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SUSTAINABLE TECHNOLOGIES FOR LUNAR DEVELOPMENT

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Abstract

The purpose of this paper was to identify the salient features of a sustainable lunar resources development mission and the consequences of such a mission on earth. To accomplish this purpose, the existing literature on energy, transportation, site selection, mining, construction, life support systems and self replicating systems as it related to the moon, was researched. The result was a proposal for a mission to the moon that involves the use of an autonomous, robotic, self-replicating “seed” factory that grows over the lunar surface using local resources, and generates lunar industrial capabilities and energy for human civilization.

Acknowledgements

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1 Introduction

Man has always possessed a compelling drive to explore his surroundings, beyond the limits of his experience. We wonder what exists beyond our world, in the vast reaches of space, a concept so enormous that our minds cannot even imagine its extent. The number of questions we have about our universe is as limitless as the universe itself, and the mystery and intrigue of the unknown, with its possibilities and challenges, make it impossible to resist.

Most will say that curiosity alone is just cause for all the effort, but there are other powerful motivations for space exploration. In the age of exploration on earth, people crossed vast, indomitable, tempestuous oceans in search of myths, legends and elusive fairy tales of treasure and warm, exotic, fertile, bountiful lands. They strayed far from their homes in search of the unknown, driven not by hunger or fear of extinction, but by curiosity and a quest for profit, danger and glory. These are the people who discovered the world and all its precious resources. Today, a commercial airliner can circle the planet in a day.

Man has not traveled very far at all. We dream of traversing galaxies and tearing through space in warp drives to reach distant starts at the opposite end of the universe and of zipping back and forth in time but, in reality, we have traveled a despairingly small distance from our home, the earth. Though we have scrutinized the sky for countless hours with ever-improving telescopes and sent hundreds of satellites on endless, lonely journeys through our solar system to relay information about our closest neighbors, the farthest man has ever reached is our own moon. What mind-boggling magic would man have to invent to travel to another solar system, or even to Mars? Where do we start?

One place to start is the moon. Our closest neighbor may serve as the perfect proving ground for space technologies and, more specifically, sustainable space technologies. It may also serve as a launching platform for missions to other destinations because of its low gravity. If we attempted a journey to Mars in a conventional, current-day spacecraft, it would take a crew almost a year to reach the red planet, at immense cost, effort and risk due to the zero-g transit time and intense space radiation. This would be a one-way ticket and we would gain little more than an addition to our collection of data and pictures from the red planet. Developing the technology to get us to distant places is only half the game. The other half is planning our survival, activities, colonization and further expansion once we get there. Though we have some knowledge about the environments we will encounter at these destinations, our information is limited to the sensing tools we use, and is partial. We do, however, know a great deal about the survival needs of human beings and, as such, can work on that half of the problem with the use of current technologies. This report focuses on the technologies and methods that will lead to a self-sustaining lunar base.

In addition, the moon may be of economic importance. Helium three and solar energy are two resources that are abundant on the moon, and harvesting these powerful fuels is a pressing impetus to establish a presence there. Our energy demands are increasing with our population, and the fossil fuels in our earth's crust are not going to last forever. Though we are developing nuclear and solar energy technologies to someday eliminate our dependence on these limited fuels, we may someday simply run out of space for our enormous population. Unless we devise some means of population control, at a level where we can support the earth's residents with natural resources in a sustainable fashion, we will have to leave the earth in search of a new home or lose population due to starvation, overcrowding and epidemics, and pollution and contamination of the environment, until our numbers dwindle to a size that can be adequately sustained by our depleted, exhausted planet. This report will also look at some of the economic and societal benefits of establishing a permanent base on the moon, and at the potential for increasing industrial productivity and efficiency through the use of technologies developed for and energies harnessed from the moon.

In colonizing new planets or satellites, we can make controlled decisions in a way that we were not able to make when colonizing the earth. Many of our practices destroy our environment and use its resources in wasteful, damaging ways. In making a new start on some other planet, we will have to plan to live in a sustainable fashion, wasting nothing, reusing everything, and paying dearly in effort and resources for any increase in population. When human beings first spread over the earth, they killed only what they needed to eat, and cut trees only to construct modest dwellings for shelter. The land they lived on, under these circumstances and with these practices, could sustain them indefinitely, because they did not disturb nature's equilibrium mechanisms. As their numbers increased, these people cut down more trees for farmland, pastureland, fuel and construction, and began the process that has changed the face of our planet so drastically. In recent times, human beings are becoming more aware of the ideas of conservation and sustainable living. This report will consider the ways in which sustainability technologies developed for the moon could be used on earth to reduce the near-sighted exploitation of our environment.

The cost of sending one kilogram of mass to the moon is anywhere between ten and forty thousand dollars, using conventional rockets. Very few agencies are able to spend this money, and the prospect of maintaining a base on the moon, with resources from the earth, is prohibitively expensive. Hence, we turn to sustainability to reduce this towering barrier of cost. In this report, we present many approaches to the problem, a comparison of their advantages and shortcomings, and a recommendation of our personal favorite.

The ideas we present here run the gamut from short-term missions that house people in small bubbles next to a nuclear reactor, to dramatically long-term missions that transform part of the lunar surface into a habitable earth-like state so that lunar residents can walk around in shorts as they do on earth and roll around in the grass with their dogs. Some of these ideas are very speculative and some more conventional and proven, but all have merit and must be further studied.

2 Objectives, Content and Methodology

2.1 Objectives of the Presented Study

The objectives of the study presented here are as follows:

1. Identify motivations for establishing a presence on the moon
2. Identify the scope and purpose of a self-sustaining moon base
3. Identify those technologies which will likely be applicable or vital to the successful establishment of a self-sustaining base on the moon
4. Identify areas and directions in which further research, development and demonstration must be conducted in order to realize a self-sustaining lunar base
5. Identify a methodology for the construction of the self-sustaining moon base
6. Identify the supporting infrastructure that would be required for the construction of such a base
7. Identify a timeline and timescale for a complete self-sustained moon base mission
8. Investigate the applications of the technologies developed for the self-sustaining moon base, on earth and in other space missions
9. Investigate the social and economic consequences of these technologies

2.2 Content of the Report

Chapters 2-8 contain a comprehensive literature review of technologies that the authors of this report felt would be relevant, applicable or vital to the successful establishment of a self-sustaining base on the moon. The literature review in each of these chapters is followed by a comparison section, in which the various methods, technologies, approaches and ideas described in the literature review are compared to each other under the same categories as they were presented. In Chapter 9 we propose a complete mission for the establishment of a self-sustaining lunar base. This chapter contains our contribution to the existing body of literature on this subject. Finally, in Chapters 10 and 11 we examine the potential for technological breakthroughs and the social implications of the technologies described and discussed in the report. Our report ends with Chapter 12, a concluding section in which we summarize our findings and share our opinions on the current state of progress of the second moon race. We have tried to include both conventional and speculative ideas in this report to strike a balance between what is now possible and what may soon be possible.

2.3 Methodology

The methodology used in this report was almost solely one of literature review. In addition to this, the authors consulted Dr. Yiming (Kevin) Rong (Professor, Department of Mechanical Engineering at the Worcester Polytechnic Institute) in their research on Self-Replicating Robotic Systems. The authors comprised one group among a number that collectively formed the Space Initiatives IQP team at the Worcester Polytechnic Institute. This report expands on work from the previous year, seeking to look at the development of a self-sufficient lunar base in much greater detail than was previously done.

3 Energy

3.1 Solar Energy

Solar energy is up to five times more plentiful on the moon, per unit surface area, than it is on earth, because of a lack of any attenuating atmosphere. It is a predictable, dependable, free and abundant resource. A lunar base that operates solely on solar energy will not require fuel supplies from the earth and would be more economical.

There are, however, several problems with this power source. To harness large amounts of energy, extensive solar arrays will have to be constructed. This will require labor and materials, both of which will be extremely expensive if imported onto the moon. Current solar cells are not very efficient, and those that have better efficiencies are heavier, more expensive, more complicated to build, and are composed of a greater number of different elements and compounds. In addition, there will need to be a power source in place in order to drive the machinery that will be used to construct these arrays. Further, most of the lunar surface experiences a two week long night during which these cells would not harvest any energy. As such, there may be a need for large batteries, which are also expensive and heavy to transport from the earth.

Several solutions and strategies have been proposed for the utilization of solar energy for a moon base. A conglomerated view of various technologies and ideas is presented here, drawing on a number of concepts to produce a comprehensive picture.

Companies such as Texas Instruments have developed solar cells composed of silicon dioxide, with the remainder made up of a blend of oxides of 12 metals, including aluminum, titanium, magnesium and iron. These elements and compounds are abundant in the lunar soil and, if mined, could be used to produce these cells without requiring any supply from earth. On earth, these cells are manufactured by the spray deposition of particles in conducting bands on a substrate in a vacuum chamber. There is already a near-perfect vacuum on the lunar surface and substrates for these cells can easily be made from glass or some other ceramic, also manufactured from the silicon dioxide in the lunar soil. The crude cells thus produced will have very low efficiencies of around 1 percent, compared with 35 percent efficient cells produced with other elements and compounds and more complicated manufacturing techniques and machinery, on earth. However, the lunar cells will be fast and easy to construct and, if built in great numbers covering a large area, will produce large energy yields. These cells can be networked by an extensive grid of wires made from local metals or superconducting ceramics and insulated with local ceramics. If built on the ground, the cells will require no superstructure for rigidity and will not, in any case, encounter corrosion or erosion due to precipitation and dust, as they would on earth. Accordingly, they can be expected to function without repair or maintenance for large periods of time and will be very material efficient. Improvements to these low-efficiency cells are always being made. If desired, a small amount of critical doping materials or nano-engineered surface layers could be supplied from earth to boost the efficiencies of these cells to above 35%. Dr. Neville Marzwell, technical manager of the Advanced Concepts & Technology Innovations program at NASA's Jet Propulsion Laboratory, estimates that current technologies allow us to build cells with efficiencies between 42 and 56 percent. If lunar factories develop quickly and reach a high level of sophistication, these extra materials may not need to be supplied from earth and could also be provided locally.

The location of these solar cells is also crucial. Arnold G. Reinhold[1] proposes that a Polar base location be sought, and solar arrays be placed on tall towers at these locations, so that they experience constant illumination. Because of the low angle of inclination of the Moon's equatorial plane with respect to the ecliptic, the altitude of the sun at the poles would never be higher than 1.533 degrees and would drop no more that 1.533 degrees below the horizon. A solar array at a lunar pole, at an elevation of 622 meters, would always see at least half of the solar disk. Brief periods of blockage by a mountain or crater rim near the horizon might be acceptable, with the station running from stored power. The feasibility of this proposal depends on the actual topography at the lunar poles. Unfortunately, photo coverage of the poles is very oblique and incomplete. A resulting, realistic specification might be 100% power for 28 weeks per year with the addition of auxiliary collectors on the moon surface, 100% power for 9 weeks per year with the ground surface dark, at least 80% power for 6 weeks per year, with brief drops to 50%, and at least 50% power for 9 weeks per year, with loss of solar power for no more than five periods per month, each of less than 12 hours duration and each separated by at least three days.

The tower assembly would have to rotate through one complete revolution every 29 days to track the sun. This idea seems impractical perhaps because if the moon was the size of the earth with the same inclination of its axis to the ecliptic, the tower required to obtain constant illumination of the solar array would have to be 355 miles high. However, on the moon, where the horizon is only 45 km away, this height is reduced to 622 meters. Further, this height is based on the assumption of a perfectly spherical moon. In fact, the Moon's North Pole seems to be located on a hill on the rim of crater Peary. Depending on the height of this hill and its surrounding features it might be sufficient to erect a collector on top of this hill, with no tower. The South Pole is in the center of a 22 km diameter crater. A collector on the high point of the rim of this crater might also suffice, or a series of collectors arranged radially around the rim.

Since lunar gravity is only one-sixth of earth gravity and there is no wind or tectonic activity, these towers, if required, could be very lightweight, and could be constructed from lunar materials such as concrete or ceramic. In addition, instead of elevating the solar arrays, simple plane mirrors mounted on the tower can reflect sunlight onto solar arrays on the ground below, further reducing the need for structural strength and rigidity of the tower. The solar constant in vacuum is 1.353 KWe/sq meter, so a collector of 50 by 100 meters could produce 1.7 MW of electricity, assuming a 25% conversion efficiency. NASA estimates electrical power requirements of 25 to 200 kW for a lunar outpost, 500 kW for an interim base and 2 MW for a permanent base. Some of the concentrated sunlight could simply be transmitted by relay mirrors into buildings and facilities to be used directly for lighting, heating, photosynthesis, and as process heat for chemical synthesis, metallurgy, etc. Other mirrors could supply outside flood lighting. Power used this way could be transmitted with efficiencies of 80% or more. In addition, concentrated sunlight could be transmitted significant distances by relay mirrors, reducing the need for an electric grid. This setup could also be used as an interim power source, providing power while a more extensive ground-based solar farm is being built.

Robots can provide the large labor force that would be required to build a solar farm capable of gathering enough energy to sustain a fully functional permanent lunar base. They would mine, separate, process and refine the necessary compounds and elements from the lunar soil and then use them to synthesize cells on site. The robots would, to begin with, be limited by their initial power source, which may be a small pre-fabricated nuclear reactor transported from earth or a deployable solar array on the landing craft that bore them to the moon. As a result of this extreme limitation, work may begin very slowly, but the energy harnessed with every additional cell produced will be used to further power the robots, so that the initial power source will soon be obsolete and the energy available to the robots will no longer be the limiting factor in their solar cell production. After this, construction can progress very rapidly, depending on how resources, labor and production are managed and organized. The robots could build solar farms that span vast regions of the lunar surface, and may begin simultaneous construction at diametrically opposite lunar locations, converging at two midway points around the circumference of the moon. These seed farms on opposite sides of the moon could be expanded outward in both circumferential directions, perhaps with more productivity in the direction of the moon's rotation because of longer daylight times, finally resulting in a networked, closed diametric ring of solar cells around the moon that could harvest solar energy day and night. Other strategies may be to begin at polar locations and expand from there. Such activities may take place long before any humans are sent to the moon, and would require a large degree of automation in the robotic force. These solar farms could be continually added to, with newer sections networked to the older ones, as deemed necessary by the growing demands of an ever-maturing lunar base. The potential for growth is limited only by the area available to construct solar cells on the lunar surface. Different robot-building strategies, including the notion of self-replicating robots, could greatly affect the time that it would take to cover large areas of the moon's surface with solar cells. The materials used in such an undertaking would be free, and the cost of such a system may be staggeringly low.

David R. Criswell (Director, Institute for Space Systems Operations, University of Houston) estimates that it is technically and economically feasible to harness at least 100 TWe of solar electric energy from facilities on the moon[2]. Criswell claims that a system with 35% overall efficiency that occupies only 0.15% of the lunar surface can supply 20 TWe. This is the projected power consumption of the entire earth, with a population of ten billion people, in the year 2050.

Another technology being considered is the use of solar power satellites in geosynchronous orbit around the moon. These satellites would receive constant illumination and could be constructed from lunar materials and launched from the moon. They would be inexpensive, as they are made from free resources, and would provide constant power to a lunar station, without limitation from the long lunar night. Because of the low lunar gravity, absence of atmosphere and the small height to which they must ascend, the solar cells on these satellites would not need to be very rigid, and these satellites would be very lightweight. Enormous cell banks could be grown on the lunar surface and then propelled into orbit by any of a number of different methods. The satellites would beam energy to receiving antenna on the lunar surface using microwave beams. This technology is current, feasible and has been demonstrated ready. The satellites would act as energy collectors, producing their own energy beams, and also as relaying devices, transmitting power from other satellites when they are not in view of the receiving antennae. Thus, a lunar station could receive energy beams from a number of orbiting lunar satellites simultaneously, and could enjoy constant, uninterrupted, reliable power.

3.2 Nuclear Energy

3.2.1 Fission Energy

The second option is nuclear fission energy. This would require the transportation or construction of a nuclear reactor that would run on nuclear fuel such as uranium, thorium or plutonium brought from earth or mined on the moon. This reactor, if transported from earth, would be a ready source of energy, available as soon as it arrives, and independent of the long lunar day-night variation. It would be constant and long-lasting and would not require much extra construction or maintenance. The problem with this power source is that it would probably require a large mass to be sent from earth, at huge cost. However, this may be a one-time cost and, as such, be tolerable. Further, dependant upon revolutionary improvements in our space transportation systems in our foreseeable future, these costs may not be very large.

The SP-100 program, conducted jointly by NASA, DARPA and the Department of Energy in the 1980's, had as its goal the development of nuclear power plants that could generate 100 to 1000 KWe of power for two years, with potential growth to seven years, designed for space use [3]. The reactor designs that were considered used thermoelectric, thermionic, Stirling or gas turbine heat conversion cycles to generate electricity, with different heat exchange fluids and different heat rejection strategies. This resulted in a range of possible efficiencies, lifetimes, machine complexities and radiation levels. There was also the potential for using the excess heat generated as a further power source. People living on a lunar base powered by such a rector would require substantial shielding from the radiation produced. This shielding could be provided by approximately fifty metric tons of lunar soil heaped onto and around the reactor. Alternatively, the reactor could be situated far from the base, but one would have to accept the accompanying decrease in overall efficiency due to transmission losses in the long power lines. If radioactive shielding was used, heat dissipation into the surroundings could become a problem, with the possibility of the reactor overheating. Further, it is accepted that some amount of maintenance and inspection will have to be carried out on the reactor. For this to be possible, those sections of the reactor which will undergo inspection by humans will have to be adequately shielded from the reactor core, a precaution which will introduce further complexity and weight. Extensive testing of such a reactor will have to be carried out before it is sent to the moon. Any failure of the reactor could be dangerous because of radiation and the loss pf power. The reactors were designed to weigh less than 3000 kg, a mass that could be transported to the moon using a conventional rocket. Samples of lunar soil brought back to earth from the Apollo and

Luna missions showed concentrations of up to 3.48 and 13.5 ppm for Uranium and Thorium, respectively, from basin ejecta material, with more typical concentrations between 1 and 2 ppm for other soils.

Joseph A. Angelo, Jr. (Space Technology Program, Florida Institute of Technology) and David Buden (Science Applications International Corporation) proposed designs for different nuclear reactors and capabilities for a lunar base during its various levels of maturity[4]. Using smaller reactors in the initial stages to breed fuel for larger reactors later on, a complete nuclear fuel cycle will be established, taking advantage of native thorium and uranium resources, with the final reactors generating hundreds of MWe for an Autonomous Lunar Civilization numbering over one hundred thousand inhabitants, with a Self-Sufficient Lunar economy. The applicability of some of these reactors, such as the radioisotope generators, has long since been proven in their applications on spacecraft, where "long life, high reliability, solar independence, and operations in severe environments" is critical. These authors claim that total materials self-sufficiency for nuclear power will be possible, even for a growing energy demand. It is their contention that the development of nuclear technologies will be the key to civilization on the moon and in space because of its compactness, longevity and independence on environment.

3.2.2 Fusion Energy

Fusion is a process by which light nuclei are combined to release energy and nucleons. In contrast, fission relies on the breaking up of large, radioactive nuclei to yield energy. The nuclei used in fission reactions are large and unstable and decay naturally into lighter nuclei. In a fission reactor, these large nuclei are bombarded with slow moving neutrons to cause them to break up and further release neutrons and energy. The neutrons produced go on to break up more heavy nuclei or be captured by those nuclei or by neutron-absorbing control rods.

A fission reaction at equilibrium is one in which the rate of production of free neutrons from the breakup of the heavy nuclei equals the rate of absorption of free neutrons by heavy nuclei without breakup, plus the rate of absorption of free nuclei by the material of the control rods. These reactions are regulated by introducing more or less control rod material to the reactants and either absorbing more or less free neutrons. At equilibrium the reaction yields a constant power output, in the form of heat. This heat is carried away by highly conductive heat exchange fluids run through pipes in the reaction chamber. The hot fluid is then used to turn a turbine that turns a generator to produce electricity. The conversion of this energy from thermal to mechanical to electrical forms, results in a low overall efficiency for fission reactors. However, since the free neutrons required to bombard the heavy nuclei must be moving relatively slowly and the velocity of particles in a gas increases with the temperature of the gas, the temperature that the reactants must be raised to is comparatively low. A neutron is without charge and, as such, it experiences no electrostatic repulsion from nuclear protons as it approaches its target nucleus. As such, it does not need a high kinetic energy to overcome the large potential barrier that would arise from electrostatic repulsion (these reactions have a low activation energy). The neutrons produced serve only to continue the reaction, and though a large fraction of the energy put into the system appears as the kinetic energy of these neutrons, this energy cannot be harnessed.

Fusion, on the other hand, relies on the collision of entire light nuclei with each other to form new nuclei, with the release of energy. These nuclei contain both protons and neutrons and, as such, have strong electrostatic repulsion for each other. Because of this, the small nuclei must be moving at much larger speeds in order to successfully collide and produce a reaction. Thus, much higher temperatures are required (higher activation energy). In some fusion reactions, such as the deuterium-tritium (commonly-occurring isotopes of hydrogen having one and two neutrons, respectively) reaction, eighty percent of the energy produced is in the kinetic energy of a stream of high-energy neutrons. These neutrons, because of the high reaction temperatures, are moving incredibly fast and are highly destructive to anything they strike, including the containment vessel. Such radiation damage to structures may allow tritium, a highly radioactive isotope of hydrogen, to be released, leaving highly radioactive waste behind (Professor Gerald Kulcinski, Associate Dean for Research, Grainger Professor of Nuclear Engineering, and the Director of the Fusion Technology Institute, University of Wisconsin, and recently selected member of NASA's Advisory Council, in an interview with Eric R. Hedman, January 2006).

In contrast, other fusion reactions, called *aneutronic* fusion reactions, do not produce any neutrons, but protons instead. Since a proton—unlike neutrons produced by deuterium-tritium reactions—has a charge, it can be captured by a reverse particle accelerator, inducing a current and directly converting the power to electricity, avoiding the need for a heated working fluid to spin a turbine connected to a generator, and eliminating the efficiencies associated with such a system[5]. One of Professor Kulcinski's graduate assistants is working on a solid-state device to capture the protons and convert the energy in them directly to electricity in a process similar to photon capture in a common solar cell.

One of these aneutronic fusion reactions is the Helium 3 reaction. It involves the collision of two He-3 nuclei (two protons and one neutron) to produce a He-4 nucleus (two protons, and two neutrons) and two highly energetic protons, which can be used to directly generate electricity. Kulcinski runs the only helium-3 fusion reactor in the world. His design uses an electrostatic field to contain the plasma instead of an electromagnetic field, and is much smaller and cheaper than the multibillion dollar tokomak reactors being developed for the same purpose. His reactor can produce a sustained fusion reaction producing a milliwatt of power while consuming about a kilowatt. He predicts that the fusion process as a viable source of energy will require another twenty years to develop.

There are only a few hundred kilograms of He-3, the ideal fuel for aneutronic fusion reactions, on earth. It is a by-product of the maintenance of nuclear weapons and is not renewable at an appreciable rate. However, He-3 is an intermediate product of the fusion reactions in the sun, and significant quantities of it are released in the solar wind. This He-3 never reaches the earth because the planet's magnetic field diverts the charged particles in the solar wind. The moon, however, does not have any such field and has been bombarded by the solar wind for billions of years. Lunar soil samples from the

Apollo missions all contain He-3, regardless of where each sample was taken. Based on these soil samples and the mass of solar wind that would have hit the lunar surface since its formation, Kulcinski estimates that there are approximately one million metric tons of He-3 on the moon. Forty metric tons of He-3 is the energy equivalent of all the power pumped into the US power grid in 2005.

He-3 can be released from the lunar soil by heating it to 700 degrees Centigrade and condensing all the other gaseous components, until only He-3 and the more common He-4 remain in the gaseous state. These two isotopes can then be separated by well-known diffusion techniques, and He-3 bottled and shipped back to earth. The process depends on the development and demonstration of lunar mining technologies that can harvest this precious fuel in sufficient quantities to make the enterprise economically viable.

The problem, Kulcinski claims, is that the Department of Energy (DOE) does not trust NASA to get access to helium-3 in a reasonable amount of time and NASA does not trust DOE to fund and develop a working helium-3 reactor[5]. The result is that neither agency is willing to make the commitment necessary for the maturation of this technology and the viability of this fuel source. Hopefully, he says, access to the helium-3 will come as a byproduct of returning to the Moon, and as the DOE sees the return to the Moon advancing, they will be willing to put more money into helium-3 fusion research.

He-3 fusion is extremely potent, nonpolluting and does not produce radioactive byproducts. On the moon, where the fuel is abundant and disposal of radioactive wastes is not desirable, this technology may be the ideal source of power production. It is estimated that the one million metric tons of He-3 on the moon could produce 20,000 terawatt-years of thermal energy. This is about ten times the energy we could get from mining and burning all the fossil fuels on earth and twice the energy we could get from burning all our earthly uranium, without the smog and radioactive waste. The value of He-3 on earth may be 3 billion dollars per metric ton, if equal to the price of its energy equivalent in oil. This may mean that establishing a permanent mining base on the moon would be an extremely profitable enterprise.

3.3 Geothermal Energy

Yet another option is the use of geothermal energy during the long lunar nights. The lunar regolith, below a depth of 30 cm, remains at around 250 K, while the surface oscillates between night and daytime temperatures of 110 and 390 K, at the lunar equator (Meeting Nighttime Power and Thermal Requirements by Manipulation of the Lunar Surface Albedo and Emissivity, Garrick-Bethell, MIT Department of Earth, Atmospheric and Planetary Sciences). Garrick-Bethell suggests that coatings or paints with low reflectivities and emmisivities could be applied to the lunar surface over large areas. This would mean that very little solar radiation would be reflected away from these surfaces during the daytime and would, instead, be absorbed slowly, raising the temperature of the subsurface soil. This soil would retain more of the incident absorbed energy instead of radiating it away through the surface in the nighttime. This works because of the differential temperature-dependant conduction rates in the soil layers. The subsurface temperature of these areas could then be raised to 380 K in six years, or roughly 1.8 K per lunar month for a particular surface coating with emmisivity and reflectivity of 0.1. This temperature would stay constant even during the lunar night, raising the temperature difference between the surface and subsoil from 160 K to 270 K. At this temperature, 1 KW of power can be provided for 14 days from a 2 K temperature decrease in a volume of regolith 50 cm deep over a 40 m surface radius, assuming a conversion efficiency of 15%. A field of this area would require approximately one metric ton of surface coating material. The energy would be extracted by running pipes containing a heat exchange fluid through the hot subsurface, and then converting the heat to electricity using a rising fluid turbine system or a solid state Peltier-effect generator (essentially a large scale thermocouple), using the temperature difference between materials on the surface and the subsurface soil[6].

The generation of such an "energy field", therefore, merely requires the painting or coating of the selected lunar surface and could be undertaken by robots well before any humans arrive on the earth, during periods of daylight, when they can use solar energy to work. An additional advantage would result from coatings with the desired properties that can be synthesized from local materials. The amount of energy that can be harnessed from this geothermal method is limited by the slow rate of replenishment of energy in the soil by the sun. Once an energy field is created, it can be used in a sustainable manner by only extracting that amount of energy from it, each night, which can be replenished by the sun in the following daytime period. This amount of energy is larger for larger, deeper fields. Accordingly, a sufficiently large, deep field could power a lunar station during the lunar night. The generation of such a field is a one-time effort, if the field is used in a sustainable fashion. A field of the type described above would require a 2 km surface radius (at 50 cm depth) to provide the 2 MW of power required by a mature lunar outpost, as estimated by NASA. Some mechanical methods of storing energy for the long lunar nights include the use of flywheels and lifting masses to store potential energy.

Of course, a mix of these options is always possible and may, in fact, be better than the use of any one technology alone. Each may be best suited to the moon base at different stages in its maturity, as we will discuss later. In order to be self-sufficient, a lunar base must have a reliable source of power. Without this, the base will not achieve sustainability.

4 Transportation

The current cost of transporting matter to the moon is immense. It is estimated to range from ten to forty thousand dollars, per kilogram, with the use of conventional rockets. As such, many alternate methods of delivering and receiving payloads to and from the moon are being researched to lower this cost. The feasibility of a large lunar base may depend on the cost of transporting equipment, machinery and materials to the moon.

The primary problem is the large gravity of the earth. Large amounts of energy are required to propel masses into earth orbit and even more to propel them beyond orbit. Most conventional rocket systems provide this energy by chemical combustion of a solid, liquid or gaseous fuel in the presence of an oxidizer. Both these materials are carried with the rocket and are usually the largest fraction of the rocket's mass. Rockets must lift not only their payload, but also the fuel for the remainder of their journey. Conventional rockets are built in stages that are discarded mid-flight as the fuel that they contain is consumed. For each launch, a brand new rocket must be constructed. For these reasons, there is a huge cost barrier to leaving the earth, a barrier that can be overcome in a number of innovative ways. The common feature among these new ideas is complete reusability of systems and the elimination of the need to carry on-board propellant.

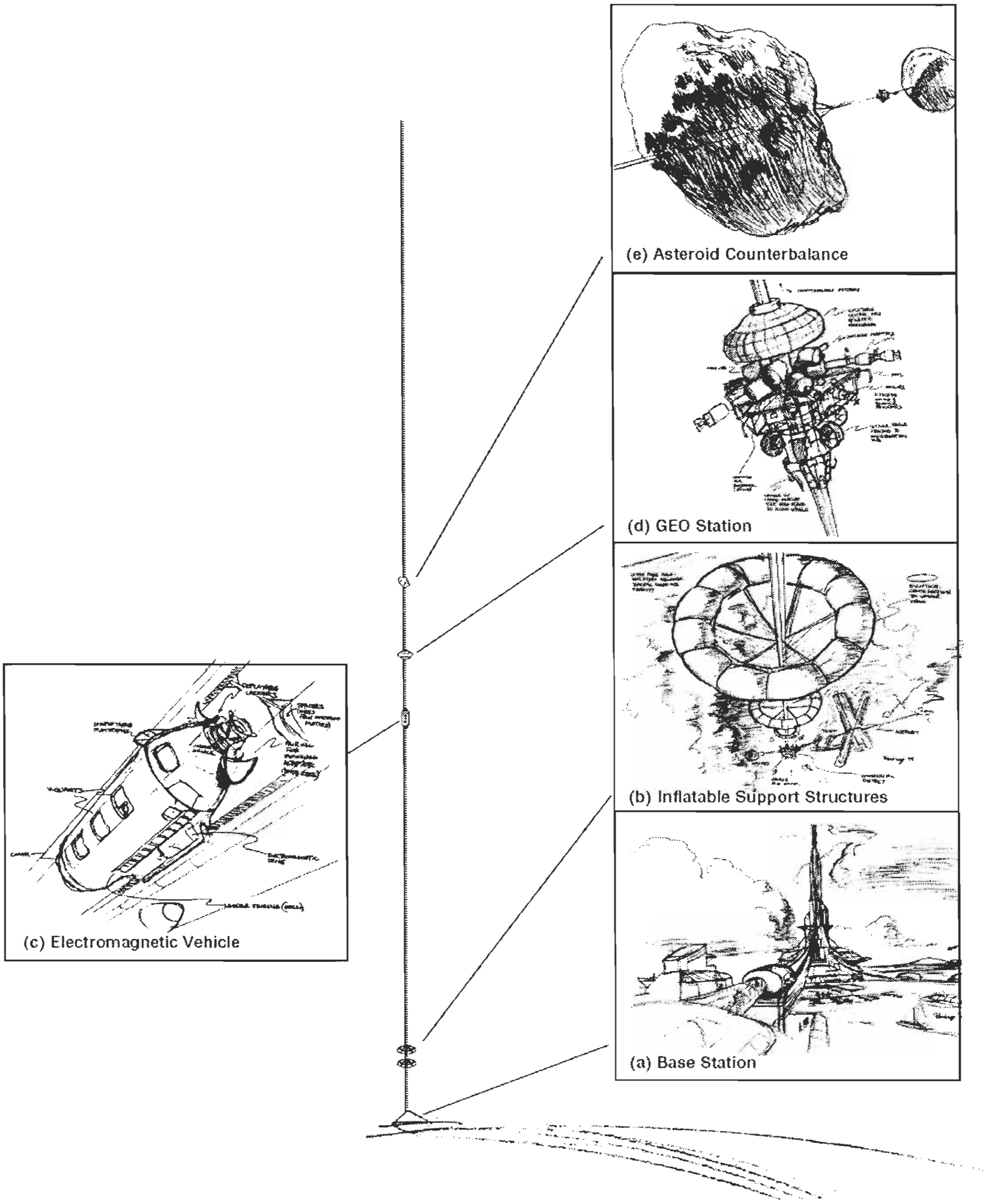
4.1 Space Elevator

The ideas now being researched and studied as viable alternatives to rocket-based propulsion into orbit and the moon have existed in science fiction and mythology for many ages. More recently, they have appeared profusely in popular science fiction, and are now generally accepted as serious candidates for means to deliver cheap, reliable and continuous transport to earth orbit and the moon.

The most famous and promising of these ideas is the Space Elevator. The writings of Moses (ca. 1450 BC) in his book, Genesis, reference an earlier civilization that tried to build a tower to the heavens out of brick and tar, in ca. 2100 BC. This tower is commonly known as the tower of Babel, and was purported to be located in Babylon, a city in ancient Mesopotamia. The book also describes a staircase or ladder built to heaven, commonly referred to as Jacob's ladder[7].

A NASA publication titled "Space Elevators, An Advanced Earth-Space Infrastructure for the New Millennium" was compiled by D.V. Smitherman, Jr. of the Marshal Space Flight Center in August, 2000. It is based on the findings from the Advanced Space Infrastructure Workshop on Geostationary Orbiting Tether "Space Elevator" Concepts, held at the Marshal Space Flight Center in June, 1999.

The most ambitious of the space elevator concepts is the Earth to GEO elevator, displayed in Figure 4 - 1[7]. This is essentially a long cable extending up from the surface of the earth to a distance of 47,000 km, past geostationary earth orbit at 36,000 km, with its center of gravity residing at GEO. The cable has a 24-orbit above the equator, in sync with the earth's rotation. Payloads (people, power, gases) can ride up this enormously long cable, into geostationary orbit or to an escape altitude, where they can be released. It is literally a highway, power line or pipe to GEO. The participants in the Space Elevator Workshop envisioned the elevator to begin from a platform at sea, either anchored to the seabed below or free to float. This



(e) Asteroid Counterbalance

(d) GEO Station

(b) Inflatable Support Structures

(c) Electromagnetic Vehicle

(a) Base Station

Figure 4 - 1: GEO Space Elevator Concept

platform would work like a seaport, transferring cargo and passengers from terrestrial transportation systems to the space elevator vehicles. It would most likely resemble a small city, with its own airport, hotels, restaurants and medical facilities. A sea platform for the first space elevator was selected for various reasons. The first is that, from a safety standpoint, the remoteness of the location would afford reduced risk of loss of life and damage to property in the event of a failure, such as would be more likely in the operation of the first elevator. Another is that a location in international waters would be appropriate for a project that would likely require international consensus and cooperation in order to work. Other possible locations identified were land sites along the equator in South America, Africa or equatorial island nations. An equatorial site would the ideal location for the construction of a space elevator because of the mild weather and physical impossibility of hurricane and tornado formation[7].

Vehicles similar to today's Maglev (Magnetic Levitation) Trains, with large superconducting electromagnets along their undercarriages would run up and down the cable, suspended in a track by the magnetic fields of levitation and guidance coils and accelerated by the reversing magnetic fields of propulsion coils along the track. These hovering vehicles would never come in contact with the rails and, without the friction of rolling wheels or sliders, could travel at speeds of thousands of kilometers per hour. Such a propulsion system is considered necessary because the traction wheels of any purely mechanical system would be too slow to complete the long journey to GEO in a reasonable time and would cause the rails and wheel bearings to wear away quickly. The same coils that accelerate the vehicle to its top speed can be used as induction coils to decelerate and brake the vehicle, recovering its kinetic energy and making the whole process incredibly efficient. Further, when elevators are descending to the earth surface, using the same induction effect to brake them would result in a gain of the potential energy difference between GEO and the earth surface. The vehicles would carry no on-board propellant and would be completely reusable and long-lasting. For comparison, current commercial Maglev trains reach top speeds of 500 km/h. Their speed is limited by the large density of air at the earth's surface (air resistance and drag) and by the straightness of the tracks that they run on. The vehicles on the space elevator will use more powerful propulsion systems, run in a straight line at all times and see almost no air resistance for most of their travel. Three quarters of the mass of the earth's atmosphere resides within 11 km of the earth's surface. An altitude of 120 km (75 mi or 400,000 ft) marks the boundary where atmospheric effects become noticeable during re-entry. The Karman line, at 100 km (62 mi), is also frequently used as the boundary between atmosphere and space (Wikipedia). This altitude is 0.3% of the distance to GEO[7].

At the station at GEO, docking ports would provide access to space transfer vehicles, and there may be an inflatable habitation structure to provide living and working environments, perhaps rotating to provide some artificial gravity. Beyond the GEO station, vehicles can continue on the elevator track to the end of the structure at 47,000 km, where they will be traveling at near escape velocity. Launch from this end could provide easy earth escape, and minimal energy would be required for launch to the moon, because of the slingshot effect of the payload's orbit.

The assembly of this vast and complex system will likely be broken down into more manageable phases. Several approaches to the problem were proposed, including the use of inflatable platforms (balloons, essentially) along the cable's length to provide high altitude support and control, and the progression to a GEO space elevator from an LEO elevator (Figure 4 - 2[7]). In the latter scheme, a smaller cable with its center of gravity in a low earth orbit, unconnected to the earth and revolving around it twelve times per day, will be unrolled from the desired altitude of its center of gravity, until its lower end is about 150 km from the earth's surface and its upper end is 4,000 km away. This system will be extended in both directions until a GEO elevator results. The GEO station will then be the center of gravity of the entire system, and large reels will be placed there to adjust the location of the station and counterbalance masses and the tension of structure. Without counterbalance masses, the elevator structure would have to be 144,000 km in length. The LEO elevator, as an end in itself, has some useful qualities. Payloads can be carried to the lower end of the elevator by space planes that will rendezvous with the elevator, matching its velocity. Since it is a freely orbiting system and is not attached to the earth, it may be placed in an inclined orbit aligned with the plane of the ecliptic. This has advantages for traveling to the Moon and other planets as it would avoid plane change maneuvers and would greatly increase the number of launch windows for a given timeframe. Further, if a resonant orbit is used, the system will pass within range of most of the world's major airports twice a day on a fixed schedule. Once the velocity required to reach the lower end of the elevator is brought down to the Mach 16 range or less, it may become technically and economically feasible to transfer payloads to the elevator using horizontal takeoff and landing space planes operating out of those airports[7].

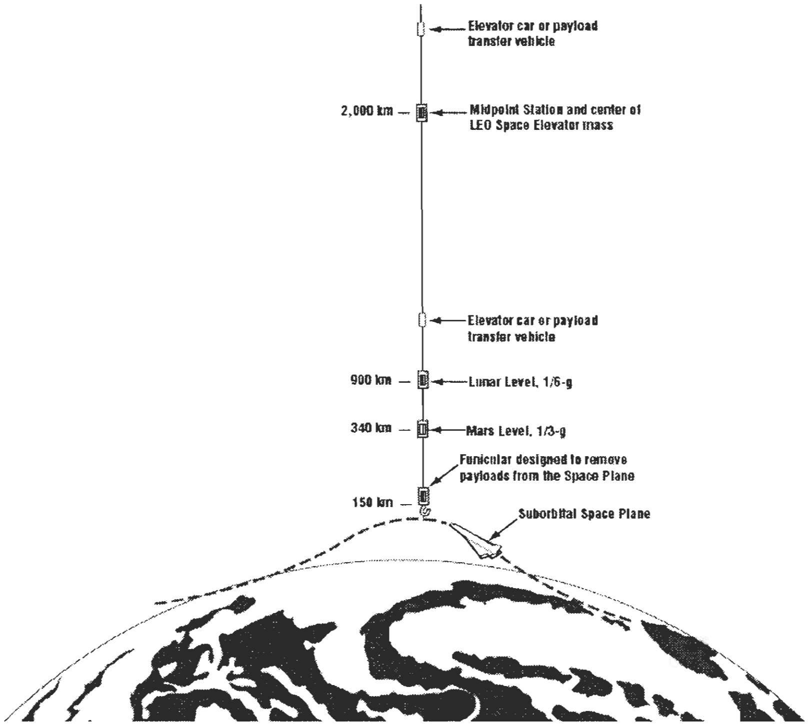


Figure 4 - 2: LEO Space Elevator Concept

Contrary to popular belief, it is possible to build a structure tall enough to span the distance between earth surface and GEO with any common construction material. This simply involves increasing the thickness of the structure to compensate for the tension and compressive stresses. However, this is simply not practical due to the massive quantity of ordinary material that would be needed, and the associated cost. The key to success is using the right material in conjunction with the right construction method. Because of the enormous height of this structure, gravity affects on its mass decrease dramatically and continuously with altitude, and centripetal forces increase with altitude. The result is that the upper sections of the structure are in tension, and the lower sections in compression. It was found that, for materials of the same strength to density ratio, it is most mass efficient to connect a tether structure in tension to a base tower in compression. The taller the tower, the better, since it is this lower section which most greatly influence the systems structural strength and diameter at GEO. For example, a tower 3,000 km in height built with PBO fibers (a high-strength polyaramid fiber available today with a strength of 5.8 GPa), connected to a tether extending the rest of the way to GEO could be 150 times less massive than a tensile structure alone. Most materials, however, are stronger in tension than in compression and compression columns usually fail through sudden, catastrophic buckling. The tall tower concept, therefore, uses pressurization of the tower's structural members, like balloons, to convert the compression structure into a tension structure[7].

It was determined from the study that the energy required to lift a payload along the length of a space elevator from the ground to geostationary orbit could be as low as 14.8 kWh per kg. At today's energy cost of $0.10/kWh, this would be $1.48 per kg. A 12,000-kg Shuttle payload would have an energy cost of $17,760 for a trip to GEO and a passenger with baggage at 150 kg would have an energy cost of $222. All current mass transportation systems operate at a total cost that is only a fraction above the actual energy cost. It is the high usage of the system that will make it economically feasible. Further, some designs include solar arrays positioned along the length of the cable, harnessing solar energy above the atmosphere, where it is most plentiful. Such elevators could power themselves and would be even more cost-efficient[7].

The participants of the workshop found that the materials technology needed for the construction of a space elevator is in the development process in laboratories today, and that continued research will likely produce high-strength carbon nanotube materials, a material that promises to be strong and light enough for this application. They also noted that a cable of such length is inherently flexible and can be designed to avoid major impacts from asteroids or other projectiles by inducing vibrations of significant amplitude in the structure, though minor hits from debris are inevitable and will produce the need for frequent, standard repairs and maintenance[7].

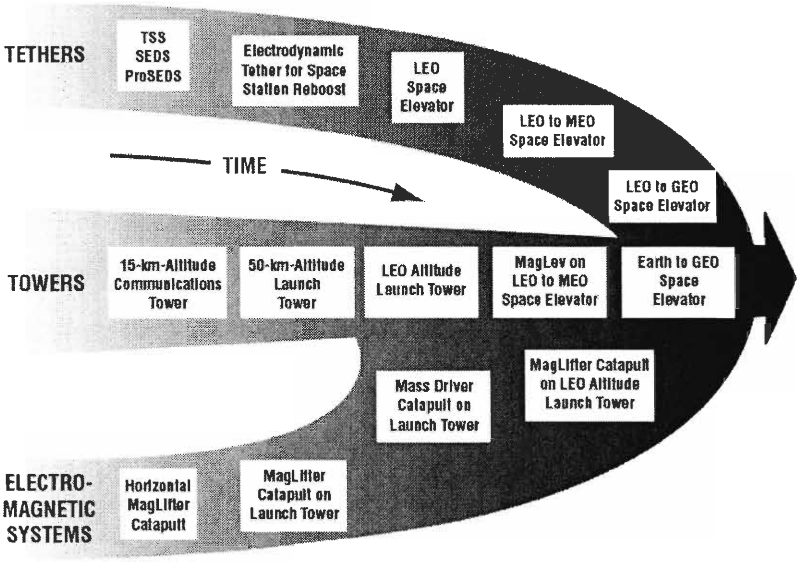


Figure 4 - 3: Technology Demonstration Roadmap

The team identified several areas for future development. The first of these includes the development of high-strength materials such as graphite, alumina and quartz whiskers, the continued development of carbon nanotube materials that exhibit ten times the strength of steel, and the introduction if these materials and lightweight composite structural materials into the commercial construction and design, space and military markets to enhance and expedite the development of new products and the development of multi-kilometer-height towers for applications such as communications, observatories and launch platforms. Other areas discussed were the development of robotic maintenance systems and high-speed electromagnetic propulsion for mass transport systems, launch assist systems and high velocity launch rails, and the integration of these devices into conventional construction systems such as doors, elevators and conveyors, and the development of transport, utility and facility infrastructures to support space construction in between Low-Earth Orbit and Geostationary Orbit, including highly reusable space launch and in-space transportation systems[7].

The study also identified several intermediate, critical technologies that must be demonstrated before a space elevator system can become a reality. These are summarized in Figure 4 - 3[7] and include kilometer-altitude launch towers, tethers up to various altitudes, and a perfection of several types of electromagnetic propulsion, including high and low-g Maglevs, Maglifters, coil guns and rail guns. The construction of a space elevator is, in fact, being planned by a company named HighLift Systems for completion in as soon as 15 years. The project could cost up to 10 billion dollars for a dozen or so elevators, capable, in total of transporting 50 tons of payload into LEO per day[7].

4.2 Momentum-Exchange Electrodynamic Reboost

Another technology currently being developed by NASA's In Space Propulsion Lab is the MXER tether (Figure 4 - 4[7]). MXER stands for Momentum-Exchange Electrodynamic Reboost. In this scheme, a long cable in earth-orbit rotates end over end as it circles the earth. It picks up payloads hanging in orbit, transfers its rotational momentum to them, and flings them out into space along some desired trajectory. After this maneuver, it has lost some portion of its rotational momentum. This is replenished by running a current down through the cable, in one direction. The electricity for this current is supplied by solar cells all along the cable length. When a wire containing a current is put in a magnetic field, such as the one enveloping the earth, the wire experiences a force normal to the magnetic field direction at that point and normal to the direction of the current. When such a current is passed through the MXER cable, the cable begins to spin more rapidly due to the induced normal force, until its rotational momentum has been regained. It then simply waits for the next payload that it must slingshot into space. It requires no external power and can be used indefinitely, with repairs and maintenance[7].

A system of cooperating space elevators and MXER tethers could form a complete link between the earth and the moon, with similar elevators, tethers and electromagnetic guns and decelerators constructed on the lunar surface. The space elevator would bring payloads to earth orbit, where the MXER tether would grab them and hurl them towards their other destinations or, in this case, into a Lunar Transfer Orbit, where they would be picked up by similar systems on the moon for safe arrival on the lunar surface, or vice versa. If such systems were erected, they would open up new avenues for exploration, travel, tourism, mining, trade, research and experimentation and possibly transform the global economy. They would be invaluable for the initial stages of development of a lunar base and would further allow increased and unlimited use of the base during its maturity.

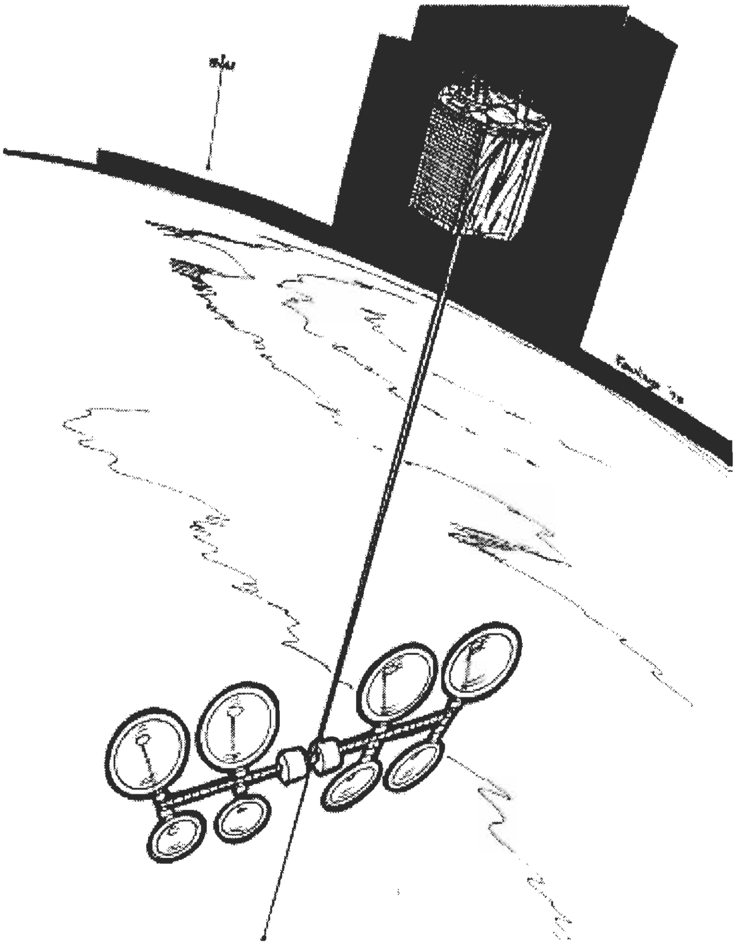


Figure 4 - 4: Momentum Exchange Tether

Transit systems consisting of fleets of more conventional airborne vehicles are also being envisioned and planned. These designs vary greatly in the their propulsion methods, ranging from ion drives to power beams, but all will essentially be spacecraft that will travel frequently between stations in various orbits and the earth's surface, carrying cargo and humans, and refueling as necessary. They will be reusable, modern, and will be the basis of the extensive infrastructure that would be required for the creation of the previously mentioned, more ambitious projects.

5 Site Selection

Selecting a site for a lunar base is dependent upon its intended purpose and functions. Many considerations must be made in determining this location. Once a purpose is established and the operational functions that the base must carry out are recognized multiple variables must be looked at. The construction, development, and sustainability of a base as well as the desire for its future expansion lead us to seek a location that has valued resources for mining. Locations containing elements which provide extractable fuels are also desirable. Choosing a suitable location for mining will depend upon the composition of the regolith. Different locations on the moon are abundant with different resources[8]. Multiple options must be explored in order to sufficiently determine the compositions of regolith in different locations on the lunar surface. These methods can range from physical analysis in situ to satellite analysis of the moon. Since the purpose of a lunar base is not only to mine for developmental reasons a desirable location for scientific study must be researched. Geological study of the moon will again depend upon the regolith's composition however many other scientific studies may be carried out on the moon, all having specific requirements that can only be met in certain locations. These requirements must be accounted for in the selection of a site. Solar power is a likely source of sustainable energy for a lunar base, therefore, a location that is exposed to the suns light for a significant portion of the moons day-night cycle must be considered. The last two points that must be looked at are the safety of the lunar bases inhabitants and the ease of communication with earth. All of these variables must be explored and their significance decided to determine an optimum location for a lunar base.

Maintaining a sustainable base requires that materials and resources can be gathered in situ. Water, oxygen and light are the main resources that a sustainable environment will require a significant constant supply of. Water is extremely rare on the moon even at the poles therefore it will most likely have to shipped from earth in some form so this will not inhibit the selection of a location. An abundance of light would be necessary as a source for solar power. This poses two concerns. A site that has near constant light would be needed to produce for the use of solar power to be effective. Locations near the poles would be optimal. There are points on the north-pole of the moon that have constant light. On the south pole of the moon there are locations that would allow two separate solar arrays to be placed within a reasonable distance where at least one will always be receiving light[9]. The second consideration is the materials needed to create photovoltaic cells. This needs to be taken into account because the most efficient way to put solar panels on the moon would be to build them in situ out of local resources. Transporting large solar arrays from earth would be incredibly expensive as well as inefficient. Oxygen is a relatively abundant resource on the moon and will not greatly inhibit the selection of a site. It is most abundant in the volcanic soil on the moon followed by the Mare soil then the Highland soil. Volcanic soil is found in locations throughout the moon and can be looked more closely at when more restrictive aspects of the site location are considered.

Other consideration is selecting a site are the locations of other important extractable resources. These include Iron, Helium-3, Aluminum, Magnesium, Titanium, Manganese, Chromium, Carbon, Silicon, Phosphorus, Boron, Fluorine, Nitrogen, Hydrogen, Sodium, Chlorine, Calcium and Sulfur. These resources will provide a wide range of applications. Finding the specific locations of these different elements will not only be a useful tool in determining an initial moon base, but will be useful in long term applications should the need arise that a specific element will have to be mined that had no previous uses.

There are a few different ways to search for these elements. One way that would not require a mission to the moon would be to perform gamma ray spectroscopy from a satellite. This method would allow the study of locations of separate elements on the moon's surface through imaging. Gamma ray spectroscopy of the moon has already been performed[10]. An analysis of the iron content on the moon can be seen in Figure 5 - 1: Clementine Iron Map of the Moo[11]. This data along with the measurements of other important elements must be used as a guide to sighting a location on the moon. More comprehensive and precise data will most likely be necessary however in determining the location of a lunar base. Multi-spectral imaging is another option that can be done in a similar manner. Both of these methods would have a significantly lower cost compared to the cost of the third method which is sending a mission to the moon. This option would require either a manned or unmanned trip to the moon that could collect and analyze samples of the regolith. Besides cost, this approach would take a longer time to complete a comprehensive evaluation of the moons surface because of the need to physically go to each site that is going to be tested.

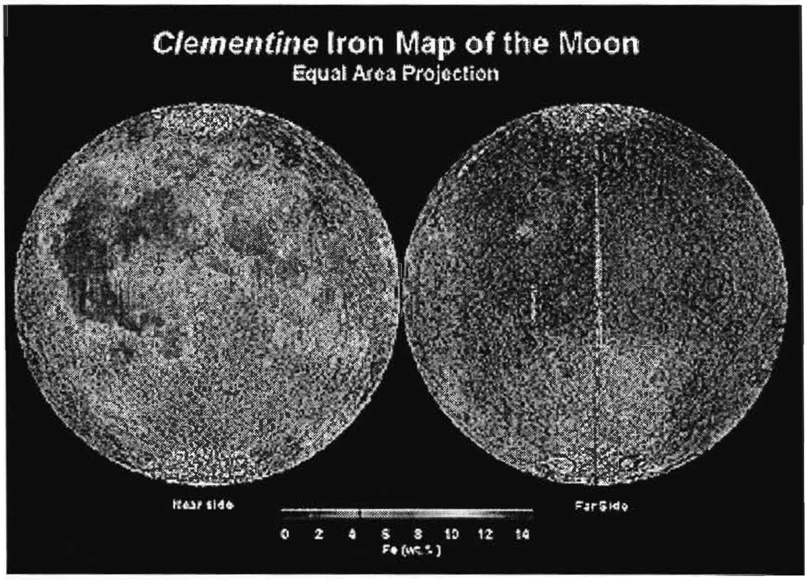


Figure 5 - 1: Clementine Iron Map of the Moon

Having the knowledge of the topography of the moon is also necessary. This has also already been done by satellite, notably during the Clementine mission. Many images were taken of the moons surface during this mission and from these images topographic maps were formed. The previously mentioned gamma ray spectroscopy data was also able to be overlaid on these images. Figure 5 - 2[12] and Figure 5 - 3[13] display two styles of topographic maps of the moon. These do not, however, include significant data on the poles. While these images do provide comprehensive data of the entire surface of the moon, when the point comes to determine a more specific location for a lunar base, more precise and higher resolution mapping of the surface may be necessary, especially on the indicated pole areas where there currently seems to be less data collected.

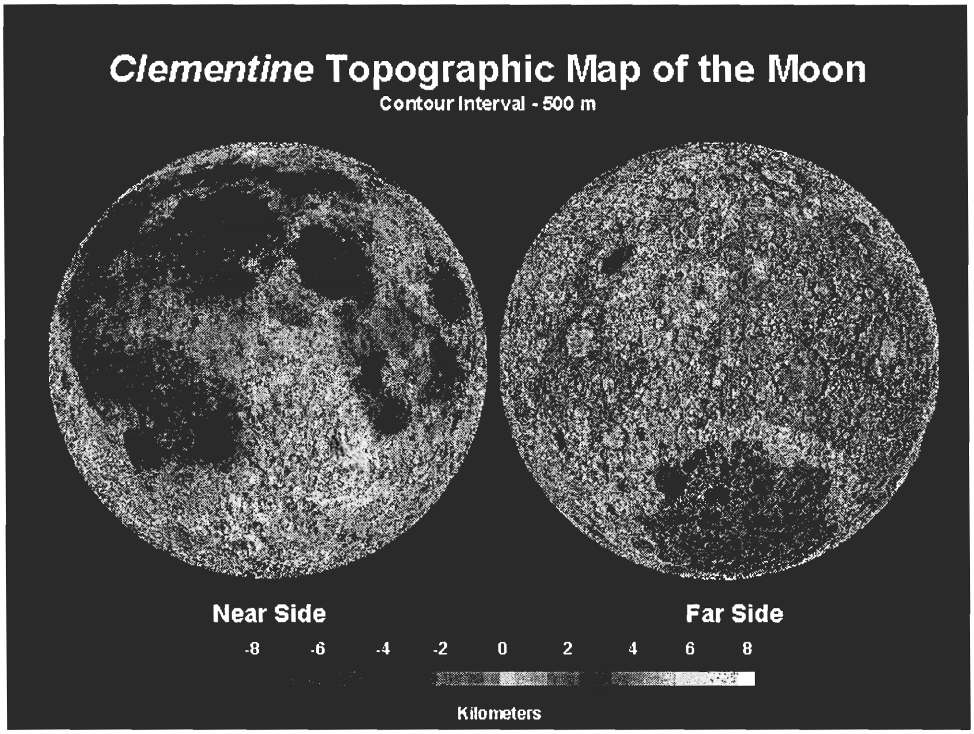


Figure 5 - 2: Topographic Map # 1 of the Moon

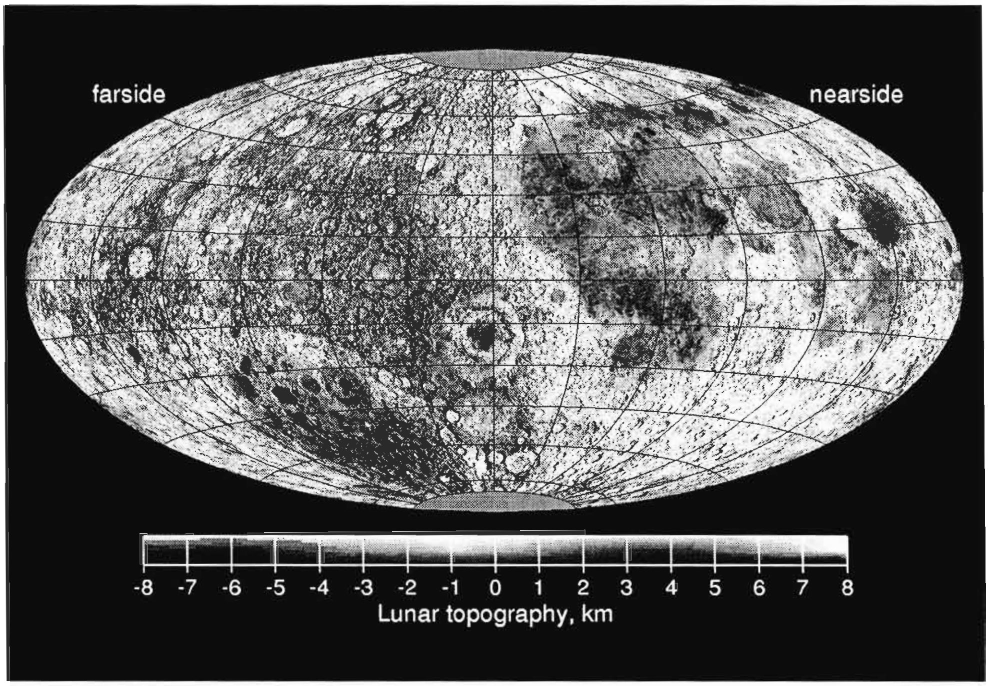


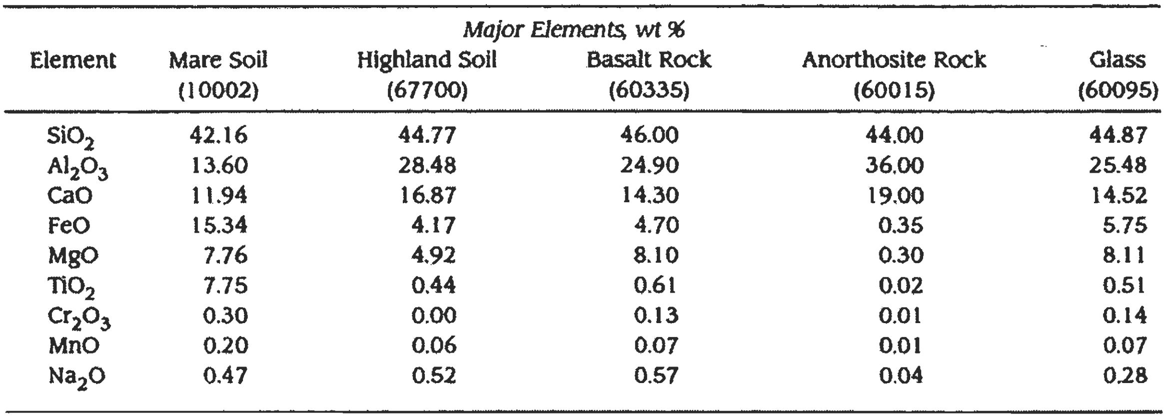
Figure 5 - 3: Topographic Map # 2 of the Moon

Determining the scientific needs would be the next consideration in choosing a site. Locations such as certain craters and the far side of the moon provide shelter from the RF interference and magnetic fields from the earth[14]. The many types of interference produced by the earth are detrimental to the operation of most devices used in astronomical research. Three different examples of these devices are Optical Interferometric Arrays, Radio Telescopes and devices used in Gamma Ray Astronomy[15}. Much more could be learned about the universe if these could be constructed on the moon. Along with astronomy the needs for the study of geoscience and geophysics on the moon would prompt the desire for a location containing useful, historical and geological features. These would be places where studies on the moons evolution, active life, origin and more could be done.

Compiling all of the data gathered from previous missions and further researching the areas in which there is a sparse amount of knowledge will be the first step in deciding a suitable site. Once an objective for this mission is established this knowledge can be used to find the site with the proper components to best benefit this objective.

6 Mining

Mining resources on the moon will be a necessity with the construction and operation of a sustainable lunar base. Though different approaches to this mission involve varying levels of dependency on these resources, the elements and compounds found in the lunar regolith have many uses. The available resources will allow the creation of a wide variety of products from machinery to structures to rocket fuels to nuclear fuels. Considering that the main elements available in the lunar regolith are combined in various compounds, extraction methods will have to be researched and tested to obtain the broken down elements or desired compounds. There are many processes that must be performed in order to properly extract these elements some of which include chemical, magnetic, and electrochemical processing. Different locations on the moon contain varying concentrations of different elements. These element concentrations and locations can be seen in Figure 6 - 1. It will be critical to site a location for the base where there are desirable mineral and elemental contents. As mentioned in Chapter 5 many methods of researching the composition of the lunar regolith are available today. These consist of gamma ray spectroscopy, multi-spectral imaging and physical analysis of the regolith.



	Major Elements, wt %				
Element	Mare Soil (10002)	Highland Soil (67700)	Basalt Rock (60335)	Anorthosite Rock (60015)	Glass (60095)
SiO_2	42.16	44.77	46.00	44.00	44.87
Al_2O_3	13.60	28.48	24.90	36.00	25.48
CaO	11.94	16.87	14.30	19.00	14.52
FeO	15.34	4.17	4.70	0.35	5.75
MgO	7.76	4.92	8.10	0.30	8.11
TiO_2	7.75	0.44	0.61	0.02	0.51
Cr_2O_3	0.30	0.00	0.13	0.01	0.14
MnO	0.20	0.06	0.07	0.01	0.07
Na_2O	0.47	0.52	0.57	0.04	0.28

Table 6 - 1: Elemental Composition of Lunar Regolith

Extracting resources from the lunar regolith can be complicated due to the fact that most desired elements within the regolith will have to be extracted separately through different processes. However, some processes that can be performed to extract elements from the regolith create by products which turn out to be useful elements. Creating the most efficient processes for extracting all desired elements from the regolith will be complicated, but a significant amount of research has already gone into the development of these processes. One example of a design to extract all necessary elements can be seen in Figure 6 - 1[16]. Since some elements require more drawn out or complicated processes to extract and other elements are not in plentiful supply considerations will have to be taken in order to keep a regular and sufficient flow of these elements.

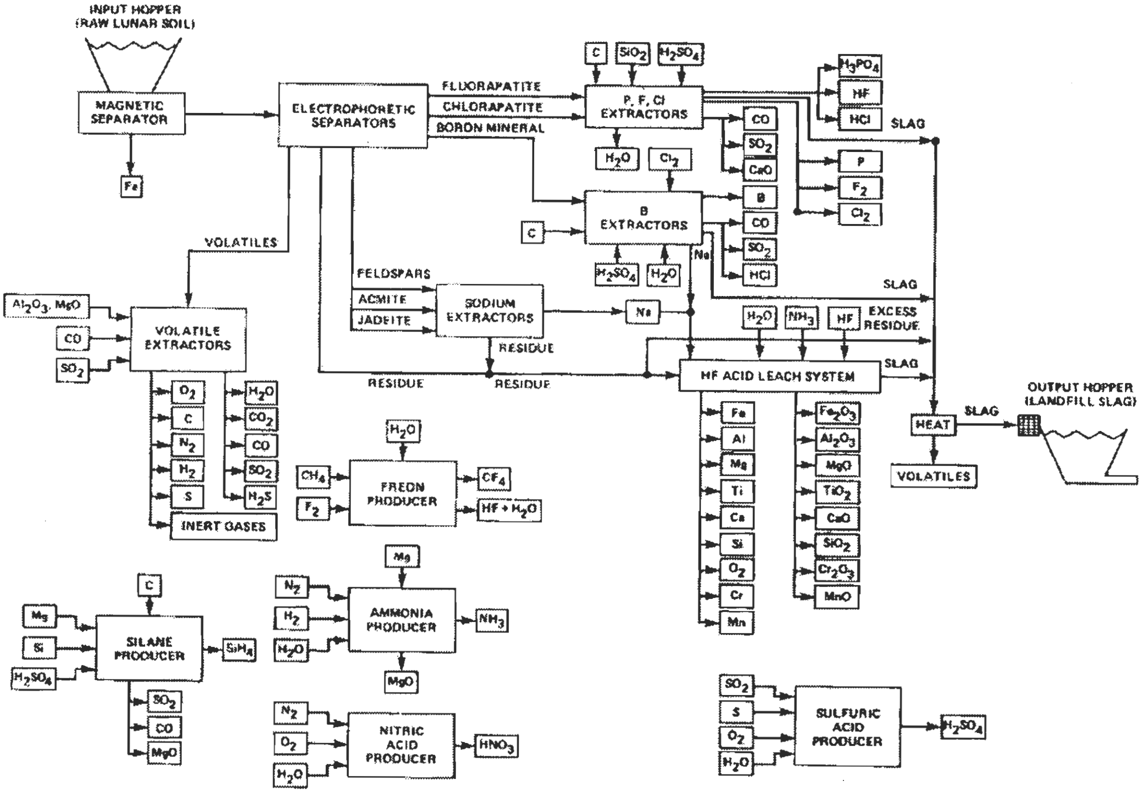


Figure 6 - 1: LMF Mining and Extraction Operations

Since the sustainability and growth of the lunar base will require this flow of resources it will be dependent on the rate at which they can be extracted. This will be the limiting factor in the starting stages of the lunar base project. Because of these limitations, processes will have to be refined and reliable before embarking on this project. This is so the construction of the lunar base will be able to occur and hopefully a reliable timescale and cost estimate will be able to be calculated so that they will not be overshot during the mission. Refining these techniques of extraction would be most accurately tested with actual lunar materials from locations in which the mining will be done. This would be quite cost prohibitive though. Retrieving regolith from the moon in large enough quantities to significantly refine these processes would cost a vast amount of money. The best, if not as accurate, method of refining these processes would then be to research the content of different soil specimens around the earth and find suitably similar materials. Large scale testing could be done on these samples, greatly reducing costs and once the refinement processes has taken place additional tests may be subject to smaller amounts of actual lunar regolith to ensure the quality of the methods being used.

While these extraction processes are being refined suitable locations to mine on the moon will have to be found. The content of the lunar regolith will have to be studied in order to determine where abundant amounts of desirable elements are located in the regolith. Because of the extremely low quantities of some of the elements on the moon it may not be possible to find rich enough deposits for the creation of a lunar base. Even with a refined extraction process these elements may only be able to be extracted at a fast enough rate to sustain the base, yet not to form. For this reason it will be necessary to determine these rare elements and transport them from earth until the supply of extracted elements is sufficient.

There are a large number of processes that must be performed in order to thoroughly breakdown compounds into the desired elements. Some of these processes include electrophoretic processes, acid leach, solution, precipitation, ion exchange and electrolytic steps, the Castner cell process and the zone-refining process. It is essential to refine these processes to perform efficiently on lunar soil since they may very well be the backbone of a lunar base operation.

7 Construction

Many methods of constructing a lunar base are available today. Each has its merits and choosing the best design is essential in the harsh environment of the moon. The main challenges that a lunar base will have to contend with are solar radiation, micrometeorites, extreme temperature fluctuation, and the vacuum of space. Designing a base that protects occupants from all of these dangers, while providing a sufficient work and research space, will be needed. The construction of shielding will have to be taken into account to protect from solar radiation and micrometeorites. In some cases shielding from hazards in space will be incorporated into the structure of the base while in others it will have to be constructed separately. Structures will also have to be built to withstand a high internal pressure compared with the vacuum of space. Construction methods currently fall under five main categories; building rigid modules on earth and transporting them to the moon, constructing inflatable habitats on earth and transporting them, creating a cement base primarily constructed out of lunar material, establishing an underground base either within a lava tube or by excavating a cavity in the lunar regolith and creating a crater base lunar habitat.

Protecting the inhabitants of a lunar base will be the number one consideration in its construction. On the earth we are protected from solar radiation by our atmosphere and magnetic field. Since there is neither of these to protect inhabitants of the moon, shielding will have to be utilized. Creating a shield out of earth based materials would be the most reliable method of constructing a shield. Aluminum and lead are both proven to be adequate shielding materials. The construction of an aluminum shield would require three meter thick walls while iron would have to be made into half meter thick walls to sufficiently reduce the radiation exposure of the inhabitants to safe levels. Transportation costs of the materials however are quite prohibitive to make them viable sources for shielding. This would limit the available materials for shield construction to lunar resources. The lunar regolith could be formed into a shield by placing two meter thick deposits over a base[17]. This is not yet a proven method however and testing would have to be done to ensure its feasibility. In the case that the lunar regolith is able to sufficiently diminish the radiation it would be quite advantageous over any earth based materials. While these shields provide safety from solar radiation they also protect against micrometeorites, however before a base can be constructed a few more aspects must be taken into account.

Radiation is isotropic and because of this the base will need to be shielded from all sides. Only covering the top of the base will not be sufficient for the inhabitant's safety since radiation will not only come from directly overhead. The sides of the base must be covered with an equally sufficient amount of shielding. The greatest radiological dangers that will have to be accounted for are solar flares and coronal mass ejections.

When a solar flare occurs, protons and electrons are released at near light speeds along with gamma rays and x-rays. The effects of coronal mass ejections are quite similar. When this event occurs huge amounts of radiation are given off from the sun. This radiation will reach the moon about eight minutes from the event occurring and have a strength of up to thirty thousand times the regular background radiation that the habitat will constantly be exposed to[18]. A cellar or "bomb" shelter with additional shielding will have to be set up within the base for the occurrence of these events. Without the current prediction and detection systems that have been set up to warn of these events a much larger shield would be necessary to cover the entire base. If additional shielding is not available for these events the inhabitants of the base could receive a dosage of radiation causing sickness or even death depending on the size of the solar flare or coronal mass ejection.

There are a large variety of options to pick from in determining the structure of the shielding under the assumption that it is being made out of the lunar regolith. The determining factor in choosing an option is the type of structure being used as a habitat. Of the five main habitat choices, inflatable structures, rigid modules, regolith based cement structures, subsurface structures and crater bases alternative methods of shielding will have to be researched. Modular and inflatable structures may be set up on the moon and simply covered with regolith until they are sufficiently shielded. Other designs have been proposed such as an arch structure built over an excavated ditch which is then covered in regolith as in Figure 7 - 1[19]. An inflatable or modular habitat can be constructed underneath this. A similar proposal is to construct a superstructure over one of these two habitats. Lunar regolith would then be piled on top of this structure shown in Figure 7 - 2[20] creating a radiation shield. If a surface cement structure was built the properties of the cement would have to be analyzed to determine their shielding effects. The walls and roof of the structure would have to either be thick enough to shield the inhabitants or regolith would have to be piled up next to and or on top of the base.

Lava tubes may also be used as shielding towards this harsh environment. These will provide ample space for the placement of modular habitats and are well suited to protect from radiation and micrometeorites. Lava tubes are located at sufficient depths below the lunar surface, approximately ten or more meters, to maintain a constant temperature over the moon's day night cycle[21].

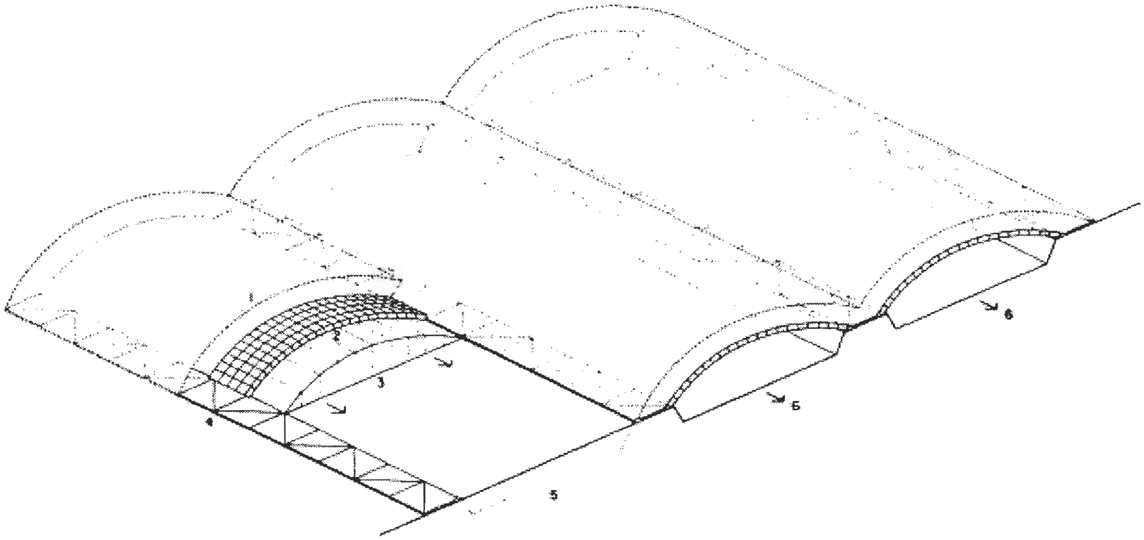


Figure 7 - 1: Arch Shielding Using Lunar Regolith

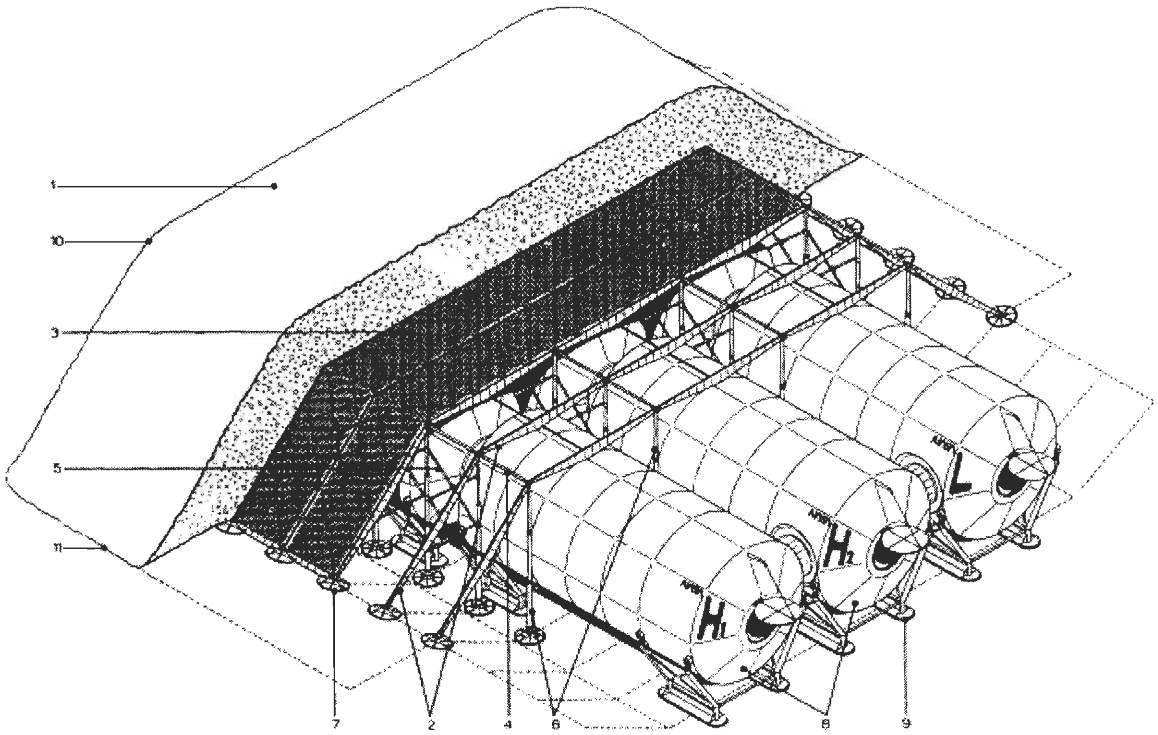


Figure 7 - 2: Superstructure Shielding Using Lunar Regolith

One viable option for the habitation of the moon is inflatable structures. These may be made on earth, set up and tested then deflated to quite a small volume to be transported to the moon. The advancement of materials usable in inflatable structures has been significant since they were first tested with the intention of use in space during the Apollo program. With these jumps in technology since 1970 very reliable pressure vessels are now being researched and developed. A lunar base will require a large, preferably open working and living space. Inflatable structures would be able to provide these qualities which would be advantageous in many ways. The scope of operations and tasks that can be carried out grows significantly with an increase in space to work with. The habitability of the base also increases with an enlarged space. With the required shielding from radiation surrounding the base no windows will be available for the crew to look through creating a very claustrophobic atmosphere which will detract from the habitability. Productivity will decrease with lowered habitability so creating an environment with more space will greatly boost moral and usefulness of the crew stationed at the lunar base.

One design for a modular inflatable structure can be found in Figure 7 - 3[22]. Multiple inflatable modules of this type could be transported to the moon independently. They could then be set up and interconnected. Having this flexibility to add and remove separate modules would allow the expansion of the base when the time came.

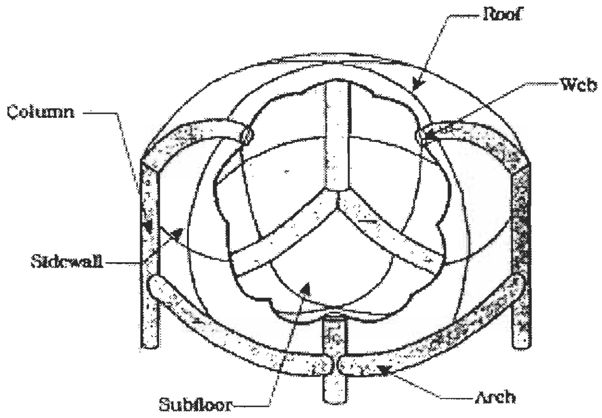


Figure 7 - 3: Inflatable Module Concept

The greatest loads on any vessel in the vacuum of space are the internal pressures within said vessel. The characteristics of inflatable structures make them highly desirable under these conditions. If there is a desire for a larger base, possibly like the design in Figure 7 - 4[23], then the stresses put on the structure by the internal pressure will have to be taken under more serious consideration. Methods of reducing stresses on inflatable structures without diminishing their habitable volume would either be to put hoops around the structure or to use cables[24]. These would support the structure sufficiently at greater volumes to provide the desired size.

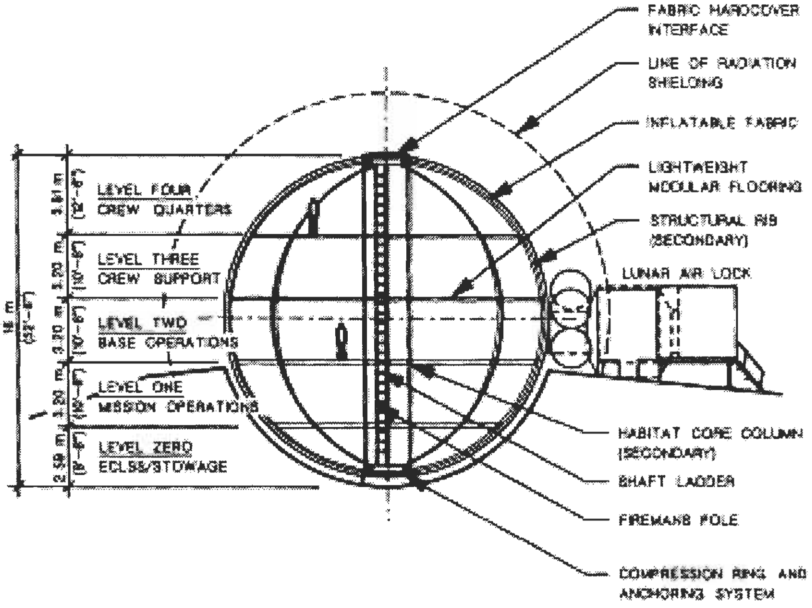


Figure 7 - 4: Dome Base Concept

Short setup or construction times would be beneficial for the workers involved in building a lunar base. Longer duration missions on the moon for workers setting up a base without the safety of shielding could be detrimental. The quick setup of modular bases would help eliminate any dangers these workers may face. Since inflatable structures are prefabricated on earth there will be minimal assembly time. Using rigid modules however would reduce setup times even further. Rigid modules could conceptually be landed on the moon and be ready for habitation.

Rigid modules are a similar alternative to the inflatable structures. These would be constructed on earth and shipped up to the moon. With the construction done on earth minimal assembly would be necessary when the module arrives on site. Systems may be integrated into the module while it is under construction reducing the need for work to be done on the moon. The size of a rigid module will be limited by the cargo space of a transport craft from the earth to the moon. Because of this multiple sections may have to be transported separately and assembled in situ.

Boring into the lunar regolith would provide another option for a lunar base. The sides of hills or craters could be bored out to provide a space for such a base. A subsurface base could be made to stand alone by using sealant that would be sprayed on the interior surfaces of the cavity or smaller modular structures could be placed inside of an excavated site. Lunar concrete may be one possibility to help support this type of base and to help seal it off from the moons hazardous environment.

Lunar concrete may also be used as a primary source for the construction of a base on the moon. The creation of lunar concrete will require the import of machinery and H_2 to the moon. Lunar regolith will have to be mined and the appropriate components, primarily SiO_2 and CaO[25], will need to be extracted to create a high quality cement mixture. There are many options in terms of the design of a concrete lunar base and extensive testing will have to go into the development of a reliable structure. This option will also require the most on site construction time so it may only be considered an option if the timeframe allows enough time between the construction of the base and the initial inhabitation. While this option may take the most time, the last option to consider is a crater base.

Designs for a crater base are much more complex than any of the other forms of bases. Because of this, high transportation costs and long construction times may exist in implementing these designs. Currently there are no viable options in terms of crater lunar bases that would have an advantage over any of the previous base designs.

Ultimately the base design that is most suited to the mission must be chosen. If there are multiple stages to this mission, combinations of these designs may be used in conjunction with one another and built upon one another as the expansion of the base becomes necessary. Regardless of the style of base, however, shielding must be carefully investigated and constructed with great care given to its quality. This will be the first safeguard against the harsh environment of the moon and must stand firm against the hazards that it will encounter. The choices presented for a lunar base provide a wide array of options of which each, if constructed properly, can make a quality habitat.

8 Life-Support Systems

Humans living on the moon will need to have their every need provided artificially. This includes oxygen, atmospheric pressure, heat, food, water, medical care and sanitation, light, satisfying work and entertainment.

The lunar environment is extremely hostile to life. It has no atmosphere, exhibits a 260 degree Celsius variation in day-night temperature on its surface and is constantly bombarded by harmful solar radiation. There are almost no biological molecules in its soil, and an almost complete lack of carbon, hydrogen and nitrogen, the basic building blocks of biological molecules. Further, though researchers were initially very optimistic about the presence of large quantities of frozen water at the lunar poles, this is becoming increasingly doubtful.

While the moon's resources alone will be insufficient to grow food and provide water for human beings, it may be possible to provide all the other listed needs using moon-materials. The question here is one of sustainability and cost. If a mission plan involves frequent re-supply of the base by payloads from earth, then oxygen, food, water and medicines can be shipped periodically, without any need for a self-sustaining biological support system. Depending on the frequency of these transfers and the vehicle used, this could be an immensely expensive proposition. On the other hand, designing and setting up a completely self sufficient moon base is a difficult, complicated task. Here, completely self-sufficient means that, once humans are sent to the moon with an initial supply of resources, no further supplies will need to be sent. The size of this initial payload is also of concern.

Designing such a system is one part of the equation, but perhaps more important is demonstrating that it works, on earth, especially since lives will be at risk. Everything will have to be recycled and re-used, indefinitely. There must be minimal loss due to waste or leaks and no contamination or infection due to microorganisms or toxins from wastes. Any losses will have to be replenished from lunar materials. All food will have to be grown on the moon base, and all wastes decomposed, detoxified and re-introduced as fertilizers. Nutrients and energy will have to successfully cycle through the system. In light of the increasing doubt of the existence of frozen water at the lunar poles, it may be necessary to transport water to the moon from earth, or ship hydrogen and react it with naturally occurring lunar illmenite to get water.

Martyn J. Fogg, author of "Terraforming, Engineering Planetary Environments", says that, fundamentally, "a life support system involves a flow of energy through a space that drives internal cycling of matter into which the specific cycles of life can be integrated."[25] In his book, Fogg enumerates the attributes of long-term, self-sufficient life support system as

1) The LSS must rely primarily on the use of free or *gratis* energy, such as solar energy and naturally powered matter cycles and must minimize its dependence on technologically processed power, such as electrical or nuclear power and other manufactured life-support infrastructure.

2) The LSS must be self-contained, ideally not requiring the supplementation of energy and matter in excess of its natural endowment. Its internal matter cycling should be *regenerative*, the system having a high degree of *closure*: production and consumption must be either balanced or capable of easy compensation from the exterior.

3) Its components should have the properties of *self-replication* and *self-maintenance*, so as to reduce the human role in manufacture and repair

4) Its internal dynamics must be *self-stabilizing* and *autonomous*, as safe as possible against dangerous perturbations and keeping essential human monitoring and control to a minimum.

5) The habitable environment provided must be pleasant to live in, having a variety of *aesthetic* and *challenging* qualities.

Fogg further defines the various categories of life systems as Open-Loop, EC/LSS, Small Contained, Large contained, Planet and Pre-civilized earth. These categories vary in their degree of closure, their balance of mechanical and biological subsystems, the presence or absence of a containing structure and their degree of autonomy. Only two of these LSS are in reliable operation today, namely the Open-Loop LSS of spacecraft and the biosphere of present-day earth. The categories of LSS, together with their defining characteristics are summarized in Table 8 - 1[25].

	Open-Loop	ES/LSS	Small Contained Biosphere	Large Contained Biosphere	Present-Day Earth or Terraformed Planet	Pre-Civilized Earth
Air revitalization	Stored supply and waste	Mechanically recycled	Biologically recycled	Biologically recycled	Biologically recycled	Biologically recycled
Water reclamation	Stored supply and waste	Mechanically recycled	Biologically and mechanically recycled	Quasi bio-hydrological cycle	Natural bio-hydrological cycle	Natural bio-hydrological cycle
Solid waste Management	Treated and stored	Treated and stored	Biologically and mechanically recycled	Biologically recycled	Biologically recycled	Biologically recycled
Food service	Stored	Stored	Horticulture	Agro-ecosystems	Agro-ecosystems	Natural ecosystems
Essential Monitoring and Control	Continuous	Continuous	Continuous	Continuous	Partial	Unnecessary
Containing Structure	Present	Present	Present	Present	None	None
External resupply requirements	Total	Total	Minimal	Minimal	None	None

Table 8 - 1: Categories of Life Support Systems

8.1 Open Life Support Systems

In an Open Loop LSS nothing is recycled. Oxygen, food and water are consumed from stores and the wastes produced are also stored. Such a system is completely dependent on external supply and requires artificial mechanical and chemical processes to remove and store wastes from the system. It also requires continuous, rigorous monitoring and artificial control over oxygen content of the air, temperature and other essentials. Such a system can support occupants only as long as the resource in shortest supply runs out, as long as there is enough space to store the wastes.

8.1.1 EC/LSS - International Space Station Life Support Systems

An EC/LSS (Environmental Control/Life Support System) is a partially closed system in which air and water are recycled by mechanical and chemical means, but food is still consumed from stores and solid wastes are similarly stored. Again, there is a need for close, continuous, exhaustive control of the concentrations of gasses in the air, and completely artificial matter cycles. Such an LSS can sustain occupants as long as food supplies last and there is enough space to store the wastes.

An example of an EC/LSS is the LSS being designed for the International Space Station by NASA/Marshall Space Flight Center. This LSS will recycle wastewater (including urine) to produce drinking (potable) water, store and distribute potable water, use recycled water to produce oxygen for the crew, remove carbon dioxide from the cabin air, filter the cabin air for particulates and microorganisms, remove volatile organic trace gases from the cabin air, monitor and control cabin air partial pressures of nitrogen, oxygen, carbon dioxide, methane, hydrogen and water vapor, maintain total cabin pressure, detect and suppress fire, maintain cabin temperature and humidity levels and distribute cabin air between ISS modules (ventilation)[26].

8.2 Closed Life Support Systems

An ideal closed life support system is one in which energy flow and matter recycling are biologically accomplished. Photosynthetic biomass production regenerates oxygen and provides plant matter that can be used as human food or as the basis for a food chain, while plant evapotranspiration provides a supply of pure water, and bacterial digestion is exploited to break own inedible material, solid wastes and toxic contaminants. Ideally, such systems should exploit the self-reproducing and self-maintaining properties of life and the self-stabilizing properties of ecosystems so that life-support is an effortless and automatic background process as it is in the biosphere of earth. In reality, however, all closed life support systems have some gas leakage that must be periodically corrected and, in space, must be shielded from harmful cosmic radiation. There are also numerous problems that arise because biospheres do not easily scale to small volumes.

8.2.1 Small Contained Biosphere

A small contained biosphere is a small closed life support system. The characterization "small" means that these life support systems have too small a volume for quasi-natural weather to occur. There are several intrinsic problems with small contained biospheres, resulting from the fact that the volume of such a biosphere is too small to adequately maintain all the functions of the terrestrial biosphere.

Because of the absence of natural weather to circulate fresh air and level temperature differences, small contained biospheres must be provided with temperature regulation systems (air conditioners or heaters) and dehumidification systems (condensation of water transpired by plants, followed by irrigation and sprinkling, to artificially operate the hydrological cycle). A further consequence of the small volume of small contained biosphere is that the dynamics of the biosphere are poorly buffered. The animals, plants and microbes are connected with a much smaller inorganic reservoir of biologically processed materials than on earth. Such materials therefore, as a proportion of their abundance, have to be recycled through the biota at a much higher rate.

For example, humans in the biosphere breathe oxygen regenerated by plants. On earth, if all our plants stopped regenerating oxygen for a length of time, we would be able to survive for some duration by breathing from the large reservoir of oxygen that lies in the atmosphere of the earth. In a small contained biosphere, a small reduction in the oxygen regenerating capacity of the plants may have quick, disastrous consequences for the occupants because of the absence of an idle oxygen buffer. All the oxygen in the small biosphere must cycle through the carbon-oxygen cycle in a very short time, whereas on earth, a large percent of our oxygen never even goes through this cycle and is always available as a buffer. This makes the smaller system intrinsically less stable. Small imbalances will significantly affect the composition of the buffer in a short period of time. The natural stabilizing biotic responses that function within the vast and massive biosphere of the earth may be too slow or inoperable in a confined space. Once the composition of the buffer has changed to some critical level, biological function is jeopardized and the system is in danger of crashing completely. Fogg makes the well-supported conjecture that this tendency for instability is proportional to the biomass-to-atmospheric-mass ratio. Table 8 - 2[25] shows rough estimates of these ratios for various life support systems, normalized to 1:1 for earth.

Biosphere	Biomass : Atmospheric Mass Ratio
CELSS “Breadboard”	2000:1
BIOS 3	1000:1
Biosphere 2	350:1
Stanford Torus	250:1
O’Neill Island 2	20:1
Bernal Sphere	13:1
Martian ‘Worldhouse”	7:1
Earth	1:1
Terraformed Mars	1:2.7

Table 8 - 2: Approximate Biomass: Atmospheric Mass Ratio for Various Biospheres (Normalized to 1:1 ratio for earth)

The solution to the problem of instability of small contained biospheres, therefore, entails the back-up of ecological life support with technology and conscious monitoring and control of the whole system. Gas concentrations may be regulated using machinery capable of manufacturing precise amounts of certain atmospheric gases and the most indigestible of solid wastes might be more reliably digested by composting, after being broken down mechanically. Uncertainties in agricultural production could also be reduced by exploiting the wide range of technologies that are available to horticulture to deliver precise fluxes of light and flows of air, water and fertilizers. Protection from complete failure of the habitat's ecological LSS would require a comprehensive back-up mechanical LSS capable of functioning in the last resort and for some considerable time following a serious emergency. Intimate integration of ecosystems with machinery is the key to continued survival within small contained biospheres.

As such, small contained biospheres have high power demands per capita. Table 8 - 2[25] shows the power consumption of various life support systems compared to earth. Note that the EC/LSS power consumption does not include the large amount of outside energy expended in supplying and re-supplying food and spare parts. If this outside energy were included in the calculation, the EC/LSS power consumption would be enormous.

Biosphere	Power Consumption/Person
Earth (Gratis Life Support)	
- World Average Primary Power	2 KW
- World Average Electrical Power	0.2 KWe
- Industrial Nations Primary Power	6KW
- Industrial Nations Electrical Power	0.7 KWe
Extraterrestrial Estimates	
- EC/LSS only (Stored Food)	2 KWe
- Stanford Torus	3 KWe
- CELSS only (fluorescent lighting)	15 KWe
- Ohbayashi Mars Colony 2057 (total power for all activities)	50 KWe
- Biosphere 2	100 KWe

Table 8 - 3: Human Power Consumption: Comparison of Earth and Contained Biospheres

For closed biospheres, the general theoretical trend is: the larger the closed biosphere, the smaller the per capita power consumption, because of the smaller need for artificial systems to drive the biosphere's several processes. In reality, top-down designed small closed biospheres such as the large and elaborate Biosphere 2 have achieved poor food production and matter and energy recycling efficiencies. In contrast, the NASA CELSS (Controlled Ecological Life-Support System), which takes a reductionist approach to bioregenerative life support and aims to reduce the size and weight of the whole system so that it can be used on a spacecraft has, through the use of precise control of lighting, nutrient flows and specially selected waste-decomposing algae, demonstrated extremely promising system efficiencies and low power consumption. The CELSS grows plants in a small pod containing racks, and the whole system is only a little larger than a mobile home.

Biosphere 2 includes seven biomes, and a total of 3000 species of plants and animals. It seems to have been the goal of the designers of this biosphere to make the appearance of their biomes as close as possible to that of the real thing, with landscaping and a large variety of species (such as one may expect to find in a large contained biosphere), in the hope that the biosphere would be large enough to be mainly autonomous, and only a small amount of artificial control and compensation would be required. As such, the system as a whole is not designed with artificial systems efficiency in mind, and the biosphere is still much too small to have anywhere close to completely autonomous bioregenerative capacity (i.e. it is definitely a small contained biosphere, not a large one). Thus, the larger a closed biosphere is, the more potential it has for lower energy consumption, though in current designs, this potential has not been realized.

Various factors and techniques such as septic treatment, separate treatment of liquid and solid wastes, generation of biogas, hydroponics, use of digesters to produce different fertilizer mixes, use of enzymes and bacteria to control rates of element fixation and release, plant and animal selection, food chain and associated mass and energy levels, conservation of mass, elimination of toxins and pollutants, sources and sinks of various compounds, greenhouses, irrigation, harvesting and fallowing, must be considered.

8.2.2 Large Contained Biosphere

The characterization "large" means that these life support systems have sufficient volume for quasi-natural weather to occur. This will replace the need for fans, pumps and rain-making machines. Biomass-to-atmospheric-mass ratios in these contained biospheres are reduced to only about an order of magnitude greater than earth, and the power consumption per capita is greatly reduced. Environmental buffering in these systems is improved and the characteristic time for imbalances to translate into serious environmental change is significantly increased. Further, the aesthetics of life in such a large biosphere will be a big improvement over those previously discussed, with room for cities and wilderness, even some landscaping to provide hills and seas. Although ecologically more autonomous, these biospheres will still require conscious control to tie up any loose ends in matter cycles and to operate technological subsystems. Figure 8 - 1[25] shows various closed biospheres placed beside two of the world's largest buildings for comparison. Only the smallest of these, Biosphere 2, has been constructed. The first three biospheres can be characterized as "small", and the last three as "large".

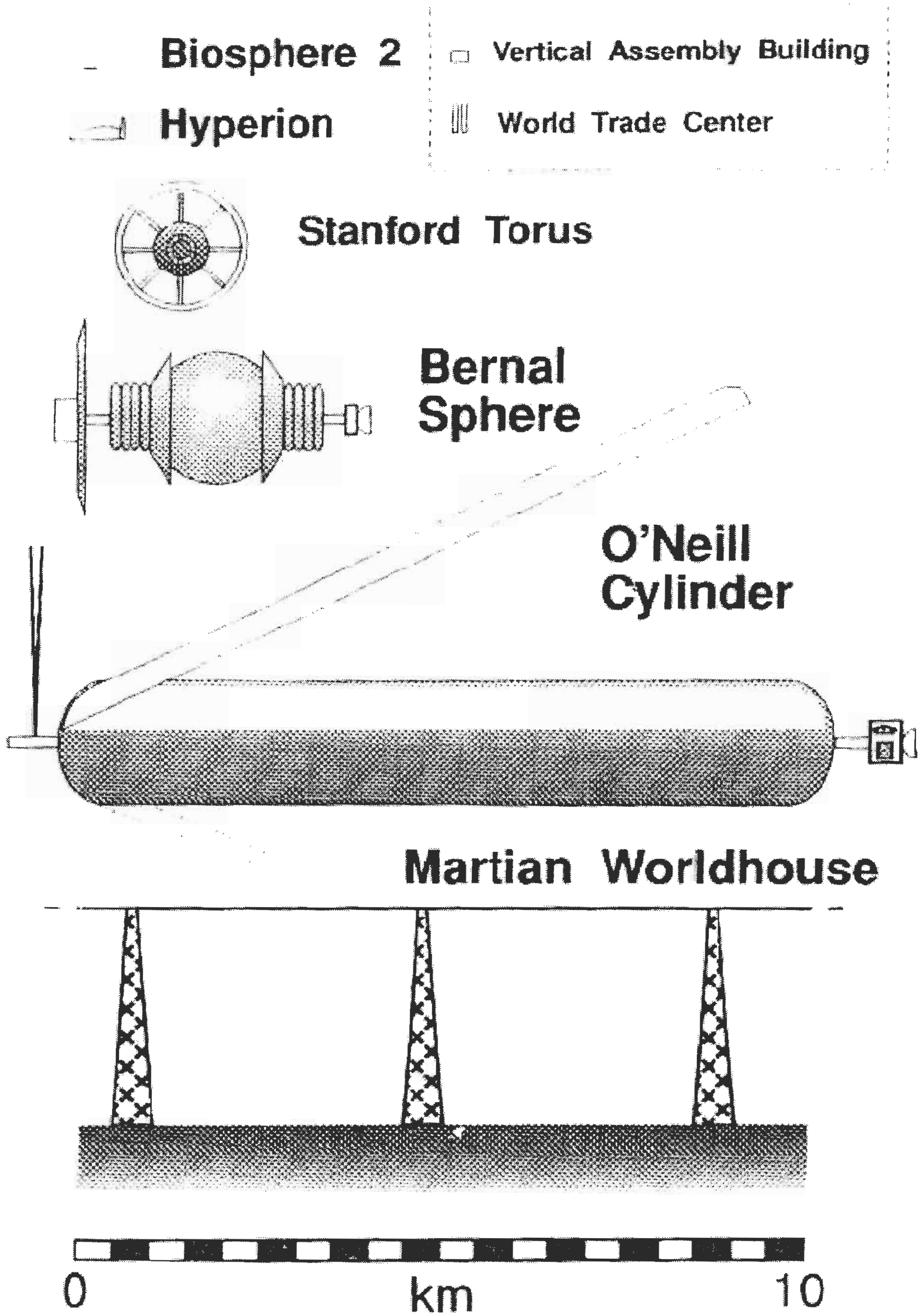


Figure 8 - 1: Various Closed Biospheres

9 Self-Replicating-Systems (SRS)

This section has been included in this report because of the universal applicability and incredible power of self-replicating systems (SRS). Self-replicating systems can revolutionize all of the previously mentioned aspects of the moon mission and, indeed, anything else it is applied to. It is the sole means for bringing the timeframe for the exploration of our galaxy or colonization of planets down to a reasonable size. It is power with minimal cost, a fire that fuels itself, an instrument of phenomenal, tireless productivity. SRS is as much a philosophy as a methodology, and though its claims may seem bold, they are entirely possible with today's technologies. Imagine cities that build themselves on other planets, free of cost, ready and waiting for humans to arrive and populate them. SRSs are exponentiating systems that defy the traditional logic that more work requires more expenditure and effort.

Most of the following section is based on the findings of a NASA summer study conducted in 1980 by the request of President Jimmy Carter[27]. The result of the study was a realistic proposal for a self-replicating automated lunar factory system capable of exponentially increasing its productive capacity and, in the long run, facilitating the exploration of our entire galaxy within a reasonable timeframe. The proposal was quietly declined and received no recognition in the press. Recently, there has been some renewed interest in SRSs, primarily in the field of nanotechnology. SRSs are not a common feature in moon and space mission plans, though automation and robotics in general, are. However, such existing systems are still only capable of linear, not exponential growth. It is a mystery to the authors of this report why this technology is not being focused on as a critical component in our quest to colonize planets and moons, especially since it does not require the occurrence of any technological breakthroughs, though the implementation of a large-scale SRS for the colonization of the moon may be considered a technological breakthrough in itself.

The timeline for the moon base project varies dramatically with various approaches to the mission. These timelines depend greatly on the size of the initial monetary investment in the mission and, as such, are divided by the agencies which may undertake the mission. Some approaches involve sending large masses of pre-fabricated machinery, parts, food, fuel and other power sources and deployable housing structures to the moon in a series of a few expensive rocket-propelled payloads. These plans will produce a functioning base on the moon, ready for human habitation, in a period of a few years, at immense cost, with very little capacity for growth without large additional cost. Such plans may be undertaken by the US government, for example, as the wealthiest agency in competition for the moon. The SRS approach, however, involves sending a small payload consisting of robots, minimal mining equipment and perhaps a small initial power source, to the moon. These robots would mine the resources necessary to construct shelters, solar cells, power stations, factories and fabrication plants, greenhouses and hydroponics facilities, and roving vehicles, as required, and build these items long before any human presence is necessary on the moon. The robots would self-replicate into a large task force, utilizing the energy they harness from solar arrays to further advance the moon base. This approach might mean that it will be fifty years before there is a habitable base on the moon, but will cost dramatically less than the quick approach because of the small weight of the initial payload and the free resources available on the moon. Such a base will also be capable of expansion, growth, modification and self-repair with no additional cost. There are a variety of approaches to the mission which fall in between these two extremes. Most mission plans are divided into sequential phases, each involving different levels of human involvement. The final goal, in any case, is a sustainable lunar base which can support research activities, demonstrate the technologies developed for it, and maybe even serve as a launching platform for deeper space missions. The degree of self-sustainability desired of the base is another topic for discussion, and depends heavily on the development of space transportation technologies in the near future. If a system such as a group of space elevators were constructed, the economic viability of supplying a moon mission from earth would increase immensely. The time scale of the mission will depend on the urgency with which the executing agency is pursuing certain milestones and on the competition that it is facing, in the race to claim territory on the moon.

Apart from constructing a habitable lunar base, a self-replicating manufacturing facility on the moon may have other immensely important applications. On earth, the cost of fossil-fuel energy continues to escalate and supplies of high grade ores and minerals are gradually being depleted. It is becoming increasingly expensive to obtain the resources we need to maintain our various industries. As such, it may be extremely desirable to use non-terrestrial sources of energy and materials and non-terrestrial industrial capacity to provide us with the energy and products that we need on earth. The moon, for example, has plentiful supplies of free materials, space and energy that make it an ideal candidate for a factory site as compared to the earth. Because of the expense and hazards of using human workers in such a hostile environment as the moon, a lunar manufacturing factory should be automated to the highest possible degree and be flexible, so that its product stream is easily modified by remote control according to changing demand. Still, such a factory would eventually exhaust local resources and fall into disrepair. The NASA summer study of 1980 proposed that this problem may be eliminated by designing the factory as "an automated, multi-product, remotely controlled, reprogrammable Lunar Manufacturing Facility (LMF) capable of constructing duplicates of itself that would themselves be capable of further replication." The study further proposed that successive new systems need not be exact replicas of the original, but could be improved, reorganized or enlarged by remote control or through a process of machine "self-evolution" so as to meet changing human requirements. As such, the self-replicating LMF could augment or eventually even replace large portions of terrestrial industry without contributing to the burden on earth's limited energy and natural resources and further straining the biosphere.

Designing an autonomous self-replicating LMF will lead to the development of advanced automated processing and assembly technologies that could be used to further enhance the productivity of terrestrial industry and spur the appearance of new forms of large-scale industrial growth and control. We will quickly be able to replace a large fraction of terrestrial industry will factories on other worlds. By self-replicating, such systems, unaided, enlarge their production capability exponentially. These systems may be considered the first step in demonstrating and developing systems that will lead to an indefinite, ever-expanding wave of automated extraterrestrial exploration and the use of non-terrestrial resources. General purpose self-replicating systems will be able to manufacture space probes, planetary landers and mobile “seed” factories that will site themselves on other worlds. They will permit the affordable, extensive exploration and utilization of space without straining earth’s resources.

9.1 Theoretical Feasibility of Machine Self-Replication

There is a deep-seeded resistance to the notion of machines replicating themselves, with claims that the process must be somehow more limited than biological reproduction, or altogether impossible, for a number of reasons. According to Kemeny (1955), "If [by "reproduction'] we mean the creation of an object like the original out of nothing, then no machine can reproduce - but neither can a human being....The characteristic feature of the reproduction of life is that the living organism can create a new organism like itself out of inert matter surrounding it."[27] Often it is asserted that only biological organisms can reproduce themselves. Thus, by definition, machines cannot carry out the process. On the other hand, others argue that all living organisms are machines and thus the proof of machine reproduction is the biosphere of Earth. Also, sometimes it is claimed that although machines can produce other machines, they can only produce machines less complex than themselves. This "necessary degeneracy" of the machine construction process implies that a machine can never make a machine as good as itself. An automated assembly line can make an automobile, it is said, but no number of automobiles will ever be able to construct an assembly line. Another common argument is that for a machine to make a duplicate copy it must employ a description of itself. This description, being a part of the original machine, must itself be described and contained within the original machine, and so on, until it is apparent we are forced into an infinite regress. A variant of this is the contention that a machine not possessing such a description of itself would have to use itself for a description, thus must have the means to perceive itself to obtain the description. But then what about the part of the machine that does the perceiving? It cannot perceive itself, hence could never complete the inspection needed to acquire a complete description. Yet another related objection is that for the process to be carried out, the machine must come to "comprehend" itself - at which point it is said to be well known that "the part cannot possibly comprehend the whole." However, a thorough examination of the process reveals that there are no fundamental inconsistencies or insoluble paradoxes associated with the concept of self-replicating machines.

The Hungarian-American mathematician John Von Neumann, the first person to seriously come to grips with the problem of machine replication, identified four characteristics and capabilities that all self-replicating systems should possess. These include logical universality, construction capability, constructional universality and self-reproduction. A machine possessing all these characteristics would be able to function as a general-purpose computer capable of manipulating information, energy, and materials, with the ability to manufacture any finitely sized machine which can be formed from a specific set of parts, given a finite number of different kinds of parts but an indefinitely large supply of parts of each kind, and self-replicate because it is composed of a finite number of manufacturable parts, if it is given a description of itself. He had in mind a full range of self-replicating information transactional machine models which he intended to explore, including the (a) kinematic machine, (b) cellular machine, (c) neuron type machine, (d) continuous machine, and (e) probabilistic machine. He never completed work on the last three models, and it is assumed that these models were intended to cast the notion of replication in a more biological format using neuron-like elements with excitation thresholds and electrochemical pulses that could be described with differential potential functions[27].

Not much was done on a fifth property also believed to be important - evolution - though there have been some more recent results in this area. If one has a machine, and it makes a machine, which then itself makes a machine, is there any proof that the line of machines can become successively "better" in some fashion - for instance more efficient, or able to do more things? Could they evolve to higher and higher forms? This problem raises issues in learning, adaptation, and so forth, and was left largely untouched by von Neumann.

The first model, the kinematic machine, is one in which the machine has instructions for its assembly from its constituent parts and descriptions of these parts residing in its memory. The machine moves around in a “sea” of the spare parts from which it is made and finds parts to put together according to its instructions until it has produced a replica of itself. It then copies its memory to its offspring and activates the new machine, completing replication. This concept involves a machine residing in a highly ordered substrate and cannot be subjected to a rigorous mathematical proof.

Accordingly, Von Neumann formally demonstrated, with mathematical rigor, the four characteristics that reproducing machines should have, in his next model, the cellular machine (Figure 9 - 1[27], Figure 9 - 2[27] and Figure 9 - 3[27]). This model consisted of an array of cells, each in one of twenty-nine states. Each cell’s state is determined by its prior state and the states of its four cardinal neighbors, according to simple rules. He devised various “organs” (merely groups of cells in specific states) that could act as a general-purpose computer and universal constructor in the cell space (capable of constructing any pattern of cell states whatsoever regardless of the initial state of the substrate cells) by performing various functions such as construction, detection, memory creation, etc. Even real-world construction and replication is essentially an information transactional device, and this model proved that machine self-replication had no theoretical flaws or inconsistencies. In a practical sense, the cell-space notion is far from providing a readily useful paradigm of actual manipulation and transformation of physical materials, though it demonstrates that machine self-replication is theoretically possible.

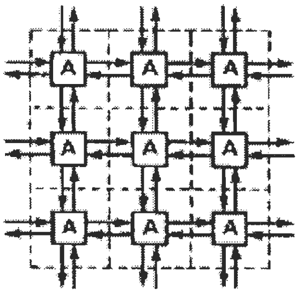


Figure 9 - 1: Finite State Automaton Cellular Matrix

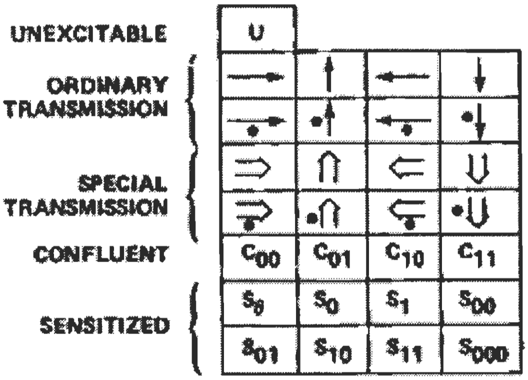


Figure 9 - 2: Twenty-Nine States of Von Neumann's Cellular Automata

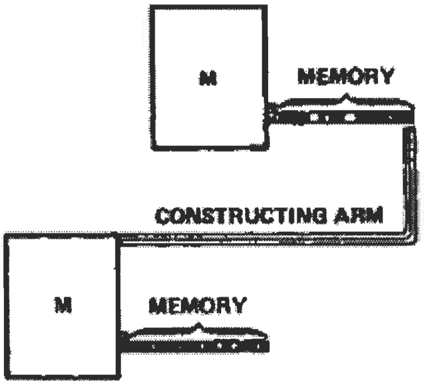


Figure 9 - 3: Universal Construction in the Cellular Model of Machine Self-Reproduction

9.2 Information Requirements of Machine Self-Replication

The design, implementation and operation of a lunar manufacturing facility will be highly complex. We have explored the theoretical feasibility of machine reproduction, but must also show that a system of this scale and sophistication will have reasonable information requirements. That is, we must show that the length of the program that instructs the self-replication and production functions of the system is reasonable. We can do this by defining some measure of system complexity, and then comparing this complexity to that of other information systems, natural or artificial, self-replicating or not. The question of whether the processing requirement of the working LMF will be reasonable is more difficult to answer. These are important questions because such systems have never been built and it is not clear to what detail the programming instructions will have to be written.

It is suggested that complexity be measured as the length of the programming code that will be required by the LMF. Reproduction can occur across a spectrum of widely varying complexity. At one extreme, there is a row of inanimate robots lacking only fuses. An identical active robot that picks up fuses from an assembly line and inserts one fuse into each inanimate robot, thereby activating it, is reproducing itself, though in a trivial sense. Here, the active robot has a highly ordered "substrate" of dormant robots available to it, and the program required to instruct its replication is extremely short. At the other extreme, a self-replicating system could be so sophisticated as to be able to reproduce from almost complete chaos – say, from a plasma that contains equal concentrations of all elements in atomic form. Here, the information necessary to describe the behavior is complete to atomic level specifications of machine structure and would be incomprehensibly complex. In this case the machine reproduction is essentially complete. Given sufficient energy, the system can make copies of itself in any arbitrary environment even if that environment contains virtually no information relevant to replication. Hence, the operational complexity of machine self-replication lies in the substrate. The complexity of the LMF will be in between these two extremes. It will begin with raw lunar soil substrate containing useful compounds of known composition, which it will mine, extract, purify and use to manufacture parts. Based on the estimates, the lunar factory replication program length should not exceed roughly 10^{12} bits of information. This compares to about 10^{10} bits coded in the human genome and about 10^{14} bits stored in the human brain. Terabit (10^{12} bits) memories are widely available today.

Human beings fall somewhere in the middle of this broad range of reproductive complexity. A 100 kg body mass, if composed of a random assortment of the 92 natural elements, would contain roughly 10^{27} atoms and require 10^{28} bits to describe the position of each atom. Yet the human chromosome set contains only 10^{10} bits. The difference, therefore, must be in the level of order of the substrate in which humans are situated – the highly ordered nutrient-rich environment of earth.

9.3 Machine Self-Replication Strategies

Now that we have shown that machine replication is practical from an information requirement standpoint, we will mention that this replication need not follow the classical reproductive paradigm. This means that a machine need not have instructions for the construction of its offspring or even a description of itself available to it, in order to reproduce. Living organisms contain some form of code (DNA) that is copied during replication so that each new half receives one complete copy. On the other hand, there are a number of ways in which a machine can observe, detect or infer its own structure using multiple sensing organs that can form a complete description of the machine in a shared or serial fashion, thereby creating its own "genetic" code before replication. In addition, multiple machines may exchange active and passive roles in a replication process in which one machine detects the components, circuitry and memory of the other machine and replicates it, and vice versa. These strategies may be used in various combinations for the reproduction of the different parts of an LMF. So far, in describing the logical process of machine reproduction we have focused on the means by which a parent system could come to possess the information needed to carry out a replication and the question of how offspring would acquire the programs needed to continue the reproduction process. There are still a number of critical issues concerning the creation and siting of offspring systems and the fate of such systems that need to be addressed. For example, we must explore the possibility of machine learning and evolution (intergenerational information transfer strategies), methods of offspring dispersal, investment in offspring survival and the reproductive schedule of the machines.

9.4 Machine Offspring Dispersal

We can approach these issues by once again employing biological analogues to organize our thought process. All living organisms use the same underlying reproductive logic of protein synthesis and nucleotide sequence copying but utilize dramatically different strategies in reproducing themselves. At one extreme, there is the case of seed-bearing plants that produce vast numbers of "minimal" genetic packets and disperse them randomly in the hope that some will end up in a site which will support their growth and maturation. At the other extreme is the behavior of humans in which protection and nurture of the offspring may continue until maturity. The local environment of the LMF will be a large factor in the selection of a dispersal strategy for offspring systems. For example, if the LMF is working in a large, rich environment, the "seed" dispersal strategy may be the best choice. If the LMF is situated in an environment that contains only small, scattered pockets of valuable resources, the "human" dispersal strategy may be employed, with the offspring receiving tutelage from the parent systems or from human operators and being more fully developed in their capacity to seek out and efficiently utilize the scarce resources available. In another scenario, if the LMF is located in a large but isolated valuable ore body, it may be best to imitate the reproduction strategy of a colonial organism such as choral, with a single machine factory consisting of many laboring sub-machines.

In order to optimize machine system growth, a number of issues must be addressed. We must determine how long a system should be allowed to grow before it reproduces and how many offspring it should produce. We must explore the broad range of offspring maturity upon dispersal and investigate the dispersal mechanisms to be used. It will also be necessary to decide how and where offspring systems are sited and the criteria for these choices. The time of reproduction and the method and duration of parental control over the offspring also needs to be investigated. Further, we must decide how the production and reproductive life-spans of the machine systems should be determined and what to do with outdated or damaged systems. For example, they could be dismantled and recycled. Most of these issues will be intensely dependant on the current conditions experienced by the LMF. We must ensure that the LMF can adequately deploy its offspring in the most efficient manner so that the explosive growing capacity of the self-replicating system can be fully exploited.

9.5 Machine Evolution

In this discussion, we have been concerned with the faithful reproduction of machines, so that the offspring may be identical to their parent. This is not a necessary constraint and may not even be a desirable one. Living organisms evolve because of random mutations in individual chromosome sets that cause the possessor of the genetic set to have some trait that increases the probability that the possessor will reproduce successfully. The offspring will also carry this genetic modification and, over time, the modification becomes common in the organism population. Biological evolution is an incredibly slow process because the improvements in the genome of a population are accidental and become more prolific because the carriers of the modification are better able to leave offspring than those who do not possess the modification. During the life of an organism, it may acquire knowledge and experience of the world and learn to think and behave in certain ways. It may also acquire distinct physical characteristics because of its lifestyle. None of these qualities or items will be passed onto the organism's offspring through its genetic code. This is because living organisms have no capacity to modify their own genetic code, nor is there any capacity for it to be modified to their advantage during their lifetime. The information contained in the human mind is completely separate from that contained in the human DNA. Machines, on the other hand, do not face this limitation. A machine that learns how to mine lunar regolith during its lifetime, can pass that information onto its offspring because the functional and genetic memory of a machine can be one and the same. Thus, acquired traits, knowledge and experience can be transmitted to the offspring. The machine can make a copy of itself in its current condition, with its current memory and current physical characteristics. Further, it can even actively design improvements into its offspring, autonomously or with human direction. As such, the production stream of a general purpose LMF can be constantly modified to reflect current human needs. With short generation times and directed (as opposed to randomly generated) evolution, self-replicating factories could reach incredible levels of optimization and efficiency. They would be ever-improving, ever growing, tireless engines of mass production. We must further research how this evolution can be controlled and directed, and how much, if any, of it should be under human control.

9.6 Engineering Feasibility of Machine Self-Replication

Now that we have seen that machine self-replication is theoretically feasible, we must determine if the self replication of these robots is practically feasible from an engineering standpoint. That is, we must decide whether it is possible to produce real robots that are capable of self replication. A four phase test can be performed on earth to verify if this is viable. In this test the first phase would be the construction of one robot by another robot using supplied parts. This newly constructed robot would then have to perform the same task to verify that it is a proper duplicate of the original. In the second phase the robot will construct various assemblies out of provided parts that are unrelated to the replication process, yet verify the production process. For the third phase the robot must be able to perform the tasks of the first two phases with the difference that it is now only provided with raw materials that must be fabricated and machined into parts. The last phase will require the robot to perform all tasks from the previous three phases, but now it is only provided with minerals, ores and soils. When all of these phases have been completed the system will be ready for autonomous replication and the proper background data will be collected for the creation of an actual SRS.

In order to better understand the problem, a few system behaviors are presented to show the system's basic structure. These behaviors, depicted in Figure 9 - 4[27], include production, replication, growth, evolution and finally repair. All of these behaviors will have to be included within the system so that it may be sustainable while performing all of its desired functions.

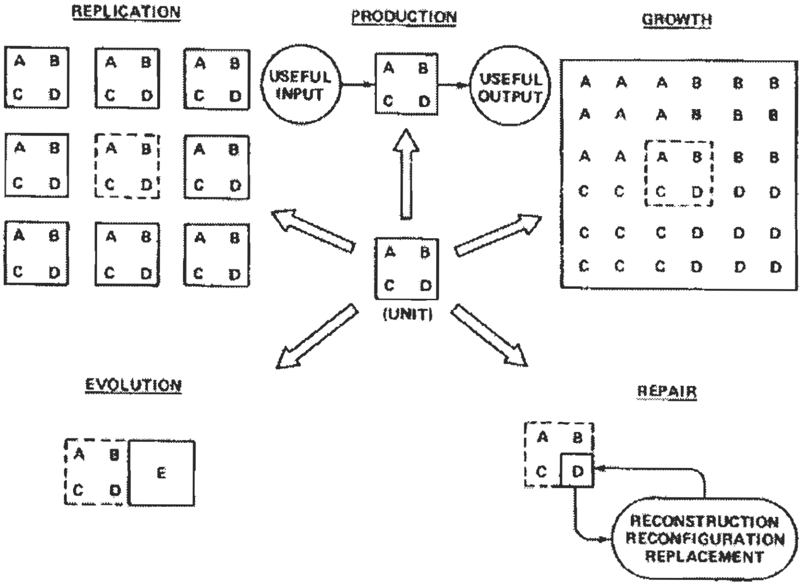


Figure 9 - 4: Classes of SRS Behavior

The main purpose of this SRS is not actually to replicate but to efficiently create structures and equipment in harsh environments such as the moon and other planets. Two designs have been proposed, the first with the capability of unit self-replication and the second with the capability of unit growth.

9.6.1 Design 1 – Unit Self-Replication

The first design, shown in Figure 9 - 5[27] and Figure 9 - 6[27], contains four subsystems that will allow the system to self-replicate.

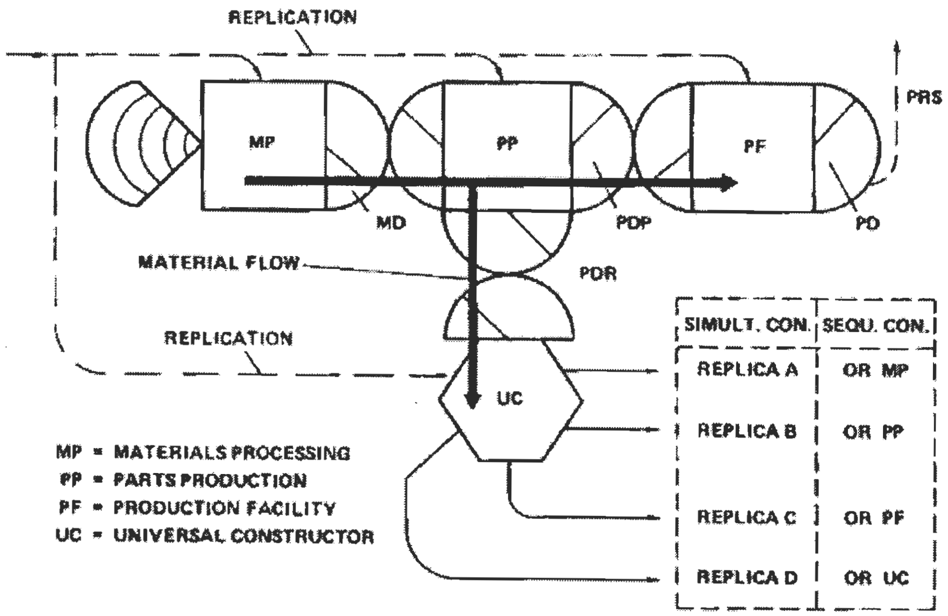


Figure 9 - 5: SRS Subsystems

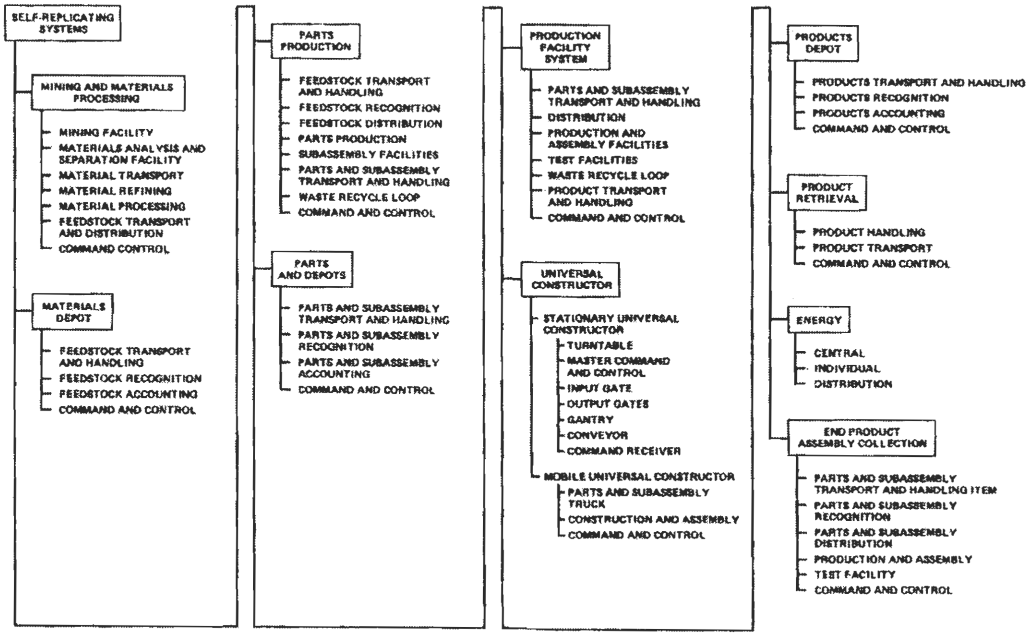


Figure 9 - 6: Detailed Breakdown of Subsystems

The key component in ensuring self-replication of this system is the Universal Constructor, Figure 9 - 7[27], and its subcomponent, the Mobile Universal Constructor,

Figure 9 - 8[27]. In conjunction, these subsystems must perform all tasks related with the physical construction and programming of new components of the self-replicating system.

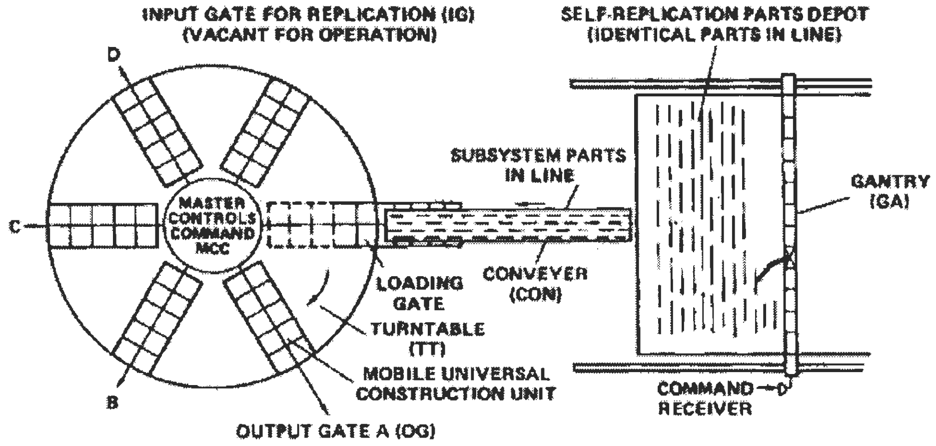


Figure 9 - 7: Universal Constructor

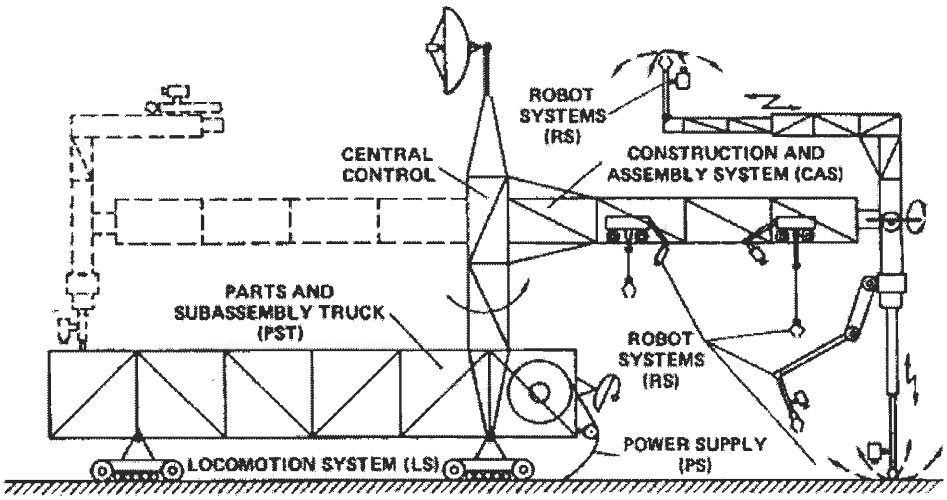


Figure 9 - 8: Mobile Universal Constructor

9.6.2 Design 2 – Unit Growth

The second design is of a growing lunar manufacturing facility (Figure 9 - 9[27]) that is divided into three main sectors. These include the chemical processing sector, the fabrication sector (the processes of which are shown in Figure 9 - 10[27]) and the assembly sector.

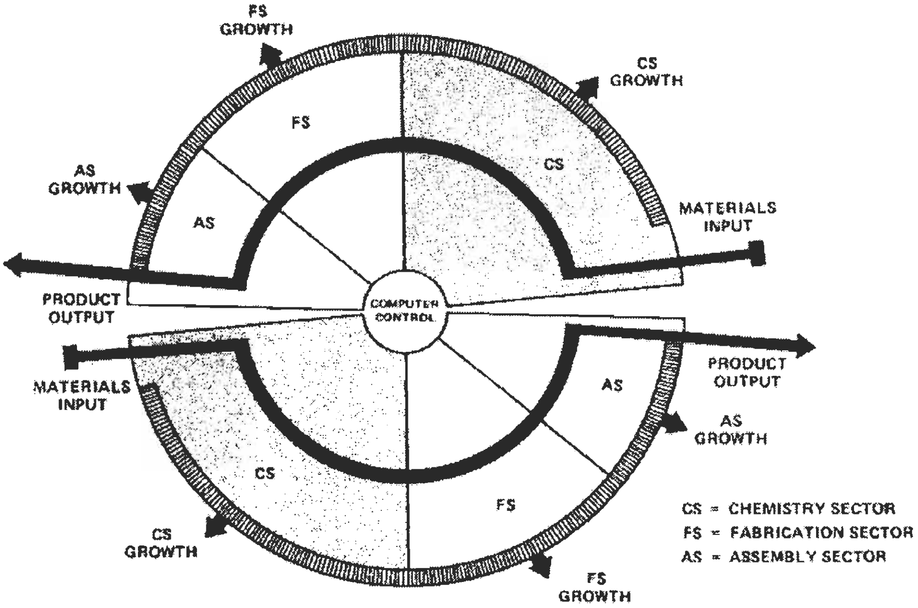


Figure 9 - 9: Lunar Manufacturing Facility

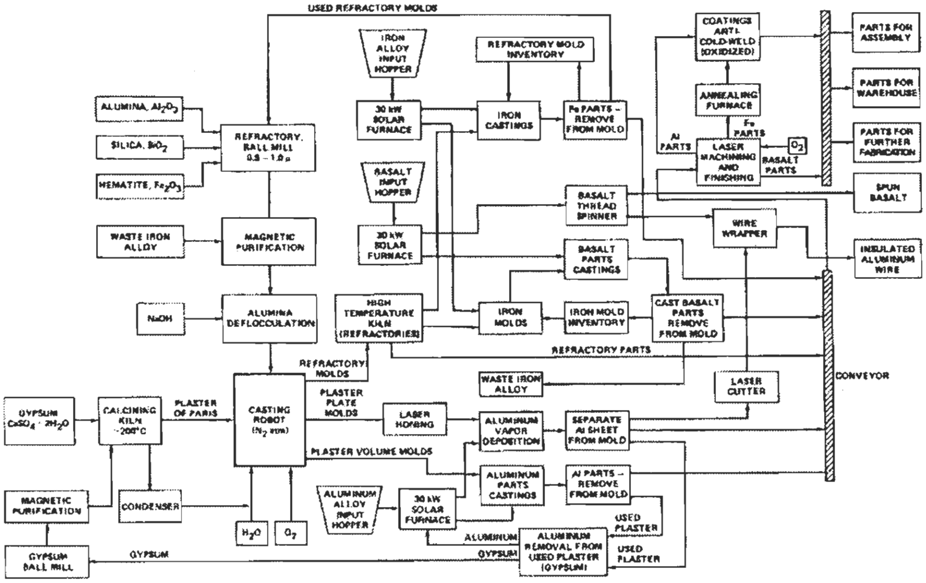


Figure 9 - 10: Fabrication Sector

9.7 Lunar SRS Growth and Productivity

Examining the two designs proposed above, we note the developing convergence between them. Both require three major subsystems - materials processing, fabrication, and assembly plus a variety of support systems, and each is capable of replication and useful production. Both display exponential expansion patterns.

In a finite environment, exponential growth cannot continue indefinitely. According to geometric arguments, the planar packing of units can only expand exponentially for as many generations as each unit has sides, assuming that once all sides are occupied no further doubling can occur by the surrounded unit. From that time on, growth is quadratic. In real physical systems, however, enclosure need not prevent material communication with the exterior units. Through the use of specialized communication, control and materials transportation channels or internal component rearrangement, we can prevent starvation in the inner regions of the system. Hence, we are not limited by the geometry of the system, and exponential growth may continue until limited by purposeful design or by the specific configuration of the external environment (limited source of ores, or physical barriers such as canyons)

Growth rates and productivities for a 100-ton seed that produces 100 tons/year of the same materials of which it is composed (accomplishing unit replication in one year) and performs only “doubling (each parent unit builds one offspring replica at a time, and each replica is built by only one parent unit)” self-replication without diversion to production, are shown in Table 9 - 1[27] under “Exponential Growth”.

If two or more units cooperate in the construction of a single replica, still more rapid "fast exponential" growth is possible. This is because new replicas or LMF subsystems become functional sooner and may begin contributing to the exponentiation earlier than before. Growth rates and productivities are also tabulated for "fast-exponential" expansion in Table 9 - 1[27], for a case where two units cooperate to build each replica. Note that in just 10 years the output of such a facility could grow to approximately one million tons per year. If allowed to expand for 18 years without diversion to production, the factory output could exponentiate to more than 4×10^9 tons per year, roughly the entire annual industrial output of all human civilization. About 3 billion seed units would completely cover the entire lunar surface.

Calendar years	Working years, T	Exponential growth, y = 1 yr		"Fast-exponential" growth, y = 1 yr	
		Number of units, N	System productivity, tons/yr	Number of units, N	System productivity, tons/yr
0	0	0	0	0	0
2	1	1	100	1	100
4	2	2	200	4	400
6	3	4	400	11	1,100
8	4	8	800	31	3,100
10	5	16	1,600	83	8,300
12	6	32	3,200	227	22,700
14	7	64	6,400	616	61,600
16	8	128	12,800	1,674	167,400
18	9	256	25,600	4,550	455,000
20	10	512	51,200	12,367	1,236,700
22	11	1,024	102,400	33,617	3,361,700
24	12	2,048	204,800	91,380	9,138,000
26	13	4,096	409,600	248,398	24,839,800
28	14	8,192	819,200	675,215	67,521,500
30	15	16,384	1,638,400	1,835,426	183,542,600
32	16	32,768	3,276,800	4,989,205	498,920,500
34	17	65,536	6,553,600	13,562,066	1,356,206,600
36	18	131,072	13,107,200	36,865,517	3,686,551,700
38	19	262,144	26,214,400	100,210,865	10,021,086,500
40	20	524,288	52,428,800	272,401,372	27,240,137,200

Table 9 - 1: Growth Rates and Productivity for Exponential SRS Expansion

A 100-ton seed which has undergone thousand-fold growth or replication represents a 2 GW power generating capacity, plus a computer facility with a 16,000 Gbit processing capability and a total memory capacity of 272,000 Gbits. These should have many useful applications in both terrestrial and space industry.

9.8 Closure in Self-Replicating Systems

A fundamental problem in the design of self-replicating systems is the issue of closure. This issue reduces to the question, “Does factory output exceed factory components or input needs?” If the answer is yes, the system cannot independently fully replicate itself.

Three basic requirements must be satisfied to achieve closure. These are matter, energy and information closure. Matter closure means that the system must be able to construct all the parts of which it was made, energy closure means that the system must be able to harness sufficient energy to make these parts, and information closure means that the system must be autonomous and must not rely on any human teleoperated input, for instance. If a system achieves only partial closure, it will be only partially self-replicating. Some vital matter, energy, or information must be provided from the outside or the machine system will fail to reproduce. These items that must be externally supplied are sometimes called "vitamin parts", drawing an analogy to the vitamins that human beings take in the pill form to compensate for their inability to assimilate these vital materials through their regular diet. The fraction of total necessary resources that must be supplied by some external agency has been dubbed the "Tukey Ratio", the most logical form of which is computed by dividing the mass of the external supplies per unit time interval by the total mass of all inputs necessary to achieve self-replication. In a fully self-replicating system with no external inputs, the Tukey Ratio thus would be zero (0%).

It is important to distinguish between “closure” and a closed system in the thermodynamic sense. If a system is truly isolated in the thermodynamic sense and is allowed no exchange of information with its environment then it cannot self-replicate without violating the laws of thermodynamics. Our system is not closed in this manner, as materials, energy, and information still flow into the system. The reason that the system can achieve “closure” is that these flows can be of indigenous origin and may be managed autonomously by the SRS itself without need for human intervention.

9.9 Closure Theory

To address the problem of closure in real engineering systems, we will begin with the issue of parts closure by asking if a set of machines can produce all of its elements. If the manufacture of each part requires, on average, the use of more than one part to produce it, then an infinite number of parts are required in the initial system and complete closure cannot be achieved. On the other hand, if the mean number of parts required to produce each part is less than one, then the design sequence converges to some finite ensemble of elements and bounded replication becomes possible. In our generalized terrestrial industrial economy manned by humans (altogether nothing more than a large physical system) "the set of machines which make all other machines is a subset of the set of all machines" and thus, parts closure is achieved.

We can tackle the issue of parts closure by using the following logic:

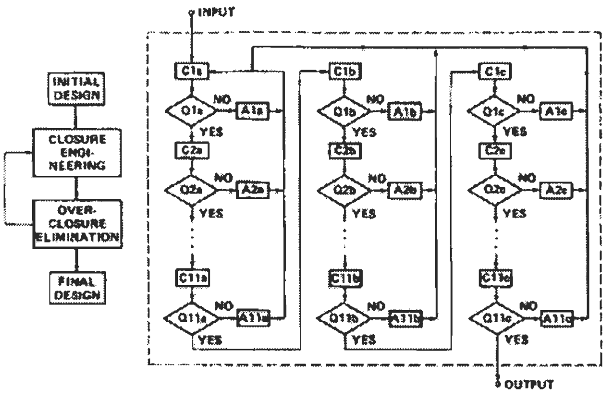
1. If all existing machines were disassembled into their individual parts there would be a finite number of parts, many of them identical, and a large number would be of common categories, such as shafts, cams, wiring, links, etc. The only differences between the machines would be a different selection, arrangement, and dimension set of this finite number of parts.
2. A finite number of parts can be manufactured using a finite number of machine operations, this number being less than the number of parts because some machines can make more than one kind of parts.
3. Therefore, the number of machines is finite and less than the number of operations.

Therefore, parts closure is realizable in a real engineering sense. Still, it would be advantageous to limit the types of parts in the system to a small number of standard elements, so that all of them can be manufactured using only a few machine operations. Further, machine operations should be limited as much as practical by substitution, in order to minimize the number of parts and machine operations. Similar arguments may be applied to materials processing and feedstock production, with standard elements such as rods, ingots, sheets, etc. being the common denominator between processing operations.

9.10 Closure engineering

In actual practice, the achievement of full closure will be a highly complex, iterative design process. Every factory system, subsystem, component structure, and input requirement must be carefully matched against known factory output capabilities. Any gaps in the manufacturing flow must be filled by the introduction of additional machines, the construction and operation of which may, in turn, create new gaps, requiring the introduction of still more machines.

Presented below is a simple iterative procedure for generating designs for engineering systems that display complete closure. The procedure must be cumulatively iterated, first to achieve closure starting from some initial design, then again to eliminate over-closure to obtain an optimally efficient design. Each cycle is broken down into a succession of sub-iterations that ensure that all parts can be made in sufficient quantities and at sufficient rates. In addition, each sub-iteration sequence is further decomposed into design cycles for each factory subsystem or component, as shown in Figure 9 - 11[27].



EXPLANATION OF SYMBOLS

PROCEDURAL QUERIES = Q

Q1a – CAN SYSTEM ASSEMBLE ALL MACHINES OF WHICH IT IS COMPRISED?
Q2a – CAN SYSTEM ASSEMBLE ALL SUBASSEMBLIES OF WHICH ITS MACHINES ARE COMPRISED?
Q3a – CAN SYSTEM MACHINE ALL PARTS OF WHICH ITS MACHINES ARE COMPRISED?
Q4a – CAN SYSTEM EXTRACT ALL MATERIALS OF WHICH ITS PARTS ARE COMPRISED?
Q5a – CAN SYSTEM MINE ALL MINERALS OF WHICH ITS MATERIALS ARE COMPRISED?
Q6a – CAN SYSTEM TRANSPORT ALL (MACHINES/SUBASSEMBLIES/PARTS/MATERIALS/MINERALS) OF WHICH IT IS COMPRISED?
Q7a – CAN SYSTEM VERIFY ALL (MACHINES/SUBASSEMBLIES/PARTS/MATERIALS/MINERALS) OF WHICH IT IS COMPRISED?
Q8a – CAN SYSTEM WAREHOUSE ALL (MACHINES/SUBASSEMBLIES/PARTS/MATERIALS/MINERALS) OF WHICH IT IS COMPRISED?
Q9a – CAN SYSTEM REPAIR ALL SUBSYSTEMS OF WHICH IT IS COMPRISED?
Q10a – CAN SYSTEM COMPUTERS CONTROL ALL SUBSYSTEMS OF WHICH IT IS COMPRISED?
Q11a – CAN SYSTEM ENERGY PLANT ENERGIZE ALL SUBSYSTEMS OF WHICH IT (THE SYSTEM) IS COMPRISED?

Q1b – CAN SYSTEM ASSEMBLE ENOUGH MACHINES TO REPLICATE THE ORIGINAL SYSTEM?
Q2b – CAN SYSTEM ASSEMBLE ENOUGH SUBASSEMBLIES TO REPLICATE THE ORIGINAL SYSTEM?
⋮
Q11b – CAN SYSTEM ENERGY PLANT PRODUCE ENOUGH ENERGY TO PERMIT REPLICATION OF THE ORIGINAL SYSTEM?

Q1c – CAN SYSTEM ASSEMBLE MACHINES FAST ENOUGH TO REPLICATE THE ORIGINAL SYSTEM WITHIN ESTABLISHED TIME CONSTRAINTS?
⋮
Q11c – CAN SYSTEM ENERGY PLANT PRODUCE ENOUGH ENERGY FAST ENOUGH (HIGH ENOUGH *POWER*) TO REPLICATE THE ORIGINAL SYSTEM WITHIN ESTABLISHED TIME CONSTRAINTS?

SYSTEM COMPONENTS LISTS = C

C1a, b, c – MACHINES
C2a, b, c – SUBASSEMBLIES
C3a, b, c – PARTS
C4a, b, c – MATERIALS
C5a, b, c – MINERALS (SUBSTRATE)
C6a, b, c – TRANSPORTATION FACILITIES
C7a, b, c – VERIFICATION FACILITIES
C8a, b, c – STORAGE FACILITIES
C9a, b, c – REPAIR FACILITIES
C10a, b, c – COMPUTER FACILITIES
C11a, b, c – ENERGY FACILITIES

SYSTEM COMPONENTS ACTION LIST = A

A1a, b, c – NEW MACHINES
A2a, b, c – NEW SUBASSEMBLY-MAKING MACHINES
⋮
A11a, b, c – NEW ENERGY FACILITY-MAKING MACHINES
A≠a – Add new machines to make . . .
A≠b – Add new machines to make . . .
A≠c – Increase replication time available or change machine design for . . .

Figure 9 - 11: Generalized Closure Engineering Design Cycles

9.11 Quantitative Materials Closure - Numerical Results.

In the context of materials processing, "closure" is a relationship between a given machine design and a given particular substrate from which the machine's elemental chemical constituents are to be drawn. Hence the numerical demonstration of closure requires a knowledge of the precise composition both of the intended base substrate to be utilized and of the products which the SRS must manufacture from that substrate.

A modified "extraction ratio" R_n is defined as the mass of raw substrate material which must be processed to obtain a unit mass of useful system output having the desired mass fraction of element “n”. Assume that the final product is to be composed of the elements x and y. An $R_x = 1$ means that 1 kg of lunar soil contains exactly the mass of element x needed to manufacture 1 kg of the desired product. $R_y = 10$ means that 10 kg of lunar regolith must be processed to extract all of element y required in 1 kg of final product. The difference between R_x and R_y may mean that y is more rare in lunar soil than x, or that the two elements are equally abundant but ten times more y than x is required, by mass, in the final product. When the output stream is identical to the machine processing system itself, then the system is self-replicating and the extraction ratio becomes an index of system materials closure on an element-by-element basis.

The net extraction ratio R is some function of the individual extraction ratios R_n, and depends on the number of elements that can be obtained from a given mass of input stream. At worst, if only one element is recovered ("parallel processing"), then R is the sum of all R_n ("parallel processing"). At best, if all elements are sequentially extracted in the necessary amounts, then R is driven solely by the R_n of the element most difficult to extract ("serial processing"). This R_n is always equal to or smaller than the sum of all R_n. Serial processing should dominate in the lunar factory and the latter formula is assumed for purposes of the present calculations. Though R_n can be less than 1 for individual elements, it must be greater than or equal to one for the entire system.

To estimate the quantitative materials closure for the two lunar SRS designs proposed above, three different approaches were taken in an attempt to converge on a useful estimate of the composition of the output stream necessary for Lunar Manufacturing Facility self-replication. First, the distribution given by the published data on the material consumption of the United States (the world's largest factory) during the years 1972-1976 was adopted. A second but less comprehensive measure called "demandite" was based on 1968 U.S. consumption data. A molecule of "non-fuel demandite" is the average nonrenewable resource used by humans, less fuel resources. Third, a direct estimate of the most simple LMF elemental composition was used to obtain additional trial values. In all cases the input stream was assumed to consist of Lunar Maria regolith, with concentration values averaged from published data listed in Table 9 - 2[27]. Following earlier work, for simplicity all extraction efficiencies were taken to be 0.93.

Element	Abundance	Element	Abundance	Element	Abundance	Element	Abundance
Al	6.80%	Bi	3.19 ppb	Ho	3.73 ppm	Ru	0.231 ppm
Ca	7.88%	Br	0.178 ppm	I	2.00 ppb	Sb	22.1 ppb
Cr	0.264%	C	104 ppm	In	32.9 ppb	Sc	48.8 ppm
Fe	13.2%	Cd	0.197 ppm	Ir	6.32 ppb	Se	0.306 ppm
K	0.113%	Ce	48.8 ppm	La	17.2 ppm	Sm	10.9 ppm
Mg	5.76%	Cl	25.6 ppm	Li	12.9 ppm	Sn	0.900 ppm
Mn	0.174%	Co	40.3 ppm	Lu	1.22 ppm	Sr	167 ppm
Na	0.290%	Cs	0.392 ppm	Mo	0.520 ppm	Ta	1.26 ppm
O	41.3%	Cu	14.4 ppm	N	95.4 ppm	Tb	2.58 ppm
P	0.066%	Dy	15.3 ppm	Nb	19.6 ppm	Te	0.0545 ppm
S	0.125%	Er	19.24 ppm	Nd	38.2 ppm	Th	2.50 ppm
Si	20.4%	Eu	1.77 ppm	Ne	2.75 ppm	Tl	1.61 ppb
Ti	3.10%	F	174 ppm	Ni	169 ppm	Tm	1.42 ppm
Ag	45.2 ppb	Ga	4.99 ppm	Os	12.9 ppb	U	0.805 ppm
Ar	0.800 ppm	Gd	14.3 ppm	Pb	3.11 ppm	V	114 ppm
As	0.206 ppm	Ge	0.626 ppm	Pd	12.3 ppb	W	0.358 ppm
Au	2.66 ppb	H	54.8 ppm	Pr	7.20 ppm	Y	84.2 ppm
B	4.78 ppm	He	28.5 ppm	Rb	3.21 ppm	Yb	8.40 ppm
Ba	195 ppm	Hf	7.77 ppm	Re	1.36 ppb	Zn	23.4 ppm
Be	2.63 ppm	Hg	0.019 ppm	Rh	0.192 ppm	Zr	311 ppm

Table 9 - 2: Average Chemical Element Abundances in Lunar Maria

The closures calculated from these data are plotted against extraction ratio in Figure 9 - 12. Note that complete (100%) closure is achieved for the "U.S. Industrial" estimate (84 elements) at R = 2984, for "Demandite" (28 elements) at R = 1631, and for the LMF Estimate (18 elements) at R = 45. This suggests that if fewer, more commonly available and efficiently extractable elements are sufficient for factory self-replication, then the factory will have to mine a smaller quantity of raw material in order to self-replicate. Note also that in all three cases, nearly complete (>90%) closure is achieved for extraction ratios of 2 to 14. The small gains in closure after 90% are achieved at a great price: from 1 to 3 orders of magnitude more raw materials, by mass, must be processed to achieve the last bit of complete materials closure.

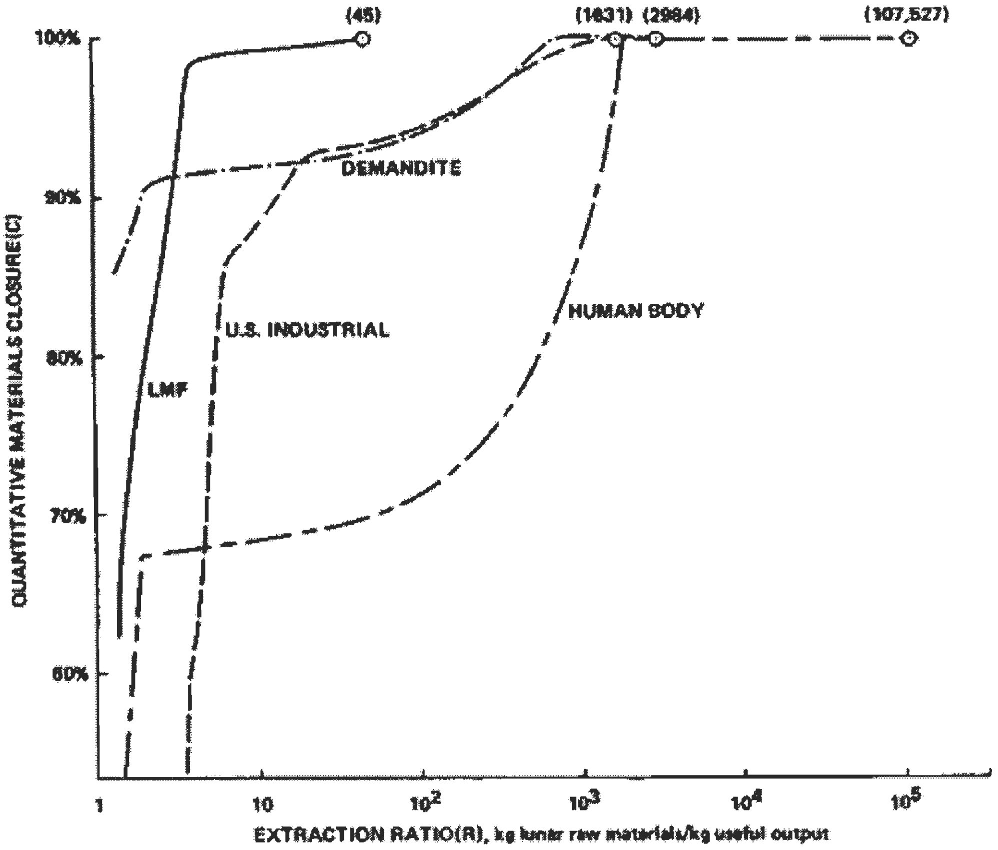


Figure 9 - 12: Quantitative Materials Closure Data for Various Self-Replicating Systems

Two conclusions may be drawn from these observations. Firstly, for any given SRS design it may well be more economical to settle for 90-95% system closure and import the remaining 5-10% as "vitamins" from Earth. Secondly, in those applications where complete closure (full materials autonomy) is needed, great care must be taken to engineer the self-replicating system to match the expected input substrate as closely as possible. This requires, in the case of quantitative materials closure, a design which minimizes the value of R by using only abundantly available, easily extractable elements.

9.12 Lunar Solar Power Using Self-Replicating Systems

This section is based upon the testimony of Dr. David R. Criswell, Director of the Institute for Space Systems Operations, University of Houston[2, 28].

By 2050, approximately 10 billion people will live on Earth and demand 5 times the power now available. It is highly unlikely that terrestrial options such as conventional fossil, nuclear, and terrestrial renewable power systems will be able provide the needed minimum of 2 kWe/person, or at least 20 terawatts globally. These systems are restricted by limited supplies of fuels, pollution and wastes, irregular supplies of renewable energy, and costs of creating and operating the global systems. It is technically and economically feasible to provide at least 100 TWe of solar electric energy from facilities on the Moon. A Lunar Solar Power (LSP) System can supply the Earth with power that is independent of the biosphere and does not introduce CO_2, ash, or other material wastes into the biosphere[2].

We may construct lunar solar power bases that collect a small fraction of the Moon's dependable solar power and convert it into microwave power beams that will deliver power to receivers on Earth. On Earth, each power beam will be transformed into electricity and distributed through local electric power grids. Each terrestrial receiver will be able to accept power directly from the Moon or indirectly, via relay satellites, when the receiver cannot view the Moon. The intensity of each power beam will be restricted to 20%, or less, of the intensity of noontime sunlight. Each power beam can be safely received, for example, in an industrially zoned area[28].

The LSP system does not require any new technological developments. Adequate knowledge of the Moon and the essential technologies to design, build, and operate an LSP system have been available since the late 1970s. Self-replicating systems could be sent to the Moon to build the lunar power bases, since the construction of vast arrays of solar cells on the moon represents the organization of a vast quantity of matter at a remote location. The machines would build the power components from the common lunar dust and rocks, thereby avoiding the high cost of transporting materials from the Earth to the Moon. The LSP system will be distributed and open and can readily accommodate new manufacturing and operating technologies as they become available. LSP is practical with a low overall efficiency of conversion of sunlight to Earth power of 0.15%. Higher system efficiencies (35%) will be possible by 2020 so that an LSP system will occupy only 0.15% of the lunar surface and supply 20 TWe to Earth[2].

An LSP system can grow quickly to 50% of averaged U.S. electric consumption, 0.2 TWe, within 15 years and be profitable thereafter. When LSP provides 20 terawatts of electric power to Earth, we can sell the electricity at one-fifth of today's cost, or 1 ¢/kWe-h. This would mean LSP could generate 1.8 trillion dollars per year of net income. As a result, gross world product may increase by a factor of 10 and the average annual per capita income of developing nations may increase from today's \$2,500 to \$20,000[2].

The LSP System is an unconventional approach to supplying commercial power to Earth. However, the key operational technologies of the LSP have been demonstrated at a high technology readiness level. Power beams, for example, are considered esoteric and a technology of the distant future. However, Earth-to-Moon microwave power beams of near-commercial intensity are an operational reality. The intensity of microwaves scattered from the beam will be orders of magnitude less than that allowed for continuous exposure of the general population[2, 28].

Any handful of lunar dust and rocks contains at least 20% silicon, 40% oxygen, and 10% metals (iron, aluminum, etc.) by mass. Lunar dust can be used directly as thermal, electrical, and radiation shielding, converted into glass, fiberglass, and ceramics, and processed chemically into its elements. Solar cells, electric wiring, some micro-circuitry components, and the reflector screens can be made out of free lunar materials. Solar cells can be manufactured in the near perfect vacuum of the moon by spray deposition onto beds of concrete. On earth, a vacuum chamber would have to create these conditions artificially[2].

Unlike Earth, the Moon is the ideal environment for large-area solar converters. The solar flux to the lunar surface is predicable and dependable and is five times the solar flux on the surface of the earth due to a lack of any attenuating atmosphere. There is no air or water to degrade large-area thin film devices. It is devoid of weather and biological processes that degrade terrestrial equipment. Solar collectors can be made that are unaffected by decades of exposure to solar cosmic rays and the solar wind. Sensitive circuitry and wiring can be buried under a few centimeters of lunar soil and completely protected against solar radiation, temperature extremes, and micrometeorites[2]. Figure 9 -

13[2] shows an artist's interpretation of a lunar solar farm, complete with mobile factories for manufacturing solar cells.

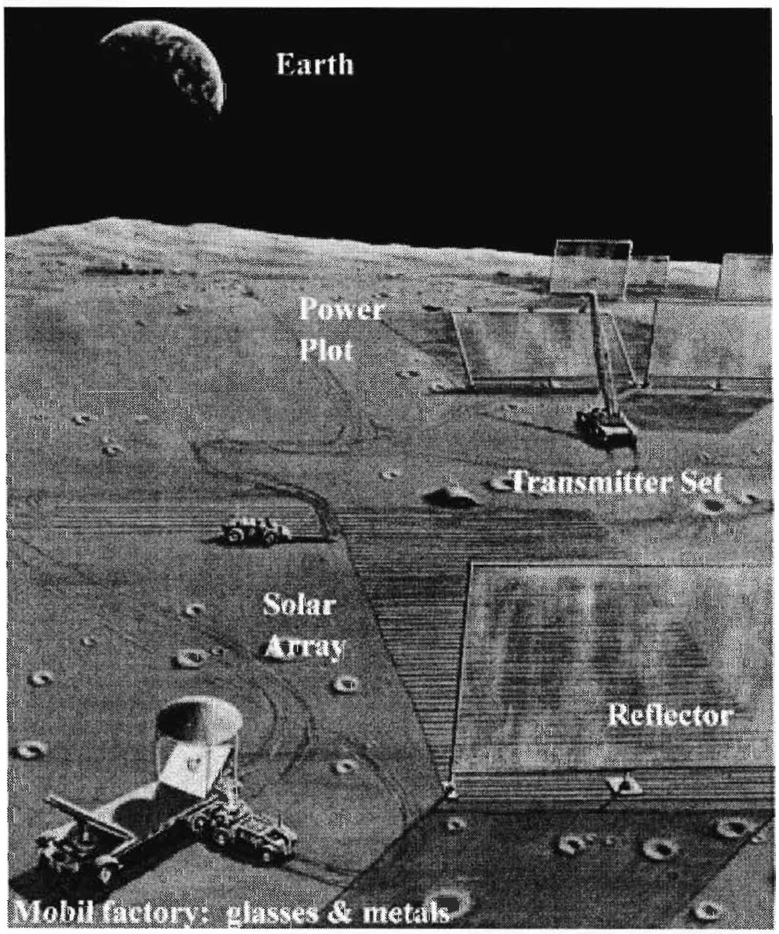


Figure 9 - 13: Artist's Representation of a Lunar Solar Farm

9.13 Self-Replicating Systems in Nanotechnology

After conducting research in self-replicating systems, it became obvious that most of the world is entirely unaware of such a notion. Since most of our research was based upon a study conducted twenty-six years ago, we felt the need to investigate the present state and popularity of this idea. The only sphere of technology in which self-replicating systems has experienced a rebirth of sorts is in nanotechnology. Proponents of this relatively new and powerful field claim that nanotechnology has the potential to make the cost of all terrestrial products comparable to that of plant matter or meat, per unit weight. Current large-scale manufacturing techniques are all top-down, requiring the use of several machines and processes in the production of parts. These techniques are horribly inefficient compared to the delicate, highly specialized biological process of assembly that occurs in all living cells.

Nanotechnology proposes to manufacture parts using a bottom-up methodology that roughly mirrors the biological paradigm of molecular assemblers, such as ribosomes in animal cells, immersed in a sea of amino acids, merely stringing them together according to the interaction of their structure and energy with that of the amino acid molecules and the coding material that they are "reading" (RNA). These artificial assemblers would each be composed of only tens of molecules, engineered so that they possess active sites at which some useful work can be done. The use of these highly specialized nano-assemblers might mean, for example, that we could grow computer chips out of a bath of silicon, and that one kilogram of these chips would compare in cost to one kilogram of beef. It is interesting to note that the molecular organization of beef is more complex than that of our most advanced computer chips. It is proposed that molecular assembler self-replication can be accomplished in a shared fashion[29].

The Lunar Manufacturing Facilities described in this section are examples of what have come to be known as "clanking replicators". This term has evolved to distinguish such macro systems from nanoscale assemblers that nanotechnology might make possible, and is meant to evoke the image of a nineteenth century factory, powered by steam, pushing gears and rods, noisy and clamorous[30].

These nano-building blocks can also be used to produce shape-shifting "smart" materials. Parts made of such materials, on the moon, could be used for a large number of different tasks by changing their shape, physical and electromagnetic properties. Such materials may make the problem of parts closure disappear. Also, imagine ways in which solar cells can be "grown" on the moon in tanks filled with silicon and aluminum solutions by a few strains of artificial microbes, with extremely low power consumption and no need for bulky conventional production machinery[31].

The applications of this intriguing new technology must be investigated so that we may exploit its growing potential in future space missions. Though still in its infancy, nanotechnology promises to become the manufacturing method of the future. If we can implant the doctrines of self-replicating systems into the foundation of this new field, we may have a tremendous chance of making SRS an omnipresent feature of our civilization.

9.14 SRS Conclusions

After exploring the feasibility of using Self-Replicating Systems to develop lunar resources, we may make some preliminary conclusions. The first is that the concept of physical machine self-replication seems to be entirely credible from both a theoretical and practical standpoint[27]. Further, it is clear that we have had the technology to begin designing self-replicating systems for several decades now, and that it would be extremely advantageous to begin work on this promising technology without further delay.

Let us consider an example to illustrate the phenomenal difference in output between linear and exponentiating systems and to demonstrate the power of the self-replication technique in large-scale enterprises. Assume a sample task of manufacturing of 10^6 tons of solar cells on the Moon for use in a Lunar Solar Power system. A goal of 500 GW generating capacity - to be produced by entirely self-contained machinery, naturally occurring lunar materials, and sunlight for energy - is established. From an initial investment estimated at $1 billion, to place a 100-ton payload on the surface of the Moon, a non-replicating or "linear" system would require 6000 years to make the 10^6 tons of solar cells needed, whereas a self-replicating or "exponentiating" system needs less than 20 years to produce the same 10^6 tons of cells[27].

Replicating machine systems offer the enticing possibility in the near future that we could embark on incredibly ambitious projects in distant space exploration and extraterrestrial resource utilization without the need for excessive funding requests from either public or private sources. In practice, this approach might not require building totally autonomous self-replicating systems, but only a largely automated system of diverse components that could be incorporated into a production system able to grow exponentially to reach any desired goal. Such systems for large-scale space use would come as the end result of a long research and development process in advanced automation, robotics, and machine intelligence, with developments at each stage finding wide use both on Earth and in space in practically every sphere of technology[27].

10 Mission Description

We will assume that this mission will be carried out by an international consortium of governmental entities. Discussed here is the scope and purpose of a self-sustaining lunar base.

None of the probable functions (solar energy harvesting, He-3 mining, extraterrestrial industry and research of various kinds) of a lunar base require the presence of human beings, and can all be carried out by robots, instead, at much lower cost. Still, most existing plans for an initial moon base involve the presence of a small human crew. This is probably in large part due to the glory and publicity of establishing a human presence on the moon. It is our view that the presence of humans on the moon can only be of *scientific* advantage if we wish to study the effects of low-gravity on humans themselves or use the moon base as a demonstration of life support technologies that will be of use in future space exploration and colonization. The presence of humans on the moon can only be of *economic* advantage if they are there as tourists.

We know that we want to demonstrate some life-support capability for application to future space and planetary exploration and colonization. However, we are limited in the *types* of life-support systems that we can demonstrate on the moon. From among the various classes of LSSs described in Chapter 7, all but the planetary LSS can be demonstrated on the moon. The reason that we cannot terraform the moon is because it is too small to retain any atmosphere introduced to it. If and when humans do colonize space or other planets, the LSSs they could potentially use vary enormously in their scale. For example, the first colonists on Mars may live in a number of small modules and rely on an entirely synthetic, artificially regulated life-support system, or may arrive after Mars is “terraformed” by a previously sent fleet of robots and bacteria, in which case they would be relying on a self-regulating planetary life-support system. Without a mission plan for the colonization of space or other planets, it is difficult to demonstrate the readiness of life-support technology for those applications. Accordingly, we will plan to establish a moon base that has the capability to demonstrate a Large Contained LSS, and all lower classes of LSSs, other than the Open-Loop LSS, which has already been demonstrated in submarines, space-faring vehicles and the International Space Station.

The progressively larger classes of LSS can be demonstrated using a moon base of increasing maturity and productivity, as would naturally occur during the development of any such base. We would begin with short-term EC/LSSs when we first arrive on the moon, and progressively work toward a permanent Large Contained LSS with the increasing capability and productivity of the base. The EC/LSS demonstration will be short-term because it will be very expensive to continuously ship stored food to the moon. This phase will last as long as food supplies brought along with the first humans to arrive on the base, last. Humans will then not make an appearance on the moon base until a Small contained LSS has been constructed for them. This LSS phase will be longer than the EC/LSS phase because though it will consume enormous amount of energy per occupant, this power can be supplied locally and will be free. Still, this power could be beamed back to earth or used to power robots to mine He-3 and thus, does represent a significant opportunity cost. Finally, a permanent Large-Contained LSS capable of accommodating up to 800,000 occupants will be constructed. Once this LSS has been sufficiently tested, it can be opened for tourism. Indeed, it would be impractical and expensive to recruit 800,000 astronauts to populate the Large Contained LSS when members of the general public would jump at the opportunity for a space vacation.

Another of the primary functions of the moon base will be to demonstrate SRS technologies. The entire mission will be one long experiment in the efficiencies, regulation, control, dynamic behavior, replication, production, growth, communications, and mass and energy flow-rates of a large-scale SRS system. Indeed, the construction of a Large-Contained LSS would hardly be possible without it. The SRS would make possible a powerful moon economy, generating solar energy and beaming it to earth, mining He-3 and selling it for 3-billion dollars a metric ton on earth, maintaining a hotel, acting as a general-purpose Lunar Manufacturing Facility and renting out space launch platforms for missions into space.

In this self-sustaining moon base mission, getting people onto the moon is not an end in itself. Rather, the primary goal is to demonstrate technology with has the capacity to permanently support large numbers of people on other planets or in space colonies. The entire mission hinges on the development of SRS technology. The mission also takes into account the advances in space transportation technology that are expected to evolve within the next few decades and stays abreast with these technologies, expecting to utilize them to their maximum potential as they are concurrently developed. For example, by the time the Large-Contained LSS is ready for tourist occupancy, space elevators and MXER tethers may become available, allowing for inexpensive transportation to the moon and back.

Therefore, the moon-base will have the following purposes, with the byproduct that it will accommodate tourism:

1. To spur the development of technologies that will be required for future space exploration and colonization
2. To harvest solar energy and beam it to earth
3. To mine He-3 for use on earth
4. To create and run a general-purpose Lunar Manufacturing Facility to outsource production from earth
5. To conduct research in astronomy, geology and space physics
6. To demonstrate SRS technology
7. To demonstrate Large Contained LSS and all lesser LSSs, other than Open-Loop LSS
8. To serve as a launching platform for other space missions
9. To generate immense profit

In this section, we describe our proposal for establishing a self-sustaining lunar base, incorporating selected ideas from the literature review and presenting them as part of a comprehensive plan. The description is divided into six chronological development phases, namely 1) Research and Development, 2) Earth-Based Testing and

Demonstration, 3) Deployment, Mining, Production and System Self-Replication, 4) Initial Base (EC/LSS), 5) Intermediate Base (Long-Term Small Contained LSS) and 6) Mature Base (Permanent Large Contained LSS)

The Research and Development and Earth-Based Testing and Demonstration Phases (Phases 1 and 2) continue throughout the life of the mission. In later stages of the mission, Phase 2 will be modified to Lunar-Based Testing and Demonstration.

10.1 Phase 1 – Research and Development

Energy – solar cell efficiency, microwave beams, reduction in the need for rare elements or compounds in solar cells, fabrication in low-g environment

Transportation – space elevator, carbon nanotubes, tall tower construction, magnetic propulsion, control of tall towers and long cables, development of reusable flying vehicles, intermediate stations, economics

Site selection – mapping, topography, sunlight availability, volcanic activity, distance from natural resources, communication lines of sight, trajectories for receiving and launching payloads, scientific areas of interest (experimentation, astronomy, observatories). Extensive use of lunar orbital probes and landers.

Mining – natural resource distribution, composition, texture, depth, size of particles, and dynamics of flowing soil, extraction, separation, refinement, purification of ores by chemical, electrochemical, mechanical and magnetic means, gases, minerals, extraction efficiencies and rates, development of simulant materials, design of machinery and processes, energy and material flow

Construction – design structures for various levels of base maturity, investigate potential for growth, gas leakage, multi-purpose structures, materials, construction times, safety factors, meteorite impacts, research radiation shielding and effects of solar and galactic cosmic rays on human occupants

LSS – determine size, plants, animals, requirements, level of active control, matter and energy cycling, waste, toxins, buffers, emergency measures, agriculture

SRS – programming structures, command hierarchies, artificial intelligence, navigation, image recognition, multi-purpose design, materials closure, replication information transmission, protocol for inheritance of traits and knowledge, directed evolution, method of replication, time of replication for maximum productivity, dispersal methods, level of autonomy, repairs and maintenance, materials and energy flows, buffers, production rates, projected timescale.

Human Role and Involvement – investigate effect of sending humans to developing base at different times and determine the resulting variation in productivity and time scale to mature base. Determine needs and activities.

10.2 Phase 2 – Earth-Based Testing and Demonstration

Sequence of Tests:

1. Process lunar regolith simulant into materials desired for the manufacture of parts and solar cells
2. Produce solar cells and all parts in the system inventory from pre-processed lunar regolith stimulant materials
3. Assembly of complex structures and machinery from pre-fabricated parts
4. Short-term accelerated run of SRS replication, production, growth and dispersal
5. Test quality of solar cells produced: efficiency, durability
6. Modify and verify theoretical extraction rates, energy and mass flow rates, production quotas
7. Produce updated experimentally supported production, growth, power and economic timeline.
8. Test properties of concrete structures made from regolith simulant – pressurizing structure interiors to 1 atmosphere above external pressure, impact testing for simulating micrometeorite impacts, testing against ground vibrations modeling moonquakes of magnitude 2 on the Richter scale.
9. Test radiation and micrometeorite shielding measures
10. Test rocket transportation logistics

10.3 Phase 3 – Deployment, Mining, Production and System Self-Replication

Overview:

This phase involves the deployment of the initial seed factory on the moon, and all subsequent activities until power production and construction reaches a level capable of sustaining a ten person EC/LSS. When deployed, robots work using power harnessed from the small deployable solar array on the landing vehicle. At this stage, power is their limiting factor. They first work towards creating an appreciable solar cell network on the lunar surface, and then begin production of parts for concurrent factory growth, with the amount of new solar cells being produced matching the power requirement of the new robots produced. At some pre-determined level of power production and parts production capability, the factory will begin producing parts for self-replication and will self-replicate according to some pre-determined dispersal strategies. The parent and offspring factories will continue to grow and self-replicate until some pre-determined level of power production and parts production capability is reached, at which time they will concurrently begin constructing structures, machines and electronic feedback systems to satisfy the requirements of a ten person EC/LSS. Phase 3 will end when this EC/LSS is complete, tested and ready for human occupancy.

Sequence of Operations:

1. deploy initial seed factory on moon
2. unfold pre-fabricated solar arrays from landing vehicle
3. begin mining raw lunar materials (robots begin work)
4. begin extracting, separating, refining and processing ores necessary to current phase
5. begin manufacture of solar cells
6. begin manufacture of parts for system growth
7. begin system growth
8. begin manufacture of parts for system self-replication

9. system self-replication
10. begin production of parts/ construction elements for EC/LSS
11. Increase power production to meet needs of EC/LSS
12. Complete construction of EC/LSS
13. Test LSS capabilities of EC/LSS

Current Means of Transportation:	Chemical Rocket
LSS Being Demonstrated:	None
Goal/Final Condition:	Power production and construction meets needs of ten person EC/LSS

10.4 Phase 4 – Initial Base (EC/LSS)

Overview:

To initiate this stage ten people will arrive to populate the EC/LSS for a short period of time. The SRS will continue operating with considerations being made for the ratio of replicating robots to working robots. Continued expansion of the SRS and all other previously implemented systems will be necessary for physical and economical growth. Solar energy will start being beamed to earth via the use of microwave beams and the mining of He-3 will also begin. By the end of this phase a steadily increasing source of income will be established from the solar energy beamed to earth. Complete construction and testing of a Small contained LSS must occur for the completion of this phase. This involves determining the number and types of structures required, creating fabrication plants and factories, determining new energy output requirements, and creating biological systems to implement in the Small Contained LSS.

Sequence of Operations:

1. Ten people arrive to populate EC/LSS for a short period of time (until initial shipment of food lasts)
2. Continue refining all mining and SRS processes
3. Expand SRS network
4. Begin construction of microwave emitters, relay stations and focusing systems on the moon
5. Begin Construction of receiving antennae on the earth
6. Begin mining He-3
7. Expand solar cell array to meet growing power needs
8. Begin beaming solar energy collected from lunar solar array to earth by way of microwaves
9. Begin construction of Small Contained LSS
10. Increase power production to meet needs of Small Contained LSS

11. Complete construction of Small Contained LSS
12. Install and initiate biological processes to produce food for future occupants of Small Contained LSS
13. Nurture crop cycles, nutrient, water, waste and energy cycles to maturity in Small Contained LSS using artificial consumers
14. Test biological, chemical and mechanical systems in Small Contained LSS for mechanized, chemically assisted waste decomposition, water reclamation, gas concentration equilibria in LSS atmosphere, agricultural processes such as irrigation, fertilizer production, soil aeration and crop illumination, and emergency systems. Determine cycle throughput times for various nutrients and energy.

Current Means of Transportation:	Rocket
LSS Being Demonstrated:	Ten person EC/LSS
Goal/Final Condition:	Readiness for human arrival into 150 person Small Contained LSS, working energy beaming and He-3 mining

10.5 Phase 5 – Intermediate Base (Long-Term Small Contained LSS)

Overview:

150 Humans arrive to populate the Small Contained LSS, which will have high energy needs per occupant. The activities of the occupants will be designed to acquire data for a Large Contained LSS. A general-purpose Lunar Manufacturing Facility will be constructed so that earth industries may be outsourced to the moon. Simultaneously, He-3 will begin to be shipped to earth, providing an additional source of income. All systems will continue to expand by growth and self-replication. This phase of the mission will end when a complete Large Contained LSS has been constructed and tested.

Sequence of Operations:

1. 150 people arrive to populate the Small Contained LSS until sufficient data has been compiled to design a Large Contained LSS
2. He-3 will begin to be shipped to earth
3. Construction of a general-purpose LMF will begin
4. Commencement of advertising on earth for general-purpose LMF purchase, rental and use by private companies
5. Begin construction of Large Contained LSS
6. System growth and self-replication to meet energy and parts production needs of LMF and Large Contained LSS
7. Complete Construction of general-purpose LMF
8. Complete construction of Large Contained LSS
9. Install and initiate biological processes to produce food for future occupants of Large Contained LSS
10. Nurture crop cycles, nutrient, water, waste and energy cycles to maturity in Large Contained LSS using artificial consumers
11. Test biological, chemical and mechanical systems in Large Contained LSS for mechanized, chemically assisted waste decomposition, water reclamation, gas

concentration equilibria in LSS atmosphere, agricultural processes such as irrigation, fertilizer production, soil aeration and crop illumination, and emergency systems. Determine cycle throughput times for various nutrients and energy.

Current Means of Transportation: Space plane to LEO space elevator to orbital station to rocket
LSS Being Demonstrated: Long-Term Small Contained LSS
Goal/Final Condition: Meet goals for Large Contained LSS and general-purpose LMF

10.6 Phase 6 – Mature Base

Overview:

In this phase, 800,000 people gradually arrive to populate the Large Contained LSS. A byproduct of the establishment of a Large Contained LSS on the moon will be the capability to accommodate tourists that will generate additional profit. The potential for tourism on the moon may provide further incentive for the development of cheap, reliable, reusable space transportation systems to ferry tourists to and from the moon. If a Large Contained LSS able to sustain 800,000 occupants were built, and a ticket to the moon cost 5,000 USD, we would be making money and providing tourists with an unparalleled vacation in a low-gravity hotel, with low-g diving and swimming, moon-buggy races, high-altitude slam dunk contests, exotic views, guided tours of the factories, mines and fields, robotic ensemble dances and plays, spaceship rentals for dog-fighting, etc. It would be an immensely attractive destination for anyone on earth, elite and exotic, but affordable and practical. If the market was correctly evaluated and an optimum price was charged, we could permanently maintain 100% occupancy. Artificial robotic "consumers" would replace people when they left the base, so that the LSS is always running at a rate that is optimum for 800,000 people. Guests would only be permitted to stay at the hotel for a week at a time because of the adverse effects of low gravity environments on human physiology. Indeed, after further study of these guests, we may find effective methods to combat these detrimental effects.

The general-purpose Lunar Manufacturing Facility also goes into production in this phase of the mission. Sub-sections of the factory are sold or rented to various terrestrial companies, who outsource their operations to the moon to dramatically lower their total production costs.

Simultaneously, technologies such as the GEO space elevator and MXER tether have matured and are providing transportation to the moon for as little as a few dollars per kilogram.

By this time, the solar cell farm spread over the lunar surface is harnessing and delivering sufficient solar energy to meet the entire energy demand of earth and those of the Large Contained LSS and Lunar Manufacturing Facility. In short it is meeting the energy requirements of all human civilization.

This phase may extend indefinitely, with the potential for new seed factories to be produced for siting on other planets for the purposes of terraforming those planets or constructing immense life support systems on them. When fast manned interplanetary transportation systems become a reality, humans will be able to occupy these distant LSSs or Planetary LSSs. In this way, this mission cycle will continue indefinitely, moving further and further away from earth and steadily increasing the potential sphere of human habitation.

Sequence of Operations:

1. 800,000 people gradually arrive to occupy Large Contained LSS
2. general-purpose LMF goes into production
3. LMF growth and self-replication continues
4. Solar cell system growth continues
5. New seed factories are produced for siting on other planets
6. Seed factories are deployed to other planets for siting (on Mars, for example)
7. Seed factories on other planets begin growth and self-replication, also producing new seed factories for siting on still further planets

Current Means of Transportation: GEO Space elevator, MXER tether
LSS Being Demonstrated: Large Contained LSS
Goal/Final Condition: Indefinite

11 Potential for Technological Breakthroughs

Energy

- Lunar Solar Power
- Helium 3 Fusion

Transportation

- Space Elevator and high-speed rail transportation on earth
- MXER
- Reusable space planes and vehicles – advanced and esoteric propulsion systems
- Intermediate Orbital Stations

Mining

- extraterrestrial mining technologies in low g vacuum environments

Construction

- Construction technologies in low-g and vacuum environments
- Development of radiation and micrometeorite shielding
- Construction of incredibly immense structures
- Materials development

LSS

- Large Contained Biospheres
- Control and maintenance of such biospheres
- Sustainability technologies - huge opportunity for investigating the causes of weather, and the working of planetary biosphere equilibria and buffers. As Richard Feynman once said, “What I cannot create I do not understand”.

SRS

- General Purpose Lunar Manufacturing Facility (LMF)
- Advanced automation of earth industries
- Nanotechnology – Nano-assemblers
- Deep space colonization capability
- Terraforming technologies

12 Social Implications

This section details some of the questions and issues that may arise due to the execution of the mission described above. Further, it speculates as to the possible directions of growth of the human sphere of habitation and contemplates some of the long-term impacts of the new technologies and philosophies engendered by the mission. First, we will concentrate on the immediate repercussions on human society on earth.

The mission we have proposed will leave us with a large capacity for lunar tourism, a free supply of plentiful solar energy beamed to earth from the moon, access to Helium 3 from the moon, a general-purpose Lunar Manufacturing Facility (LMF), a launching platform for other missions into the solar system, a non-terrestrial research facility and an extensive and operationally inexpensive transport network between the earth, earth orbits and the moon.

The component of this mission that will most affect life on earth is the supply of solar energy from the moon. Energy thus obtained will reduce and eventually eliminate our dependence on our diminishing fossil fuel supply, and avoid the contamination of our environment due to radioactive waste from nuclear power plants. According to experts such as David R. Criswell[2, 28], this form of energy harvest is the only way to meet our global energy needs through the future. Poor countries that construct receiving antennae for the energy beams from the moon will have access to free energy that they can sell or use in industry to increase their national wealth. Indeed, the largest cost in this system is the initial construction of a receiving antenna from earth materials. The magnitude of power that can be delivered by a Lunar Solar Power farm is limited only by the area of the moon which we are willing to cover, and will provide clean, non-polluting, reliable, cheap energy to planet earth. The design of Large Contained LSS will further augment our knowledge of our planetary equilibria and ecosystems and help us to preserve the earth in its natural state.

The other high-impact component of this mission will be the Lunar Manufacturing Facility. On earth, any company must pay for the natural resources, land and labor that it uses to manufacture products. The earth is strained for such important resources such as non-renewable fuels and mineral ores so that these commodities are becoming increasingly expensive to obtain and their harvesting results in considerable destruction of the environment. If we could outsource industries to the moon, we would considerably lighten this burden on our planet. Such a factory could quickly manufacture products free of cost in immense quantities. Any company that wished to have production capability on the moon will only have to make an initial investment in a "seed" factory and collect useful output periodically, with the only continued cost lying in the transportation of the products back to earth. If the earth-moon transportation network created by this mission were functional, these transportation costs could be incredibly small. We could eventually replace almost all terrestrial industry with lunar industry, resulting in a powerful moon economy.

The potential for the development of fusion technologies for use on earth is also very exciting and could further augment our ability to meet our planet's rising energy demands. In our current situation, there is very little money being put into fusion research because of the skepticism of our ability to harvest He-3 from the moon in the foreseeable future. The success of the mission proposed here would dramatically accelerate fusion research if sufficient quantities of He-3 are collected on the moon. He-3 fusion is a highly efficient source of power without radioactive by-products, and could become widespread on the earth and moon.

Finally, tourism on the moon will mean that there will be dramatically heightened societal awareness about the potential of space technologies and resources, and increased awareness that the coming generations of human beings may move to another planet, permanently. The incredible power of self-replicating systems will become apparent and the global community will realize that they are on the verge of a colossal robotic revolution – an "age of robots", if you will. The moon base will dramatically accelerate the development of space technologies, including transportation, life support systems and further SRS - in much the same way as the "IT Boom" led to the rapid development of powerful computers and communication networks, a hotel on the moon could lead to a huge thrust for colonization. The development of advanced automation for use on the moon may also result in the use of super-automation to further enhance the efficiency and productivity of terrestrial industry, and may result in novel means of global industrial growth and control.

This scenario seems too good to be true and, in a sense, it is. There are a number of ethical, legal and economic concerns that are associated with this ambitious undertaking. Human beings, since they first appeared on the earth, have been terrified of change. What we are talking about here is surely the biggest, most revolutionary change that the human race will ever have encountered. It is uncertain whether we, as a population, will be able to conform to these radical developments.

To begin with, let us consider what might happen to the economy and the very lifestyles and roles of human beings in society as a result of the changes brought about by this mission, in the short term (within the next century). The super-automation of terrestrial industry and the replacement of a large fraction of that industry by lunar manufacturing facilities will likely lead to a staggering loss of employment on the earth. Further, there will be an unlimited supply of free products from the moon, with the cost of fabrication of products being almost completely uncoupled to the number of products made. On earth, our economy is governed by the natural laws of supply and demand, so that it will not benefit companies to flood the market with an excess of products for which there are not enough consumers. Let us consider, in a hypothetical scenario, what some of the repercussions of an LMF could be. If, for example, a single car manufacturer invests in an LMF, begins production on the moon, and allows the system to grow unbounded so that there is an ever-increasing flood of new cars arriving on the earth from the moon, a combination of things will likely happen. If the lunar-derived cars were sold at the same price as terrestrially manufactured cars, the supply would rapidly exceed the demand. Accordingly, if the price of the lunar-derived cars was dropped so that more people could afford them, the demand for the cars would increase until, once again, all the people that could afford them had already purchased them. This would also lead to the bankruptcy of all terrestrial car-manufacturers and a large loss of jobs in the automobile industry. This cycle would repeat until, theoretically, every one of the seven billion people on earth owned a car (or five), or the selling price of the cars began to approach the cost of transporting the cars to the earth from the moon. This transportation cost might conceivably be as low as, perhaps, ten US dollars ($10) per car, if transportation technologies such as space elevators, highly reusable space planes and rockets and MXER tethers become commonplace. By this time, the car-manufacturer would have long since recovered the initial investment made in the LMF. Now, imagine that this situation is what has happened to almost every industry on planet earth. On one hand, people do not have jobs anymore, but on the other, the cost of living has dropped dramatically.

Now, consider the case where two car-manufacturers invest in LMFs. They would be in competition only with each other as they could easily drop their prices below those of terrestrial auto manufacturers. As a result, they may settle on a price for their cars that is under the price of terrestrial automobiles, but thousands of times more than the cost of production of the cars (which, once the initial investment is returned, is only the cost of transportation of the cars), so as to maximize their profits. They would quickly run all terrestrial automakers out of business, resulting in a large loss of jobs and would be generating huge profits with resources that are supposed to be the common heritage of mankind, without even supplying the population with significantly less expensive cars. Again, imagine that this is what has happened to almost every industry on planet earth, and you see that there are serious dangers associated with SRS technology. The only advantage of such a scenario is that the earth will be considerably less strained for natural resources such as mineral ores.

A similar monopoly may occur with solar energy beamed to the earth from the moon. Still, it is the only way we can satisfy the global energy demand into the future. The key issue here is the proper use and distribution of the wealth gained from this free energy. If a government constructs a receiving antenna in a country, it must sell the energy to the country's citizens at no profit, and must use the free energy, along with manufacturing power from the moon, to create extensive public transportation networks (such as Mag-Lev trains and rails built on the moon and transported to earth), sponsor the research and development of electric automobiles, and ensure that private companies who buy this energy reduce the prices of their products accordingly. Further, since this will result in a dramatic loss of employment, the government must also augment its public welfare programs and ensure that its citizens have sufficient income to lead high quality lives. If a private company builds the antenna, there must be strict regulations that ensure that the country's economy and citizens benefit as a whole. However, these restrictions must be carefully assessed to avoid dissuading private enterprise in space industry and energy.

This brings us to the matter of lunar and space resources legislature. This legislature will be one of the key factors in smoothing the transition from a human labor-driven existence to a super-automated, extraterrestrial robot-driven existence. The United Nations Outer Space Treaty and related United Nations Space Treaties are the laws currently applicable to the moon[32]. The UN Outer Space Treaty is the most general in its application and briefly covers several aspects of space legislature. The related UN treaties concentrate on more narrowly-defined aspects of space legislature in greater detail. From among all the articles presented in this collection of treaties, there are two of particular concern to this mission and its repercussions. The first is Article VI of the Outer Space Treaty (formally known as UN Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies) which, in summary, states that any country that is a party to this treaty "shall bear international responsibility for national activities in outer space, including the Moon and other celestial bodies, whether such activities are carried on by governmental agencies or by non-governmental entities" and shall be responsible for the "authorization and continuing supervision" of these activities[32]. This is important because it means that private organizations will not be allowed to exploit lunar resources unchecked. This article allows for some centralized regulation of activities on the moon, and will allow the states party to this UN treaty to establish economic restrictions on private ventures on the moon so that its resources are not unduly exploited at the expense of unemployment on earth.

The formulation of these regulations may be guided by the second article of interest. This is Article 11 of the UN Agreement Governing the Activities of States on the Moon and other Celestial Bodies. This article states that the moon and its natural resources are the common heritage of mankind, that the moon is not subject to national appropriation by any claim of sovereignty, be means of occupation, or by any other means, and that main purposes of the international regime to be established shall include the orderly and safe development of the natural resources of the moon, the rational management of those resources, the expansion of opportunities in the use of those resources, an equitable sharing by all States Parties in the benefits derived from those resources, whereby the interests and needs of the developing countries, as well as the efforts of those countries which have contributed either directly or indirectly to the exploration of the Moon, shall be given special consideration[32]. This article, in essence, directs that any legislature written for the use of the moon and its resources should hold as its highest purpose the equitable distribution of all monetary income, physical products and useable energy among the people of earth.

This outline seems simple, straightforward and fair because we have not yet considered the myriad potential problems that will likely occur during the widespread use of moon resources. Though the currently valid treaties do not seem to prohibit any portion of the proposed mission, there are several delicate matters and contrary arguments which must be addressed. For example, during the Age of Discovery on Earth, a period extending from the early 15th century to the early 17th century, European ships traveled around the world to search for new trading routes and partners to feed burgeoning capitalism in Europe. In the process, they encountered lands and peoples unknown to them and appropriated much territory by occupation and force, usurping governmental control over the native peoples of those lands and displacing them from their homes. Lands that did not possess an indigenous population were also appropriated by occupation. Over time, the settlers bore children that considered the new lands their home, and the world map today bears testimony to the outcome of these ventures. The United States of America is a prime example.

The moon bears no life and is not home to any indigenous population, to a high degree of certainty. Given this fact, what right does anyone have to prohibit the ownership of land on the moon by occupation? If a private company invests a large amount of money and effort in the development of a Lunar Manufacturing Facility and deploys this facility on the lunar surface, what right does anyone have to deny them the ownership of the land under their factory and the opportunity to make as much profit from their endeavor as possible? Governmental entities such as NASA have powerful research and development programs, but most of humanity's technological advancements can be accredited to private enterprise. A large fraction of the creative power of humankind lies in our private companies and think-tanks, and it is essential that we allow private enterprise on the moon if we are to see working lunar factories in the near future. Consider, for example the last major technological revolution on earth – the IT revolution. It was companies such as Macintosh, Intel, Microsoft, IBM, Sun, Dell and HP that were responsible for the incredible advancements in networking, processing power, memory and software applications that are so commonplace today. Governmental organizations had very little to do with this transformation that has so radically improved the reach, scope and efficiency of so many of humankind's activities. Still, as we hypothesized in the preceding paragraphs, there is a very real danger of the formation of moon monopolies that would be devastating to the world economy. How do we balance these competing factors and resolve the issue of private rights on the moon, given that past precedent on earth dictates that fortune favors the bold and that the "finders" are the "keepers"?

The big difference between the 15th century and the present day is the widespread awareness of global conscience, accountability and responsibility, and the general perception of these. Any country which acts in a manner that is in violation of global sentiment and ethics may face severe economic sanctions against them and may lose precious military and tactical allies. There are several reasons for the existence of treaties such as the Outer Space Treaty. The realm of space exploration is an uncertain one. Funding for space missions oscillates wildly from year to year, and interest in these missions waxes and wanes like the phases of the moon itself. There seems to be a general perception that space and the moon will someday, somehow, prove to be very lucrative, but that that day will not be upon us for a time. Yet there is a dire insecurity about the capabilities of other countries in space, but an unwillingness to devote large amounts of money to the pursuit of one's own space ambitions because of the time scale involved and the lack of guarantee that it will come to any good. Today, it is unclear who will be the first country to establish a significant presence on the moon, and even more unclear as to what capacity this presence will have. It is the opinion of these authors that the potential and implications of the moon and its resources has been left largely undiscovered by our politicians and lawmakers. The moon is simply not seen as an arena in which huge profits are to be made, though it may very well be exactly that. Still, there is a vague but urgent tension in the second moon race. Colonizing the moon, depending on how it is done, may be an immensely expensive endeavor. Countries today are not looking at SRS technologies to reduce the costs of such a mission and, as such, as far as they are concerned, the costs may well be insurmountable or entirely impractical for a single country to spend. Accordingly, there is a willingness for international cooperation in the generation of funds for such missions. Countries may enter into treaties such as the Outer Space Treaty because of their desire to better control and regulate the activities of other competitors in the space race, genuinely not knowing who will get there first and not wanting to be left behind. The price they must pay for this insecurity is the burden of controlling the activities of their own private agents in the space race. This control may be in the form of direct or economic legislature or regulations. This situation, though it seems fraught with doubt and reservation, is fortunate. If going to the moon was easy, we might have faced a monopoly similar to that which occurred with oil. All this fear and indecision may work to centralize our efforts, so that we end up doing what is best for humankind. If, for example, an international consortium was assembled for this moon mission, that consortium may be able to rent or sell plots of a general-purpose Lunar Manufacturing Facility to private companies, thus allowing the close monitoring and regulation of the private activities. Though it is not the opinion of these authors that, taken alone, individuals should be denied their rights for owning property on the moon and the like, we do contend that, in the context of the current global situation in which there are developing countries which desperately need to be looked after, overpopulation and misdistribution of wealth and resources, an exploding energy, materials and space shortage, we are fortunate to be presented with an opportunity to correct all this with a centralized effort on the moon. Our closest neighbor may be the thing to save us all.

The key will be to balance all these factors as best as we can. Encourage private companies to go to the moon and make them aware that there are fortunes to be made, but do not allow them to make those fortunes without helping the rest of the world as well. We will need fair, proper distribution of wealth, resources and facilities on earth. Huge unemployment on earth should be coupled with immense public welfare efforts, dramatic increases in public transportation infrastructure, governmentally regulated prices on moon products, government subsidies of these products and a carefully planned, far-sighted body of space legislature. Without these measures, we are sure to face catastrophic unemployment on earth, worsened by anti-robot and anti-moon protests.

Now that we have considered some of the short term issues surrounding this mission, we will speculate as to the state of human civilization far into the future. We will attempt to describe how different the future, as a result of the continued execution of this mission cycle, may turn out to be, from the present. The authors of this report envision a human sphere of habitation that spans tens or hundreds of planets. Each of these planets is either a planetary LSS or possesses several Large Contained LSSs. All industry, innovation, product design, agriculture and services are regulated and controlled by machines. Each planet is run by either a central computer or a network of commanding computers that coordinate the myriad processes and systems that supply the planet's human inhabitants with everything they could possibly need. When these settlers first arrived on their distant planets, there was a fully operational planet-wide LSS awaiting them. Because of the ultimate ability of SRS technologies to organize vast quantities of material at remote locations in minimal time, there will be an abundance of products, food and services automatically available to all humans at all times. In short, no human being works for even a single minute of his or her life; humans merely socialize.

This situation sounds incredibly warped and is terribly difficult to imagine for today's human beings. We were raised in a world where almost nothing is free, and one must work to earn a living. The transition to such an "idle" human society would be difficult to envision. However, it is easier to imagine this scenario playing out on another planet on which the robotic systems predate the human inhabitants. It is the ultimate goal of technology to make life easier for human beings. Therefore, the ultimate technology would be one that allows humans to be entirely work-free.

Still, this scenario causes us to wonder as to the nature of human control over these ubiquitous machines, if any. If we become entirely dependent on these machines to work for us and make our decisions, and surrender all control to their judgment, will we govern the machines or will they govern us? How can we ensure that the machines always act for our benefit? Can any human being effectively control such a vast network of planets? Further, it prompts the question: Is work a fundamental human need? Can there be any purpose without work? Will such a human society survive, or is there some fundamental flaw in such a lifestyle? Will the people of earth be impossible to convert? Or will they, long defiant of the methods and practices of the outer worlds, finally accept the prevalent way of life, giving up their desk jobs, overalls and hardhats to live off the constant work of a gigantic, interstellar robotic fleet? Will it be possible to make this transition on earth before we colonize other planets?

There are an infinite number of such questions that may never arise or may be answered in time. It is not our purpose, here, to answer them, but merely to suggest that the possibilities for the future of mankind set in motion by self-replicating technologies, in conjunction with this mission, are dizzying and revolutionary. The future becomes even more incomprehensible if we were to face the ultimate reality of life on another planet.

13 Conclusions and Recommendations

One of the main problems facing the future of space colonization is the lack of human patience. Professor Gerald Kulcinski, Director of the Fusion Technology Institute, University of Wisconsin, and recently selected member of NASA's Advisory Council said that the problem with acquiring funds for He-3 research is that "DOE (Department of Energy) doesn't trust NASA to get access to helium-3 in a reasonable amount of time. NASA doesn't trust DOE to fund and get a helium-3 reactor working if they commit the resources to get the helium-3". NASA estimates that it will be able to return to the moon within twenty years and fusion researchers claim that they will develop a working fusion reactor within that same amount of time[5]. As many as 250 generations of human beings have lived and died since the known beginning of recorded history. NASA and DOE both promise to achieve their respective goals of moon return and workable fusion within the span of one generation. If the major players in the quest to explore and colonize space are so short-sighted as to refuse to fund a project that will show results in as relatively short a time span as this, we will never make it past our moon.

The common perception is that colonization of space, the moon and other planets is science fiction and the few true believers in extraterrestrial colonization form a small subculture of the population. There is an entire lack of recognition of the power of self-replicating systems both in the general public and within leading space organizations such as NASA. Instead of generating interest and funds for the development of self-replicating systems, NASA is proceeding with short-sighted, limited return missions as part of a supposed long-term space vision. The problem with this vision is that it changes every few years according to the political influences of the time. If one were to ask the CEO of a leading automobile manufacturing company where his company will be headed in fifty years, it is extremely unlikely that he will reply "to the moon." General awareness about the profitability of the moon and other planets, and the immense capabilities of self-replicating systems must be increased. The simple fact that our global energy and mineral ore demand will soon exceed our terrestrial energy production capabilities should, alone, drive leaders in industry and government to boldly seek alternative sources of these essential commodities, without constantly falling prey to short-sightedness. Organizations such as the Artemis Project and Moon Society should increase their efforts to publicize the undiscovered potential of the moon as the perfect source of materials and energy for the future of the earth.

In a venture of this magnitude and importance, we would do well to form a symposium of governmental entities and private companies interested in using self-replicating systems to establish manufacturing facilities on the moon, as the first step towards multi-planet colonization. This symposium should write legislature on the prudent use and distribution of lunar resources such that mankind as a whole will benefit to the highest possible degree, and take steps towards researching and developing the self-replicating systems that may make this mission a reality.

Though the mission proposed in this report seems far in the future, it is disturbing to note that feasibility studies on this type of mission were conducted by NASA almost thirty years ago, and that the resulting mission outline was entirely rejected by NASA executives without gaining the slightest publicity[27]. We can only imagine what advances we would now be experiencing if work on such a mission had been started in 1980, when the study was conducted. The authors of this report are perplexed and frustrated by the lack of attention given to the idea of self-replicating systems, and the apparent fear of the radical changes that they will bring about. We are concerned that, amidst all the political maneuvering and greed for immediate results, we have lost all our forward momentum in the area of space development. Other industries have not suffered a similar fate because the relatively small size of the initial investments required in the development of their technologies enable them to develop those technologies purely by private enterprise. Further, the publicity and glory of putting men on the moon has hindered our efforts to advance into space, in recent years. It is for this reason, in large part, that advanced large-scale automation has not been applied extensively to space.

The authors of this report recommend that subsequent study be conducted in the following important areas:

1) Far-sighted space legislature that holds as its highest principle the improvement of quality of life for all humankind. The Outer Space Treaty, the current international treaty applicable to the moon, does not anticipate the revolutionary use of lunar resources that self-replicating systems may make possible. Though it is sound in principle and intent, it will not be sufficient to properly direct the development of lunar resources and ensure a smooth transition into an age of super-automation and moon-earth trade. It must carefully balance the interests of private enterprise on the moon with the well-being of humanity as a whole, and guarantee that the wealth generated on the moon is equitably distributed, with special consideration for the welfare of developing countries.

2) Methods of publicizing and generating interest in self-replicating systems technologies. SRS technologies are almost unheard of in today's world, and our political and industrial leaders are not aware of their potential or existence. There is a prevailing impatience among decision-makers concerning technologies which require tens of years of development to see maturity. We must find ways to convince world leaders and leaders in private enterprise that there is a fortune to be made for all, on the moon. Without the dedicated attention of our scientific community and financiers, this mission will have no hope of ever being realized.

3) Self-replicating systems in nanotechnology. If we can infuse the notion of self-replicating systems into the foundation of this new and promising technology, we may dramatically improve our chances of seeing SRS become ubiquitous.

A mission such as that proposed in this report may produce the most drastic global revolution that humankind has ever seen. This endeavor will require patience, constancy, commitment, diligence and innovation. If we take these first steps, we may be on our way to an unprecedented explosion of prosperity.

14 References

1. A. G. Reinhold, *A Solar Powered Station at a Lunar Pole*, **America at the Threshold, Report of the Synthesis Group on America's Space Exploration Initiative**, July 1990.
2. D. R. Criswell, *Lunar Solar Power System for Energy Prosperity Within the 21st Century.*
3. J. R. French, *Nuclear Powerplants for Lunar Bases, Lunar Bases and Space Activities of the 21st Century*, 1985.
4. D. Buden; J. A. Angelo, *Nuclear Energy – Key to Lunar Development*, **Lunar Bases and Space Activities of the 21st Century**, 1983.
5. E. R. Hedman, *A Fascinating Hour with Gerald Kulcinski*, January 2006.
6. Garrick-Bethell, *Meeting Nighttime Power and Thermal Requirements by Manipulation of the Lunar Surface Albedo and Emissivity*, **Space Resources Roundtable VII**, 2005.
7. D. V. Smitherman, Jr., *Space Elevators, An Advanced Earth-Space Infrastructure for the New Millennium*, **Workshop on Geostationary Orbiting Tether "Space Elevator" Concepts, NASA Marshall Space Flight Center**, August 2000.
8. Lawrence A. Taylor, Dong-Hwa S. Taylor, *Location of a Lunar Base: A Site Selection Strategy*, **Engineering, Construction and Operations in Space V**, vol 2, pp. 741-755.
9. *Colonization of the Moon*, **wikipedia.org**
10. *Ray Spectroscopy*, **http://lunar.arc.nasa.gov/printerready/science/newresults/grs.html**
11. Nicholas M. Short, *Post Apollo Lunar Exploration*, **http://rst.gsfc.nasa.gov/Sect19/Sect19_6b.html**
12. *Clementine Topographic Map of the Moon*, **http://www.geol.lsu.edu/Faculty/Juan/PhysicalGeology_S2005/images/moon/Topography.jpg**
13. *Lunar Topography: Large Full Color Map*, **http://cosmology.berkeley.edu/Education/DEMOS/Lunar_Topography/Lunar_Map2.html**
14. Shayla E. Davidson, Robert M. Taylor, *Use of Radio Frequency Spectrum in Lunar Environment*, **Engineering, Construction and Operations in Space V**, vol 2, pp. 847-853.

15. R.C. Haymes, *Lunar Based Gamma Ray Astronomy*, **Lunar Bases and Space Activities of the 21st Century**, pp. 307-314.
16. SRS reference
17. Anthony M. Wachinski, Tony Rachwal, Colin Waters, *Protection of and From the Lunar Environment*, **Engineering, Construction and Operations in Space V**, vol 1, pp. 668-672.
18. Solar Flare, **wikipedia.org**
19. P. Land, Lunar Base Design, **Lunar Bases and Space Activities of the 21st Century**, pp. 363-373.
20. J. Kaplicky, D. Nixon, A Surface-Assembled Superstructure Envelope System to Support Regolith Mass- Shielding for an Initial-Operational-Capability Lunar Base, **Lunar Bases and Space Activities of the 21st Century**, pp. 375-380.
21. F. Horz, Lava tubes - Potential shelters for habitats, **Lunar Bases and Space Activities of the 21st Century**, pp. 405-412
22. Eligar Sadeh, Willy Z. Sadeh, Marvin Criswell, Eric E. Rice, Jenine Abarbanel, Inflatable Habitats for Lunar Base Development, pp. 301-304.
23. M. Roberts, Inflatable Habitation for the Lunar Base, pp. 249-253.
24. Jenine E. Abarbanel, Ted A. Bateman, Marvin E. Criswell, Willy Z. Sadeh, A Framing System For A Lunar/Martian Inflatable Structure, **Engineering, Construction and Operations in Space V**, vol 2, 1069-1075.
25. M. J. Fogg, **Terraforming – Engineering Planetary Environments, pp. 37-60**, 1995
26. Marshall Space Flight Center , *International Space Station Life Support Systems*, **http://www1.msfc.nasa.gov/NEWMSFC/eclss.html**
27. R. A. Freitas, Jr., editor, *Advanced Automation for Space Missions*, **Proceedings of the 1980 NASA/ASEE Summer Study, NASA Conference Publication 2255**, 1980
28. D. R. Criswell, *Testimony of Dr. David R. Criswell,* **Senate Commerce, Science, and Transportation Subcommittee on Science, Technology, and Space Hearings: "Lunar Exploration"**, November 2003
29. E. Drexler; C. Peterson; G. Pergamit, *Unbounding the Future: The Nanotechnology Revolution*, 1991

30. *Clanking Replicators*, **wikipedia.org**, last updated April 2006

31. *Nanotechnology and Space*, **thespacesite.com**

32. *United Nations Treaties and Principles on Outer Space*, **United Nations**, 2002