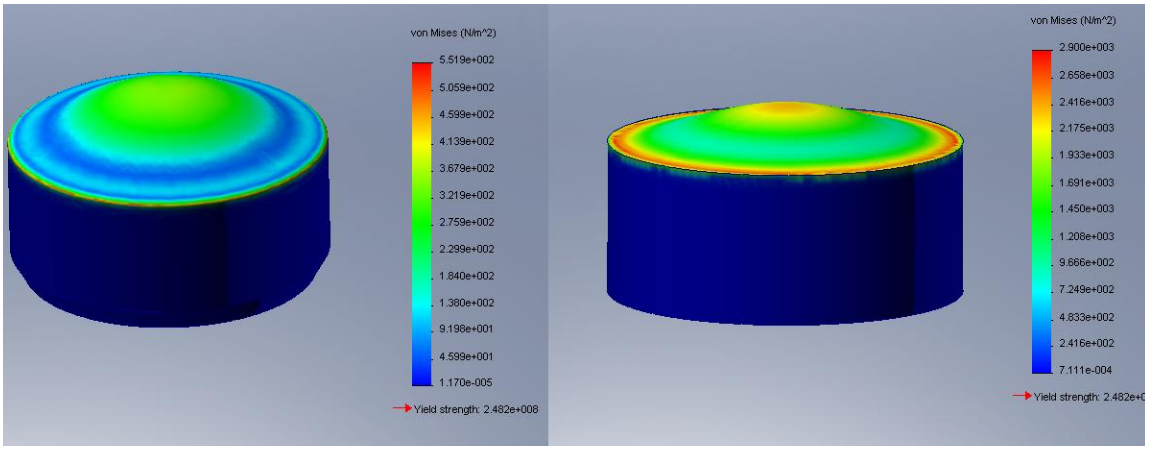

Figure 10: Stress levels in pressurized vessels with domed top (left) and flat top (right) (Developed in Solidworks, 2007).

The space between the floor of the module and the bottom can be used for storage. The available volume is about 16.5 cubic meters, which will be used for storage. Pipes and wires that bring services to and from the modules will be stored in this area.

4.5: Airlock Connectors

In order to enter and exit the habitat, airlocks must be employed. These structures will need to be five cubic meters at a minimum in order to allow two people to enter or exit the structure at once. When the door is sealed, door seals in conjunction with an air pump system will keep air loss at a minimum level (Koelle, 2003, pg. 39). This system can be built into the connectors allowing for the system to be truly modular. As the base expands, one connector can be attached to another. When the attached section is complete, the airlock can be opened, and the new section can be used. The airlock on the end of the newly attached section will be used as the new entrance. The connector and airlock system is shown in Figure 11.

4.6: Assembly of Modules

The three modules must be connected in order to function as a larger habitat. Connecting the units will allow for tasks and resources to be easily shared. This will be achieved with specially designed connectors. They will resemble hallways that can be easily placed in order to facilitate expansion, as was shown in Figure 11.

Like the habitat module, the connector will also be constructed from carbon fiber. The domed top will add strength. An air lock will be integrated into the connector. The dimensions are determined largely by practical space requirements, allowing easy movement between the modules and adequate spacing between them.

Figure 12: Final Layout

cell has the advantage of a relatively high efficiency of about η= 14%, but the large temperature gradient on the moon, particularly the higher temperatures, have a great effect on the efficiency of the single crystal silicon cell. The amorphous silicon cell has a much lower efficiency than the single crystal silicon cell (about η = 6%) but the cost of much less and is easier to manufacture. The best choice for a solar cell on the moon would be a gallium arsenide (GaAs) solar cell. The GaAS solar cell has the advantage of a resistance to degradation, meaning a more consistent power supply throughout the duration of the mission. A thinner film is also required to filter out other wavelengths, which is critical for volume storage for any mission to space. GaAs solar cells have already been proven in space applications, and have also been used to power cars (Eckart, 1996 pg. 59). Table 4 shows the various properties of the three cell types.

Cell Type	Single Crystal Si-Crystal	Single Crystal GaAs-Cells	Amorphous Si-Cells
Cell Thickness [μm]	62 (present) 50 (projected)	6	1-2
o o (( ]] v	14 (present) 20 (projected)	18 (present) 24 (projected)	6 (present) 10 (projected)
Specific Power [W/kg]	40 (present) 125 (projected)	90 (present) 300 (projected)	100 (present) 1000 (projected)
Radiation Degradation [%/year]	2	1	Higher Degradation than Si-cells
Specific Mass Cells [kg/m^2]	2.3	5.1	2.2
Specific Mass Structure [kg/m^2]	25.0	10.0	5.0

Table 4: Solar Cells (Eckart, 1996, pg. 61).

The primary stages would benefit from solar power because of the ease with which the array can be configured. A system can be configured to fold and unfold easily for initial set-up. Also, the solar panels can be made to track and follow the movement of the sun, as opposed to

K, with the minimum temperature being just above the temperature of the heat rejecter (so as to keep a temperature differential). Solar dynamic power has the advantage of creating a wide range of power levels (a few kW to a few hundred kW), while also being compact enough to compete with photovoltaic cells as a power source. Table 5 shows the properties of Stirling and Brayton engines.

Cycle	Cycle Efficiency (▯%)	Specific Mass Concentrator m [kw/kWe]	Specific Mass Receiver m [kg/kWe]	Specific Mass PCU m [kg/kWe]	Specific Mass EM Pumps m [kw/kWe]
Stirling	35%	80	26	44	9
Brayton	25%	110	36	109	-

Table 5: Solar Dynamic Cycle (Eckart, 1996, pg. 64).

5.4: Nuclear Energy

The solar array described can only produce so much power. Although additional solar arrays can be constructed, at a point this becomes impractical. The mining and production facilities will consume almost a megawatt alone, so a separate power system should be implemented. In order to properly provide for such massive power consumption, a nuclear power source will be required. A nuclear power system has many of the same requirements as that of the solar dynamic power system in that it has a central heat collector, a heat rejecter, and some way of converting the heat energy into useful energy. A nuclear power source has some advantages over a solar dynamic power source in that it will operate day and night, it does not depend on external energies, and the technology is much better known than that of the solar dynamic power system. Additionally, it takes up less area. A major disadvantage is the radiation given off as the reactor fuel is spent. This radiation can be very dangerous and must be dealt with carefully. Shielding of the nuclear power system from the rest of the base will be the biggest problem with maintaining a nuclear power source, but since the base will be

5.5.3: Flywheel

A flywheel is reasonable to use later on in the life of the lunar base because of the huge mass needed to be rotating. Early on in the lunar base, a flywheel would never be considered because the flywheel would need to be brought from earth, which would add an enormous amount of weight to the initial transportation of materials. Once a substantial supply of iron and other metals have been mined, a flywheel is much more likely to be used than methods of storage mentioned earlier. A flywheel needs to be balanced, making it a precision storage device. Balancing such a huge amount of mass will be difficult indeed, especially on the moon without the tools and resources that are available on earth (Eckart, 1996, pg. 71).

5.5.4: Batteries

Batteries are by far the most reasonable way to store such large amount of power. Batteries, such as a Na-S batteries have a high self discharge rate (about 5-10% per day) In the energy density of an Na-S battery is 0.1 kWh/kg and 0.04 kWh/kg for an Ni-H2 battery. Below is a table showing properties of such batteries.

Battery Type	Energy Density [kWh/kg]	Cycle Life n [cycles]	Efficiency η [%]
Ni-H^2	0.04	10,000	70
Na-S	0.1	2,500	80

Table 6: Battery Properties (Eckart, 1996, pg. 72).

Na-S batteries would be very large to store the large amount of power needed by the base (e.g. 112,500 kg to store 22,500 kWh).

Such an RFC system would take advantage of any excess or surplus water and put it to use in the form of storing excess energy, which could be used in case of emergency. Such a system would likely be dangerous if not properly kept under control as the hydrogen and oxygen gasses (or liquids of cryogenically stored) are under extreme pressure. Additionally, when they are recombined to release energy and create water, a lot of heat is produced. The fuel cell will ensure this is happening at a controlled rate so as to avoid any spikes in heat or energy.

5.6: Distribution of Power

Table 8 is an overall distribution of the power and weight requirements of the mining and production facility.

Equipment	Mass [tonne]	Power Use [kW]
Mining		
Lunar Mobile Miner	40	200
Load-Haul-Dump ($2m^3$)	4	20
Picks & Shovels	0.05	-
Explosives	2	-
Drills & Drillsteel	0.5	10
Tube Conveyer	10	30
Processing Plant		
Grizzlies (Sifters)	0.5	-
Electrolysis Cell	10	625
Forms	2	-
General		
Return Vehicle	18	-
Ventilation	1	25
Air Locks	3	-
Communication	1	40
Tools	0.75	-
Space Suits	0.7	-
Spare Parts	8	-
Survey Equipment	0.05	-
Medical Supplies	0.1	-
Lights / Illumination	0.05	5
Power Cables	6	-
Nuclear Powerplant	10	-
Solar Mirrors	4	-
Tunnel Liners	1	-
Totals	123.7 tonnes	965 kW

Table 8: Mining Facility Power Requirements (Sadeh, 1992, pg. 1178).

5.7: Suggestions

Overall, the base will require at the very least a megawatt (1 MW) to power its many components. The mining and production facilities alone will require the bulk of this energy, about 965 kW (0.965 MW) of power, and the living quarters requiring about 3 kilowatts of

Figure 15: Regolith moving robot (Sadeh, 1992, pg 1075).

6.2: Transporting and Processing Regolith

The automated vehicles will transport the unprocessed regolith from the strip mine to be processed. The processing plant and mining facility will be approximately 25m x 40m (1000 m^2) and require about 1 megawatt (MW) of power. Before the regolith is collected, it must be covered and have heat applied to it in order to extract certain gases trapped in the regolith from the solar winds (Kokh, 1998). The regolith must not be disturbed prior to this process so as to limit the possibility of the gasses escaping from the loose regolith. In order to extract oxygen from the regolith a mineral called ilmenite ($FeTiO_3$) must first be separated from the gathered regolith. A reduction process yields water, which is then electrolyzed into hydrogen and oxygen. This will be the primary source of breathable oxygen that the operation will gather,

crew members to survive (Mendell, 1985, pg. 64). Additional oxygen, when combined with hydrogen for Low earth Orbit will allow the base to produce water. Also the metals produced by this plant will be used to expand the base.

6.3: Profitability of Mined Regolith

The most promising product that will come out of the regolith will be the helium-3. This gas can be used in the process nuclear fusion. Even though helium-3 has a small concentration in the regolith compared to the other elements, it is still more abundant on the moon than on earth. A three quarter acre area on the moon excavated nine feet deep will yield approximately 220 pounds of helium-3. This amount of the gas will be worth roughly $141 million (Schmitt, 2008, pg. 4). A product that can be sold for this amount of money will make the base economically justifiable.

combined with hydrogen from Low earth Orbit water can be created. Once the first crops in the agricultural facility are ready to be harvested, food will be available.

Once the lunar mining colony has reached this point it will need to be expanded. Far in the settlement's future there will be a need to launch the research section of the base. The moon has no atmosphere, providing a place from which experiments requiring a vacuum can be performed. Heavy lifting is aided by having only 1/6th of the gravity on earth, and the far side of the moon can be shielded from radiation originating from earth. Certain materials, when being made, require an inert gas or a vacuum in order to properly form. The low gravity will allow for huge structures to be made and maneuvered with ease. The lunar colony could one day be a construction platform from which large structures that will later be assembled in earth orbit could be made. One needs only to use imagination to predict what other uses a lunar colony could have. Perhaps sports could find their way to the moon, or even a separate country will call the moon home. Only time will tell.

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