Lunar Base Design Contest

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The first step in designing a Lunar Base is understanding what we wish to accomplish on the Moon. I believe the key to Lunar development is to create an operation that is driven by profit. Ultimately we must separate ourselves from the charity of Congress and stand on our own. The following areas have been considered for commercial development of space:

1. Solar Power Satellites
2. Space Tourism
3. Mining of precious elements
4. The transportation and recycling of satellites
5. The on orbit servicing of spacecraft.

Space is an excellent place to build solar cells. There is abundant solar energy to refine the silicon. The vacuum of space permits continuous manufacture of the cells as opposed to batch processing on Earth. Finally there is the microgravity which allows the cells to grow larger and become more efficient converters of light into electricity, It has only been since 2012 that solar cells have become competitive with fossil fuel electricity. It is likely that solar cells will be used to complement fossil fuel plants whose principle cost is fuel. Nuclear power plants because of their greater complexity have historically produced electricity at greater cost than fossil fuel plants. Initially we can expect that the solar panels produced in space will be delivered for use on the ground. A one way delivery system could be modelled after the recovery system of the Space Shuttle's solid Rocket Boosters. Each booster weighed 200,000 pounds at recovery... Potentially two million watts of solar panels could be delivered on a daily basis with a value of two million dollars. Once production reaches ten billion watts of generating capacity then we will see a shift to keeping the solar panels in space and beaming the power to Earth. Lower cost will likely keep fossil fuel plants in operation for the next one hundred years. The competitor to solar power satellites will be nuclear fusion power plants but because of the complexity of these plants it is still expected that solar power satellites will produce electricity at lower cost.

The key to space tourism is reducing the cost from Earth to Low Earth Orbit (LEO). What we want to see is aircraft like operations where the vehicle is fueled, loaded, flies to orbit, returns, and repeats the cycle. Aircraft operations costs are normally 40% fuel with 60% of the cost being comprised of hardware and labor costs. This suggests that with every pound delivered to orbit costing $20 in fuel that the minimum cost to orbit is $50/pound. If we assume that this is for cargo alone, a passenger would need support equipment. Doubling the number seems prudent so a minimum of $100/ pound for manned spaceflight. Are these numbers reasonable in view that the Space Shuttle was said to cost $10,000/ pound to orbit. Realistically, yes for the $10,000 figure was given to discredit the Space Shuttle. The cost reflects a hidden assumption that the Shuttle would fly only twice a year. At four flights per year the cost drops to $5,000/pound. At eight flights per year the cost dropped to $2,500/pound. Fuel costs are essentially fixed on a per flight basis, while hardware (reusability) cost is amortized over the lifespan of the launch vehicle. The Shuttle lifespan was typically quoted at one hundred flights. Labor costs, essentially the personnel costs, to launch a vehicle are amortized on an annual basis. This was the major cost for the Space Shuttle. To compare the Shuttle with expendable launchers the development costs were ignored. For private industry this would not be the case and one more launch cost would be added based on development costs amortized over the estimated number of flights that occur over a twenty to thirty year period.

At $20,000 per ticket to orbit few could afford the ticket. To further lower Earth's launch cost we must pursue non-rocket concepts. The first of these concepts is the Skyhook. The Skyhook is a simple concept consisting of an anchor mass, a cable, and ballast. The cable is made of materials currently available in mass production. The cable is attached to the orbital anchor mass and extends towards the Earth. As we move along the cable we find that we are moving at less than orbital velocity and become increasingly subject to the pull of gravity. A shuttle craft would match velocities with the tip of the cable and attach itself. Basically what we have is a trapeze act. Because the shuttle craft does not reach orbital velocity its carrying capacity is greatly increased. The cable material currently available would result in an eight fold increase in the payload of the shuttle craft.

The Skyhook suffers from two major problems. The first is that the anchor mass must be at least a hundred times greater than the mass of the shuttle craft otherwise the shuttle craft would drag the cable down into the atmosphere. This makes it impractical to build the Skyhook from the Earth. The second problem is that the Skyhook must be kept in balance so the mass going up to the Skyhook must equal the mass coming down from the Skyhook. This allows the Skyhook to greatly reduce the cost of placing space tourists into orbit but doesn't help in the building of the space resort. This is where ballast comes in. It is assumed that the anchor mass is delivered from the Moon. The anchor mass may be nothing more than Lunar rocks held together by a net. Once the anchor mass is stable we can continue to ship Lunar material to the location to serve as ballast. Items such as carpeting, drapes and furnishings could be brought to the space resort by balancing the mass with Lunar material. Lunar sand would be similar to the meteorite dust that the Earth collects each year, Lunar Oxygen could be added to the Earth’s ozone layer, or Lunar iron could be dropped in the ocean to stimulate algae growth to aid in the sequestering of CO_2. A twenty thousand pound shuttle craft would need two million pounds of Lunar material for the anchor mass

Another concept for Space Tourism is Orbital Rings. Imagine a rail from a train track has been put into orbit. Behind this rail we put another and another until a ring exists around the Earth. Near-by we put a second ring moving in the opposite direction. Across these two rings we lay a platform. The platform doesn’t actually touch the spinning rings but is supported by magnetic levitation. From this platform we can drop a cable to the Earth’s surface A hundred mile long space elevator is doable with today’s materials. People brought up by the elevator would enter aircraft like cabins that would then be magnetically accelerated to orbital velocity. These cabins would then detach and fly to orbital resorts. The tourists would return in the same manner. Because energy is conserved the cost would be amortized over the cost of constructing the rings. The rings would be made of Lunar iron.

The mining of precious elements found on the Moon would provide an immediate revenue stream for the Lunar Base. Platinum Group Metals (PGMs) are mined on Earth as a secondary function of mining iron. PGMs are found in iron at concentrations of 1/10,000 to 1/100,000. PGMs with a value of $49,000/Kg, would allow a quarter of a billion dollars to be shipped back in a single shuttle craft. Helium3 also commands a high price and is used in medicine as well as fusion research. Also what must be considered is that space will have two economies: an internal economy and an external economy. This is often expressed as soft and hard currency. The PGMs are a hard currency which can be traded for real goods. A PGM miner might sell his metals to purchase an MRI machine from Earth. The miner then sells the MRI machine to the space community hospital for twice what he paid for it, but payment is in soft currency. Soft currency is used to purchase items and services in the local (Internal) economy like health care, food, housing, etc. Only imports require hard currency.

The value of the materials may not reside in the materials themselves but of the difficulty in producing the materials. Silicon is a common element. Pure Silicon however costs $220/kg because of the difficulty in removing trace elements that would interfere with its semiconductor properties. Solar panels shipped back to Earth would cost $22/kg. This is because only a small portion of the panel is actually the high purity silicon. Titanium is only a few dollars per kilogram but its high melting point makes it difficult to shape so rather than shipping ingots of titanium to Earth we would more likely send the final product, such as aircraft turbine blades, to Earth.

A lesson between price and cost. We know that there is a proven market for the transfer of satellites to Geosynchronous orbit and the mid orbits for the GPS satellites and that the owners of these satellites are willing to pay $5.000/pound to Low Earth Orbit (LEO). Launch costs have remained high because there are very few launches. Six satellite launches per year at an average of $150 million per satellite would create a revenue stream of $900 million per year. If we reduce the cost to $1000/pound and charge 10% less than our competitors we would leave a profit of $630 Million/year for the development of the Lunar base. Lower launch costs also open the door to retrieving old satellites and refurbishing them or retrieving them for their component parts or materials.

One of the first products that would be brought back from the Moon is water which could be converted into propellant. This is significant because this propellant would be used to deliver equipment and supplies to the Moon. This would make the cost of reaching the Moon only twice as much as the cost of reaching Earth orbit. The presence of Lunar water and propellant in Low Earth Orbit would enable the use of Single Stage To orbit (SSTO) spacecraft from Earth to LEO. The problem with building an SSTO is that using our best propellants we can only place 10% of the weight of our rocket into orbit. With today's materials we can build an SSTO but it would have no cargo capacity. If we assume that our SSTO uses a transpiration heatshield where the heat of re-entry is carried away by water and that the SSTO uses propulsive landing like SpaceX's first stage then 20% of the on orbit weight of the SSTO would be fluids that could be supplied from the Moon.

To land on the Moon we need a Hydrogen/Oxygen powered spacecraft to take advantage of the water that has been discovered on the Moon. To keep costs low we would want this lander to be reusable. If the Lunar Lander returns to LEO then it should be designed for aerobraking. It should also be capable of storing the volatile Hydrogen for several months on the Lunar surface. Work done for the Manned Mars Mission shows that this can be accomplished by using a multi layer insulating blanket. A second vehicle is needed to ferry the Lunar lander from LEO to Low Lunar Orbit (LLO). The Delta-V needed to fly from LEO to LLO is roughly the same as the Delta-V for a round from LLO to the Lunar surface and back. This allows us to use the Trimese approach to developing the Lunar Ferry and Lander. Essentially it is a two stage vehicle. The second stage is the Lunar Lander. The first stage is created by using two modules identical to the second stage. So only one fifty thousand pound module is developed. The dry weight of the vehicle is 10%. This includes fluids for a transpiration heatshield and a propulsive landing system. The module is designed to last 100 flights and has a specific impulse of 440 seconds. A multi-layer insulating blanket is added at the space station to allow the retention of the liquid Hydrogen over a period of several months. This blanket is lost during the aerobraking maneuver. When the three modules arrive at the Moon they separate and the first stage modules return to the Earth. Only the module needed for the landing brakes for Lunar orbit.

Delta V for the first stage is 4 Km/sec while the Lunar Lander requires a Delta V of 6 Km/sec. When the two first stage modules return to the Earth they use aerobraking to enter Earth orbit and rendezvous with a space station. Similarly, the module used for the Lunar Lander returns to LEO and the space station. At the space station the modules could be serviced for a return to the Moon or to the Earth. The modules are self ferrying from Earth to LEO or they can serve as a reusable upper stage for the Falcon 9 launch vehicle or Glenn Vehicle. Using the same two stage configuration we could introduce a new launcher from Earth to LEO that could deliver water for propellant conversion at the LEO space station.

The Moon offers us the opportunity to ship materials such as propellant to LEO at a cost less than bringing the materials up from the Earth. Cost is a matter of energy and not distance. A quarterly launch from LEO would require 600,000 lbs annually. At $1,000/lb from the Earth's surface to LEO we would need an annual budget of six hundred million dollars. If we lower the cost to $10/lb using the Skyhook we need only produce six million dollars in Lunar products to break even. When the launch module reaches the end of its life it is given one more mission as an expendable to deliver cargo to the Moon as an unmanned lander. Four such landers would deliver 80,000 pounds to the Lunar surface.

To create a commercial Lunar Base we need to make a profit and the lower the launch costs the greater the profit. When the Space Shuttle failed to significantly reduce launch costs I began to focus on why it failed. The best theory I found was put forward by the Congressional Office of Management and Budget (OMB). Their findings was that launch costs consist primarily of hardware and labor costs. Reusability addressed the hardware costs but labor costs had to be amortized over the annual flight rate. The Space Shuttle simply made too few flights to drop launch costs. One thing I also noticed was that launch costs did not vary depending on the size of the vehicle. It appeared that labor costs grew with the size of the vehicle. I hope that I am wrong and that Elon Musk and Jeff Bezos have found a way to cut back on the 10,000 personnel that were needed to launch the Space Shuttle.

Based on what I learned I came to the conclusion that to lower launch costs we must return to 1950s idea of delivering cargo to a space station using a small launch vehicle. Orbital dynamics limits us to one flight a day to a space station. The figure I use is 250 flights per year based on a five day work week and 50 week work year. A single launch site can support multiple space stations, but because these stations are in different orbital planes they cannot support each other. Similarly a single space station can be supported by multiple launch sites.

Eventually a cargo vessel will be needed to carry cargo back to Earth orbit. This vessel will be capable of delivering 45,000 pounds to the LEO space station.. This vehicle will use aerobraking, the heatshield will use water as a heatsink. Water is a basic product for the Moon and delivering it to LEO will supply the propellant needed for the return flight. When empty the vehicle will weigh less than 5,000 pounds and will be carried to LLO by a launch module. In LLO the cargo vessel will be loaded by repeated use of a launch module on the Moon used as an SSTO.

One final vessel that will be needed is an expendable cargo vessel that will carry Lunar exports to the Earth. This vehicle is modelled after the work done on recovering the Space Shuttle’s Solid Rocket Boosters. Each of these boosters weighed 200,000 pounds upon their return. The cargo vessel would be a light weight container holding rock wool and the solar panels. Slowed by parachutes and a rocket braking system the cargo carrier would land in the ocean. Designed to float it would be towed to port by a ship. The solar panels would be of commercial grade with a weight of 10 watts per pound. This requires the delivery of 10 to 100 million pounds annually to the Earth’s surface. With the sale of solar panels we will see a shift in launching from the Moon using rocket power to magnetic flight using Mass Drivers.

There are three phases to the development of the Lunar Base. In phase one all of the materials are brought to the Moon by rocket. In phase two the Lunar Base utilizes the local materials to expand. In phase three the Lunar Base exports the Lunar material to LEO. Phase one begins with the launch of an expendable Lunar Lander. This will be the first of four launches that will test the Lunar Lander's ability to safely land and delivers the 80,000 pounds of cargo that makes up the Lunar Base. The first Lander will contain the supplies needed by the astronauts when they arrive a year later. This is because the astronaut's supplies are the most easily replaced should the first lander fail. The second lander will contain the robotic work force. Use of telerobotics greatly expands the Lunar workforce. Robots are used to perform repetitive tasks. Telerobotics allows the robot to be remotely controlled by a human operator as far away as the Earth. The purpose of the astronauts is to maintain the automated mining equipment and trouble shoot any problems that arise. The largest of these robots are the harvesters.. The harvester has three functions: the first function is to use a magnetic field to capture small particles of iron in the Lunar regolith; The second function uses electrostatic fields to remove small beads of glass; the third function is to sample the regolith and create a resource map of the area. A one ton harvester will process one 1.5 tons of regolith per hour and collect 0.36 tons of Iron per day. A fleet of ten harvesters is assumed for a total of 3.6 tons of iron per day. Other robots include a water miner, excavators, haulers, Solar thermal processor, humanoid, and specialty robots like a truss builder or conveyer belt robot. The robots can range in size from an RC toy to a family car.

Before the astronauts arrival there are several projects that the robots could do. The first project is a solar power plant. Sunlight comes in parallel to the land at the Lunar poles. To capture this sunlight a fifty meter truss is formed and placed upright. Without winds it is possible for the reflector to be a square 300 meter by 300 meters that weighs less than 100 pounds in the Lunar gravity. The reflector is attached to the top of the truss with a motor that rotates the reflector which allows it to track the sun and reflect the sunlight downward to the land. In discovering craters of perpetual darkness it was realized that there are peaks of perpetual sunlight so the poles provide us with a continuous source of energy,

The initial Lunar base will be on the rim of Shackleton Crater. A disadvantage of this is that the rim is still subject to the Moon's Two week night. Shackleton crater is needed to supply the water needed for Hydrogen and Oxygen propellant. As energy needs grow we can expect the permanent base to be established at the Malapert plateau where it is possible to tap into a continuous supply of solar energy. Shackleton and Malapert are separated by a one hundred miles. The two locations will be tied together by a power line, a water pipeline, and a road. The powerline will supply continuos energy from Malapert plateau to Shackleton crater, using native Iron and glass. Copper is not readily available on the Moon, Aluminum is commonly used on Earth as a conductor but will need to import carbon and have the added complexity of recycling the Carbon Dioxide to be cost effective. Iron is the most readily available conductor, its greater weight and resistance being of little importance on the Moon. An out of the box solution is to use Calcium as a conductor on the Moon. It is a superior conductor compared to iron or aluminum but there is little experience with it because of its strong reaction to Earth's atmosphere.

A second project is artificial caverns. These caverns provide radiation protection for the astronaut habitats and provide insulation during the Lunar night to support the robots. The artificial caverns make it easier to expand and run checks on the habitats. The caverns would be ten meters by ten meters. The ground would be excavated to a depth of one to two meters. Trusses five meters high would be place on the lip of this excavation. The trusses would be buried beneath a berm that surrounds the excavation. A Kevlar type roof would then be attached to the trusses to cover the excavation. Regolith would then be added to cover this roof providing three metric tons per square meter of radiation shielding as well as insulation against the Lunar night.

The final robot controlled project is a landing pad to support the astronauts. This would be a 30 by 30 meter square. The chosen area would be built up using the regolith. This would smooth over any depression while covering any small rocks. A ceramics factory would produce tiles that would provide a hard surface for the landing pad. A two hundred Kilogram factory would produce one ton of tiles per hour. 40% of the weight of the tile comes from the glass that is harvested. Power is derived by a solar thermal concentrator six meters in diameter and weighing twenty Kilograms.

The most important project is the mining of water in Shackleton crater. The key problem is that we do not know what form the water may take. The water could be in discrete ice crystals mixed in with the sandy regolith, it might be found in pure pockets of buried ice, or it might be a mixture of sand and water that has frozen into a dirty ice material. Each type requires a different form of extraction. To explore Shackleton crater we would use a one ton vehicle that would rappel down the side of the crater using a cable. The cable would be a conductive wire that would supply power to the vehicle. The vehicle would carry four probe vehicles of 100 Kilograms each. These four probes would explore the crater and report on the availability of the water. These probes would be battery powered and would have to return to the larger vehicle to recharge. Water Harvesters would arrive on the last unmanned lander. These harvesters would be designed to make use of the latest data.

The water harvester would be a mobile platform. Since battery power is limited for high power operations, a corridor is created using power lines on either side of the water harvester. The water harvester then taps the power across these lines. The water harvester has compartments to increase the weight and hence the traction of the vehicle. Regolith or iron is loaded into these compartments, A rectangular box of 0.1 meters by two meters is lowered from the harvester to the surface Hot dry air is pumped through the box extracting the moisture of the ice crystals. The hot air is then cooled and the moisture is collected. Once the site is no longer productive the box is withdrawn and the harvester moves forward a tenth of a meter and repeats the process. One kilometer of power lines allow a long shallow trench. A second vehicle, an excavator removes the now dry regolith that is shielding more ice crystals. If the water is in the form of dirty ice, the box sits on the ice and uses hot water to dissolve the dirty ice and slurps up both the water and sandy regolith. The harvester then separates the mixture. If large ice deposits are found a drilling rig would drill into the deposit. Hot water would then be circulated through the ice to melt and retrieve it. The energy needed to melt the ice is minor compared to the energy needed to turn the water into liquid hydrogen and Oxygen. 2.5 Kilowatt hours is needed for every pound of water processed into cryogenic fuel.

A team of six astronauts then land and build the base from the delivered cargo. The first Lunar base will be constrained by the mass that can be landed, so it is probable that we will rotate our people every three months. The use of robotics and telepresence greatly expands the workforce on the Moon. The astronauts will live in aluminum cylinders 2.4 meters in diameter and 5 meters in length. The diameter is dictated by the width of our roads.. Life support equipment will be designed for two people although normal habitation will be one astronaut per cylinder. This provides redundancy in the event of any damage to a cylinder. The cylinder is divided into an airlock, 1.5 meters long, and the living quarters, 3.5 meters long. The toilet and shower is located in the airlock. The toilet is nothing more than a chamber pot in which Lunar sand is added to keep the smell down. The pot is emptied each day as the astronaut exits the cylinder. Urine, faeces, and carbon dioxide are collected and stored for phase two where they are recycled.

The key question with the cylinder is the choice of the atmospheric gases. Nitrogen is an uncommon element on the Moon which means that it must be imported from the Earth. A single gas system is simpler to design so the cylinder is designed for only Oxygen at 5 pounds per square inch (psi). The 5 psi is a safety measure. Once pressure drops below 3 psi the body can't take in the Oxygen and the astronaut would lose consciousness. By using 5 psi we give the astronaut the time it takes to go from 5 psi to 3 psi to locate the leak. Concentration of Oxygen at greater than a partial pressure of 5 psi is toxic. The level of damage is dependent on exposure time. Additionally, the threat of fire is dependent on the concentration of the Oxygen. Normal concentration of Oxygen for Earth is a partial pressure of 3 psi. The Apollo fire occurred with Oxygen concentrated at more than 15 psi, five times the normal concentration of Oxygen on Earth. I would add a novel concept, moving from a pure Oxygen atmosphere to a mixed gas atmosphere at higher pressure. Space suit design has focused on using Nitrogen and Oxygen at 8 psi. While the suit is at a higher pressure the partial pressure of the Oxygen is less than the 5 psi of the cylinder. Assuming a six to eight hour work day with a lunch break in the cylinder, this period is short enough that decompression will not be needed. During suit time the concentration of the Oxygen is reduced.

The cylinders are considered a temporary shelter. The permanent shelters will be made of Lunar iron and designed for an Earth normal mixture of Nitrogen and Oxygen. I propose the permanent base be divided into two atmospheres. The exterior workers would have a four day work week where they live in a 5 psi Oxygen environment and use the two gas 8 psi suit. Using a six hour work day would expose the worker to one day of radiaiion damage for every week spent on the Moon. Three days though are spent in an Earth normal atmosphere of the main base. Atmospheric pressure has a great impact on the individual. Moving between the Earth normal atmosphere and the 5 psi Oxygen atmosphere requires four hours of purging Nitrogen from our bodies by breathing Oxygen in a mask at 15 psi. In the 5 psi environment sound does not carry as far so voices become strained, people move closer to be heard resulting in violating our sense of personal space. Smells actually travel farther so we find ourselves more sensitive to them. Low pressure also lowers the boiling point so that cooking must use pressure cookers and still accept a tepid cup of coffee.

Radiation is a common concern in the space community. Damage is caused by the energy released as the particles pass through our bodies. The amount of energy released is proportional to the square of the atomic number of the particle. What this means is that while 98% of the particles are protons with an atomic number of one, the bulk of the damage is caused by a single Iron nuclei with an atomic number of 26. Particle numbers are the most significant factor in assessing biological damage. The kinetic energy of the particle which is measured in electron volts is important to assessing how much shielding material is needed to slow and absorb the incoming particles. An example are solar flares. The number of particles from the solar flare is so great that the solar flare could be fatal to an astronaut in a spacesuit, The typical solar flare though ejects particles that have a kinetic energy in the 100 Million electron volt range. So while solar flares can be lethal, they are easily blocked.

The primary problem is cosmic rays which have kinetic energies of a billion electron volts or more. These particles are not numerous but are difficult to shield against. The longer we are exposed to them the greater the risk of developing radiation induced cancer. The first ton/square meter of shielding has little impact on this risk. The reason for this is that in front of the shield most of the damage is caused by the heavy nuclei but this diminishes as the Iron nuclei pass through the shield. As biological damage diminishes from the Iron Nuclei, secondary particles, neutrons, are generated and keep the damage level up. Two Metric tons/square meter are needed to reduce the neutrons by a factor of ten. So a total of three tons/square meter of shielding is chosen to reduce Cosmic ray damage by a factor of ten while the mature Lunar Base will use five metric tons/square meter for a protection factor of one hundred.

A space suited individual would have little protection against radiation and there is no theoretical means of providing protection. Particular care would be taken to monitor solar flare activity and assure a shielded shelter was close by. Against cosmic rays the astronaut would rely on limiting exposure so that the risk of developing cancer is limited. A limit is set of receiving one Sievert of radiation which corresponds to a risk of three out of one hundred astronauts developing cancer. Accepting the risk of developing cancer from the exposure to the radiation we need to limit exposure time. A very rough estimate of how much time we can spend in interplanetary space is two years, an exposure rate of 0.5 Sieverts per year. On the Moon, half of the exposure would be blocked by the bulk of the Moon so we would have roughly four years of suit exposure, 1,460 days. Given the four day work week and six hour work day for space radiation hazard workers this translates into 1,460 weeks or a 28 years career length.

In the second phase of the mission the Lunar Iron is used to construct cylinders ten meters in diameter using additive manufacture techniques. This forms the pressure vessel for an Earth Normal Atmosphere. Living quarters increase in size for long term stays. The number of astronauts increase both in the numbers delivered and increasing stay time. In phase one the number of astronauts delivered to the Moon is six for a three month stay. In phase two the propellant manufactured on the Moon allows the capacity of the lander to double so that 12 astronauts are delivered on a quarterly basis to the Moon. With the more comfortable quarters the stay time is increased so that with a one year stay the number of astronauts increases to 48.This leads to another project, a Lunar farm. The large cylinders would incorporate glass to provide a Lunar greenhouse.

Because of the radiation hazard it is commonly assumed that the Lunar base would be buried. However, plants are not as sensitive to radiation as are people. The Lunar farms can be shielded from solar flares, leaving them open to cosmic radiation. Although in a shirt sleeve environment the Lunar Farmer faces the same radiation hazard as a space suited astronaut but the farmer too can adopt the six hour work day, four day work week. A hotel built on the Moon could exceed the highest skyscraper on Earth, Unless the tourist is a radiation worker, a two week exposure to cosmic rays would be negligible. .

Requirements are based upon needs. So the question is where do we begin. At a minimum we should have the capability to launch six men on a quarterly basis. The first year we are dependent on what we bring from the Earth. In year one of the expedition I would expect four expendable craft to deposit a total of 80,000 pounds of payload. This includes robotic vehicles that prepare the base for the arrival of the astronauts. In year two the astronauts arrive and focus on shortfalls found with the robotic staff. Mining of Lunar water, iron, and glass. would begin in year two. Water is the number one priority for this provides for both life support and the basis for Hydrogen/Oxygen propellants. The need for propellants at this point is to replace the return propellant used by the lander. This increases the payload of the lander from 7,000 pounds to 20,000 pounds. The increased payload can be used to bring in more people or equipment.

By year 7, energy becomes the primary need and the base relocates to Malapert plateau where continuous solar energy can be tapped. The larger, more comfortable base is constructed using Lunar Iron. This would be the cylinders with spherical end caps. These cylinders would be ten meters in diameter and forty meters in length. The cylinders provide a pressure envelope to support an Earth normal atmosphere. These new cylinders can also incorporate glass windows converting them to greenhouses to feed the astronauts. The cylinders are double stacked to provide radiation protection for the astronauts in the lower section while the upper section is reserved for agriculture, The Malapert base, located roughly 100 miles from Shackleton crater is connected to Shackleton crater by a road, a pipeline that carries the water during the Lunar day, and power lines from the Malapert's solar powered generators.

Electrical power is critical on the Moon. Building solar power plants in turn needs electrical energy. At first we would be limited by the Moon's day/night cycle. This would push us to creating a permanent base on the Malapert Plateau. A seed source of solar power such as 100 Kilowatts could increase one hundred fold at Malapert over the space of a year. By the end of year 7 we could expect to have 10 Megawatts. By year 8 power production could be 1 Gigawatt, and by year 9 we would have full production capability for Solar Power Satellites.

In year 7 we have expansion of propellant production. The Lunar lander now becomes a cargo vessel carrying 24,000 pounds to LLO at a cost of 21,000 pounds of propellant. Another 10,000 pounds of propellant is consumed to send 35,000 pounds of cargo to LEO. I use the figure of 250 flights per year based on one flight per day, a five day work week, and fifty week work year. This delivers six million pounds to LLO and 4.7 million pounds to LEO. This requires 5.25 Million pounds of propellant for LLO flights and 1.33 Million pounds of propellant for the LEO flight. A total of 6.6 Million pounds of propellant are produced over a period of 365 days or 18,000 pounds per day

The loss of water which is vital to life in space is unacceptable so in year 7 we also begin construction of the Mass Driver, an electromagnetic accelerator to deliver cargo to the Eartth. The Mass Driver is estimated to move ten times its own weight per year. A two million pound Mass Driver would be able to move 20 Million pounds of cargo to LEO. This cargo would be used to construct a space resort and serve as the anchor mass of a Skyhook. After the space resort is completed the Mass Driver could continue to launch to provide solar panels for use on the Earth. Launch costs for Earth to LEO and LEO to LLO would be lowered by the Skyhook. Hydrogen/Oxygen powered spacecraft would be limited to personnel flights. This too would be short lived as orbital rings are constructed for moving people first from the Lunar surface to LLO and then from the Earth's surface to LEO.

The assumptions I use for the Lunar base is that each harvester processes one and a half times its weight per hour so that a two thousand pound harvester processes 72,000 pounds of regolith per day.. Only one percent of this mass is assumed usable, and this is applied to the extraction of iron, glass and water. One harvester delivers 720 pounds of iron and is assumed to produce 720 pounds of glass per day. The water harvester produces 720 pounds of water per day. During the first six years the harvesters only operate during the Lunar day, producing   131,400 pounds of product per year

Electrolysis and liquification of the water into Hydrogen/Oxygen propellant requires 2.5 Kilowatt hours of energy per pound of water. To convert the water from a single water Harvester requires a power plant of 75 Kilowatts. Using a figure of 10 watts /pound for the power plant requires a power plant mass of 7,500 pounds. Space qualified solar panels would weigh less but the 10 watts/lb reflects the weight of commercial solar panels that cost $1 per watt and would be the target for manufacturing on the Moon. The power plant dominates the initial mass we put on the Moon but solar panels are also considered one of the first products we would manufacture on the Moon. With continuous sunlight it is estimated that a solar power plant can increase one hundred fold per year while with the day/night cycle the growth would be limited to about an eight fold increase per year

The permanent base is made up of cylinders ten meters in diameter and forty meters long. The structure is actually a cylinder thirty meters long with two hemisphere end caps which add the additional ten meters. Yield strength is assumed to be 40,000 psi and a maximum internal pressure of 20 psi is used. This results in a thickness of 0.157 in or 0.4 cm. The role of this cylinder is to retain the Earth normal atmosphere at a pressure 15 psi. The cylinder is produced from Lunar Iron and masses 46 Metric tons. On the Moon this would be equivalent to lifting a an eight ton structure on Earth. The cylinders are buried to a depth of two meters to assure their stability. These cylinders are used to house the astronauts. Six 250 square foot apartments are constructed inside the cylinders. Two metric tons per square meter of regolith shielding is placed on the roof of these apartments, The apartments are roughly five meters by five meters with four meter ceilings. On top of these cylinders a second layer of cylinders is added. These cylinders though are half glass. They serve as the farmland for the Lunar Base. Crops are grown in regolith which also provides two Metric tons per square Meter radiation shielding for the apartments below them. Additionally the glass structure provides one metric ton per square meter of shielding against solar flares. With continuous sunlight roughly 500 square feet are needed to feed one astronaut so two agricultural cylinders are needed for each residential cylinder. Farm cylinders can be converted to residential cylinders as the base grows. Farm cylinders are also placed at ground level surrounding the residential cylindesr. Inside these farm cylinders a wall is formed surrounding the residential cylinders with a wall equal to 5 Metric tons/ square meter. This protects the settlement from radiation particles that come in parallel to the Moon’s surface..

Lunar Base
Front view

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