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Sustaining Agriculture on the Moon

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SUSTAINING AGRICULTURE ON THE MOON

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Abstract

Mankind cannot go into space by itself. Plants and animals that are part of a sustainable biosphere will have to go with us. The key to developing a colony on the Moon, or anywhere else, will be the question of how it can feed itself. Tuber (Yam and Potato) agriculture on the Moon is not just a matter of finding water and building a greenhouse. First you have to create soil, then you have to go at least 10 meters underground to avoid cosmic rays, and still you need solar energy.

Division of Labor

Robert Groezinger – Alternative Energy Sources

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1 Introduction

A main objective of several of the Space Policy IQPs is to determine the feasibility of a permanent or self-sustaining lunar settlement. Other IQP groups are researching important aspects of this settlement; in particular, the Gas Harvesting group is investigating the profitable harvesting of vital gases from the Earth's exosphere. While their focus is the low Earth orbit (LEO) market, some of the gases are also essential for the creation of an artificial lunar base atmosphere. A Lunar Habitat group is examining general issues of the habitat's infrastructure and focusing on the cosmic radiation shielding question. Our group has chosen to focus on the question of permanence, in particular with regard to the settlement's food supply. Can it be self-sustaining in this regard or must it forever be dependent on trade from Earth for food?

Permanence implies a certain degree of self-sufficiency: a base whose continued existence depends on monthly shipments from the Earth cannot truly be considered permanent. The food supply is a crucial part of this; so far every manned space mission has relied completely on food brought with them or transported to them from Earth at a later time. While this is adequate for a three-person station crew or a week-long Space Shuttle mission, this will not be the case for the staples of a larger settlement. It seems inevitable that, within the first twenty years of arrival to build a base (about 2020-2040), lunar inhabitants will need to learn to produce some of their own food.

The objective of our project, therefore, is to determine the feasibility of a completely self-sustaining system of lunar agriculture, requiring little to no supplies from Earth after its initial construction. By this we mean enough to live on, though "luxury" foods would still be imported. We have determined that there are three main issues that are pertinent in meeting this objective: providing an energy source, creating and maintaining an artificial atmosphere in the lunar habitat, and providing an adequate supply of soil and water for the crops.

We have accessed articles in scholarly journals and books, previous and current space policy IQPs, and other related sources of information that we deemed necessary in order to complete our objectives. For example, we have consulted with a knowledgeable inventor, who has served as an informant and provided unique insight into the development of a lunar base.

We have ascertained that potatoes would be an ideal crop to grow in a lunar habitat, due to their ability to grow in relatively harsh conditions. In addition, potatoes would be an ideal food source, since they would provide several vital nutrients to the inhabitants of a lunar base who would possibly be limited in their selection of food.

The first issue that was examined is the source of energy required for agriculture on the Moon. This energy source is required for the potatoes to be able to photosynthesize. Solar energy has been chosen as the energy source best suited for the lunar environment because the Moon is about as far from the Sun as Earth and solar energy supports Earth agriculture. However, the Moon has no atmosphere, and, as a result, the solar radiation reaching the Moon's surface is much more intense. However, this also means that the habitat must be shielded from solar as well as cosmic radiation. Therefore, we have determined that it would be necessary for a lunar habitat to be constructed under the surface of the regolith, for reasons involving the need for shielding. However, the lunar "day" of 14 Earth days followed by 14 Earth nights is also an issue. The extremes of "light" and hot, cold and dark faced by the plants will be a second issue except at the poles.

The three main methods for harnessing solar energy and converting solar energy starch that we considered are as follows: convert solar energy to electricity to power grow lights, implement a bionic leaf, and directly convert solar energy to laser form. There are many different photovoltaic systems available for converting solar energy into electricity, and the main differences between them are cost and efficiency. Basically, a "bionic leaf," which may resemble a factory rather than an Earth leaf, artificially carries out all of the photosynthetic functions of a leaf and can be placed on the surface of the Moon as it is made of silicon and iron, steel, or aluminum. Converting sunlight into a laser facilitates reflecting it via mirrors so that it can be directed around the radiation shielding and into the habitat. In order for the plants to be able to use this laser energy, it must first be converted back to full spectrum lighting once underground. Each of these methods has its own strengths and weaknesses. The two main criteria for comparison are feasibility and efficiency. Regardless of what method is implemented, it is vital to determine the location where the solar collectors should be placed. The solar collectors are exposed to varying amounts of sunlight based on their location on the Moon's surface.

The second issue that was examined the creation of an "atmosphere" for lunar plants. This will require careful balancing of the plants' gas needs against the ease of transporting or locally producing those gases. (It should be noted that, if the plants were grown in a traditional greenhouse, this atmosphere would also need to meet the needs of the settlement's human occupants. It may in fact be better to isolate the plants' atmosphere from the humans' atmosphere and optimize the atmosphere for plants which flourish in a higher concentration of CO_2.)

The habitat will need to include systems for maintaining this artificial atmosphere. The same systems which maintain overall pressure and temperature for the human habitat will also work for the plants. A more important question is maintaining the concentration of gases, especially carbon dioxide, in the air.

While an increased concentration of CO_2 can be deadly to humans, plants can tolerate, and in fact thrive in, substantially higher concentrations than that found naturally in the Earth's atmosphere. Thus, although the habitat could simply arrange for a natural, passive flow of carbon dioxide from humans to plants, it may be better to actively remove CO_2 from the human areas of the habitat and transport it to the plants.

Moreover, carbon in any form will be a precious resource on the Moon. Unlike the filtering systems currently in use, carbon dioxide cannot simply be vented into space or absorbed in a non-reversible chemical reaction. Therefore, some sort of fully-reversible mechanism will be needed to absorb, transport, and release CO_2. A number of such systems are currently in development: chemical "scrubbing" using a solid amine or metal oxide, physical scrubbing using a "molecular sieve", and reactions with hydrogen gas (the Sabatier and Bosch processes.)

The third issue that was examined in order to determine the feasibility of sustaining agriculture on the Moon is how the composition of the Moon and the availability of water would affect the ability to successfully grow potatoes and other plant life under the Moon's surface. Since there is a significant difference in the composition of the "soil", or regolith, of the Moon in relation to the types of organic soil found on the Earth, the ideal growing conditions for potatoes in the soil present on the Earth was examined. Thus, the composition of the lunar regolith must be adjusted in such a way that it is able to support an agricultural system.

For example, the substances that are required to be present in the soil in order to ensure minimal to optimal growth of potatoes have been considered. The approximate percentages of these elements and compounds and their roles in the growth of potatoes have also been taken into consideration in order to determine how cavernous spaces on the Moon can be transformed into a suitable environment in which plant growth can occur. Since these spaces will be expensive to create they must be highly productive, so optimizing them for plant growth is our goal. Although it may be possible to add to or alter the composition of the lunar regolith in the region that will be designated for agricultural purposes, it may be just as feasible to import a sample of soil from the Earth that is known to have a composition that allows for optimal potato growth, or if the water shortage on the Moon can be alleviated, turn to hydroponic systems. However, we selected potatoes since they are capable of growing in poor Earth soil conditions.

In addition to the compounds present in the soil found on the Earth, it was determined that certain types of organisms that are present in the soil may be necessary in order to maintain an environment that can support the growth of potato plants. Organisms that are found in the Earth's soil, such as certain species of bacteria and earthworms, may be useful in that they consume chemicals found in the soil. The resulting waste that is excreted from these organisms could then be used as nutrients that the potato plants would need in order to remain healthy. This act of replenishing the soil with nutrients that are necessary for the potato plants to grow could also be aided through the use of a compost system in the lunar base.

Other factors pertaining to the lunar regolith, such as the optimal acidity of the soil needed to grow potatoes and the ability of the lunar regolith to hold water without continuous irrigation have been addressed as well in order to understand how composition of the lunar regolith must be modified, such that it is capable of sustaining the growth of potatoes on the Moon. Since the regolith found on the Moon has a different consistency than the soil found on the Earth, it may not be able to allow the roots of the potato plants to fully support the plants during growth in its present state. In addition, the water that will be used to irrigate the soil may either turn the regolith into a cement-like substance or not have the ability to hold the water at all. Thus, as mentioned earlier, it may be necessary to transport a quantity of soil found on Earth to the lunar base in order to provide an environment that is capable of growing potato plants. However, we hope to take some lunar regolith to Earth first and try to convert it into an acceptable medium.

Therefore, after research into the three aforementioned issues, it has been determined that the idea of a lunar habitat capable of being self-sustainable is indeed feasible. We predict that, given a few, surprisingly minor, scientific breakthroughs, the first stages of such an agricultural system could very well be implemented within the next twenty years.

2 Literature Review

The idea of constructing a lunar habitat is not new, but many scientists, engineers, and other professionals in space policy have varying ideas of what a typical lunar habitat would look like. We have determined that a lunar habitat would most likely be constructed by building a base under the surface of the Moon and covering the top of the habitat with a layer of lunar regolith several meters thick. This protective shield would prevent solar radiation from entering the habitat, as well as protect the inhabitants from the freezing temperatures on the lunar surface (Harrison, 2001). A layer of regolith alone, however, may not be completely impervious to the harmful ultraviolet rays from the Sun. Thus, a layer of water, in addition to the layers of regolith, would be used to better protect the inhabitants of a lunar base from the hazards of radiation.

In addition to the requirement of the lunar habitat being located under the lunar surface, due to the harshness of the environment on the Moon, space experts have tried to determine the composition of an artificial atmosphere that would be optimal for both humans in the residential areas of the base, and plants located in designated agricultural sections of the habitat. A system in which an atmosphere that is oxygen rich found in the areas primarily used by humans and an atmosphere that is carbon dioxide rich in the agricultural areas of the habitat would be beneficial for both groups. Also, it would be possible for the gases expelled by each group to be transferred to the other area of the habitat, such that humans would benefit from the oxygen produced by plants, and plants would be able to take advantage of the carbon dioxide exhaled by the human inhabitants (Harrison, 2001).

As mentioned previously, a means by which potato plants and other future crops that are grown in the lunar habitat can convert solar energy to starch needed to be considered. One such invention, referred to as a "bionic leaf", is loosely based off of an idea by physicist Freeman Dyson. Although the original idea involved bioengineering the leaves of a plant such that they would be able to more efficiently convert solar energy into a usable food source for the plant (Dyson, 2000), we have envisioned that a bionic leaf would more closely resemble a type of factory placed on the surface of the Moon. This piece of machinery would process solar energy and convert it to a nutrient source that would be usable by plants. The bionic leaf would effectively be "cooking" carbon dioxide and water for the potato plants to store carbohydrates in the tuber under the lunar surface. Not only would the potato plants be receiving a sufficient amount of energy from the bionic leaf, they would also be protected from any solar radiation that may adversely affect the growth of the plants. Although we foresee this kind of breakthrough would be very useful fifty years after an agricultural system has been established on the Moon, we feel that the technology required to bring this idea to fruition is not available at this current time, and it is not necessary to get the job done in a less efficient manner.

3 Investigation and Analysis

Discussed in this chapter are the three main issues that were investigated in this project: providing an energy source for a lunar agricultural system, creating an artificial atmosphere for the potato plants, and providing a suitable amount of soil and water for the crops. In addition to these issues, we also addressed concerns about the lunar habitat that would house not only an agricultural system, but also a growing population on the Moon.

3.1 Energy Sources

One issue of living or growing plants on the Moon is the fact that there is no atmosphere to protect its surface from solar radiation. Therefore, the base must be shielded from cosmic and solar radiation. The easiest solution is to build the base underground. Initially, one expert stated that a 20 foot layer of lunar regolith would provide adequate radiation shielding for the habitat. However, after further consultation with an expert at NIAC, it is evident that this would not be enough and some radiation would still pass through. Her estimate was that 10 meters would block about 90% of the incoming radiation. One possible solution is to have a layer of water included along with the layer of regolith. This would decrease the amount of radiation traveling through the shielding, but this method would still not eliminate the radiation. Another possible solution is using a layer of hydrogen. This would block most of the radiation, but requires a large amount of hydrogen. Besides the radiation problem there is the problem of the plants needing some solar energy for photosynthesizing underground.

Energy for photosynthesis is essential for the potatoes to grow. The four main sources of energy are converting solar to electric energy, the bionic leaf, solar pumped lasers, and the reflecting of a concentrated beam of light. Each of these methods has its own positive and negative aspects.

The first method examined was the idea of converting solar energy to electricity. This electricity would then be used to power grow lights. The use of grow lights is a popular idea among science fiction writers. For example, it is mentioned in <u>The Moon's a Harsh Mistress</u>, by Robert A. Heinlein. However, most of them call for the use of a nuclear generator to power them. This is because an enormous amount of energy would be needed to power a large number of grow lights. Since the problem is too much solar energy on the surface, ignoring that source and building a nuclear reactor seem silly.

There are many different approaches for converting solar energy to electricity. The most popular method in use is photovoltaic cells. Photovoltaic cells convert sunlight into direct current. The advantages of such a system are that there are no moveable parts, low maintenance, and long operation lifetime (Trieb, 1997). However, photovoltaic-systems are relatively inefficient and very expensive. On the other hand, the main component of photovoltaic cells is silicon, which is found all over the surface of the Moon. Therefore, it may be possible to manufacture mass quantities of photovoltaic cells for low costs. This idea was explored last year by a team that wanted to literally pave the Moon with solar collectors made by a self-replicating system (Gupta, 2006).

The most efficient system to convert solar energy to electricity is the Dish-Stirling system (Trieb, 1997). It consists of a paraboloidal dish reflector and sterling engine. The sterling engine converts the heat generated by the sun to electricity. “Stirling engines have multi-fuel capacity, high efficiency, low emissions, long life, and operate very quietly.” (Trieb, 1997). However, it requires gaseous hydrogen or helium for cooling. Moreover, it requires perfect tracking of the sun. Also, since it has moving parts some maintenance would be required.

The next system for obtaining solar energy is the bionic leaf. A previous group determined that this is the best system for the Moon. The bionic leaf was inspired by Freeman Dyson. However, Freeman Dyson had a distinctly different idea of how a bionic leaf would look. Dyson described the bionic leaf as having a black leaf-like structure. He believes it would be fifteen times more efficient than real Earth leaves mostly due to the change in the color of the leaves pigment (Dyson, 2000). Therefore, he sees it as being a device that requires bioengineering. Conversely, our current concept of the bionic leaf is that it may resemble a factory rather than a leaf, and it artificially carries out all of the photosynthetic functions of a leaf. This would allow the photosynthesis to take place on the surface of the Moon. H2O and CO2 are piped up to the “leaf” system and the nutrients would then be sent to the potatoes that are the “roots” growing underground. The feasibility and efficiency of a system is still unknown since it has not been invented yet. However, a recent survey of a NIAC panel showed that most experts believe it will take at least 30 to 50 years before a silicon and steel “leaf” is invented.

The third system for using solar energy for photosynthesis is solar pumped lasers. Instead of converting solar energy into electricity we examined the possibility of using lasers to harness solar energy. It is possible to convert the light emitted from the sun into focused laser form. This laser could then be reflected via mirrors so that it can be directed around the radiation shielding and into the habitat. In order for the plants to be able to use this laser energy, it must first be converted back to full spectrum lighting. One benefit of using lasers for transporting the light energy is that it is theoretically more efficient than using solar panels. One study had record collection efficiency for a solar side-pumped laser of 6.7 W/m^2 of primary mirror surface (Lando, 2003). The main issues with solar lasers on Earth are an unstable input power source caused by clouds and heliostat tracking errors. The issue of clouds or other weather related problems would not be an issue on the Moon. However, solar pumped lasers are still in development and are still relatively inefficient.

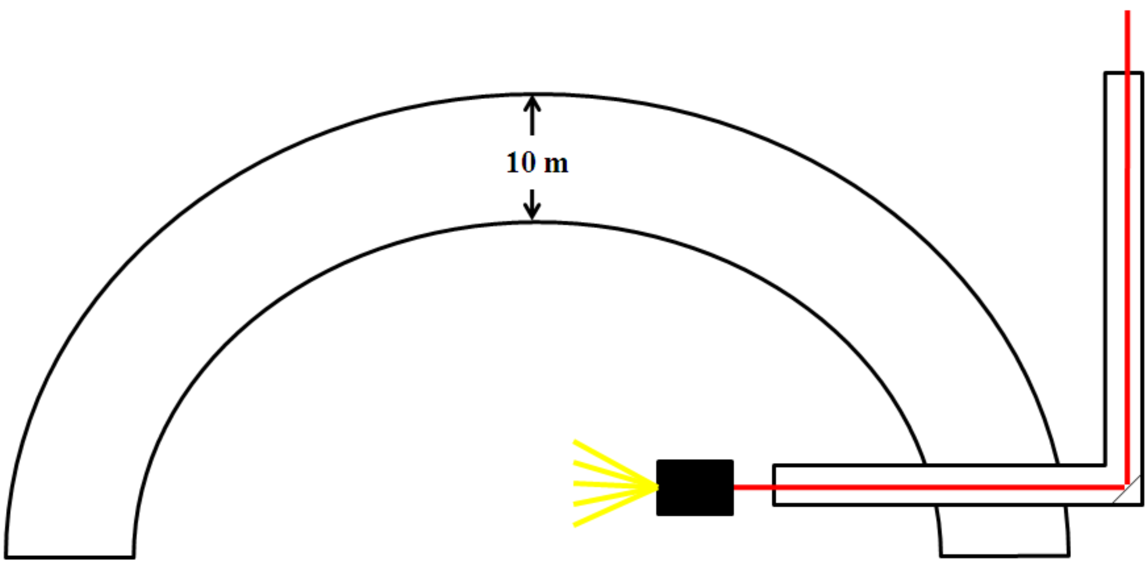


Figure 1 – Underground Lunar Base with Solar Pumped Lasers

The fourth system is the simple method of using mirrors to reflect full spectrum light into the habitat. A solar concentrator would transform sunlight into a concentrated beam of light. Current solar concentrators and reflectors can create beams of light that have maximum intensity of 5 times the energy of the sun (Nilsson, 2007). Then a series of mirrors would reflect the light around the radiation shielding and into the habitat. This method is highly efficient since no energy conversion process takes place.

The best system for providing the necessary energy for photosynthesis underground is the use of mirrors to reflect concentrated sunlight. The result is a side lit underground “greenhouse” with a glass side wall. This technology currently exists and would require no major scientific breakthroughs. However, the other technologies should still be monitored because they may prove useful in the future. When the bionic leaf finally exists it will provide a far more efficient means to grow the potatoes and many other types of plants in a much cruder and cheaper underground facility that could be integrated with the human habitat. You could grow food with the roots in the radiation shield roof of the Biodome and have it dangle down into the Biosphere for easy collection.

A further concern is the storage of energy. As mentioned earlier, each side of the Moon only receives light for half of the time over the course of one revolution of the Moon. This presents a problem concerning how grow lights or bionic leaf would be powered during the 14 days of darkness if solar energy is to be used. This will only be a problem if the agricultural facility is located in a place other than the South Pole. Earth based solar systems usually rely on fossil fuel backup systems to provide power when it is dark. However, this would not be feasible for the Moon so you want a place that is usually nearly continuously lit, like the South Pole. The best backup solution for other lunar sites would most likely be an electrochemical battery system (Trieb, 1997). However, if lasers are used, a satellite equipped with the necessary elements to turn sunlight into a laser can be used to focus and direct energy to any point on the lunar surface even when the sun is not visible above the habitat.

3.2 Artificial Atmosphere

In any space habitat, perhaps the most immediate and pressing challenge to the occupants' survival is the maintenance of the artificial atmosphere. The problem is magnified further when the habitat contains hundreds of people as well as plants, and when supplies from the Earth are few and far between.

A permanent, self-sustaining lunar settlement, therefore, must have the ability to recycle its own air supply, maintaining the proper concentrations of oxygen, water, and particularly carbon dioxide in the air. Carbon dioxide is a primary concern for two reasons: first, a higher-than-normal concentration of CO_2 poses immediate health risks, so it must be constantly and actively removed from human living spaces. Secondly, for plants during the "daytime," the opposite is true: CO_2 must be constantly supplied to provide a raw material for photosynthesis.

In an ideal world, these two forces would complement each other perfectly, so that the humans (and other organisms, such as composting bacteria) would exhale CO_2, which would then be fed directly to the plants, and the plants would use up all of that CO_2 through photosynthesis, returning oxygen to the humans to breathe, and so forth. The real world is far from ideal; it would be impossible to calibrate this system perfectly, and neither the CO_2 production of a human nor the CO_2 consumption of a plant is constant. So the system must be robust enough to handle these varying levels of CO_2 production and consumption. At the same time, due to its extreme scarcity on the Moon, carbon in any form will be a precious resource that must be conserved.

The most well-developed and widely used method of CO_2 removal is, unfortunately, completely incompatible with these goals. This method is also very simple and relatively easy to implement for a short-duration space mission: filter the air through a chemical filter that will spontaneously react with carbon dioxide, leaving the product in solid form. The most commonly used reaction is that with lithium hydroxide:

$$2LiOH + CO_2 \rightarrow Li_2CO_3 + H_2O$$

The difficulty is that, since this reaction is spontaneous, it is also effectively irreversible. If this were used in a Moon base, all of the base's available carbon would be "locked up" in used filters, with no way of extracting it and returning it to the plants. (The non-reusable nature of LiOH filters was one of the many serious problems that plagued the Apollo 13 mission.) Thus, new methods will be needed in order for the base to be self-sustaining.

There are essentially three different scenarios that such a system must cope with:

- The CO_2 production of the base's human occupants greatly exceeds the CO_2 consumption of the plants. This will be true in the early stages, while the base is still relying on shipments of food from the Earth. At this point, the best thing to do is to provide the plants with as much CO_2 as they can handle, and store the rest (either as compressed CO_2 or in some other form, such as solid carbon or methane) in a "reservoir" for later use.

- The CO_2 consumption of the plants greatly exceeds the CO_2 production of the humans. This is unlikely to happen often; due to the other difficulties of setting up agriculture, it is unlikely for there to be substantially more plants than necessary. In this situation, however, there is presumably a surplus of food, so the crops could be fed from the reservoir temporarily, then harvested early and stored, or even shipped back to the Earth.

- The CO_2 consumption of the plants approximately equals the production of the humans. Carbon dioxide will be removed from the humans' air and added to the plants'. Small variations in the production and consumption rates would be absorbed by the reservoir, and compensated by varying the number of plants growing at a time and the concentration of CO_2 provided to those plants.

One fairly well-tested alternative system is the Regenerable Carbon Dioxide Removal System (RCRS), which has been designed for use on the Space Shuttle orbiters (Ouellette, 1990). The RCRS works using a solid amine which "sticks" to and traps CO_2. The CO_2 is released by exposing the filter to vacuum, and the filter itself can then be reused. This method, though far superior to an irreversible reaction, would still be difficult to use in a lunar agriculture system, since unlike the Space Shuttle, the lunar base needs to be able to trap and store the removed CO_2. This could be done either by creating an artificial vacuum, or by heating the filter (which has a similar effect to exposing it to vacuum.) Either way would involve considerable energy expenditure; and in any case the amine could not, at least initially, be produced on the Moon. There is, however, considerable ongoing research in this area, and an amine-based system may well be the first implemented, in the early stages of the lunar base.

Another system similar to the RCRS has been proposed, which would use a metal oxide, such as silver, zinc, or magnesium oxide, rather than an amine (Nacheff, 1989). Although this has not yet been used in a life-support system, metal oxides have been used successfully as CO_2 scrubbers for industrial processes. Similar to an amine system, air would be pumped through a filter, which would stick to CO_2 and trap it. Releasing the

CO_2 would require heating the filter. This system has the distinct advantage that it might be possible to find all of the needed materials locally, since metal oxides make up a substantial fraction of the Moon's crust, and relatively little processing would be required. Therefore a metal-oxide based system will most likely be the first system that can be constructed locally.

A third possibility, which has been used on a few spacecraft such as the Skylab and Mir space stations, is to use a "molecular sieve" which physically strains the carbon dioxide from the air, rather than a chemical sorbent. The most common sieve materials are zeolites, crystal structures made primarily from aluminum and silicon, with small amounts of other elements such as calcium and sodium. This requires substantial processing and will probably not be done on the Moon for some time. Eventually, however, as the settlement expands, it may well become possible to produce molecular sieves on the Moon, and they may even end up becoming the filters of choice, if they require less energy input than the amine and metal-oxide methods.

Once the carbon is removed from the air, it must be stored in a reservoir of some kind. This could be simply a tank of compressed CO_2, but another possibility is to retrieve the oxygen and store either solid carbon or methane – the advantage being that the oxygen is then available for other uses. Converting carbon dioxide to methane is a simple, exothermic reaction known as the Sabatier process:

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$$

Obtaining hydrogen gas, of course, is a separate problem; but all of the hydrogen will later be retrieved along with the carbon when the methane is burned. A similar reaction, known as the Bosch process, converts carbon dioxide to solid carbon:

$$CO_2 + 2H_2 \rightarrow C + 2H_2O$$

Unfortunately, the Bosch reaction is less efficient, slower, and solid carbon is more difficult to transport and store. In any case, the form used for carbon storage will ultimately depend on the supply and demand for other gases in the base; but there are several possibilities.

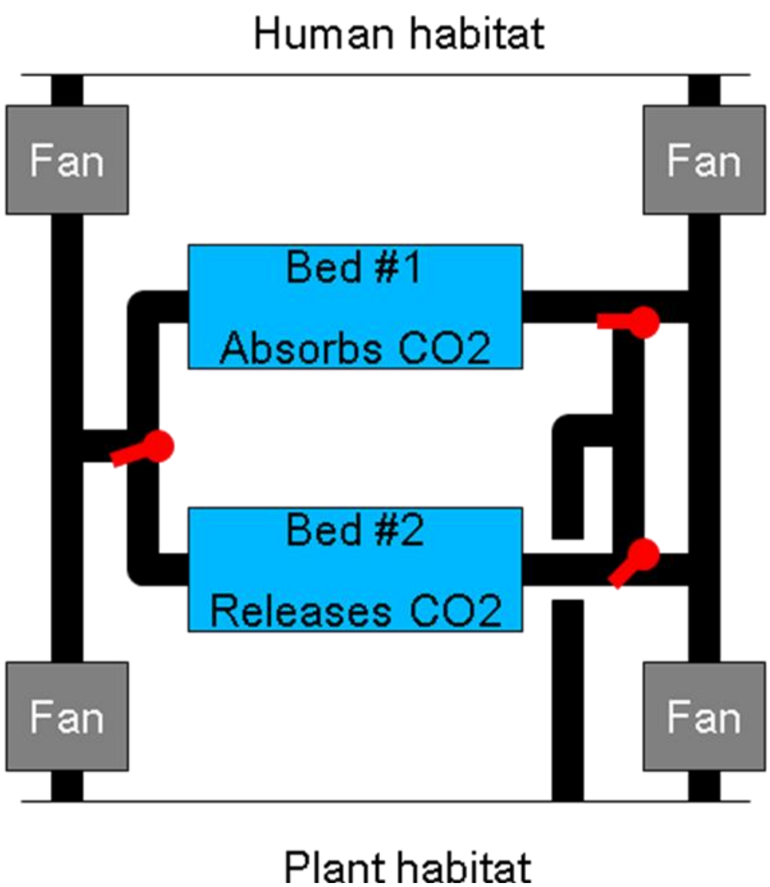


Figure 2 – Gas Exchange System

One final point worth mentioning in terms of the atmosphere is the level of CO_2 that will be supplied. It has been well established that increased CO_2 levels in earthly greenhouses can stimulate growth (Wong, 1979), but the relationship is not clear or well understood, and varies greatly from one species to the next. Current research with potatoes suggests that increased CO_2 levels will lead to faster growth but not to a substantially larger final product (De Temmerman, 2002). Faster growth, however, is exactly what is needed for a lunar base. The more quickly a potato can be grown, the fewer potatoes need to be growing at once in order to supply a given amount of food.

Sweet potatoes, in contrast, will apparently continue to grow larger and larger under increased CO_2 concentrations (Dempster, 2005). Different plants react differently, and each crop will need to be studied thoroughly to determine its suitability for growing on the Moon. Nevertheless, it seems clear that it will be possible, by manipulating the CO_2 level, to substantially improve the rate of production.

3.3 Soil Composition

The final issue that needed to be addressed in order to determine the feasibility of an agricultural system on the Moon is the composition of lunar regolith and how it differs from the soil found on Earth that is typically used for growing crops. Several elements that are vital to potato plant growth, such as nitrogen, phosphorus, and potassium (Peet, 2006), are not present or are only available in trace amounts in the upper layer of the lunar regolith (Prado, 2002). Although potato plants are known for their vitality and ability to survive in relatively harsh conditions on Earth (Peet, 2006), an attempt to grow these plants in a region of soil that lacked a sufficient amount of these key elements would prove to be “fruitless” (or in our case tuberless.) Thus, a method of either supplementing the lunar regolith with these elements or transporting a sample of soil from Earth needed to be considered.

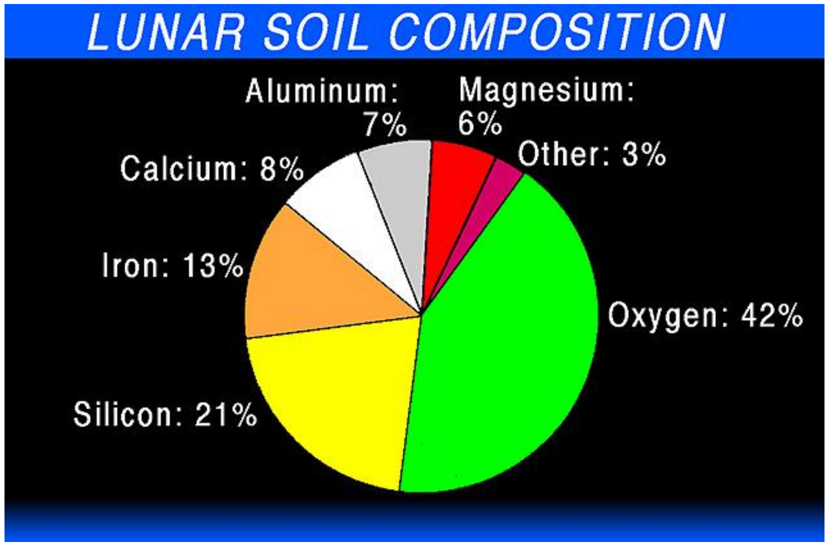


Figure 3 – Lunar Regolith Composition by Element Weight (Space Studies Institute, 2007)

Nitrogen could certainly be gathered in LEO, but the potassium and phosphorus would need to be imported from Earth. These elements could probably be shot into space by a mass driver or ram accelerator and later retrieved from orbit; since this would not be fragile freight, it would be able to withstand massive G forces.

In addition to the differences in the types and amounts of elements present in lunar regolith and Earth soil, differences in the texture and consistency of the two "soils" needed to be addressed. The upper layer of the Moon's surface has a dusty composition, while lower layers of the lunar regolith contain fragments of minerals and glass-like particles (Robens, 2007). Thus, any attempts at growing potato plants in the lunar regolith may prove to be completely futile, due to the dusty composition of the soil. One possible reason may be due to the roots of the potato plants not being able to grasp the soil and support themselves when growing. Another reason for the plants being unable to grow in the lunar regolith due to its consistency is that the water that would be used in irrigation may either turn the soil into a cement-like substance or not be able to be held near the roots by the particles in the regolith. Thus, the idea of transporting a sample of soil from the Earth's surface was considered to be a possible solution to this problem, due to the difficulties in converting the lunar regolith into a soil that is optimal for plant growth. However, it would certainly not be cost-effective to transport a massive quantity of Earth soil to the Moon.

By implementing a compost system, a significant amount of soil may not need to be imported from the Earth, and instead be recycled. However, since the Moon is in principle made of the same compounds as the mantle of the Earth, but Earth soil has been "processed" by the action of water, wind, plants, and animals, it is in principle possible to "process" it in a lunar rock-crushing and -sorting factory to approximate the right mix of minerals, particle sizes and the like, and add in the water and organics at the end. Then, real plants and animals such as worms can finish the "processing" of the soil.

One possible alternative for dealing with the issue of the composition of the lunar regolith and its possible effect on plant growth would be to implement a system of hydroponics in the lunar habitat. Thus, instead of requiring the lunar regolith to be a consistency and composition similar to the soil found on Earth, potato (and other) plants may instead be grown in a water solution containing all of the elements needed for optimal plant growth. While such a system may have other advantages, such as the ability to grow the same amount of potato plants in a smaller area in comparison with potato plants traditionally grown in soil, the implementation of hydroponics in a lunar habitat may be far more expensive and require a more significant amount of manpower than that needed by traditional methods of plant growth (University of Arizona, 2000). The method of using hydroponics would be considered a last resort, however, especially as it requires more water – a scarce resource – than is actually needed to do the same process on Earth.

It might make sense on a space station or long duration mission spacecraft constructed on Earth. However, in our opinion, it is currently not the right solution for lunar agriculture.

3.4 The Water Question

The problem concerning a lack of a substantial source of water on the Moon was to some extent related to the issue dealing with the differing soil composition found on the lunar surface. Since some scientists believe the Moon was formed from an Earth mantle whose surface had not yet cooled (Taylor, 1998), many of the compounds commonly found on the surface of the Earth are not naturally available on the Moon in substantial amounts. Just as elements such as nitrogen and phosphorus are only found in trace amounts on the lunar surface, only a small quantity of water is also believed to be present on the Moon. Although some scientists speculate that there may be sizable regions of water in the form of liquid and ice in the craters found on either of the poles, the majority of the water, like other trace elements on the lunar surface, is considered to be the result of solar winds and meteor or comet impacts (Cocks, 2002). Even if a significant amount of water was confirmed to be present on either of the Moon's poles, such an amount of water would most likely not be sufficient for supporting an agricultural system in a lunar habitat, in addition to sustaining all of the other needs of a human population.

Thus, in order to solve this problem, a supply of water (or the necessary elements for creating water) would need to be gathered in space or imported from Earth. Several possible methods for water delivery and recycling then needed to be considered in order to determine which method would not only be the easiest to implement, but also the least costly. One means for supplying water from an outside source would involve simply importing water either in liquid or ice form from the surface of the Earth. A ram accelerator would have to be built into the side of a mountain and devoted to shooting water and carbon, in the form of ice and dry ice, into space to meet the Moon's requirements. Due to the large cost of transporting water in this form to LEO much less to delivering it to the Moon, other methods for water delivery or production would need to be devised. This method should be a last resort, however.

A second method for water production would be implemented by mining hydrogen gas from the surface of the Moon deposited by the solar wind (Cocks, 2002) and combining this local hydrogen with oxygen extracted from lunar rocks. One of the major disadvantages of this method is that a fission or fusion nuclear reactor would most likely be required in order to provide enough energy to extract oxygen from the rocks found on the lunar surface. The method used to extract oxygen from the lunar rocks probably could not be solar-powered. Due to the small size of a starting human population on the Moon and the challenges and dangers involved concerning settings up a nuclear reactor on the Moon, this method of oxygen extraction may not be feasible for decades. To be truly self-sufficient, the reactor would need to be able to use the local nuclear fuel, Helium-3, as well, which is hard to get to fuse given the capability of current technology. On the other hand, deuterium and tritium reactions will most likely be available by 2040. We feel that Helium-3 will be a 22^{nd} century fuel rather than one in our proposed time frame for the initial implementation of an agricultural system (D'Souza, 2006).

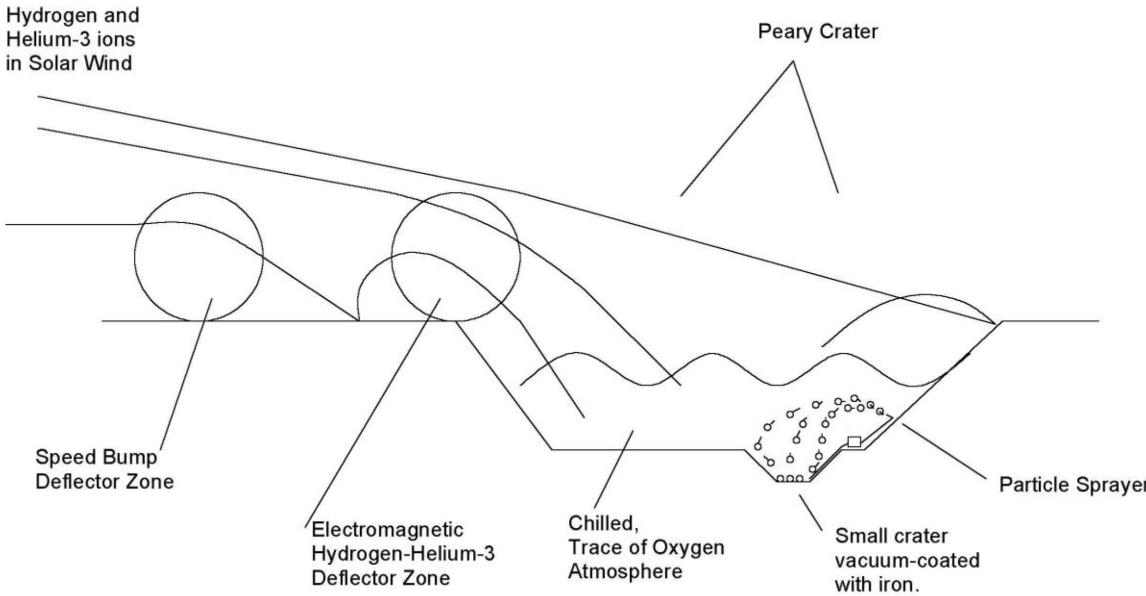


Figure 4 – Lunar Hydrogen Trap Prototype (Klinkman, 2007)

A third method for obtaining water for an agricultural system would involve the extraction of hydrogen and oxygen gas from LEO and a means for combining these two elements in order to create water. The water could then be delivered to the Moon in the form of ice. This method of water retrieval may prove to be the best choice. However, hydrogen is much harder to retrieve in LEO than oxygen. In the short run, before the inhabitants of a lunar base have built a nuclear reactor, a hybrid solution may be best. One such solution would involve gathering oxygen in LEO at approximately 325-400 km in altitude and turning it into liquid oxygen (LOX). Then, if hydrogen cannot be easily obtained to manufacture water in LEO, the LOX can be brought to the Moon. There it can be used to combine with hydrogen gathered from the regolith of the Moon, or trapped as it streams by the Moon on the solar wind. It is the same thing really; the hydrogen in the regolith was deposited there and trapped in the top meter of the regolith as it tried to pass the Moon on the solar wind.

Anything that disturbs the regolith will release it, so it must be in an enclosure, preferably one filled with oxygen, with which it would bind, to become relatively heavy and valuable water, before the regolith is disturbed. Each area of regolith can be "mined" this way only once.

In the long run, a sustainable water source will require gathering hydrogen from the solar wind on or near the Moon or capturing that which escapes the water-soaked Earth. The primarily-hydrogen layer of the Earth's exosphere starts at about 1000 km from the surface (Liwshitz, 1966). The dominant layers are nitrogen from sea level to about 300 km, then oxygen, helium, and hydrogen (Vercheval, 2003). As they are increasingly light and diffuse as one travels away from the Earth, hydrogen is the hardest element to gather from this source. On the other hand a balloon full of hydrogen is lighter than air, and with no load will rise naturally to about 30 km (Geerts, 1998). Since LEO starts at about 120 km, there may be some way to carry hydrogen that critical 90 km which could be devised. In any case, the key to lunar agriculture is water, and hence a hydrogen supply, given that there is a local source of oxygen once there is enough energy available to extract it. So, local ice is used first, then LOX is imported from LEO, and finally oxygen is locally produced. The question is where best to obtain hydrogen.

3.5 Lunar Habitat

In order for an agricultural system in a lunar environment to be feasible, a population of at least five hundred people should be present on the Moon. This number of people would provide the necessary labor pool to require and maintain an agricultural system, in addition to having the agricultural system starting to pay for itself. Once the human population living on the Moon increases and the size of the lunar plant-animal balanced habitat increases, more interior gas-sealed spaces may be able to be designated for agriculture.

Once it has been established that it is entirely feasible to grow potato plants on the Moon, other crops in addition to potatoes may be grown. Certainly other tubers such as sweet potatoes, carrots, and beets will follow rapidly. Then tomatoes and other fruits that do not require a tree, like strawberries and grapes, may be grown in order to provide a more diverse selection of fresh foods available in the habitat. Further advances in the development of the agricultural system could result in the growth of cereals and then another starch, such as corn or rice that is harder to grow than potatoes. Finally, fiber plants such as flax and cotton could be grown in order to allow the inhabitants of the colony to make their own clothing.

Although potato plants were chosen to be grown on the Moon and are able to support a lunar habitat due to the several essential vitamins and minerals present in potatoes (Ismail, 2002), an all potato diet is not very healthy. A vitamin supplement would most likely need to be administered to the lunar inhabitants in order to prevent diseases that would be caused by deficiencies in certain vitamins if other plants are not grown as well. In addition, while the agricultural system is in its initial stages of implementation, with a staple crop of tubers only it will be necessary for the lunar habitat to import food from the Earth so as to diversify the diets of the inhabitants. The point is that there would be luxury imports with health advantages.

The inhabitants of the lunar colony must be able to avoid starvation without imports from Earth if a calamity befalls the Earth and interrupts supply trips. The colony must be fully capable of supporting itself should a situation arise in which all contact with Earth has been disrupted for six months to a year—or longer. The lunar inhabitants would be the first human population at a remove from the Earth. Therefore, the Moon will be the “cradle” of off-Earth civilization, the Tigris-Euphrates River Valley of the shift toward an agricultural revolution in space. In case of disaster befalling the human population of Earth, the lunar colony must survive until it can repopulate the home planet.

4 Social Implications

If successful, devising an agricultural system for the Moon may have many social implications on Earth. There are numerous regions on Earth with harsh environments where it is difficult to implement a traditional agricultural system. For example, many of the deserts around the world are currently too dry to support vegetation, and there are many other climates such as the tundra that have relatively uninhabitable environmental conditions. Consequently, lunar agriculture could provide a blueprint for growing plants in such harsh environments. Growing agriculture on the Moon presents a far greater level of harsh conditions for plant growth. Therefore, if it is possible to grow plants on the Moon it should prove to be much easier to grow plants in harsh conditions on the Earth.

The social implications of the technologies being researched for lunar agriculture would have significant social implications on Earth. If developed, the Bionic Leaf could be used to exponentially increase the level of agriculture production on Earth, since it could operate at the poles or the Sahara Desert. Moreover, the gas exchange system that is being developed for the lunar base could be used in underground facilities on Earth.

A Moon base also leads to other unique societal implications. Agriculture on the Moon would allow for a permanent Moon base. The idea of people eventually living on the Moon for long periods of time, or even for an entire lifetime, would be one step closer to becoming reality. This presents the possibility of an entirely new society developing on the Moon.

A Moon base would also have a significant impact on public interest in NASA and the space program. With a lunar base proven to be feasible, the idea of extending space colonies to other planets in the future could be considered. Thus, the implementation of a lunar agricultural system could be the catalyst that ignites interest in further deep space exploration where supplies from Earth could not be counted upon.

5 Conclusion

After examining past and current research in a variety of areas related to lunar agriculture, we feel fairly confident in stating that not only is it feasible for a lunar settlement to be self-sustaining, but it may well be possible using current technology. This conclusion came as something of a surprise to us, given that our project began as a study of a theoretical agriculture system centered around the bionic leaf. Considering how little information we could find about the bionic leaf concept, we were initially at a loss as to how to proceed. If large-scale lunar agriculture requires a technological breakthrough that no one has even heard of, we assumed we were dealing with something far off in the future. When the same idea was presented to a panel of NASA experts, their consensus was that while the bionic leaf described was theoretically possible, it would not be developed until the “late” time frame (2035 to 2050.)

We came to realize, however, that there were other ways of obtaining the necessary energy -- solar-pumped lasers, and later, simple concentrators -- that already exist and are being actively developed. At the same time, we also realized that the bionic leaf concept presented to us could be substantially improved by creating it in the form of a factory rather than thousands of individual leaves. While impractical at present, we feel this “factory” concept is likely to be developed sooner, and once developed will help to make lunar agriculture much easier. On the other hand, a prior IQP team seems to think a self-replicating system to build solar collectors is possible in the time frame we see for the bionic leaf (Webster, 2006). If so, we suggest that the idea of thousands of leaves each capable of supporting one potato plant at a time, but thousands over time, does not look so outlandish for the next century.

It should be clear from the preceding pages that constructing a lunar agriculture system will not be easy. Many of the technologies we have discussed are still in the early stages of development. They are under development, however, and they have ten years or so to mature before we will need to use them on the Moon.

It should also be clear that our concept of lunar agriculture is one possibility, and we feel it is currently the most feasible one, but it is not the only possibility. From energy, to soil and atmosphere, to the basic material requirements of the system, we have found validation of the engineering principle that “there's more than one way to do it.” These decisions will depend on which of the technologies become cheapest, easiest to use, and most reliable.

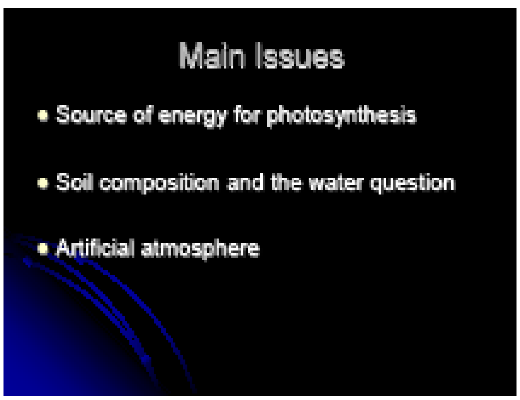
When humans next set foot on the Moon, perhaps ten years from now, it seems a virtual certainty that they will bring plants with them. Ten years from then, people living on the Moon may very well be relying on locally-grown food for much of their diet. Ten years from then could also see thousands of people living in fully self-sustaining lunar colonies -- humanity's first steps into the universe beyond. At that point the demand for a bionic leaf will be great and one will probably be invented. After that, humanity will experience its second agricultural revolution.

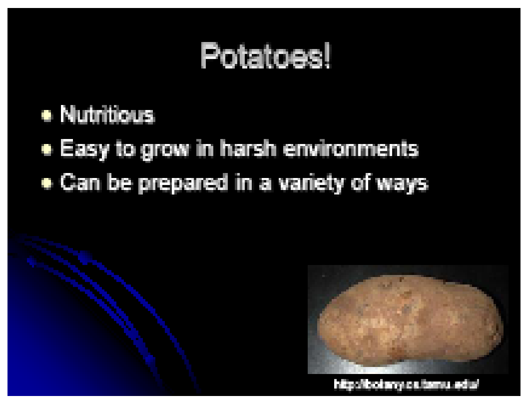
Appendix A

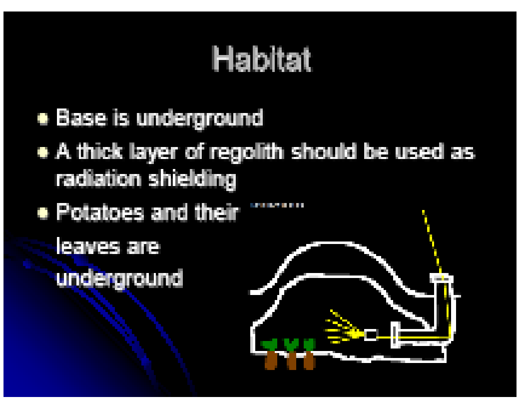
The following slides were presented at the 2007 International Association for Science, Technology and Society Conference on February 2, 2007 in Balitmore, MD. This presentation outlined our initial problem in determining the feasibility of a self-sustaining agricultural system on the Moon and described the challenges of implementing such a system.

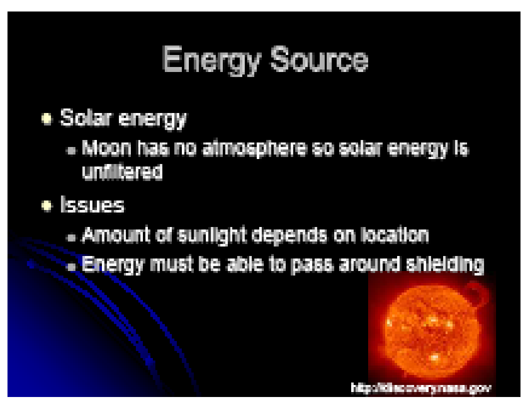

Sustaining Agriculture on the Moon
Rob Groezinger
Ben Moody
Christopher Songer


Goals
Self-sufficient
Not reliant on Earth for majority of food
Can survive if supplies from Earth are cut off
Trade System
Helium-3 for resources
Other necessary supplies


Main Issues
Source of energy for photosynthesis
Soil composition and the water question
Artificial atmosphere


Potatoes!
Nutritious
Easy to grow in harsh environments
Can be prepared in a variety of ways


Habitat
Base is underground
A thick layer of regolith should be used as radiation shielding
Potatoes and their leaves are underground


Energy Source
Solar energy
Moon has no atmosphere so solar energy is unfiltered
Issues
Amount of sunlight depends on location
Energy must be able to pass around shielding

Solar Energy Sources

- Conversion of solar energy to electricity to power grow lights
- Bionic Leaf
- Solar pumped lasers
- Mirrors focus light into a concentrated beam

Solar to Electricity

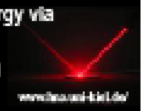
- Pros
  - Established technology
  - Large amounts of silicon in regolith
  - Electricity has additional uses
- Cons
  - Inefficient

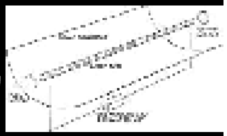
Bionic Leaf

- Pros
  - Highly efficient
  - Passes around radiation shielding
- Cons
  - Does not exist…yet
  - Experts predict it will take at least 50 years to invent

Solar pumped lasers

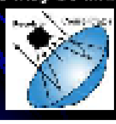
- Pros
  - Can be used to redirect solar energy via satellite
  - Passes around radiation shielding
  - Long range
- Cons
  - Currently inefficient
  - Not a mature technology

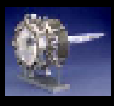




Solar Concentrators and Mirrors

- Pros
  - Simple
  - Established technology
  - Passes around radiation shielding
- Cons
  - Range may be limited



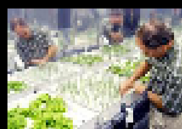


Soil Composition

- Lunar regolith lacks significant amounts of certain elements needed for plant growth.
  - Nitrogen
  - Phosphorus
  - Potassium
  - Microorganisms
- Consistency of regolith may not be ideal.

Hydroponics

- Lack of suitable soil for plant growth would not be a concern.
- Less water may be needed in relation to soil irrigation.
- May take up less space in the lunar habitat.



The Water Question

- Water is not guaranteed to be present on the lunar surface.
  - Possibility of lunar ice caps.
  - Trace amounts of water due to comet/meteor impact or solar wind.
  - Even if present, may not be sufficient to support a lunar habitat.

The Water Question

- Water may be transported from another source at first.
  - Transported in ice form.
  - Hydrogen and oxygen transported in gas/liquid form.
  - Hydrogen on lunar surface
  - Majority of lunar rocks are oxides
- Water could be later filtered/recycled in order to lessen dependence on other sources.

Potatoes in Space!

- Potatoes grown in microgravity are not much different compared to Earth-grown potatoes.
- Potato plants are known to be able to survive in arid environments.
- Changes in water usage, environment temperature, etc. may be used to optimize potato growth.

Artificial Atmosphere

- We also need to provide the proper mixture of gases for plant growth
  - Supply carbon dioxide
  - Remove oxygen and water vapor
- At the same time, we can recycle the carbon dioxide exhaled by humans.

Requirements for Gas Exchange

- Must allow storage and retrieval of carbon dioxide
  - Dumping it into space is not sufficient!
- Must be regenerable
- Must allow fine-tuning of the rate of CO_2 uptake and release

Existing Systems

- Lithium hydroxide filter
  - Easy to use, no power required
  - Absorbs CO_2 by reacting irreversibly
  - Non-regenerable
  - Doesn't allow CO_2 retrieval

Existing Systems

- Shuttle RCRS (amine sorbent)
  - Regenerable, but works by releasing CO_2 into space

Possible Alternatives

- Metal oxide or amine sorbent using a heater
  - Requires energy to retrieve CO_2 (but not to absorb it)
- Molecular sieve
  - Requires energy both to collect and release CO_2
- Sabatier or Bosch reactor
  - Requires hydrogen

Gas Exchange System

- CO_2 is filtered from the plant and human atmospheres
- Appropriate mixture of gases is returned to each
- Nitrogen and oxygen are passively exchanged

Summary

- Self-sufficiency is possible!
- Technology 20 years from now will probably be adequate
- More research is needed into certain technologies
  - Bionic leaf
  - Solar-powered lasers
  - Carbon dioxide filtering systems

Summary

- Feasible for 500+ inhabitants
- However, constructing the base will require a large amount of material that is not present in large quantities on the Moon
  - Carbon
  - Nitrogen
  - Hydrogen
  - Trace elements
  - Microorganisms

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