

## Lunar Settlement Structures

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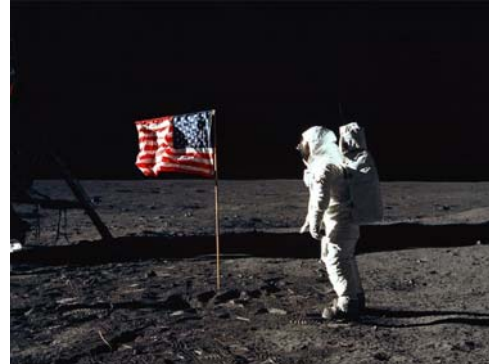
### **ABSTRACT:**

NASA's next major mission is to construct a permanent settlement on the Moon. With such aspirations come many difficulties such as radiation, pressurization, and human health. Many possible complications and solutions were analyzed before selecting a single, optimal first stage design for the lunar structure.

Based on the complications presented, the best possible design was found to be an inflatable, cylindrical structure.

### **INTRODUCTION:**

July 27, 1969. Man finally conquered the heavens and stepped foot on the Moon. Apollo 11 landed Neil Armstrong and Buzz Aldrin on the lunar surface. Twenty-four Americans took a giant leap for mankind over the course of the various Apollo Missions. However, after Apollo 17 no man has again set foot upon the Moon. Mankind's progress has stalled and the glory of space exploration has slowly disappeared. In the movie *Apollo 13*, the main character, astronaut Jim Lovell is confronted with the question why we should continue missions to the Moon if we have already been there. In response, he wisely replies, "imagine if Christopher Columbus had come back from the New World and no one returned in his footsteps".



**Figure 1 - Apollo 11 saw the first man on the Moon and instilled a national pride in our Space Program that needs to be revived.**

The time has arrived for another giant leap to be made. For a number of reasons, including scientific knowledge, human civilization, exploration preparation, global partnerships, economic expansion, and public engagement, we need to return to the Moon, this time establishing permanent settlements and beginning the process of colonization [11].

### **PROJECT CONSTELLATION:**

NASA's newest venture, Project Constellation, a modern day Apollo program, aims to return America to the Moon by 2020, this time establishing a permanent base on the Moon. This endeavor will seek to replace the aging space shuttle fleet. Project Constellation will consist of a new look that includes the Orion service module (five meters in diameter and over 22 metric tons), the Ares I Rockets capable of lifting a payload of 55,000 pounds (including the Orion Module) from Earth to lower orbit, and the Ares V Rocket

which can carry over 144,000 pounds to the Moon. [11].

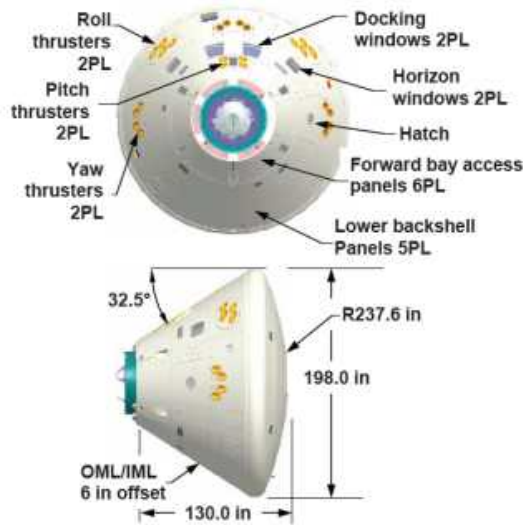


Figure 2 - Model of the Orion Module

### REASONS TO RETURN:

NASA's plan for a future permanent lunar base foreshadows great strides in history as well as a foundation for man's curiosity. Therefore, the ever-present reason to return to the Moon is man's ceaseless desire to try new things and explore the unknown [3]. Next, an undertaking of this magnitude would undeniably unite foreign nations, much like the International Space Station does. It would give them an opportunity to cooperate with one another towards one common goal [3].

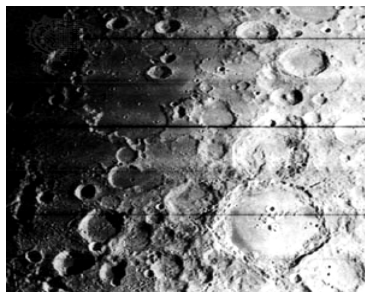


Figure 3 – Craters on the Surface of the Moon of the moon like those seen above can be studied to reveal a great deal about asteroids.

The Moon also provides the ideal environment for long-range telescopes. This is largely due to the fact that there is no atmosphere to obscure our view of space on the Moon. Therefore, these long-range telescopes would be more accurate and far more effective. The Moon has a great deal of economic potential as well: it is a source of raw material and solar energy, as well as a possible vacation destination [3].

The most important reason to resume missions to the Moon is for the sake of science. Geological studies of old Earth rock that has impacted on the Moon will uncover a great deal about the history of our own planet [3]. Study of the Moon's well-preserved craters will also reveal a significant amount about asteroid patterns and future threats to our existence [3]. Creating settlements on the Moon will provide valuable practice and knowledge on how to one-day land Man on Mars [3].

### COMPLICATIONS:

A permanent lunar base will be much more difficult than traditional Apollo missions to the Moon. Along with the usual hazards of space travel, there exists a whole new set of problems to create a settlement on the Moon.

### GRAVITY

On the Moon g forces are 1/6 of what they are on Earth [3]. Long-time exposure to reduced gravity has adverse effects on the human body. There is continuous calcium loss from the bones, which causes them to become brittle. Also, since there is decreased gravity, our muscles have to work less to do any activity such as walking or simply standing. This leads to muscle atrophy.

However, this can be counteracted if the astronauts exercise sufficiently.

In addition to atrophy, this is a net loss of fluids in the body, which can easily lead to dehydration. Although extreme, with proper caution, we may overcome these health obstacles [5].

### **SHIELDING**

Because there is no atmospheric protection on the Moon, radiation is another constant health threat. Excessive exposure to radiation will cause severe cell damage and can also lead to cancer. A possible solution to this problem is applying a three-meter layer of regolith, or lunar soil, over the entire base [3]. In the extreme cases of solar flares, the inhabitants will have to resort to staying in a flare shelter until it is safe to resurface [3]. Such caution will especially have to be observed every eleven years, the cyclic period of solar flares.

### **LUNAR DUST**

Regolith is an extremely coarse composite that can be dangerous to both the astronauts and their equipment. It is composed of razor sharp particles that have the ability to work their way into everything from astronaut suits to mechanical equipment [3]. In order to prevent the entrance of this damaging lunar dust, a special abrasion-resistant material called Kevlar may be used [12].

### **TEMPERATURE**

Temperature is another major threat to the crew's well-being. The temperature on the Moon ranges from  $-150^{\circ}\text{C}$  at night and  $100^{\circ}\text{C}$  during the day. The base will need efficient heating and cooling systems. Any exposed equipment will require materials resistant to such extreme temperatures.

### **LIFE SUPPORT**

To sustain life on the Moon, oxygen and water will both have to be supplied for our astronauts [3]. Fortunately, oxygen can be extracted from the lunar regolith through the process of Carbothermal Reduction [13]. In this process, lunar ilmenite ( $\text{FeTiO}_3$ ), a type of lunar rock, is taken and the oxygen is extracted from it. Ice can be mined from the ice on the poles of the Moon. In addition, water conservation system like the ECLSS Water Recycling System (WRS) used on the International Space Station will be integrated, allowing the astronauts to recycle a great deal of the water brought with them to the Moon [10].

### **BUDGET CONSTRAINTS**

It costs roughly \$20,000 per kilogram of cargo launched into orbit [2]. To put this in perspective, it would take \$1,600,000 to put a 160lb astronaut into space. Thus, it is vital that the limited space is used efficiently.

### **DESIGN CRITERIA:**

When picking a structural concept, there are a number of design criteria to consider that will make our selection much easier. A structure that can mostly be assembled on Earth is ideal. We hope to have astronauts spend as little time possible constructing their habitat on the Moon. The design should be strong enough to withstand the stresses of pressurization and any weight of an outer shell. Another key consideration is that the module must be spacious, both for the ability to store supplies as well as the mental well being of the astronauts who will be confined to this habitat for long stretches of time [3].

The design structure must also factor in the various extreme lunar conditions. For example, when choosing

a material, it is critical to consider the effects of extreme temperatures on the metals, fibers, etc. In addition, it is important to note that lunar regolith is composed of 60% Oxygen by weight. Thus, it is important to avoid metals that oxidize rapidly [14].

## DISCUSSION OF POSSIBLE SOLUTIONS

### INFLATABLES:

One possible design structure is the inflatable. There are many advantages to this type of structure. They can be easily compressed, making them convenient and cheap to transport, but provide large living spaces at the same time. Construction would be relatively quick and easy, which is important for our astronauts. Due to their light weight they are low in cost and do not require expensive heavy metals.

Inflatable structures do require stabilizing beams. Inflatable beams could be incorporated into our structural design and later solidified using foam. The foam would be injected into the inflatable beams and would naturally harden and expand over time.

There are generally two types of foam composites: thermosetting and thermoplastic. Thermosetting composites cannot be reshaped once they have been injected, while thermoplastic can be remolded by reheating the polymer. To ensure that the habitat does not deflate once pressurized, the thermosetting composite would be the better choice for the structure.

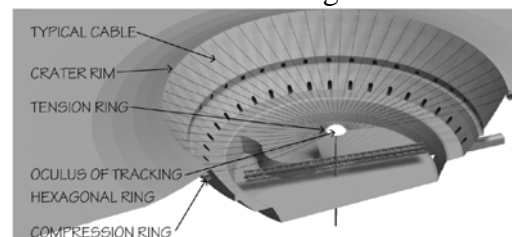


**Figure 4 -Inflatable structures can be assembled easily, like the one seen above. As you can see, large volume is provided while using limited amounts of material.**

Finally, inflatable structures require a pressurization system. Ideally, the structure should keep an internal pressurization of around 15 psi (103.4kPa) [2]. The threat of air leaks is a serious concern. Airlocks will lose 10% of their air by volume per usage [12]. Therefore it is important that there is a constant supply of air to be pumped into the structure.

### CABLE STRUCTURES:

Cable-based structures are another option for more advanced lunar settlement. They use an inflatable roof structure spread over a crater and are then secured to the surface of the Moon with cables. The advantages of cable-



**Figure 5 Cable structures are another possible design concept. As seen in this picture, they cover a large area and would be difficult for the astronauts to construct on the moon's surface.**

based structures include previous experience on Earth with similar structures (such as bridges), and the strength of cables, which can carry

heavy loads with tension, making use of the gravity on the Moon.

On the other hand, cables must be pre-stressed on Earth and these structures can only be built in certain areas. The compression ring surrounding the structure must also be pressure-sealed to the ground, which can be difficult. This makes the cable structure more advanced and possibly better for a later phase of lunar development. However, cables could be utilized as nets for safety, beams for support, fabrics, or an aid for transportation [4].

#### **RIGID STRUCTURES:**

The simplest structure design would be a rigid lunar structure made from a metallic alloy, most likely aluminum. The structure could either be in a “tin-can” design or a cylinder on its side. Our familiarity with the materials and structure geometry (successful launches of Apollo aluminum structures) would make designing a structure easier as we would have previous structures upon which to base our model. Also, we can conclude that aluminum is a reliable material and will be able to endure the harsh conditions of space.



**Figure 5 - Example of a rigid structure, one of the proposed designs for the lunar base. It is evident the structure's bulk would be very costly to transport from Earth.**

A major advantage of a rigid structure is our ability to check the module before launch and preinstall the equipment necessary for lunar habitation [8]. However, limited volume in the shuttle would prevent a rigid structure to be sent in one trip, so the benefits of being ready to use are lost. The high density of aluminum is the main disadvantage, as we want to transport the materials in the most cost and space efficient manner. Also, construction would be particularly laborious if the structure comes in pieces. In regards to radiation protection, there is no clear advantage of using rigid structures over inflatable [15].

#### **POWER METHODS:**

A large supply of energy is needed to run a lunar base. Not only must we power all the life support systems, but also it is suggested that our energy supply exceed our energy needs by 20% [7].

##### **Solar Power**

Solar energy is one solution. Panels can be shipped from Earth or made from silicon extracted from lunar regolith. [7].

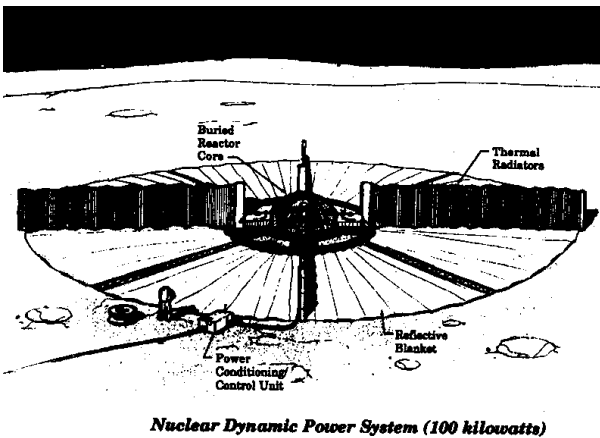
Lunar made cells would be about 5% less efficient than those made on Earth, [7] but when considering the cost to ship the material from Earth, it is six times more cost efficient to build them locally than to ship from Earth [1]. It will be necessary to bring storage cells to hold excess energy created by the solar units. This energy will then be used at night when solar energy is not available. Nickel Cadmium, Nickel Hydrogen, and H<sub>2</sub>O<sub>2</sub> are all possible types of fuel cells that can be used [9].



**Figure 6 -Solar panels imported from Earth can be quickly unraveled and used. This will be the complementary power supply, providing power in case the nuclear reactor fails.**

**Nuclear Power**

Nuclear Power is another potential source of energy. Experts have suggested two different models of nuclear reactor. One is the SP-100 model, which weighs in at 4600 kg (10,141 lbs) and has a 100 Kilowatt output. [9]



**Figure 7 - SP-100 model nuclear reactor provides a 100 kilowatt output. A reactor similar to this will be sent before the first crew arrives on the Moon and will be the main source of power for the lunar base.**

The other is a model suggested by Washington University weighing 51000 kg (112,983 lbs) and capable of

producing 3.366 megawatts. This model has a ten-year life span, more importantly requires no humans for operation [9].

Mobile equipment such as a lunar rover or any construction equipment is best left battery operated due to the limited usage of these machines.

**PROPOSED DESIGN AND RATIONALE:**

We decided the inflatable structure best fits our needs of a permanent lunar base. Its compressible nature enables us to package the structure in the rocket with minimal volume thus saving us launching costs.

In addition, unlike the rigid structure, the inflatable further provides perceptible volume, an important factor for the psychological well being of the inhabitants [12]. When the earth-made product is finished, it can be tested in a controlled environment before deployment.

Past success with inflatable structures such as the Echo satellite and Genesis by Bigelow Aerospace (seen below) make us confident in the ability of inflatable structures.



**Figure 8 -Genesis, created by Bigelow Aerospace, is one of the successful uses of inflatable structures in space. The inflatable design used to make this was initially developed by NASA's TransHab Project.**

### **CYLINDRICAL SHAPE:**

We chose a cylindrical shape over a spherical or torus design for our inflatable structure. A cylindrical shaped inflatable is preferred because both the sphere and torus have doubly curved walls that result in an inefficient use of volume [12]. Cylindrical shaped inflatables have walls curving in only one direction. In addition, sphere and torus shaped inflatables are taller, requiring more regolith to be dug up from the Moon's highly compacted lower soil. Less dirt is required to be dug up when using the shorter cylindrical design.

The only downfall with the cylindrical shaped design is that it lacks uniform distribution of pressure [12]. Because of this, support structures will be needed. We propose the use of built-in inflatable beams that will be blown up with the rest of the structure and then hardened by injecting rigidizing foam made from a thermosetting composite.

### **OUR BASE, THE INFLATABLE:**

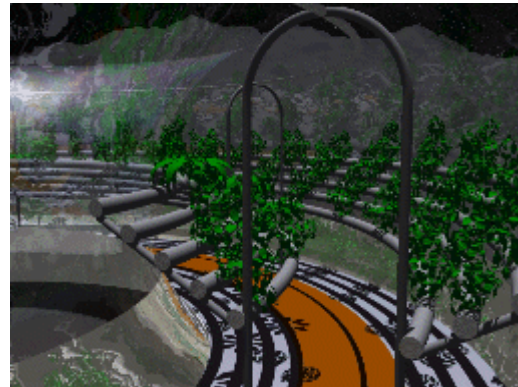
The initial lunar base will be cylindrical in nature, with hemispheres on either side. This design provides a large volume of approximately 1173 m<sup>3</sup>, with the hemisphere on either side providing structural support. The design dimensions used here are vital to the efficiency and success of the lunar mission. The inflatable module will be twenty-six meters in length, with the diameter being eight meters.

The living quarters are 3.25m x 3m for each crewmember to provide adequate room for the crew to be comfortable, decreasing psychological stress. The hallways are 1.5m in width to allow for two fully suited

crewmembers to traverse through them side-by-side, in case of emergency.

The airlock will be located at one end of the habitat. While this may be somewhat out of the way for anyone on the far side of the habitat wishing to go outside, there is precautionary logic behind this location. If the airlock is to leak, fail, or in some other way malfunction, only a small portion of the inflatable will have to be sectioned off. If the airlock were placed in the middle, we would instead lose half of our habitat. The airlock is two meters wide at the base, allowing crew members to come in two at a time. Such an entrance style would allow each to check the other's life support and other equipment before entering and exiting.

The "greenhouse" will also be equipped with an airlock, which will only be activated should the other one fail. The greenhouse itself will be 15 meters high to support the plants grown, which will eventually provide the crew with food and oxygen.



**Figure 9 - Possible greenhouse design for lunar base. This will provide the crew with food and will recycle the air.**

The recreation room will be 3 meters in length, providing the crew with much needed relaxation activities, and it can double as a place to meet and plan out missions.

Located at the bottom of our inflatable will be an emergency room for protection in case of a solar flare. If such phenomena were to occur, the astronauts would retreat to a bunker that is encased by our water supply. The water will serve as a shield from the harmful radiation. There will be enough food and supplies in this bunker to last the astronauts a couple of days, allowing the solar flare and its hazards to the astronauts' health to pass by.

For protection from radiation and micrometeorites, we will cover our base with a three-meter thick shell of lunar regolith. We will sandbag the regolith with Kevlar material. Panels will be placed on the roof of our habitat, allowing for even distribution of sandbags.

**KEVLAR:**

The harsh condition of the Moon require a material that will endure the extreme temperature gradient, micrometeoroids and the various stresses put on it, while our choice of an inflatable structure requires it to be flexible. We chose to use Kevlar 29, an aromatic polyamide fiber made by the DuPont Company, as the material for our inflatable structure. Kevlar, which has a high tensile strength, is chemically stable when exposed to various substances and degenerates only with strong acids and bases. The extreme temperatures of the Moon will not affect Kevlar; it does not melt, only degenerates at very high temperatures (427°C to 482°C in air) and tensile strength is minimally affected by cryogenic conditions (-196°C as cited in DuPont literature). Although Kevlar is susceptible to breakdown with extended exposure to UV rays, it will be assumed

that the material will last until the regolith is packed on top. The following data was given by the DuPont Technical Guide of Kevlar for 1000 filaments of Resin Impregnated Strands (ASTM D2343):

Property	Unit	Kevlar 29
Density	g/cm <sup>3</sup>	1.44
Tensile Strength	psi (MPa)	525,000 (3,600)
Tensile Modulus	psi (MPa)	12.0 x 10 <sup>6</sup> (83,000)

DuPont defines tensile strength as the ultimate strength exhibited by a material at the moment of a failure based on a unit of the original (i.e., no-load) cross-section. Frequently, the term tensile strength is used synonymously with ultimate stress. Modulus is defined as the property describing a material's resistance to extension. Modulus is area-specific, that is, it is expressed based on a unit of the original cross section. [6]



**Figure 10 - Spools of Kevlar 29 (the same material used for bullet proof vests) will provide some level of protection against micrometeorites.**

Using the density of the Kevlar 29 (1.44 g/cm<sup>3</sup>) we can compute the volume of material needed and solve for the mass. The volume of the two hemispheres on the end:

$$V_s = \left(\frac{4}{3} \cdot \pi \cdot 4.001026^3 m\right) - \left(\frac{4}{3} \cdot \pi \cdot 4^3 m\right) = 0.2603 m^3.$$

The volume of the cylindrical section of the module:

$$V_c = (\pi \cdot 4.001026^2 m \cdot 18m) - (\pi \cdot 4^2 m \cdot 18m) = 0.4642 m^3.$$

The total volume = (0.2603 m<sup>3</sup>) + (0.4642 m<sup>3</sup>) = 0.6705 m<sup>3</sup>.

The mass of the Kevlar 29 would then be:

$$M_K = \frac{1.44g}{1cm^3} \cdot \frac{1 \times 10^6 cm^3}{1m^3} \cdot 0.6705m^3 \cdot \frac{1kg}{1000g} = 965.52kg$$

### PRESSURIZATION:

To compute the stress from the internal pressure on the Kevlar 29 material, we use:

Assuming that one layer of Kevlar 29 is 0.144 mm thick [3] then the nine layers that we will use will then be 1.026 mm. The ideal internal pressure that we chose was 101.4 kPa and the radius of our module is 4 meters. Therefore,

$$\delta\phi = \frac{P \cdot r}{thickness} = \frac{(101.4kPa) \cdot (4m)}{(0.001026m)} = 3.953 \times 10^5.$$

is well below the maximum tensile strength of Kevlar 29 (3.6 x 10<sup>6</sup> kPa). Therefore, when the module is inflated upon arrival, the material will be able to withstand the internal pressure. During construction, inflation will be first (the

nuclear reactor would have been sent already and begun to create energy) and then distributing the foam in the structure. Next the astronauts will pack the regolith and place the sacks above the structure. The stress that the regolith places atop the inflatable is also tolerable. In the case of the inflatable depressurizing, the material should not collapse, but be able to withstand the weight of the regolith. Since the internal pressure and regolith loads are in opposite directions, the net stress is lowered significantly.

### NUCLEAR/SOLAR POWER COMBO:

We decided upon a combination of nuclear power and solar power as the best means of providing energy to our base. We chose the heavier but more powerful model of nuclear reactor to be used. This reactor will be shipped to the Moon before the astronauts, providing them with a power source upon arrival. The nuclear reactor will serve as our main power source in our beginning stages.

Complementing the nuclear reactor will be solar panels made from regolith-based materials. As our base grows so will our energy demands, therefore more solar panels will be constructed as needed.

### FUTURE

The designs presented above are those for a first phase lunar base. It is hoped that this type of base would allow us the time and means to create a more permanent habitat for our astronauts. The first base will set up the groundwork for mining lunar resources to build larger habitats.

For example, in the future, lunar soil could be heated like clay and used to build a larger base suitable for greater endeavors. To power these new bases we would have to ship in new nuclear reactors. However, it would be preferred that we became more independent of Earth and instead used a vast system of solar cells made from lunar silicon.

Finally, our experiences on the Moon should help prepare us for an eventual trip to Mars. Much of the technology used on the Moon can be incorporated into a trip to the Red Planet. Also, trials, new ideas, and tests can all be performed on the Moon before making the trip to Mars.

### **CONCLUSIONS:**

Given the current technology, an inflatable design would be the best suited for the primary mission objectives. An inflatable structure would be able to provide the most volume per mass ratio while still being the cheapest to transport. The base design is fairly large to provide the astronauts with enough room in which to work and live comfortably. To protect the base against micrometeorites and solar radiation, a combination of Kevlar and regolith will be used. The vital human resources of food, water, and oxygen will either be recycled or produced using native resources. Power is provided through a combination of solar panels and a nuclear reactor. All of these design choices would best be able to support an initial lunar base, which can later be expanded.

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