Power Generation on the Moon

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Abstract

The goal of this report is to examine three different power sources, and to determine which is the best suited to running a lunar base. The examination consisted of a literature review, followed by an analysis of the three different sources. The scope of this report was limited to technology available in 2006, though consideration is given to future possibilities. This report determines that nuclear power is the best solution, though at a polar site solar power is a possibility.

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Chapter 1: Introduction

Space Exploration

On April 12th 1961, Yuri Gagarin of the former Soviet Union was the first man in space. Since then hundreds of launches have taken many more astronauts to space, and some even to the moon. At this time many speculated it would not be long before a colony on the moon would be established. Now, almost 45 years later, there is still no progress towards establishing a lunar base. In fact, current plans dictate that it will be at least another 15 years before even a small base is established.

Why is there so much focus on a lunar base? Since Yuri's first space flight, space has been seen as the next "frontier." With large amounts of overcrowding, and dwindling resources, humanity needs a means of expanding. Space is clearly the only direction, and the moon is seen as a stepping stone towards the goal of even greater expansion. If we can establish a working base on the moon, it will not be terribly difficult to apply the same ideas to establishing bases on other planets. Some teams have already started looking at other planets, namely Mars which is being considered as a location for a base by the Mars Homestead project.

Space Policy IQP Collaboration

In order to work towards something as complex as a lunar base, many factors regarding space and the base need to be considered. Some of these include financial considerations, social implications, and the technological aspects of designing and constructing a base. This is the second year in which Worcester Polytechnic Institute has had a collaborative effort among students with the goal of examining these considerations, and thus furthering space exploration. This report is one of fifteen this year from this collaboration being run by Professor John M. Wilkes.

Project Goal

The goal of this project as a whole is to address an issue pertaining to the possible future of space exploration. As the moon becomes a possible “stepping-stone” to further distances in the universe a permanent lunar outpost will be required. In order for this lunar base to be self-sufficient and permanent, the base will require a permanent source of energy. The goal of this project is to decide which energy source currently used on the earth would be the most feasible option for a future lunar base. This goal will be obtained through extensive literature review in such areas of lunar properties and specific details pertaining to the chosen energy options.

Study Methodology

The development of the project will begin with a discussion of the possible energy requirements of the lunar base that the energy source would have to provide to power the lunar base. Within this energy requirement discussion, the best estimates as to the energy requirements will be given. After the energy requirements are established, energy sources that are utilized on the earth will be discussed in terms of their basic operations and system types. If it is found that any particular energy sources will obviously be of no significant use on the moon then the discussion of these energy sources will be limited to the reasoning of their ineffectiveness. Once the choices for the energy production system have been established, a set of evaluation criteria will then be developed. These evaluation criteria will be the factors compared between the chosen energy sources in order to give a clear and quantitative analysis.

Once the evaluation criteria have been discussed there will be a link developed between the evaluation criteria and the energy options. This link will be a detailed analysis of the energy sources in relation to each of the evaluation criteria. Once the criteria-specific information is gathered, a summation of the findings will be provided. Once the energy sources have been evaluated in relation to the evaluation criteria they will then be evaluated in a manner comparing each of the sources to another through the evaluation criteria. In order to compare the energy sources a series of decision making matrices is formed. The matrices will quantitatively compare the impact of each of the evaluation criteria on the particular energy sources. Once the matrices are analyzed a solution will be apparent. The most feasible energy option for the future lunar base will be clear.

After the goal of the project has been defined, a decision as to the most feasible energy option and a discussion on future technologies will be provided. The purpose of this discussion is to provide a bit more information into the future of technologies such as other energy systems or energy transfer techniques that may be established by the time the lunar base project is underway. The introduction of this discussion is important because even though the discussed technologies are beyond the scope of this project they may still become relevant in the future.

Chapter 2: Lunar Base Energy Requirements

2.1 Introduction

A major factor that must be taken into consideration, as the planning for a lunar base moves forward, is the issue of power generation. In order for a crew to remain on the moon for an extended period of time, there must be a permanent source of power generation. Past lunar expeditions have used stored energy sources such as batteries in order to power equipment, but a lunar base requires a permanent energy source. The consideration of the total amount of energy that would be required to be produced on the lunar surface enables a deeper analysis of possible energy sources. If a goal is set for the energy production then more specific figures can be taken into consideration for the different energy sources.

In order to determine the amount of energy production required for a lunar base, it is necessary to break down the base into its main components; otherwise it may be quite difficult to approximate the energy requirements for the base as a whole. Therefore, the analysis of the energy requirements begins with a moderately detailed discussion of the components of the lunar base. Once the components are described, the energy requirements for each component are addressed in terms of where the figures came from along with any assumptions made in the approximation of the figure. After evaluating the specific energy requirements, another important factor pertaining to these requirements is discussed. This other factor is the location of the lunar base; whether the base will be located near the lunar equator, lunar pole, or some other significant location on the moon. It is necessary to discuss the location of the base in relation to the energy requirements because the location of the lunar base can affect the amount of energy production required as well as which energy source is the most feasible.

2.2 Lunar Base Components

In order to determine an energy requirement, the composition of the lunar base must first be provided. The first permanent lunar base will house approximately eight to ten crewmen for an extended period of time. Therefore, this initial lunar base will have to accommodate the everyday lives of these crewmen as well as the various activities on the lunar surface. Energy requirements will have to be determined for living quarters and research facilities, as well as operations facilities.

In order to break the composition of the lunar base down into fragments a previous IQP (Le, 2005) will be considered. This study outlined the development of the lunar base as it described its main components and the progression that the base would undergo in the future. The author provided a flow chart, as shown in Figure 1, outlining the major aspects of the lunar base, primarily the components. Therefore, these components are considered in the estimate of energy requirements.

In the flow chart, the lunar base is broken down into the main categories of “Habitat” and “Operations”. Within these categories, the most significant subsections, in terms of project relevance, are considered. It is not necessary to discuss each section because the flow chart does not outline the energy needs, but it outlines the base as a whole. Therefore some of the sections are not components of the base, but rather they are system properties of the base. The subsections that are considered are as follows: life support, industrial activities, and research labs. Under the industrial activities the categories of mining, manufacturing and transportation are considered.

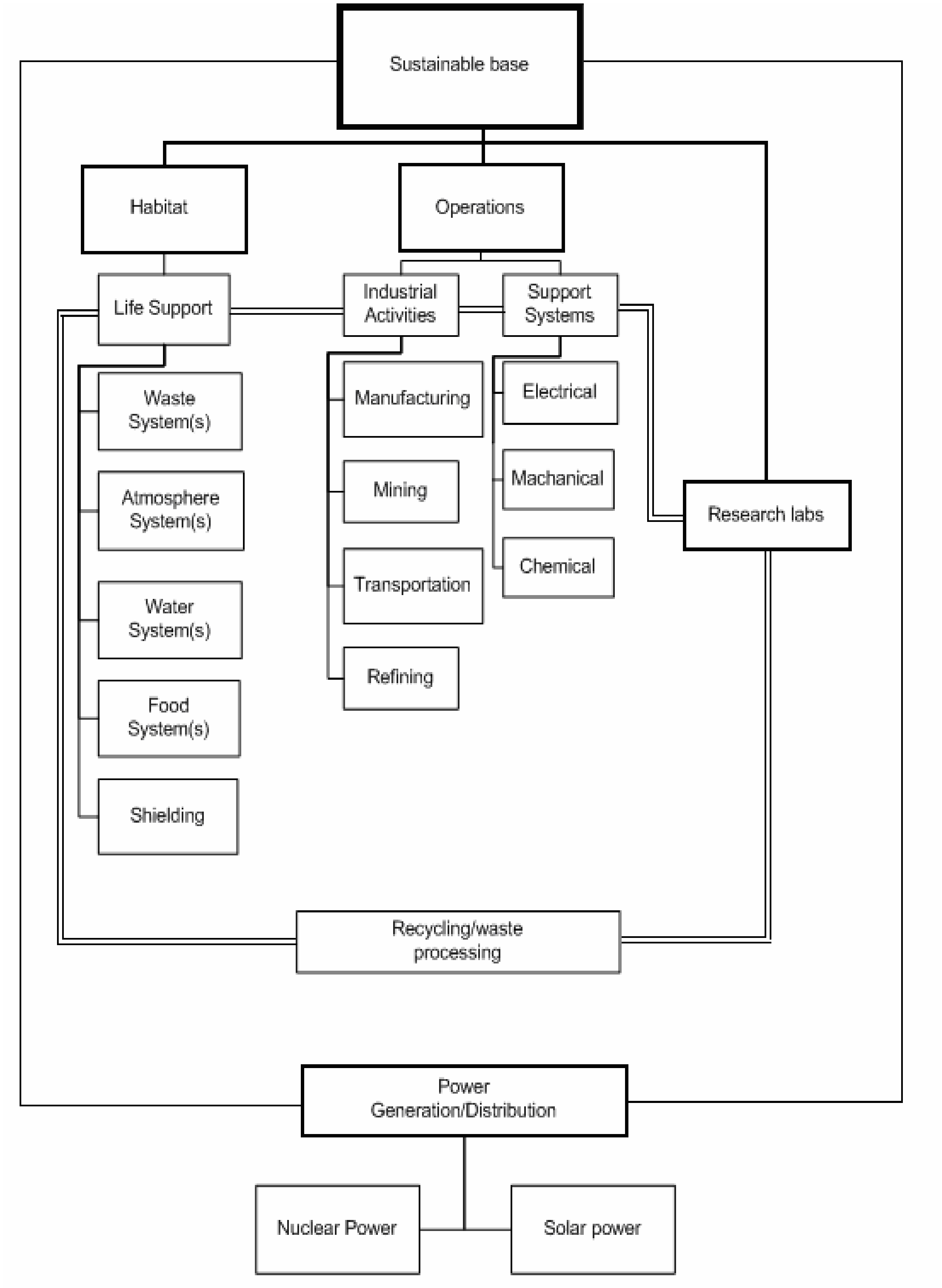


Figure 1: Functional Composition of the Lunar Base, (Le, 2005)

Habitat and Basic Equipment

The basic components of the lunar base can be considered to be the transportation equipment, communications equipment, shielding equipment, and the base modules for living quarters and research facilities. Transportation equipment can consist of vehicles to be used outside of modules for transport of people or materials around the lunar base. Within this transportation category, one could also include the equipment used for activities outside of the modules, such as robotic equipment, which can be combined together and called EVA, or extravehicular activity, equipment. The living quarters and research facilities will most likely consist of inflatable or deployable habitats for convenience and ease of assembly and will also include shielding equipment to prevent any harm from occurring due to the solar winds. Within the modules, energy will be required in order to power basic appliances and commodities within the living quarters and extensive research equipment within the research labs.

Life Sustaining Operations

More complex portions of the lunar base can be referred to as the life sustaining operations. These life sustaining operations consist of the more complex systems of the life support system and the thermal control system. The first system consists of oxygen and water production and refinement facilities as well as agricultural growth facilities. The second system is just that, a system operating in order to control the extreme temperatures on the lunar surface. If the temperatures were not controlled then human life could not exist within the lunar environment.

Mining Equipment

The energy requirements for the mining equipment will be based upon an estimate of the required energy for a lunar mining rover that was designed by The University of Wisconsin. This rover, called the “Mark-II Miner”, would theoretically have the ability to pick up an amount of lunar regolith and heat it until the (^3He) can be separated from the rest of the minerals as “it was shown that over 85% of the helium-3 could be removed from ilmenite by heating it to 700°C”. (Univ. of Wisconsin, 2005) Along with the (^3He), the miner would also theoretically have the ability to separate other products such as oxygen, hydrogen, nitrogen, carbon dioxide, and helium. These additional products would aid in the production life support systems and fuel systems.

Manufacturing Facility

Manufacturing on the moon is an activity that would most likely take place as the lunar base becomes permanent, but it is beyond the scope of this project to determine the products that would be manufactured. It would be difficult to discuss the manufacturing facilities because the operations on the moon would be entirely different than those on the earth, which is due to the fact that the moon has only one-sixth of the gravity that the earth has and thus, new technologies will be needed in the future. Though it is unknown as to what exactly the crew would be manufacturing, an assumption is made that the energy requirements of the small manufacturing facility and equipment would be approximately within the same degree of magnitude as that of the mining operation.

Possible Lunar Base Expansion

Though this project is based on an initial lunar base with eight to ten inhabitants, the expansion of the base must also be considered. It is obvious that the base will begin as a small establishment, but it will only be a stepping stone to a much larger view. The ultimate plan for the lunar base is to become a lunar colony with as many as five hundred inhabitants at any one time. Therefore, due to the expansion, higher energy requirements will have to be considered as the number of habitat and research modules will greatly increase as well as the amount of equipment and operations in progress on the lunar surface.

2.3 Lunar Base Component Energy Requirements

Now that the components of the lunar base have been established the requirements can now be discussed in more detail. In order to provide an approximation for the energy requirements of the lunar base, figures are considered from different sources. There is little literature about the main specific aspects of the lunar base that are considered in this report. Energy requirement estimates most usually focus on the base as a whole. One exception is “The Lunar Base Handbook”, (Eckart, 1999), which broke down the base into its many components and provided a large number of scenarios and figures of mass and energy requirements for different energy sources and locations on the moon. The information of Table 1 is an approximation from a bar graph of the energy requirements and mass of the basic lunar base.

Lunar Surface Transportation Equipment	~2 kW
EVA Equipment	~1 kW
Communications Equipment	~5 kW
Shielding Equipment	~1.5 kW
Lunar Base Modules	~16 kW
Total base energy requirements	25.5 kW
Thermal Control System	~37 kW
Life-Support System	~17 kW
Total life sustaining energy requirements	53.4 kW
Mining Equipment (^{3}He)	200 kW
Manufacturing equipment	~200 kW
TOTAL Lunar Base Energy requirements	**~478.9 kW**

Table 1: Approximated Initial Lunar Base Energy Requirements. (Sources: (Eckart, 1999, Figure 23.15), (University of Wisconsin, 2005))

Possible Future Expansion

The energy requirements of Table 1 are for an initial lunar base consisting of approximately eight crew members. This must be revised once the base begins to expand. With the assumption that the base should not expand much greater than to a maximum of five hundred inhabitants, an approximation of the energy requirements can be formulated. Considering that the number of modules and equipment will grow at a faster rate then the manufacturing and mining facilities, the factor is not estimated to be a direct proportion, but rather the requirements will increase at a slightly slower rate than the number of inhabitants. Rather than increasing by a factor 62.5 (8→500) as the population could, energy requirements are expected to increase a bit slower, at an approximate ratio of 50. This increase provides an approximate level of energy requirements around the area of 25 MW.

2.4 Lunar Base Location

A major issue that one must consider when assessing the lunar base and its primary energy source is the location of the base. At different points of the moon, in fact, there are different intensities and durations of sunlight, which could inhibit the production level of an energy source, such as solar energy. In general, the typical location of the base can be found in the equatorial and polar areas that provide the most extreme differences in conditions on the lunar surface. Each location will require different considerations as to energy systems.

The basic lunar conditions that change according to the location of the base are the temperature, length of day, resources, and the orientation to the sun. Due to the moon's lack of an atmosphere there is a great range of temperatures with a maximum surface temperature of 123 degrees centigrade and a minimum of -233 degrees centigrade. (Solar Views, 2005) The length of the lunar day is important because, unlike the earth, the moon rotates about its axis at the same rate as it revolves around the earth, which gives the lunar day an average length of 29.53 days. (Solar Views, 2005) The main difference in the levels of resources on the moon comes when considering the possibility of water being on the lunar surface. The extreme temperatures listed above would be too high for the existence of any water or water ice as it would have evaporated long ago. The orientation to the sun is important when considering the use of solar energy for energy production as the density of the sunlight varies at the different locations.

The most extreme of conditions come at the equator of the moon. At this location the terribly high temperature is due to the lack of atmosphere as well as the orientation of the equatorial area to the sun due to the fact that the sunlight at the equator comes in a straight line due to the minimal tilt in the axis of rotation of the moon. Also, at the equator the length of the lunar day is as stated above, approximately 29.5 days with the day being split into a daytime and nighttime with each having a length of approximately 14.7 days. Due to the high temperatures at the equator there is almost no possibility of having any form of water at this location.

At the lunar poles the sunlight is at an angle to the lunar surface, eliminating the effect of direct sunlight that the equatorial sites have to endure. Due to this difference in sunlight intensity the temperatures at the poles are considerably lower for a maximum and higher for a minimum. Researchers have found several areas in close proximity to the poles that are “bathed in perpetual sunlight” (BusinessWeek, 2005) such as the location, identified by researchers at Johns Hopkins University, “high up on the rim of the Peary crater” (BusinessWeek, 2005). “The site averages a balmy -60F, compared to the -300F typical of lunar nights. And the Peary crater’s basin is cloaked in endless shadow, increasing the chances of finding frozen water there.” (BusinessWeek, 2005) Due to the lower temperatures and the perpetual shade at the crater basin there is a far greater chance for the existence of areas of water ice on the lunar polar surface. There is also a great difference in the length of the lunar day, at least for some locations at the poles. Therefore, the Peary Crater, as shown in Figure 2, would be an ideal location for a solar dependent lunar base.

Peary Crater

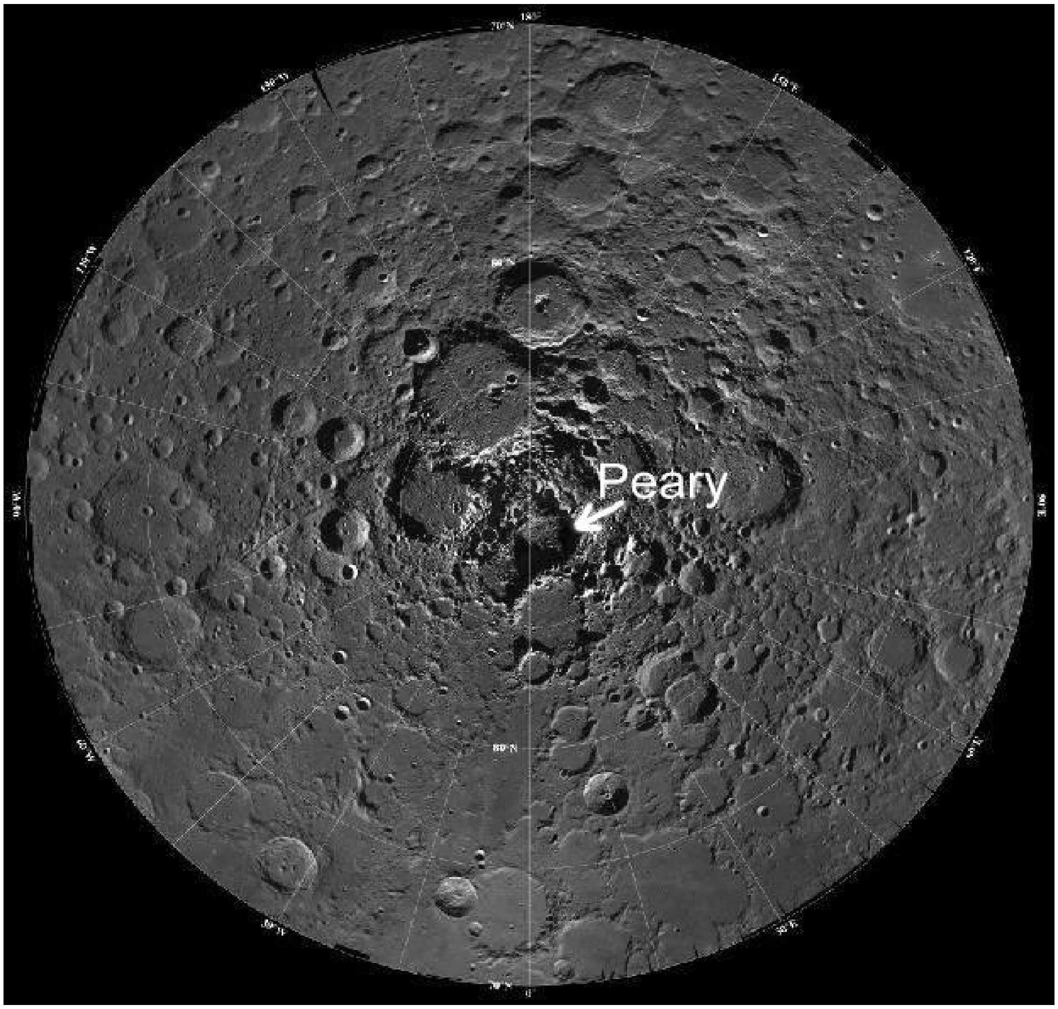


Figure 2: The Peary Crater near the Lunar North Pole

As stated above, the main differences between the two locations are the temperature and length of day time. At the poles, the chance for isolated areas of water ice, due to less extreme temperatures, pushes the choice of a polar base. Also, if the base were located at the pole the solar energy source would then be viable due to the perpetual sunlight. Solar energy would be less viable at the equatorial sites due to the need for a backup system to power the base during the lunar night. The importance of the location of the lunar base is that the different conditions may put limitations on which energy source may be the optimal source. It may be found that the optimal energy source may not be able to be applied at the optimal lunar base location. Outside of the discussion of the energy sources, the optimal lunar location may also be a location of great mining resources such as (^3He) which forces the consideration of travel to and from mining sites that may be at great distances from the established lunar base. Therefore, the optimal energy source depends on the optimal location for other operations as well as the desired conditions on the moon.

2.5 Conclusion

This chapter encompasses the initial ground work for the evaluation of the type of energy source for the lunar base. More specifically an approximate amount of energy requirement of the lunar base has been defined. These requirements reflect the various components of the considered base. Beyond the initial base, an expansion of the base has also been considered as it is highly expected to expand as the purpose of the base goes beyond being a research facility. In the future, the lunar base is expected to grow to become a lunar colony and eventually a tourism site where people will pay to travel to the moon.

Chapter 3: Lunar Base Energy Options

3.1 Introduction

The goal of this chapter is to provide a better understanding of each of the energy sources that will be considered in the later analysis that will determine the most feasible energy option for the lunar base. In each of the following sections, one for each energy source, the basic information pertaining to the operation of the systems as well as the different types of systems are discussed. It is important that the reader understand how each of the energy sources operate in order to get a better grasp on the complexity of using the energy sources to power a lunar base. Once the general use and operation details are discussed it is important to address the different types of systems that are used in order to generate the specific types of energy. This table is necessary because each system is different and may have significant advantages and disadvantages that may affect the later analysis. Knowing about the different types of systems will allow for the choice as to which of the systems will be the most advantageous for use on the lunar surface when particular attributes, such as size or weight, differ between the systems.

Therefore, the basic information provided in this chapter is meant to do just that, give basic information about the energy sources. Once the basic information is presented it may be possible to eliminate one type of system used to produce a particular energy source. One example of this would be the discussion in Section 3.2 about nuclear powered ships. The discussion about nuclear powered ships is significant because it lays out some preliminary details pertaining to a smaller-than-commercial nuclear reactor. Also, in Section 3.3, the discussion pertaining to the different types of solar panels presents the significant weight and area coverage differences for the different types of solar cells. As size and area do matter in this analysis, these details are rather significant.

3.2 Nuclear Fission

The purpose of this section is to provide a certain amount of background information on nuclear fission in order to allow a better understanding of the analysis to follow in chapter 5 of this report. In order to fully understand the feasibility analysis that will follow it is deemed to be necessary to understand the basic operation of each of the energy sources as well as typical applications of the energy sources on the earth.

Nuclear energy was first discovered in the late nineteenth century when Marie Curie and her husband made the discovery of radiation. Though the concept of nuclear energy was theorized when radiation was discovered, it was not until much later, nearly a half century, that scientists developed techniques to harness the power of nuclear energy.

Nuclear Fission Operations

Nuclear energy comes from breaking apart the high strength bonds in the nuclei of atoms. Due to the strength with which these bonds are held together, there is a tremendous amount of energy released when the bonds are broken. If these reactions can be controlled, they can be strung into a chain reaction that produces incredible amounts of power for us to harness. If they are not controlled, however, the end result is a nuclear bomb. The most commonly used atoms as fuel for nuclear fission are different isotopes of Uranium and Plutonium, such as uranium-233, uranium-235, and plutonium-239. (Glasstone, 1981)

The energy released by the nuclear fission reaction is thermal energy. Therefore in order to make use of this thermal energy for electrical applications, the thermal energy must be converted. The most common process used in order to convert the thermal energy into electrical energy is the use of a nuclear reactor. Within this reactor the thermal energy released by the reaction will heat a fluid, most usually water. The water, or other fluid, then boils and becomes a hot gas that will be used to pass through a turbine and make it spin. As the turbine blades spin they are attached to an electrical generator that will produce electrical energy, therefore converting the thermal energy to electrical energy.

Nuclear Fuel Cycle

The nuclear fuel cycle consists of a series of stages in which the fuel of a nuclear reactor will pass through during its time of use; from the mining of ore to the final disposal of waste. Figure 3 is a schematic of the general nuclear fuel cycle, including the different options taken after the fuel is used. These options consist of reprocessing the spent fuel for further use or going right to final disposal.

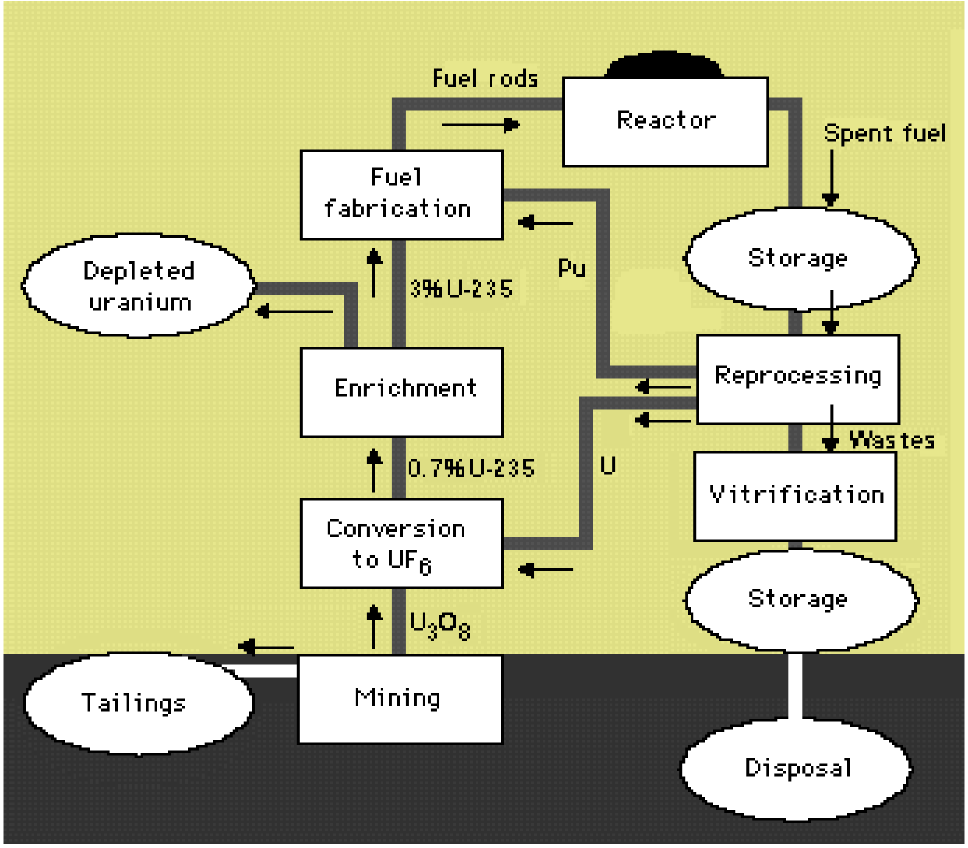


Figure 3: Nuclear Fuel Cycle Representation (UIC, 2004, briefing 65)

As with fossil fuels, the first stage of the nuclear fuel cycle is the mining of uranium. There are three main methods of mining being used today: open pit mining, underground mining, and in situ leaching. (Bodansky, 2004, pg.197) The choice as to which method is used depends on the environmental and economical issues at hand, such as the depth of the ore and the cost of the mining process. Open pit mining is primarily used when the uranium ore is no deeper than 120m under the earth's surface. Underground mining is primarily used when the uranium ore is too deep to reach by the open pit method. In situ leaching (ISL) is a process in which oxygenated water is circulated through a very porous ore body in order to bring the uranium ore to the surface. (UIC, 2004, briefing 65)

After mining is completed, the mined ore must be milled. Milling is the process of separating the uranium from the mined ore. When first mined, the uranium ore may contain as little as 0.1% uranium. After milling the remaining product usually consists of 80% uranium. The milling produces a uranium oxide product that is known as "yellowcake" (UIC, 2004, briefing 65). The process of milling is performed through leaching as a strong acid or a strong alkaline solution is used in order to dissolve the uranium from the ore, which is later precipitated in the solution. The remnants, or tailings, of the milling process are discarded, usually in the mined out open pit.

Before the milled materials can be used as fuels they must first be converted into a form that will allow them to be enriched more easily. The conversion begins by chemically altering the milled product to form uranium dioxide, which is then converted into uranium hexafluoride. The uranium hexafluoride is then ready to go through the process of enrichment.

Enrichment is the process of separating the two isotopes of the uranium product. Uranium consists of U238 and U235, but the U235 is the only isotope of the uranium that is fissile, or able to be used as a nuclear reactor fuel. The process of enrichment removes a large percentage of the U238 in order to increase the percentage of the U235 within the product as a higher concentration is required for the use as a fuel. The product of enrichment is enriched uranium hexafluoride, which is then reconverted into enriched uranium oxide. (UIC, 2004, briefing 65)

Following enrichment, the uranium oxide, with a new higher concentration of U235, goes through a process called fuel fabrication. In this process, the uranium oxide is pressed into ceramic pellets through sintering at high temperatures. The pellets are then encased with metal tubing in order to form nuclear reactor rods. The sizes of the pellets and rods are case-specific for each individual reactor type.

The nuclear reaction continues in the nuclear reactor until a point is reached where the concentration of usable U-235 has decreased and the concentration of fission fragments is too great for normal operation. At this point the nuclear reactor is shut down in order to remove the spent fuel. The spent rods are removed and placed in a storage pond where the water will help to contain the radiation as well as dissipate the heat. The used fuel will be held here until it is ready for permanent disposal or reprocessing.

Once the spent fuels are removed from the reactor there are two operations that may take place. The spent fuels can either all be treated as waste and disposed of permanently or it can be recycled, reusing some of the spent fuel. Spent fuel contains about 95% U-238, but it also contains a small percentage of U-235 and plutonium that have not fissioned. The spent fuel can be reprocessed, which is the separation of the components of spent fuel; U-238, U-235, plutonium, and fission fragments. The U-235 and plutonium are recycled and sent back through the conversion and enrichment stages. (UIC, 2004, briefing 65)

The disposal of remaining spent fuels consists of two main steps. First of all, the spent fuels go through a process called vitrification in which they are encased with a large amount of Pyrex glass and then an outer layer of stainless steel. After the vitrification, the nuclear waste capsule will be disposed of in deep geological repositories. Though there are no repositories operational as of yet, there are several in planning stages. Therefore, all spent fuels are stored at this point and have yet to be permanently disposed of.

Nuclear Fission Reactors

In today's production of electrical energy by nuclear fission, there are two prominent types of reactors being used. The light water reactors "account for 88% of the world's present generating capacity and 85% of the capacity nominally being built or on order." (Bodansky, 2004, pg.177) The light water reactor is a reactor in which water is used as both the moderator and the coolant. The fuel for the light water reactor (LWR) is enriched uranium in UO2 pellets. There are currently two types of light water reactors in use: the pressurized water reactor and the boiling water reactor, as shown in Figure 4 and Figure 5.

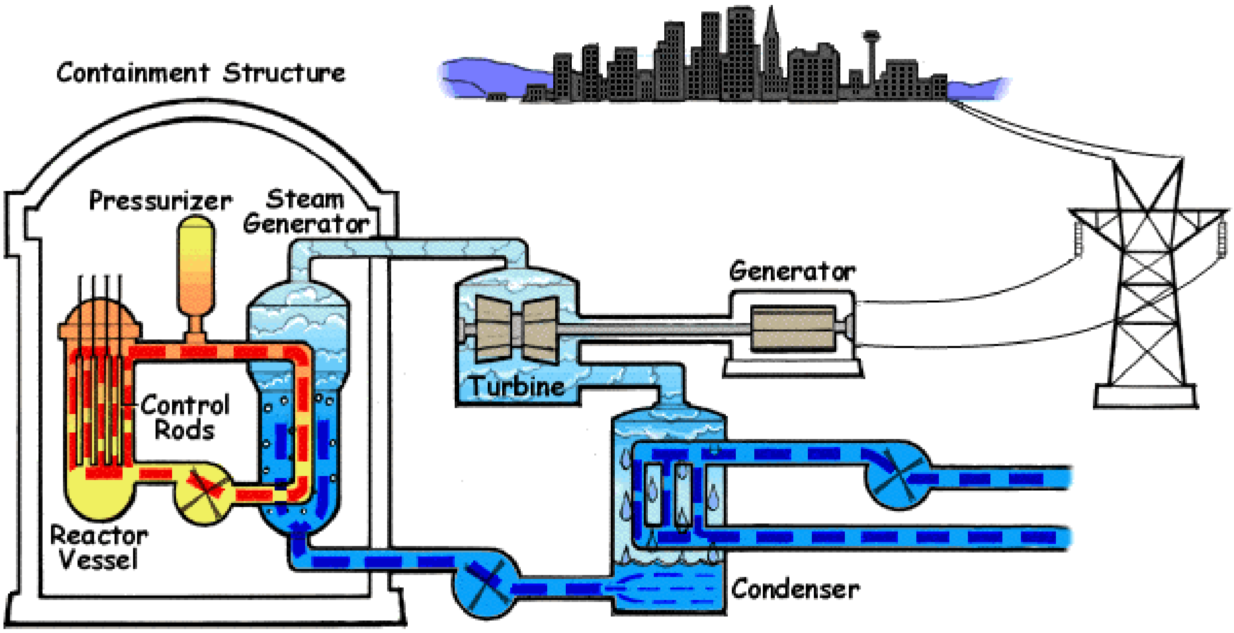


Figure 4: Schematic of the Pressurized Water Reactor (nrc.gov, 2005)

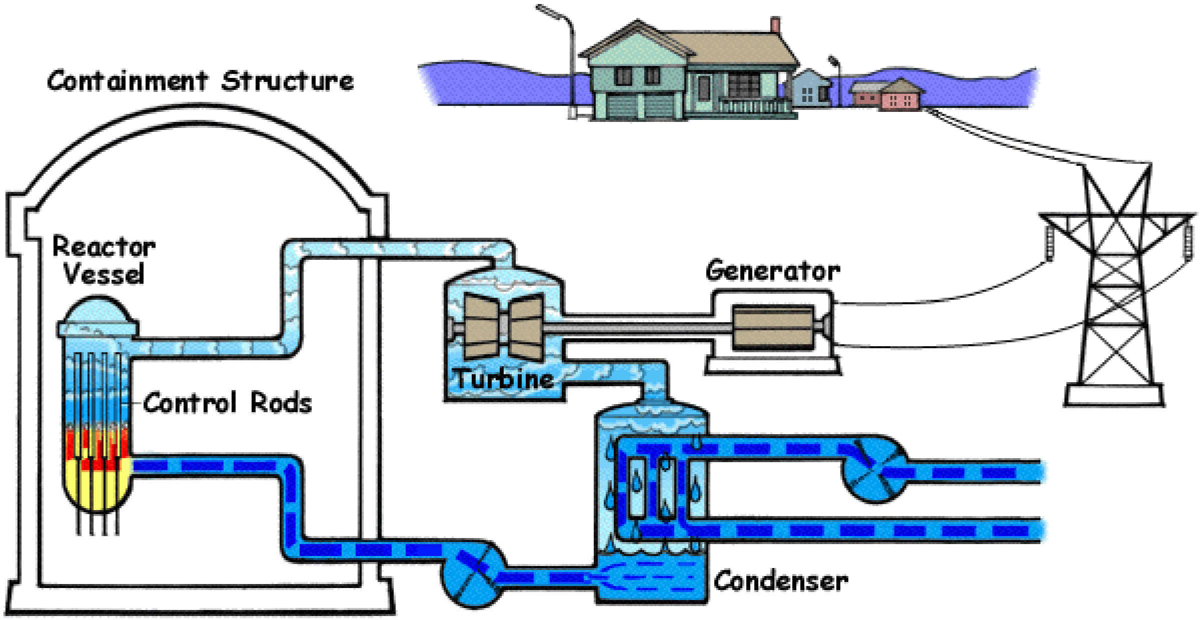


Figure 5: Schematic of the Boiling Water Reactor (nrc.gov, 2005)

These two light water reactors are very similar in that many of their main components are the same. The general setup of each reactor is the same, with minor differences in the operations. One can see that in the pressurized water reactor, the control rods containing the nuclear material are not in direct contact with the water like in the boiling water reactor, rather there is a steam generator in use that uses the thermal energy in the pipes of the reactor vessel to heat the water. The boiling water reactor foregoes the steam generator and uses the water in contact with the control rods by boiling that water to turn the turbine.

Civil Applications of Nuclear Energy

Nuclear power was first harnessed in the 1940's as the production of nuclear weapons was underway during war time and was not used for civil purposes until the 1950's. The main civil use of nuclear power is the production of electricity. The ultimate purpose of nuclear energy in the civil market is to replace the need for irreplaceable fossil fuels and to eliminate the negative side effects of the consumption of fossil fuels, such as pollution and global warming. Through the production of nuclear energy in the past few decades, numerous countries rely on nuclear energy for a great deal of their overall electricity production, altogether, the world now relies on nuclear energy for 16% of its electricity needs. At this current time France relies on nuclear energy so much as to produce approximately 78% of its necessary electricity through nuclear energy. (UIC, 2005, briefing 7)

Though the supply of uranium for nuclear energy production is not limitless, it is still considered to be in great abundance in numerous countries such as Canada and Australia. Nearly every country involved in the use of nuclear power has some level of capabilities to mine and mill uranium, but the countries of Canada and Australia lead the world. The sum of the uranium mining and milling in the countries of Canada and Australia makes up nearly one half of the world’s total mined product as these countries mine for their own use as well as the production of a lucrative export.

Through the utmost necessity of having nuclear power due to the lack of fossil fuels, France has developed an ideal nuclear energy program over the last three decades. France is entirely capable of converting, enriching, and fabricating its own supply of nuclear fuel. France also has large scale capabilities to reprocess their spent fuel as well as provide for long-term storage for waste disposal. Beyond the production of the fuel, France has perfected its nuclear reactor systems as they have standardized their development far more than any other country. Each of France’s 58 units is one of three sizes of pressurized water reactors (PWR’s) and all were designed and produced by the same company, Framatome. Considering France’s success in the development and production of high quality nuclear reactors, France has begun to export their PWR’s to such countries as South Africa, China, and South Korea.

Nearly every country with a stake in nuclear energy is in the process of planning a location for a final repository for spent fuel. The United States is the only country with plans approved and is set to proceed in the near future, approximately 2010. The location that the United States government has chosen is a deep geological site called Yucca Mountain located in Nevada. In this deep depository, the spent fuel supplies will be encased in so-called “casks” and sent down a shaft into the mountain for storage, and for possible retrieval in the future if reprocessing is desired.

Nuclear Powered Ships

Nuclear reactors on nuclear powered ships are substantially smaller in size and weight than commercial nuclear reactors. Therefore, the use of a nuclear reactor similar to the reactors used on nuclear powered ships will lessen any issue of size or weight for the lunar reactor. The use of nuclear energy to power ships was first utilized in 1955 with the commissioning of the USS Nautilus, a nuclear-powered submarine. The use of nuclear power in submarines allowed for weeks of underwater travel without surfacing and a great increase in power output. The United States expanded the use of nuclear reactors in naval vessels when the USS Enterprise, an aircraft carrier, was powered by eight pressurized water reactors in 1960. The U.S. also commissioned cruisers with two nuclear reactors. At this time the U.S. has 11 nuclear powered aircraft carriers.

Along with Naval vessels, Russia has taken advantage of nuclear power in civil vessels such as icebreakers. This allowed the ships to go prolonged periods without refueling as it would be difficult for fueling ships to get to locations that the icebreakers were working. The nuclear power also gave the ships a great power output for more effective icebreaking. The nuclear fleet has allowed for marine travel in the arctic to increase from 2 months out of the year to 10 months and has allowed for year-round access to the Western Arctic.

From 1955 until the end of the cold war in 1989, there were nearly 400 nuclear powered ships built or in stages of construction. After the cold war there was a large amount of decommissioning of nuclear powered ships, but to this day there are still 160 naval and civil ships powered by nuclear energy. To this day, the United States has logged 5500 accident-free reactor years of experiences compared to Russia's 6000 reactor years with accidents in the early years of production. (UIC, 2005, briefing 32)

The main differences between marine and civil nuclear reactors are as follows:

- they deliver a lot of power from a very small volume and therefore run on highly-enriched uranium (>20% U-235, originally c 97% but apparently now 93% in latest US submarines, c 20-25% in some western vessels, and up to 45% in later Russian ones),
- the fuel is not UO_2 but a uranium-zirconium or uranium-aluminum alloy (c15%U with 93% enrichment, or more U with less - eg 20% - U-235) or a metal-ceramic (Kursk: U-Al zoned 20-45% enriched clad in zircaloy, with c 200kg U-235 in each 200 MW core),

- they have long core lives, so that refueling is needed only after 10 or more years, and new cores are designed to last 50 years in carriers and 30-40 years in submarines (US *Virginia* class: lifetime),
- the design enables a compact pressure vessel while maintaining safety. The Sevmorput pressure vessel for a relatively large marine reactor is 4.6 m high and 1.8 m diameter, enclosing a core 1 m high and 1.2 m diameter.
- thermal efficiency is less than in civil nuclear power plants due to the need for flexible power output, and space constraints for the steam system.

(UIC, 2005, briefing 32)

3.3 Solar Energy

Solar energy has been utilized for power generation for over 50 years. Solar energy research and production has come about as a reaction to growing global energy and pollution concerns. With supply of crude oil, and natural gas diminishing, and greenhouse gasses increasing, people are turning their attention towards alternative energy sources. Solar cells while once incredibly costly and inefficient, are very rapidly becoming a viable source for energy as a result of the extensive research that has taken place over the past 2 decades.

Applications

Solar cells first saw widespread use in small devices, such as hand-held calculators. These devices require very little power to operate, so by putting a small solar cell in it removed the need for batteries. As they became a more efficient energy source, photovoltaic cells began seeing use in larger applications. Some common applications are for exterior devices, such as lights or pumps. In the case of lights, a battery is charged from the cell by day, then running the light at night. More and more frequently people are putting small solar arrays on their roofs in order to cut their electric bill. Some areas even offer tax breaks and rebates for those installing their own small solar arrays. Another application of solar energy is heat generation. Rather than turn the light into electricity, this method runs water in behind black panels, which heat the water, thus heating homes among other things.

The application where solar energy has seen its greatest use is in the aerospace industry. Almost all satellites, space probes, space stations, and landers are powered primarily by solar energy. This is primarily due to the lack of light interference in space. On the earth, the atmosphere reflects a high amount of solar radiation, approximately 30-60% depending on location and weather. This is not the case in space, where solar radiation travels unhindered.

Method of Collection

Solar energy can be harvested in multiple ways. The most widely known and used method involves use of photovoltaic(PV) cells. These cells use semi-conductive materials that generate current in the presence of irradiant light. The other method of using solar power for energy generation involves using an array of mirrors to concentrate the irradiant light to a point where water can be boiled, then used to drive a turbine in much the same way modern power plants generate power. A similar method that is now drawing attention involves using mirrors to focus light onto a small stirling engine, which creates movement directly from heat. SoCal Eddison currently has plans with Stirling Energy Systems to build two large scale desert based solar plants off of this concept. The proposed dishes will be 40 feet tall each, and will be capable of producing 25 Kilowatts apiece. At a claimed 30% efficiency, these arrays will give conventional photovoltaic cells serious competition. The two proposed plants will be 300, and 500 Megawatts. (Wade, 2005).

Advantages/disadvantages of solar energy

Solar energy has a number of advantages and disadvantages. The biggest advantage that it offers is that it can be safely assumed that it will never run out. With petroleum reserves gradually dwindling, this is a very promising prospect. The other advantage is that solar energy creates no harmful byproducts or pollutants, making it very safe for the environment. Also, while not yet incredibly cheap, solar cells are less expensive compared to some other forms of power plants, and with research steadily progressing, the cost of solar cells is expected to continue to drop fairly consistently. Photovoltaic cells also have no moving parts, which reduces the amount of maintenance that is required (Solar Experts, 2005).

Solar energy, while clean, cheap, and indefinite, still has several significant downsides. The most clear disadvantage is that photovoltaics will not work without sunlight. This makes them useless at night time, or when the weather is particularly bad. The other clear disadvantage, is the area necessary to generate a meaningful amount of electricity. Solar power plants take up incredibly large amounts of land area, and are thus limited in their locations. The least obvious downside to solar cells is lifespan. Most photovoltaic cells only last about 20 years. The need to replace the cells every 20 years is not something to take lightly.

Photovoltaics

Photovoltaic cells are made up of semi-conductive materials, and conductors to generate current from sunlight. The irradiant light hits the semi-conductive material releasing an electron, which then travels down the conductors, thus generating useful current. There are many different materials used as the semi-conductor for producing photovoltaic cells. Among these different materials, there are also many different production methods. Each different material and production method has its own advantages and disadvantages.

The most common material used in modern photovoltaic cells is pure silicon. This material is used so commonly due to its abundance in nature, the lack of harmful chemicals required to create the cells, and the ease of manufacturing. Silicon, most commonly found in silicon oxide (sand) makes up approximately 1/3rd the earth's crust (Lenardic, 2005). This silicon needs to be refined into pure silicon before it can be used. Once it is refined, there are numerous ways of manufacturing it into photovoltaic cells. Silicon can be made into monocrystalline, polycrystalline, or amorphous cells. These descriptors describe the basic structure of the silicon inside the cells. Monocrystalline cells are presently the most efficient of the silicon cells. They range in efficiency from 15% commercially available to 24% in lab tests (Solar Experts, 2005). Polycrystalline cells, while being less efficient have the potential to be made as thin ribbons, lessening production costs, and easing implementation. These cells have efficiencies between 14% and 18% (Solar Experts, 2005). Amorphous silicon like polycrystalline silicon can be made more easily than monocrystalline silicon, but at the moment the efficiency and lifespan of amorphous silicon cells is significantly less than either the mono or polycrystalline cells (Lenardic, 2005).

Aside from silicon, there are numerous other materials commonly used in PV cells. These include gallium arsenide, cadmium telluride, and copper-indium-diselenide. Like silicon, these each have their own advantages and disadvantages. Gallium arsenide cells are typically used in space applications due to their extremely high efficiency, up to 30% (Lenardic, 2005). The downside to these cells is that they are costly to produce due to the chemicals involved, and the relatively low abundance of the necessary materials. Cadmium telluride cells have the advantage that they can be produced as thin films with efficiencies demonstrated in labs of up to 16%. The disadvantage of these is the poisonous chemicals involved with their production. Copper-indium-diselenide cells, similarly to cadmium telluride cells, can also produce thin films with efficiencies around 17%, however due to incredibly difficult processing, these cells don’t see frequent use (Lenardic, 2005).

Other potential PV cells include compound cells where multiple different cells are stacked to absorb a wider spectrum of sunlight, and polymer cells which are made entirely of polymers. These two technologies are still highly experimental, and neither has demonstrated high enough efficiencies to be yet commercially viable.

The next big decision when it comes to choosing a specific technology, is what form it will be used in. This choice comes down to typical hard cells, or thin film technology. Thin film technology is easier to produce, and is lighter, but is usually about half as efficient as the best hard cells. Thin film cells are about 1/100th the thickness of conventional cells dramatically reducing weight and material cost (Energy Conversion Devices, 2005).

Other Considerations

Unfortunately photovoltaic cells can not just be set in place alone. In most instances they need mounting hardware to go with them, and in many cases they need rotational equipment as well. The rotation equipment allows the array to angle itself towards the sun as the sun moves across the sky. This allows the array to always be collecting the maximum amount of sunlight. Without rotary equipment, a stationary cell is significantly less efficient.

3.4 Fuel Cells

Fuel cell technology is one of the options for power on the lunar base. This section introduces the basics of fuel cell technology, possible fuel cell options and Table 2 comparing the characteristics of some of the fuel cell options. The fuel cell options discussed are Alkaline, Direct Methanol, Molten Carbonate, Phosphoric Acid, Proton Exchange Membrane and Solid Oxide Fuel Cells.

Fuel Cells Basics

Most fuel cells take in hydrogen and oxygen to produce heat, electricity and water. A typical fuel cell system consists of the fuel stack, the fuel processor, current inverter, conditioner and the heat recovery system.

The fuel stack contains large numbers of individual fuel cells. Fuel cells are combined into a fuel stack because each individual cell does not generate much energy; only on the order of a few watts each. Therefore they must be combined into a stack in order to generate a significant amount of energy.

A fuel cell consists of the cathode, the anode, and the electrolyte. The anode hosts the proton element, the cathode hosts the supplementary element and the electrolyte allows the components to exchange atoms. Generally the anode side of the fuel cell contains hydrogen, while the cathode side contains oxygen. The electrolyte acts as a platform for anode and cathode to interact and react so the energy conversion can take place. Fuel cells are generally named after their electrolyte element.

The fuel processor or reformer processes the fuel into its components, usually hydrogen and oxygen. The fuel used depends on the fuel cell system, such as methanol for the direct methanol fuel cell.

An external reformer is necessary if the fuel cell system runs at low temperatures. This is because a fuel cell system that runs at very high temperatures can purify the fuel internally because of the high heat. So for low temperature fuel cells, an external reformer is required for purification of the fuel. The catalyst used in external reformers is usually made from platinum. Because of platinum's characteristics, it is very expensive to obtain, especially one of extremely high purity. Due to the high cost of platinum, there are many companies that are investigating alternatives to the platinum catalysts. QuantumSphere is one of the companies doing research and development on alternatives to using platinum catalysts. They have “developed a nano nickel material that costs only a quarter as much as platinum.” (Gartner, 2005) If and when QuantumSphere can perfect this advancement, it would lower costs for manufacturers and consumers.

When the fuel is processed by the fuel cell, energy is generated in DC currents. The purpose of the current inverter is to convert the DC current into AC current. This conversion is necessary because AC current is easier to transport and easier to use. The conditioner adjusts and controls the current and voltage, which need to be set and controlled at specific values for usage.

The heat recovery system is not always used in a fuel cell system. However, for the fuel cell systems that operate at very high temperatures, incorporating a heat recovery system is useful for converting the excess heat into more energy, thereby increasing efficiency.

Fuel Cell Types

Alkaline Fuel Cells. These cells are the most reliable option for fuel cell technology, since they are one of the oldest and the most developed of the fuel cell systems available. Figure 6 shows the energy process of an alkaline fuel cell.

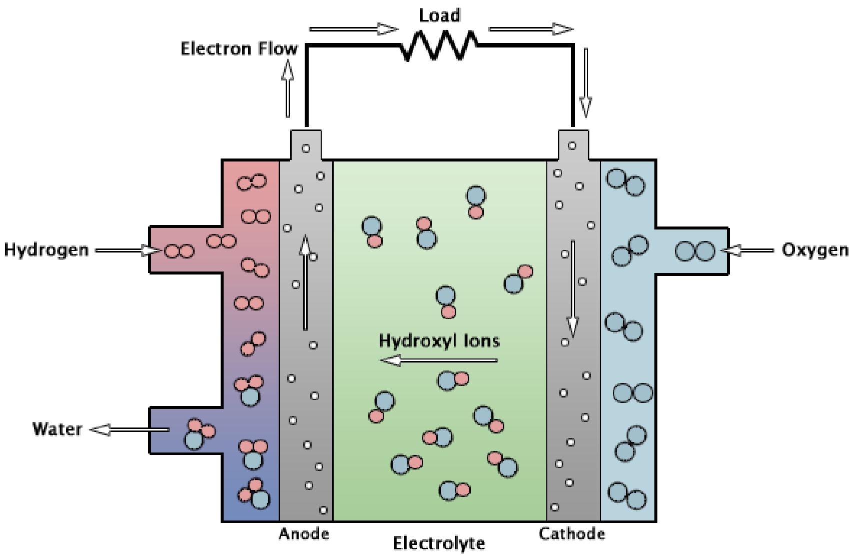


Figure 6: Alkaline Fuel Cell.

Alkaline fuel cells were used for the Apollo missions to produce water and electricity. These cells take in hydrogen and oxygen to produce electricity and drinkable water. They use a solution of alkaline potassium hydroxide as the electrolyte. Alkaline fuel cells can run between large ranges of temperatures, from (60 – 70 °C) or at approximately 200 °C, depending on the system setup. The advantage of running at a low temperature is that the system can start quickly, however because of this same reason, alkaline fuel cells requires the use of a catalyst. The latter causes the anodes and cathodes of the fuel cell to react with each other. The catalyst used in external reformers is usually made from platinum; however because alkaline is a noble metal, it is not necessary to use platinum as the catalyst. Alkaline fuel cells do, however, require pure hydrogen and oxygen for fuel since the system does not tolerate contamination from carbon dioxide. Carbon Dioxide contamination may lead to poisoning of the system, which would greatly shorten the lifespan of the system. Alkaline fuel cells can have efficiencies up to 70%, so their use on the moon would greatly conserve the amount of fuel wasted. Because of the solution used in alkaline fuel cells, the cathode reacts faster with the anode in the electrolyte, thus allowing alkaline fuel cells to generate higher performance

Direct Methanol Fuel Cell. This type of cells uses pure methanol as fuel to produce water and carbon dioxide. DMFC have efficiency of about 40%. Even though its efficiency is lower than most fuel cell systems, DMFC have a redeeming factor of using methanol, which has a higher energy density than hydrogen. Another factor is liquid methanol is easier to transport than compressed hydrogen cylinders. Direct Methanol Fuel Cells runs from 50 – 100 degrees Celsius. The low temperature would generally mean the system needs platinum catalysts for the reformer, but because “the anode catalyst itself draws the hydrogen from the liquid methanol”

(Fuel Cell 2000, 2005), it eliminates the need for a fuel reformer. The low temperature and the advantage of not requiring a fuel reformer mean that it would be useful for mobile applications.

Molten Carbonate Fuel Cells. This type of fuel cells consists of "a molten carbonate salt mixture suspended in a porous, chemically inert ceramic lithium aluminum oxide ($LiAlO_2$) matrix" (U.S Department of Energy, 2005). Molten Carbonate Fuel Cells can achieve about 60 – 80% efficiency. This type of fuel cells runs at over 650 °C, which has its advantages and disadvantages. The advantage is that cost is reduced because there is no need for an external reformer for the fuel. However, the high temperature and the impurity of the materials accelerate the wear and corrosion of the system. Also the high temperature needed to start the system means there will be a delay in starting the system. As shown in Figure 7, hydrogen interacts with oxygen in the carbonate solution to extract energy and carbon dioxide.

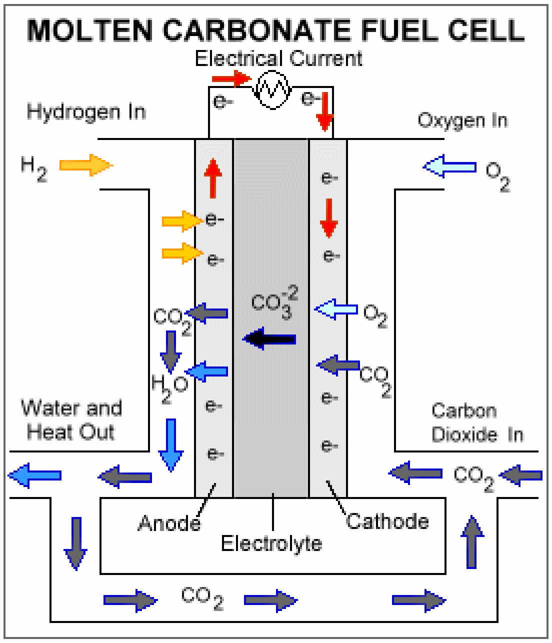


Figure 7: Molten Carbonate Fuel Cell
(Source: www.eere.energy.gov)

Phosphoric Acid Fuel Cells. These cells are also one of the oldest and most researched fuel cell technologies, they use hydrogen and oxygen as fuel and liquid phosphoric acid as the electrolyte. Because of the properties of phosphoric acid, PAFCs can use impure hydrogen as a fuel source. PAFCs require inputs of hydrogen and oxygen, and output water and carbon dioxide. Although these cells produce carbon dioxide, the amount produced is much less than that of a conventional combustion automotive engine. Phosphoric Acid Fuel Cells run at about 150 - 200°C with approximately 37 – 42% efficiency, but with a heat recovery system, they can run at about 85% efficiency. Because of the relative low temperature of the system, PAFCs require an external reformer, which means it would need platinum catalysts. Partly because of the catalyst, "a typical phosphoric acid fuel cell costs between $4,000 and $4,500 per kilowatt to operate" (U.S Department of Energy, 2005). The advantage of this low temperature system is its ability to start faster than those that need to be run at high temperatures. The main disadvantage of PAFC is that it has a low power density compared to other fuel cell technologies.

Proton Exchange Membrane Fuel Cells. These cells also use hydrogen and oxygen as the anode and cathode, respectively. Figure 8 illustrates how a PEM cell works.

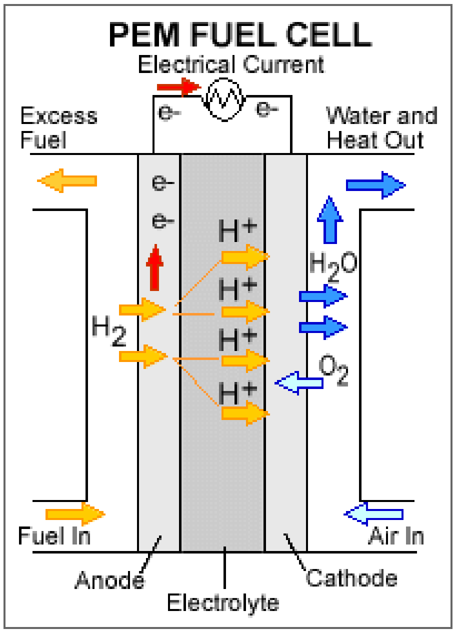


Figure 8: PEM Fuel Cell
(Source: www.eere.energy.gov)

“The electrolyte used is a solid organic polymer poly-perflourosulfonic acid” (Fuel Cell 2000, 1), this allows the fuel cell to produces only energy, heat and water as a result of the reactions within the cell. These cells run at approximately 80 degrees Celsius and can achieve 40 to 50% efficiency. PEM fuel cells can generally output up to 250 kW. Because of the low temperature they run at and their high power density, these cells are suitable for automotive applications. Again however, the down fall of the low temperature of operation is that these cells also require platinum catalysts for the reformer which drives up the cost.

Solid Oxide Fuel Cells. These cells use hard ceramic material for the electrolyte instead of a liquid solution like most fuel cells. The ceramic material used is usually made of zirconium or calcium oxide. Similar to most fuel cell system, SOFC run on hydrogen and oxygen. Figure 9 shows how a solid oxide fuel cell works.

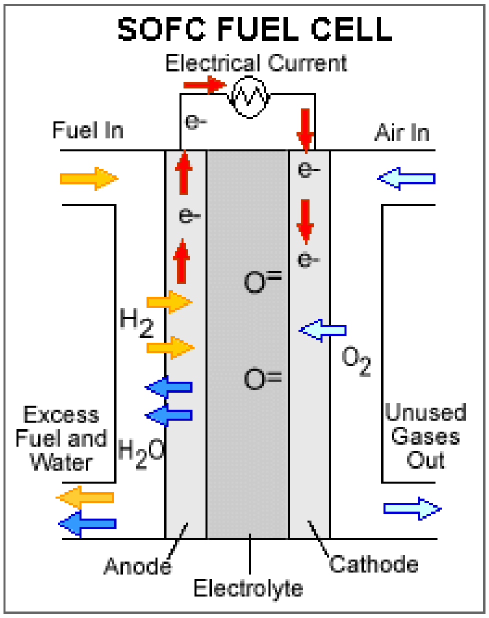
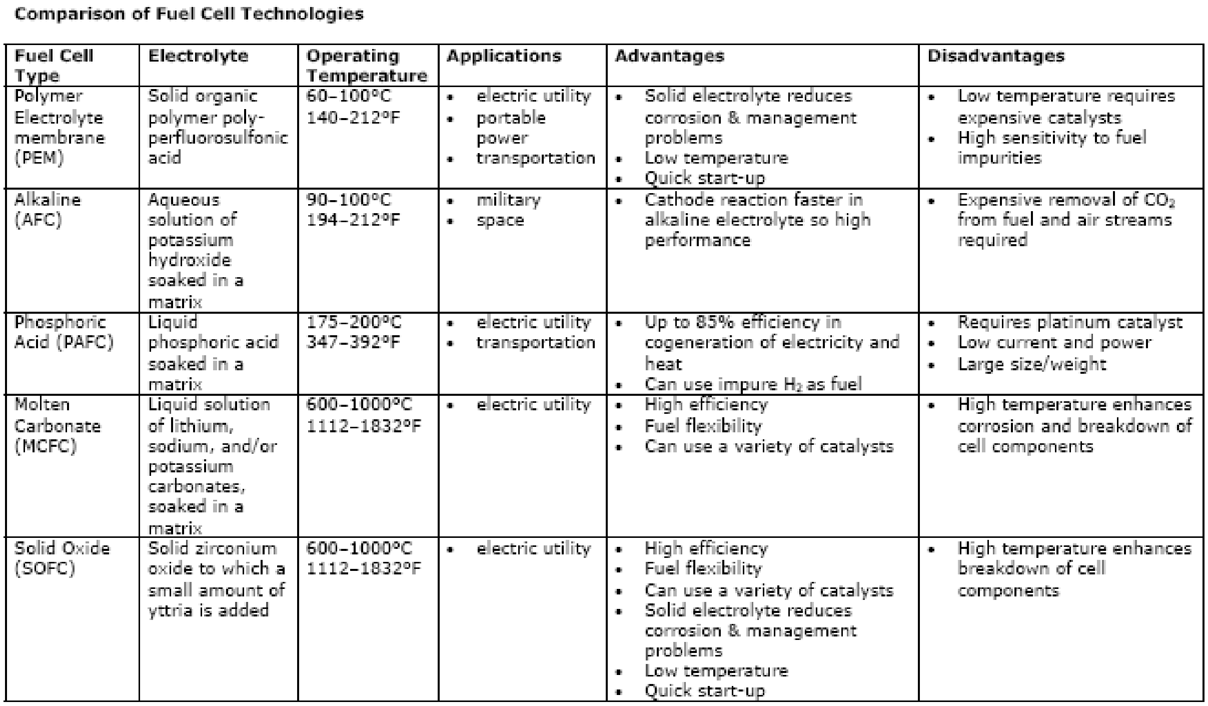


Figure 9: Solid Oxide Fuel Cell
(Source: www.eere.energy.gov)

By running at roughly 1,000 degrees Celsius, SOFC has both advantages and disadvantages. The advantage is that it does not need an external reformer, thereby saving on cost. The system however has a slow startup time. Also, the system would need a great deal of thermal shielding to protect people from the heat. However, the high temperature can also be useful for supplying heat. High system temperature also reduces durability of the system. SOFC have efficiency of around 50-60 percent and with the addition of a heat co-generator can reach efficiencies of 80-85 percent.

Summary of Analyzed Fuel Cells

Table 2 shows some of the characteristics and applications of the fuel cells discussed. The table compares differences such as the electrolyte used, the operating temperature, possible applications, advantages and disadvantages.



Comparison of Fuel Cell Technologies

Fuel Cell Type	Electrolyte	Operating Temperature	Applications	Advantages	Disadvantages
Polymer Electrolyte membrane (PEM)	Solid organic polymer poly-perfluorosulfonic acid	60–100°C 140–212°F	• electric utility • portable power • transportation	• Solid electrolyte reduces corrosion & management problems • Low temperature • Quick start-up	• Low temperature requires expensive catalysts • High sensitivity to fuel impurities
Alkaline (AFC)	Aqueous solution of potassium hydroxide soaked in a matrix	90–100°C 194–212°F	• military • space	• Cathode reaction faster in alkaline electrolyte so high performance	• Expensive removal of CO_2 from fuel and air streams required
Phosphoric Acid (PAFC)	Liquid phosphoric acid soaked in a matrix	175–200°C 347–392°F	• electric utility • transportation	• Up to 85% efficiency in cogeneration of electricity and heat • Can use impure H_2 as fuel	• Requires platinum catalyst • Low current and power • Large size/weight
Molten Carbonate (MCFC)	Liquid solution of lithium, sodium, and/or potassium carbonates, soaked in a matrix	600–1000°C 1112–1832°F	• electric utility	• High efficiency • Fuel flexibility • Can use a variety of catalysts	• High temperature enhances corrosion and breakdown of cell components
Solid Oxide (SOFC)	Solid zirconium oxide to which a small amount of yttria is added	600–1000°C 1112–1832°F	• electric utility	• High efficiency • Fuel flexibility • Can use a variety of catalysts • Solid electrolyte reduces corrosion & management problems • Low temperature • Quick start-up	• High temperature enhances breakdown of cell components

Table 2: Comparison of Fuel Cell Technologies
(Source: http://www.eere.energy.gov)

3.5 Conclusion

It has been demonstrated in this chapter, that each possible energy source is very unique. The three energy sources examined were: nuclear fission, solar power, and fuel cells. These systems are very different from each other, have unique advantages and disadvantages, and have seen various forms of implementation here on earth. The information presented in this chapter will later aid in the choice of which variant of each system will be chosen. This chapter merely presented the systems and their differences. These differences force a closer inspection of the systems in order to arrive at a conclusion of which will be the best suited for the lunar base. The method of examination will be set forth in chapter four, and the analysis will follow in chapter five.

Chapter 4: Evaluation Criteria

When comparing various energy generation systems for implementation, a qualitative assessment of the strengths, weaknesses, and limitations of each system must be established. These criteria are broken down quantitatively for purposes of analysis and conclusion. This study considers the following main evaluation criteria:

- Transportability
- Location
- Assembly
- Fuel consumption
- Upgradeability
- Maintainability

Some of these criteria are multidimensional, encompassing several parameters. Each criterion has a significant impact on the usefulness of any given energy generation system.

Transportability

The selection of a given system must take into account its transportation to the moon. At the moment, bulk transport to space is very limited. With NASA planning on retiring the shuttle by 2010, it must be considered what type of launch system will be available for use in the 2020s when the lunar missions are proposed to take place. NASA's present plan is the Crew Exploration Vehicle (CEV) which has already passed design stages, and could begin to see use in as little as 5 years. (NASA, 2005)

The primary concern when looking at transportability is weight. The CEV is capable of putting 125 metric tons into Low Earth Orbit (LEO). This is approximately five times the payload of the shuttle that NASA has used for the past 20 years. This number is only for what a rocket can put into lower orbit however. To get the payload out of this orbit and onto the surface of the moon, solid state boosters will have to be used to get out of LEO and to slow down for a safe landing on the moon. Because of this, it can only be assumed that 10-20% of these launch payloads will actually make it to the lunar surface (Schrunk, 1999). This yields a range of about 12.5 to 25 metric tons of cargo space per launch. The volume of the cargo is also an issue, but NASA has not released yet the exact dimensions of the CEV; so the discussion and analysis is limited to weight.

The reason that launch payload is being assessed is for financial reasons. Launches are expensive, and for that reason the number of launches must be kept to a minimum. Unfortunately NASA has yet to announce the proposed cost of each of these launches. Because of this analysis will be limited to the number of launches required to get the entire system to the moon, as opposed to the actual dollar cost. Simply for reference purposes, previous launches with the shuttle have cost approximately 300 million dollars per launch (Schrunk, 1999). Clearly, keeping launches to a minimum will dramatically reduce cost, and make the possibility of a lunar base much more feasible.

Location

The moon has many areas that would be suitable for lunar bases. Each region has its own advantages, and disadvantages. The choice of location comes down to two main options: polar, and equatorial.

A polar base could be at the north or south pole. The primary reason for chosing a base at one of these sites would be the abundance of ice at the south pole, or helium-3 at the north pole. Both of these are commodities that we would be looking for on the moon. The other significant advantage of a base at either of these locations would be the constant availability of sunlight.

With constant lighting, less energy would be needed for artificial lighting, and solar power would be a much more viable option.

The equator also offers a unique blend of advantages for a lunar base. The primary economical reason for a base at this location would be the abundance of natural minerals and metals. Due to meteorite bombardment, the equator on the moon has very high concentrations of precious metals that are less common on earth. Another advantage that the equator offers is the ease of landing there. It is far easier to land at the equator, than at a pole.

Different systems will function differently at different locations. Because of this, each system is to be examined at each location, and the optimum location for each system is addressed. Then, a conclusion is drawn from these data as to which energy source is most viable for each location.

Assembly

After the energy system is transported to the moon, it must then be made operational. With the harshness of the lunar environment, and the difficulty for astronauts to work on the lunar surface, lunar assembly must be kept to a minimum. Because of this, a majority or assembly must take place on earth. Different systems, requiring different components, will each require a certain amount of lunar assembly despite all efforts to keep assembly localized to the earth.

One primary focus in designing a system for assembly would be modularity. The premise behind this is to do most of the assembly on earth, then simply do finishing touches on the module once it is on the moon. For some systems, this is impossible as the base system weighs too much to be taken in one launch. For other, lighter systems, this is a much more feasible option.

Another option for assembly is to have lunar robots take landed materials and assemble them into energy systems. The benefits of this approach would be that robots can work very efficiently without atmosphere, and they can work around the clock. These two advantages make them superior to astronauts in a large scale assembly operation. This would add the cost and weight of transporting said robots, though the benefits could potentially outweigh these costs.

Assembling a large energy system on earth generally takes a lot of time and manpower. On the moon, neither of these luxuries are available. Due to these limitations, a significant portion of the assembly must take place on earth.

Fuel Consumption

Fuel consumption is the next evaluation criterion. While this may seem like an obvious criterion, it must be discussed to ensure that it is not neglected. Different systems require different amounts of fuel. Some systems need to be constantly refueled, some never do. For example, if a fossil fuel plant were to be selected for the lunar base, coal or oil would have to be shipped to the moon on a very regular basis. By comparison, solar cells would never need refueling. Constant refueling creates enormous additional cost through additional launches. Because of this, fuel mass and size must be considered as well as energy per unit mass of fuel in every given system.

Upgradeability

While the initial design requirements specify that the lunar base be capable of supporting ten inhabitants as well as some basic mining and research operations, the expansion of the base will inevitably lead to a higher requirement of power generation. Because of this, any design must have the capacity for easy expansion. The preceding concepts of modularity also apply to this design criterion. If all lunar power plants are designed in a modular way, to expand the power output all that is required is to land another module and connect it to the “grid.” Cost vs. power increase would then need to be assessed to see which modules would be the most effective. Qualitatively, a single nuclear module would be expensive, but it has the capacity to create a large amount of power, whereas a group of solar array modules would be fairly cheap, but would not generate as much power.

Maintenance and Lifespan

The last major selection factor is maintenance and lifespan. Having to perform maintenance on the energy system detracts from the astronaut’s ability to mine and conduct research. Also, maintenance on the lunar surface is significantly more complicated than on earth due to the bulky spacesuits that must be worn. Clearly maintenance must be kept to a minimum in order to ensure a productive environment on the base. A good nuclear generator could run for many years on a single fuel rod, though inspections would need to occur frequently. Solar cells, unlike on earth, would require next to no maintenance. With no wind to kick up dust, and no birds to leave droppings on the cells, they would hardly (if ever) need cleaning.

Aside from maintenance, the lifespan of the system being implemented must also be considered. Having to replace worn out, or broken systems creates extreme additional costs through additional launches. For an efficient lunar operation, the chosen energy system must have a long lifespan.

Other Considerations

Every system is unique enough that the preceding five criteria may not fully assess all the potential problems that could be encountered. The most prevalent concern regarding all the possibilities is the environmental challenge. On earth we are beginning to see the effects of pollution on our planet, and no one wants to see the same mistakes repeated on other planets.

Primarily this concern applies to nuclear energy. Will it irradiate portions of the moon? What will we do with the waste? What will happen if the shuttle explodes before leaving earth's atmosphere? These are all questions that need to be addressed to ensure nuclear energy will not be too dangerous an option. Almost all systems require additional support structures which must be considered as well. Nuclear needs cooling, and radiation shielding. Solar cells need mounting equipment and rotating supports to stay with the sun's movement. All plants will also require inverters for energy transmission, and batteries for energy storage in the event of a power failure. These other considerations can have a significant effect on our system, and as such must be evaluated.

Conclusion

The outlined evaluation criteria clearly have significant effects on the selection of a power generation system. Every system must be evaluated on each of these criteria, and then quantitatively compared to each other proposed system. After this quantitative assessment is complete, a conclusion can be reached as to which system is the most viable for the lunar base.

Chapter 5: Analysis of Energy Sources

As the next step in the process to formulate a decision as to which energy source would be the most feasible on the lunar surface, the considered energy sources are analyzed in contrast to the evaluation criteria. Each individual energy source has strengths and weaknesses that need to be quantitatively assessed in order to come to a proper conclusion. The energy sources of nuclear fission, solar energy, and fuel cell technology are analyzed according to the previously established evaluation criteria: transportation, location, assembly, fuel consumption, upgradeability, maintenance and reliability.

5.1 Nuclear Fission Analysis

When considering the energy source of nuclear fission, it is apparent that this choice comes with few downfalls. One may consider a nuclear fission reactor to be a relatively advanced system with a long lifespan and with little need for repair or replacement. Though, because it is important to compare all of the energy sources with the same criteria, nuclear fission is analyzed according to each of the previously mentioned evaluation criteria.

Transportation

The issue of transportation is a major factor for each of the energy sources considered due to the complexity of transportation from the earth to the lunar base. The problem that must be overcome is the limited weight that the current day shuttles can carry. Therefore, the weight of the entire nuclear fission reactor must be considered in order to determine what the minimum number of trips to the moon would have to be in order to transport the entirety of the nuclear fission system. The weight must be considered because any shuttle will only be capable of lifting a certain amount of weight from earth to the lunar surface for each launch. As the weight of the power system increases the number of required launches increases. Therefore, as the number of launches increases, the total cost to launch the components multiplies.

As previously mentioned in the evaluation criteria section, the current day NASA shuttle will be replaced with its successor, the Crew Exploration Vehicle (CEV), by 2010. The advantage of this unit is that it has a potential to lift nearly 125 metric tons into low earth orbit (LEO). In comparison, it is believed that the unit will potentially be capable to lift 12.5-25 metric tons from earth to the low earth orbit and from there to the lunar surface. Therefore, the total number of launches required for the energy source alone can be estimated through the estimated total mass of the energy unit divided by the mass per launch figure of 12.5-25 metric tons.

In considering the total weight of a nuclear fission reactor, one must use both the estimated energy requirement for the intended reactor as well as an estimated specific weight, a ratio of units of weight per unit energy produced (Kg/KW). In the determination of a specific weight that should be considered for a nuclear reactor one should consider the specific weights of smaller reactors than the reactors used for general commercial electricity production. The specific weight of a marine nuclear reactor should be considered because these reactors are closer to the size and energy requirements for the lunar base. According to Adams (1995), the average specific weight of a nuclear reactor used for marine purposes is approximately 54 Kg/ KW.

For a specific weight of 54 Kg/ KW for a nuclear reactor and an initial required energy amount of 500 KW, the total weight would be approximately 27000 Kg. This total weight is equal to 27 metric tons, which could hypothetically be transferred from the earth to the moon in approximately 2-3 launches using the NASA design for the future CEV.

According to Eckart (1999), the specific energy of a typical nuclear energy reactor used for commercial energy production can be estimated to be 100 Kg/ KW. Therefore, with the initial estimate of 500 KW of energy for the lunar base energy source, the total weight of the energy source can be approximated to be 50,000 Kg or 50 metric tons. With a total weight of 50 metric tons, the energy source alone would require approximately 2-4 launches from the earth to the moon in order to transport all of the components of the nuclear fission reactor.

Therefore, by comparing the values for the specific weights and the total weights of the nuclear reactors of both the standard nuclear reactor used for electricity generation in grids and the marine nuclear reactor, one can see that the marine nuclear reactor will provide the same energy generation with a much lower weight. This advantage shows that the high weight of a commercial nuclear reactor can be avoided by using a reactor that is designed to be more compact, such as reactors designed for the use of powering marine vessels.

Location

The location of the lunar base is an important factor to consider because of the limitations that it will set on the use of solar energy; which will be discussed in the following section. Depending on where the lunar base is located there are different conditions, primarily the length of the day and the night. Two main locations are being considered, the equator and at particular sites at the poles. These specific sites at the poles are considered to have perpetual sunlight due to the near plumb rotation of the moon about its axis. This rotation allows these locations to nearly be in constant view of the sun.

Though location is an important factor to consider in the analysis of the energy sources it is not all that important to consider when discussing nuclear fission. Nuclear Fission is not directly affected by the location of the base because this application relies on the fuel inserted into the reactor and not how much sunlight the location will have at any point in time. Therefore, a nuclear fission reactor would work as efficiently at any location on the lunar surface.

Assembly

The issue of assembly is important in analyzing the feasibility of an energy source because it will be easier to assemble a less labor-intensive energy production unit on the lunar surface. The difficulty arises because on the moon the astronauts will be forced to do all of the labor outside in the bulky spacesuits. The only other option to the manned assembly would be robotic assembly being controlled by remote.

With nuclear fission, a reactor is used to produce energy and consists of several large parts, such as in the pressurized water reactor, including the condenser unit, turbine system, generator, reactor vessel, pressurizer, containment structure, and the steam generator. The problem with the overall structure of the reactor is that there is a limit as to how much it can be assembled before it is launched to the moon. If too much is pre-assembled then the structure will be too large to launch in a single shuttle and if the sections are not pre-assembled at all then the various portions of the system will prove to be too complex to fully assemble on the moon. Also, if most of the work is performed on the moon, then heavy equipment will be needed in order to assemble the portions, the equipment being manually or remotely operated. Therefore, the choice of using nuclear energy may create a need for heavy equipment for the labor intensive nature of the work.

Fuel Consumption

Fuel consumption of the chosen energy source is an important factor in the final decision because any system that requires a large amount fuel will not be considered feasible. The issue with the fuel consumption is that these excessive amounts of fuel would have to be launched to the moon at intervals of time that would be set by the energy source need. Unlike the fossil fuel energy sources, such as oil and coal, nuclear fission does not require a large amount of fuel to continuously run for extended periods of time.

According to the Uranium Information Centre of Australia (UIC), "U_30_8 is the uranium product which is sold. About 200 tonnes is required to keep a large (1000 MWe) nuclear power reactor generating electricity for one year" (UIC, 2004). When converting that figure to adapt to the estimated size of energy generation of 500 KWe, the total uranium product consumption per year for the reactor would be approximately one-tenth of a ton or 100 Kg of $U_30_{8.}$ Therefore, the fuel needed for the production of energy on the moon adds no significant weight to the reactor weight for transportation.

Upgradeability

It is known that the initial lunar base will house a small number of crewmembers, probably about 10. Though, as time passes there will be a need for a larger lunar base, or rather a lunar colony. As this base transforms into a colony, the need for energy will increase. Therefore, the production of energy must increase and this should be taken into consideration when deciding on a certain energy source.

With nuclear energy, there are two feasible options for the expansion of the energy source for the growing lunar colony. The first of the choices may be to initially launch a larger reactor than necessary. This larger unit would provide the power necessary for the initial lunar base at a lower than capacity production level, but also as the lunar base grows to a lunar colony the energy production may be increased by simply increasing the usage percentage of the nuclear reactor. Sending the larger reactor up to the moon would be a good choice for the expansion of the base, but it would also largely increase the weight and assembly needs of the unit. Therefore, if this method were to be chosen as the main choice for upgrading then the previous criteria of transportation and assembly would have to be reconsidered.

Rather than initially launching a larger unit, the second choice for the expansion of the nuclear energy system would be to begin with the initial size of the unit and send up subsequent units in the future. In the future a secondary nuclear fission unit could be sent up to the moon in order to facilitate the addition energy needs as the base grows. Initially this method for expansion would not increase the criteria of weight or assembly needed to be considered in the initial construction of the base. Also, at the time that the second or third units are required the methods of launch may be more efficient. Therefore, in terms of expansion, the best choice would be to launch the initial nuclear reactor required for the start of the lunar base and ultimately send up subsequent units in order to fill the increased energy need.

Maintenance and Reliability

The maintenance and reliability associated with a given energy source is a very important factor to consider because of the downfalls of having to repair or replace the energy production unit. Maintenance of any energy source on the lunar surface will take time away from the everyday activities as well as force the astronauts to perform labor-intensive work in the spacesuits outside of the lunar base habitats. A unit’s reliability is in direct correlation with the maintenance of the unit. If an energy system is unreliable then the maintenance or even replacement of the system will be required much more frequently.

Over the past 50 years nuclear reactors have proven to be relatively reliable, at least in most countries. For instance, in the Unites States, there are several nuclear reactors that have been running for nearly 30 years without any significant problems. According to the department of energy, the oldest reactors currently operational in the United States are two reactors that began commercial electricity production in 1969; the “Nine Mile Point-1” and the “Oyster Creek” (eia.doe.gov, 2004), both being General Electric produced boiling water reactors. The only major catastrophe caused by a nuclear fission reactor malfunction is that of “Three-Mile Island”. Therefore, the general nuclear fission reactor has proven its reliability over the last 50 years since commercial operation originally began in 1955.

If one were to take a closer look at reactors closer to the size that would be required for the lunar base, those of marine vessels, one will find that the reliability may even be of a higher level. According to the Uranium Information Centre of Australia, “The US Navy has accumulated over 5500 reactor years of accident-free experience, and operates more than 80 nuclear-powered ships” (UIC, 2005). Therefore, in general, nuclear energy provides for a relatively reliable source of energy which one may count on to provide the required energy without much worry of catastrophic events or large repairs. The only maintenance issue needed to be considered would be routine maintenance checks to ensure the integrity of the system.

5.2 Analysis of Solar Power

Presently the most efficient solar cells are Gallium Arsenide cells. With proper refinement and processing, these have been demonstrated to have efficiencies as high as 35% (Knier, 2002). Assuming this efficiency, as well as an irradiant light intensity of 1367.6 W/m^2 (Lettner, 2000), it is conceivable that about 479 W/m^2 could be achieved through modern photovoltaic cells on the moon. This is a stark contrast to the advertised efficiencies of commercially available photovoltaic cells. Most commercially available cells are advertised at yields of about 125 W/m^2. Why the discrepancy? Several factors play into this. First, advertised powers assume 1000 W/m^2 light intensity. Second, the atmosphere of the earth must be taken into consideration. On all but the best days, the atmosphere will disperse, reflect, and scatter 30-40% of the light. Lastly, these high efficiency cells are incredibly costly next to the relatively cheap silicon cells. Because of this, most commercially available cells have efficiencies of about 20%. All of these factors taken together result in yields of approximately 125 W/m^2.

Other photovoltaic technologies in the works are Multicrystalline silicon cells, and polymer cells. Multicrystalline cells have a very high theoretical efficiency, due to their ability to absorb multiple spectrums of light, though in practice the best cells to date are only hitting efficiencies in the mid-teens. Polymer cells are theoretically the cheapest to produce, as well as the lightest, but to date the most efficient polymer cells run at about 5% efficiency. Breakthroughs are expected in all technologies due to the amount of research being conducted, but the facts regarding these breakthroughs are insufficient to assume what will be feasible by the time of the lunar base establishment. For this reason this assessment is very conservatively assuming existing values for both weight and efficiency of these technologies.

As research continues, more and more materials are being tested for photovoltaic cells. Many of these, however, are still experimental and generally have very low efficiencies. Due to these two facts, experimental photovoltaic technology will be sidelined during this discussion. Similarly, due to the complications of pressurizing and maintaining a water system, the concentrated light boiling water reactor will also be sidelined.

Transportability

It was already stated that given current technology about 479 W/m^2 could be realistically achieved on the moon’s surface. Using this figure along with the estimation of needing approximately 500kW to power the lunar base, it can be seen that the solar array necessary to power this base must be approximately 1044 m^2. Using this figure, along with modern photovoltaic cells weighing approximately 20lbs/m^2 (Southwest PV systems, 2003), the total weight of this assembly will be around 20,880lbs.

An alternative to conventional hard cells are flexible silicon solar cells. Flexible solar cells are significantly lighter, and smaller, and thus would be cheaper to transport to the moon. Their downside comes from their lower efficiency. The efficiencies of the best flexible solar cells at the moment is approximately 1/4th that of the best conventional hard cells. Going with these numbers, approximate four times the area would be needed (4176 m^2 of flexible solar cells) to generate the same amount of power as the conventional hard cells. By comparison however, these flexible cells weigh only about 3lbs/m^2 (Southwest PV systems, 2003), so thus the total weight of this array would be 12,528lbs. Mounting hardware would still be a consideration, and would at least double this number, but this is still significantly less than the total weight of the hard cells. The big drawback is clearly the increase in required area, which was already large.

One alternative to transporting solar cells to the moon, is to simply create them there. A blueprint has already been established for a rover that will harvest the lunar regolith, react the necessary elements, then process, manufacture, and lay solar panels on the moon's surface. This would be phenomenal, as only the rover would have to be transported, which would save tens of millions of dollars. This idea, however, is only a theory, and a working prototype is yet to be manufactured. Also, due to the rudimentary construction of said cells, the efficiency would only be several percent, so a much larger array of cells would need to be created. Also, this rover would only be able to lay flat panels, and as such would be useless for a polar location.

Location

The biggest concern when analyzing solar power on the moon is the exact location of the base. The two clear options that emerge are the equator, or one of the poles. Both locations have advantages, and disadvantages.

A polar base would be ideal because it has perpetual sunlight. This would mean a non-stop source of power. The disadvantage to this location would be the angle that the solar cells would need to be set at in order to best take in the irradiant light. At the pole, the irradiant light is tangential to the surface, and as such, the solar arrays would need to be positioned vertically in order to have the maximum surface area. Clearly this already presents several problems. Firstly, heavy support infrastructure would be needed in order to keep the panels upright. Secondly, the arrays would need to be positioned far enough apart so that they wouldn't block out the light from other panels. This would increase the length of transmission lines, and would also have a significant impact on efficiency due to the losses in the wires. The other implication to having vertical solar cells, is getting them to face the sun. At an equatorial site, the mirrors would barely have to rotate as the sun comes up on one side, goes overhead, and goes down on the other side. At the pole however, the sun pans a 360 degree arc around the horizon. To compensate for this, there are two options that can be followed. The first, is to have some arrays facing each direction. This would significantly increase the number of panels to put up, but it would save on the positioning equipment, namely the motors. The other idea is to put the panels on motors that turn around the axis normal to the lunar surface. This would mean the overall number of panels would be reduced, but it would mean we would have to add potentially heavy motors and turning equipment into our considerations. Of these two options, the first would probably about quadruple the size of the array, and thus would quadruple the previously assumed weight, as well as adding the supports to keep the cells upright. These supports, if made from a light weight material shouldn't be heavier than the cells they're holding up. An exact judgment as to how heavy the motors and mounts would be in the second option is beyond the scope of this evaluation, but it would seem reasonable to assume the weight of the mount and motor would be two to three times the weight of the panel itself. Thus it can be assumed that the total weight will be three to four times the originally assumed weight with the second option as well.

At the equator, the sunlight is less consistent than at the poles. The lunar day at the equator is 14 days, followed by a 14 day nighttime (Hamilton, 2005). To have power in the lunar night, the base would need batteries which charged during the lunar day. Also, on top of batteries, the array would need to be doubled in size, so that the original array can take care of running the base as previously designed, and the secondary array can charge the batteries for the lunar night. Just the increase in panels doubles the initially planned weight. The batteries then would add an incredible amount of weight on top. For fourteen days worth of power, at 500kw continuous, batteries would be needed that could store 168 megawatt-hours. Those would be huge batteries (A typical AA battery can hold as much as about 10 watt-hours, so imagine 16.8 million AA batteries.) On top of this, angling and mounting equipment would also be necessary to achieve maximum efficiency. With the sun going directly overhead however, extra panels could be added on to the array as was done with the polar base. In this case, all the panels would be left flat on the ground. This would also increase the size of the batteries, as it would effectively be extending the lunar night, as panels parallel to the irradiant light are effectively worthless, but by removing the weight of the mounting equipment, it may end up being a worthwhile tradeoff.

Assembly

Solar cells have the large disadvantage that they need more assembly than any of the other energy options. With all the mounting that is needed for the arrays, assembly becomes a serious issue. Ideally all the fabrication would take place on earth, and then the built panels will be strategically placed on the lunar surface. The down side of this is that the assembled materials take up a lot more volume than the raw stock, and would thus increase the number of launches to get all the material to the moon.

One option to cut down on the amount of assembly required would be to make modular mini arrays that could fold up. The idea would be to make an array that when unfolded yielded a large area, but could be folded up to conserve space on the shuttle. This would be a challenging design problem, especially considering the requirement to have the panels rotate in some situations.

Fuel Consumption

Solar power's greatest advantage is its lack of required fuel. Solar cells run off of light from the sun, and nothing else. Because of this, they would never need refueled. This very significant, as lunar transportation is incredibly costly.

Upgradeability

A solar array has the distinct advantage that it can be upgraded by almost any amount as needed. If a modular design were established, all that would be required would be to ship another couple modules, deploy them, then connect them to the grid. In this way, standard supplying missions could bring a few additional modules within the unused cargo space, without having to have a dedicated launch solely for more cells.

Maintenance and lifespan

Assuming solar energy were the chosen option, maintenance on the array would then have to be considered. Fortunately, with next to no wind to pick up dust, and nothing falling from the sky, keeping the array clean will be incredibly easy. As far as lifespan goes, modern photovoltaic cells last usually between 20-30 years. Studies have shown, however that the silicon in the cells tends to degrade more rapidly in harsh environments, i.e. under extreme light, or heat. The lunar surface exhibits both of these properties, and as such the lifespan of said cells would have to be assumed to be significantly less than the normal lifetime. This is a real hurdle to overcome, as rebuilding the array every 10-15 years is very expensive.

Final Considerations

Solar cells have very few other considerations to consider. They are neither harmful to the environment, nor the people around them. They don't need expensive shielding, or cooling. They can also be placed almost anywhere that there is available light. Table 3 shows the breakdown of the options previously discussed. The weights of mounts and motors have been approximated at the weight of the cells being mounted and rotated. This approximation was based on the assumption that heavier cells will require stronger, and thus heavier mounts, as well as stronger and heavier motors. Due to the assumed weight of these components being a scalar multiple of the base weight of the cells, any error in estimating these weights will equally affect all options. As such, these numbers are meant more for comparative purposes than as actual figures. Also, the weight of the batteries was calculated using the assumption that 168 megawatt-hours will need to be stored, and also using the assumption that using modern lithium polymer batteries, power densities of 130 watt-hours per kilogram can be achieved. (Plantraco, 2006)

	Component Weight (lbs)	Polar		Equatorial	
		Rotating	Still	Rotating	Still
Hard cells	Cells	20880	83520	41760	83520
	Mounts	20880	20880	41760	0
	Motors	20880	0	41760	0
	Batteries	0	0	2840000	2840000
	Total	62640	104400	2965280	2923520
Flexible cells	Cells	12528	50112	25056	50112
	Mounts	12528	12528	25056	0
	Motors	12528	0	25056	0
	Batteries	0	0	2840000	2840000
	Total	37584	62640	2915168	2890112

Table 3: Solar Energy Mass Comparison; Masses of Equatorial and Polar Location Solar Energy Systems

As can be seen in Table 3, an equatorial site is out of the question due to the weight of the battery back up that would be required. The only way an equatorial site would work would be if the base ran in a mode of power conservation through the lunar night, thus requiring fewer batteries. This would present the problem that half the time the base would be useless. Considering this fact, the polar base is clearly the better option. Regardless of which type of photovoltaic cell is used, it is obvious that the rotating arrangement will be lighter despite the inclusion of motors. The last choice Hard cells or flexible cells depends on which is more critical. The flexible cells will clearly require fewer trips to get the materials on the lunar surface, though they will also take up around four times the area that the hard cells will take up. Depending on how limited area is in the chosen site, the hard cells may be the better option despite being heavier.

Clearly solar cells are a very viable option for powering the lunar base, so long as the base is at a polar location. Solar energy is not feasible at an equatorial site. The two significant downsides to solar power are the short lifespan of the cells, and the amount of assembly that’s required to get them operational. The area of the array is also of concern, but with the amount of open area on the lunar surface, this will not likely be a factor in the end decision.

5.3 Fuel Cell Analysis

This section will analyze fuel cell technology to determine if it would be possible for power applications on the lunar base. The topics discussed are as according to the evaluation criteria specified in chapter 4.1. The evaluation criteria covered are transportability, location, assembly, fuel consumption, upgradeability, maintenance and lifespan.

Transportability

Transportability of fuel cell systems vary with different fuel cell technologies and different power outputs. The following are examples of different fuel cell systems. One important factor to consider when reading the following information is that the Crew Exploration Vehicle can carry 12.5 to 25 metric tons of cargo per launch.

A solid oxide fuel cell system developed by Rolls-Royce Fuel Cells Systems Limited designed as a stationary fuel cell system can produce 1 MW of power. This system has dimensions of 40 ft by 7.66 ft by 8.5 ft and has a weight of less than 20 tons.

The Andromeda is a 100 kW proton exchange membrane fuel cell designed for automobiles. It has dimensions of 3 ft by 1.8 ft by .7 ft and weighs 140 kg (309 lbs). However, because we need 500kW of power, we would need 5 of these, making the total weight as 700 kg (1,543 lbs).

Location

Location is a relevant consideration since fuel cell systems require a large amount of fuel. Thus the location is important because of the ease of transportation and costs associated with transporting the fuel to the lunar base. Based on this consideration, it would be easier to set up the lunar base at the equator if fuel cell technology is chosen as the main source of power. This is because it is easier to land spacecrafts at the lunar equator than the lunar poles

Assembly

The weight of the 1 MW fuel cell system as made by Rolls Royce Fuel Cell Systems is less than 20 tons. Using this datum as a comparison, the Civilian Exploration Vehicle should be able to carry a fuel cell system as well as some fuel. Since the Civilian Exploration Vehicle can carry the fuel cell system within one launch, there would be no need for disassembly for the launch and therefore no need for reassembly after landing.

Fuel Consumption

The efficiency of a fuel cell system without a heat recovery system varies roughly from 40% - 80% efficiency. The system with the highest efficiency is the molten carbonate fuel cells at 60 - 80%. The system with the second highest efficiency is the alkaline fuel cells at 70% efficiency. The third most efficient system is the solid oxide fuel cells at 50 - 60% efficiency. The direct methanol fuel cells, phosphoric acid fuel cells and proton exchange fuel cells have roughly the same efficiency of around 40%.

However, some fuel cell systems can be equipped with a heat recovery system, which converts the excess heat into more energy. Two such systems that can use a heat recovery system are the phosphoric acid fuel cells and the solid oxide fuel cells. The heat recovery system greatly increases their efficiencies. Both systems mentioned can reach 80-85 % with a heat recovery system.

The Andromeda can serve as an example for fuel consumption. The Andromeda "consumes 1.5 grams of hydrogen per second" (Mitchell) at maximum power. Since water is composed of two part hydrogen per one part oxygen, the Andromeda should consume 12 grams of oxygen per second, since oxygen is 16 times heavier than hydrogen. Total fuel consumption should therefore be 13.5 gram per second. If one multiplies this figure by five, (since the lunar base requires 500 kW to run) the total fuel consumption would be 67.5 grams per second. Through further calculations, the lunar base would require approximately 5.8 metric tons to power per day.

Upgradeability

In principle, fuel cell systems are very upgradeable because they are composed of fuel cell stacks. Fuel cell should therefore be easily upgradeable by added to or removing fuel cells from the stack. Although this condition is possible, in practice, it may not be the most efficient method (Appleby, 1993).

Since high efficiency is one of the main selling points of fuel cell systems, maintaining this high efficiency through upgrades or downgrades to the system should be an important consideration. With increased fuel stack size, simply adding on more stacks to the system is inefficient. To make the system efficient, one needs to reroute how the fuel and cooling is distributed. The system will certainly run without these changes, but the system may lose efficiency. To increase efficiency for these increasing fuel cell stacks, the piping system for the fuel and the piping system for the cooling agent need to be rerouted for more efficiency. Completing these two tasks on a fuel cell system will help to increase the efficiency of the system after upgrades have been made to the system.

Maintenance

The fuel cell system used by the First National Bank of Omaha has a reliability of 99.99999 % (Fischbach, 2005). Fuel cells have high reliability because of their “lack of highly stressed moving parts operating under extreme conditions" (Appleby, 1993). The lack of highly stressed moving parts also positively affects fuel cell systems' lifespan.

Lifespan

Fuel cell systems are generally assumed to have a lifetime of 40,000 hours, or 5 years of continuous use. Phosphoric acid fuel cells however, have been tested to exceed 100,000 hours of usage in laboratory conditions (Appleby, 1993). Molten carbonate fuel cells have a lifetime of 25,000 – 40,000 hour because of its susceptibility to corrosion. The molten carbonate fuel cell's susceptibility to corrosion is due to the high operation temperature and the lack of external reformers.

Summary of Findings

The strong point of fuel cell systems is transportability, assembly, upgradeability and maintenance. The downfall of fuel cell systems however, is fuel consumption and lifespan. These two points are important considerations since solar and nuclear technology do not share these same faults.

5.4 Conclusions

Each of the previously discussed systems has been shown to have unique advantages and disadvantages depending on the manner of implementation. In this chapter, these characteristics were discussed quantitatively. This provides an understanding of each system. To reach a reliable conclusion as to which system will be best suited for a lunar base, these characteristics need to be addressed simultaneously in a side-by-side fashion that allows for direct comparison. This comparison is shown in Table 4.

	Nuclear	Solar	Fuel Cell
Transportability	27 Metric tons 2-3 launches	17 Metric tons 1-2 launches	.7 Metric tons <1 launch
Location	Polar or equatorial	Polar only	Polar or equatorial
Assembly	Moderate	Extensive	Minimal
Fuel Consumption	0.1 Metric ton/year	None	6000 Metric tons/year launch every 18-36 hours
Upgradeability	Complicated due to size of reactors	Simple due to light weight of panels	Very simple due to light weight, and modularity
Maintenance	Moderate	Low	Low
Lifespan	40+ years	~15 years	5-12 years
Other considerations	Radiation, cooling, shielding	None	Can be useful for making H2O

Table 4: Comparison of Findings

The first row shows a comparison of the different systems in terms of weight and transportability. Each system is analyzed by overall weight, which is then interpreted as a total number of launches to get the system to the moon. Fuel cells are by and large the lightest of the systems. The full set of fuel cells will take up only a small fraction of a single launch. By way of comparison, the full solar set up will take a full launch, and probably a small portion of a second launch. A nuclear plant is the heaviest of the compared systems. At 27 metric tons, a full nuclear plant will take at least two full launches, with potential for more on a third. The differences here are not drastic. Establishing a base on the moon will take many launches, so adding another launch or two will likely be relatively insignificant. That said however, it is still a very significant consideration to keep in mind.

The second criterion assessed was location. This assessment looked at how different systems would react to different locations. For nuclear power, and fuel cells this was not a significant concern. For solar cells however, it made a huge difference whether the base was established at a polar or equatorial site. This location dependence is a downside of solar energy.

The next characteristic examined was assembly. Each system was examined under this criterion qualitatively based on approximately how difficult the system would be to assemble.

Fuel cells required by far the least assembly. All that is required for fuel cells, is to drop them in place, then hook them up to the grid, and the fuel source. A nuclear reactor would be as easy, if it were transportable in one load. Because it can not be transported in a single load however, all the components which must be shipped up individually must then be assembled on the lunar surface. A solar array is the most assembly intensive system. All the panels need to be mounted, and connected to the grid. The mounting of these panels, along with the motors that rotate them, is a serious challenge.

The next criterion was fuel consumption. In this section, each system was evaluated by how frequently the base would need refueled. Solar energy has the distinct advantage that it does not need refueled. Just behind solar energy, is nuclear. Nuclear energy uses incredibly energy dense fuel. Because of this, only one tenth of a metric ton of fuel would need transported per year. This is only a tiny fraction of a launch, and with constant supply missions going back and forth, it would be very easy to just add the fuel to another launch's payload. Fuel consumption is one of fuel cell's greatest disadvantages. To power the base, fuel cells will require 6000 metric tons of fuel per year. With the limitations of rocket payload, this generates the need for a launch every 16 to 32 hours. This frequency of launches is simply impossible.

Next, upgradeability was examined for each of the possible energy sources. Fuel cells proved to be the most upgradeable, due to their small size and weight, as well as their modular design. Solar cells are the next easiest to upgrade. This is due to their small weight. Nuclear energy would be the most difficult to upgrade. An upgrade for nuclear power would involve landing a whole additional reactor, which would involve multiple launches, as well as all the required assembly.

Maintenance and lifespan was the next considered criterion. Each of the three systems was qualitatively assessed in terms of expected maintenance, and quantitatively assessed in terms of lifespan. None of the three systems require much maintenance, though all will require some. The assessment of lifespan however, yielded some large differences. Fuel cells have by far the shortest life span. Fuel cells are predicted to last between 5 and 12 years. Solar cells have the next longest lifespan, with 10 to 15 years. Nuclear energy has the distinct advantage, in that the expected lifespan of a nuclear generator is more than 40 years.

The last criterion looked at was any factor that does not play into the previous discussions, but is still of importance. Nuclear reactors have the most other factors associated with them. The radiation potential from a nuclear reactor is certainly something to keep in mind. Fuel cells have the added advantage that the result of the reaction is pure water.

Chapter 6: Evaluation & Conclusion

6.1 Introduction

Having addressed the relevant data pertaining to each energy source in this chapter these data are quantitatively analyzed to provide a clear decision as to which energy option proves to be the most feasible for a future lunar base. In order to completely evaluate the data collected, two comparative matrices were developed to quantitatively assess the value of each of the evaluation criteria as well as the significance of each criterion in accordance to each energy source. The two matrices refer to the equatorial and polar lunar bases respectively.

The matrices are set up in a manner where the criteria are listed in the columns and the energy sources make up the rows across the matrices. Once the importance for each criterion was assessed, weights were assigned to each criterion, with the weights summing to a total of 1 across the top column. In order to fully analyze the impact that each criterion has on each energy source different values were set for the relevance of the criterion in a range of zero to one hundred with the total values for the three energy sources summing to one hundred. The higher values signify greater advantages, over the other sources, in accordance to the corresponding criterion. After the criteria and relevance values were assessed they were summed by multiplying each relevance value by the corresponding criteria weights and summed at the end, with the highest total value being the predicted energy source choice.

6.2 Explanation of Criteria Weighting

In order to properly analyze each system according to the evaluation criteria, each criterion needs to be assigned a weight relative to the other criteria. Not all of the criteria are equally important; therefore they must be weighted accordingly.

Of the primary criteria, fuel consumption is by far the most significant. Higher fuel consumption causes very frequent transport runs. This creates an enormous expense, making sustainability of the base far less feasible. Clearly the chosen energy source must require little to no fuel, or it will simply not work. For this reason, fuel consumption was ranked as the most important of the evaluation criteria.

The next most important criteria, is the lifespan of the system. Systems with short lifespans will need fixed and replaced more frequently. This will create additional expense, not only through the replacement of parts, but also through the cost of sending those replacements to the base. For this reason, system lifespan was ranked second amongst the evaluation criteria.

Following shortly behind lifespan is the transportability of the system. Heavier systems will require more launches to get to the moon, and as such will be less feasible as sources of power. Transportability was ranked behind lifespan, because a heavier system with a longer lifespan will be significantly better than a light system with a short lifespan.

Assembly is the next most important of the criteria. More complicated assemblies will detract from the astronauts' ability to work on other more important operations. Assembly is weighted this low, because it is a one time event. Once it is assembled, it will run with only maintenance required.

Maintenance goes along with assembly as far as weighting is concerned. Similarly to assembly, maintenance will hinder research and other operations. Also, maintenance could cause downtime in energy production, yielding a dangerous situation for the base.

Upgradeability is the least most important of all the evaluation criteria. When upgrading the system, all of the above factors will apply again. For that reason, all of those criteria have been more heavily weighted than upgradeability.

6.3 Energy Evaluation at an Equatorial Site

Introduction

This section contains an evaluation of each of the energy sources in relation to the evaluation criteria present for a lunar base at an equatorial site. Section 6.1 outlined the basic setup of the evaluation process for each of the sites and Section 6.2 goes into the details about the weighting of each evaluation criterion. Below, Table 5, is a decision matrix outlining the significance of each of the criterion for the analyzed energy sources. The following section is an analytical breakdown of the values set within the matrix.

	Transportation	**Assembly**	**Fuel Consumption**	**Upgradeability**	**Maintenance**	**Lifespan**	**Total**
Weight	0.2	0.1	0.3	0.05	0.1	0.25	1
Nuclear Fission	30	30	47	20	20	65	**41.35**
Solar	0	15	53	35	40	25	**28.15**
Fuel Cell	70	55	0	45	40	10	**30.5**

Table 5: Evaluation of Criteria at an Equatorial Lunar Base.

Analyzing the Given Values for Each Energy Source

As anyone could imagine, each of the three energy sources - nuclear fission, solar technology and fuel cell technology - have different advantages and disadvantages. A summation of these advantages and disadvantages at the equator is presented in Table 5 in a quantitative manner. Each of the values in the columns represents either an advantage or a disadvantage. The higher of the values represent the strengths of the individual energy source in accordance to that particular evaluation criterion, as the lower values represent weaknesses or downfalls.

Transportation

The evaluation criterion of transportation is one of the major issues being considered because of the effect that increased weight has on the number of required shuttles for the energy source alone. As shown above, fuel cell technology has the highest value, depicting the greatest advantage, and solar cell technology has the lowest value for the greatest disadvantage. Fuel cell technology has the greatest advantage due to the extremely low weight of the fuel cells that must be considered for the system alone. A nuclear fission reactor would have a weight much greater than the fuel cells, but not nearly as high as the solar cells. The weight of the solar cells is so much greater than a nuclear fission reactor and fuel cells at the equator due to the necessity to transport batteries with the system in order to prevent a loss of energy during the lunar night.

Assembly

When considering the evaluation criterion of assembly, one must consider the relative difficulty in assembling each individual energy source on the lunar surface. Fuel cells, once again, have the greatest advantage and solar cells have the great disadvantage, with nuclear energy in the middle. Fuel cells are assumed to be the easiest to assemble because of their relatively compact size, which allows them to be placed on the lunar surface in one piece and attached to the electrical system grid. Assembly of a nuclear fission reactor is assumed to be a bit more labor-intensive than the fuel cells as the reactor would be transported to the lunar surface in an estimated two or three launches. This would force the reactor to be divided into sections and assembled on the lunar surface. The assembly of the solar cell would be the most labor-intensive due to the fact that each panel or array of panels would have to be transported to the moon and then assembled on the lunar surface, thus creating a labor-intensive operation outside on the lunar surface.

Fuel Consumption

The required fuel consumption for each individual system is an important factor to consider as it very closely relates to the transportation criterion. As a system consumes more fuel it will have to be replaced with a shipment from earth. Though it is an important factor to consider, fuel cells are the only energy source with any significant fuel consumption. Nuclear fission consumes a very small amount, approximately one-tenth of a metric ton of fuel. Solar cells consume absolutely no material product as a fuel, only sunlight. Therefore, a nuclear fission reactor and solar cells consume nearly nothing in comparison to fuel cells. Fuel cells would consume an enormous amount of fuel each year, nearly 6000 metric tons, which would be a shuttle launch every 16-32 hours. Therefore, fuel cells have a value of zero while the values of solar cells and nuclear fission are nearly the same, with solar cells just a bit higher than nuclear fission.

Upgradeability

Upgradeability is important as the lunar base is bound to expand in the future. As the matrix shows, fuel cells would be the easiest to expand as the operation of expansion would only entail the addition of subsequent fuel cells. Solar cells would also be expanded by the mere addition of solar panels onto the already existent electrical grid. Nuclear fission would be the most difficult energy source to upgrade as a secondary reactor would have to be shipped to the moon or a larger unit would have to be shipped in the initial stage. Therefore, nuclear fission would be the most complex system to upgrade in the future.

Maintenance

As Table 5 shows, the maintenance required for solar and fuel cells are quite comparable. Each of these two systems primarily only need occasional checks to assure proper working order as the systems age. A nuclear fission reactor would require a greater amount of maintenance because of the amount of time that would have to be spent checking on the system. The increased time in checks is due to the volatile nature of the fuel, fissionable uranium. Therefore, solar and fuel cells are given equal values in Table 5 and nuclear fission is given a relatively lower value to represent the increased concern and maintenance requirements.

Lifespan

As was presented in the previous chapters, the lifespan of a nuclear fission reactor has proven over time to be much greater than that of solar cells and fuel cells. The lifespan of a nuclear fission reactor has been proven to be in the range of forty or more years. Solar cells have proven to last approximately fifteen years while fuel cells last about five to twelve years. Therefore, a nuclear fission reactor has the longest lifespan and the highest value in Table 5 accordingly. The value for solar is lower than nuclear and higher than fuel cells, as would be expected considering the relative lengths of lifespan.

6.4 Energy Evaluation at a Polar Site

Most of the considerations for a polar site are identical to those considered for an equatorial site. Assembly, fuel consumption, upgradeability, maintenance, and lifespan will all be the same at a polar site as for an equatorial site. The only significant difference between the two sites comes from the feasibility of using solar power at a polar site. This difference is seen through the difference in ability to transport the system. Table 6 is the same as Table 5 except it has altered values for transportation.

	Transportation	**Assembly**	**Fuel Consumption**	**Upgradeability**	**Maintenance**	**Lifespan**	**Total**
Weight	0.2	0.1	0.3	0.05	0.1	0.25	1
Nuclear Fission	20	30	47	20	20	65	**40.35**
Solar	30	15	53	35	40	25	**35.4**
Fuel Cell	50	55	0	45	40	10	**24.25**

Table 6: Evaluation of criteria for energy sources for a polar lunar base.

As seen in Table 6, the values for transportation are different than those at an equatorial site. As with at the equator, fuel cells are significantly easier to transport than a nuclear plant. The prime difference is that solar is now nonzero in terms of transportability. At the equatorial site, solar had a zero value due to the immense weight of the batteries that were required. At the pole, these batteries are no longer required. Without the batteries, solar cells are slightly easier to transport than a nuclear generator, but still not quite as easy as fuel cells.

6.5 Conclusion

Tables #5 and #6 give a quantitative comparison between all the possible systems. These tables, while helpful, do not fully explain exactly how the system must be implemented. Both tables come to the same conclusion, that nuclear is by far the best choice at either site, however Table 6 shows that at a polar location solar is not very far behind.

As seen in Table 5, nuclear is really the only option for an equatorial site. A solar array will require too much weight in batteries to be at all useful at this site. Similarly, fuel cells will require too much fuel to be even remotely feasible. A nuclear plant must be utilized at this site despite the incredibly difficult start up. A nuclear plant will take two to three dedicated launches, and will require a significant amount of assembly at the lunar surface. For this reason, it will be very hard to get started, but once it is working it is set for forty or more years.

At a polar site, nuclear does not dominate solar by that much. Nuclear still has its edge over solar in lifespan, but it also is still very difficult to get started. This is where the quantitative analysis previously set forth loses its strength. All the previous assumptions take into consideration a base of ten astronauts, requiring a power of 500 kilowatts. Clearly even a base of this size will not appear instantaneously, but will take some time to construct. This is where a tradeoff between nuclear and solar can be reached. During construction of the initial base small arrays of solar panels can be launched with the other building modules. This allows for a gradual build up of power while gradually building up the base. Once the initial base is established, then it becomes feasible to launch a nuclear reactor to the moon. This solution allows for an easy gradual start up of the base, while still in the end having all the benefits of a nuclear plant, namely the very long lifespan.

One might ask, having read thus far, why fuel cells were even considered given their incredible fuel requirement. Clearly fuel cells are not even remotely possible as a primary energy source. However, fuel cells do have their own usefulness. As seen in Chapter this tendency has very little weight. It also has the added benefit of being able to turn gaseous hydrogen and oxygen into water. For this reason, it makes sense to have some fuel cells in the base. First, they are light enough that they barely take up any launch space. Second, leftover rocket fuel from each launch can then be utilized to produce energy, as well as pure water. Fuel cells clearly have their own advantages and uses, and for these reasons they could be implemented as a secondary system at both sites.

Using the qualitative analysis presented in Chapter 5 along with the quantitative analysis in this chapter, it becomes more clear which system will be the best for the moon. Nuclear is the best at either site, although at a polar site solar panels can be used to aid in starting up the base. At neither site will fuel cells work as a primary system, though due to their many advantages they make a great secondary system at both sites.

Chapter 7: Future Technological Advancements

The purpose of this section is primarily to slightly expand upon the research work for the main report and extend the analysis to technologies that were not covered. The reason that these technologies were not covered is that they are not yet in stages of commercial use or have not even had a prototype produced. Though this report addresses much of today's technologies, it is important to look ahead and take a brief look at what the future may behold. It is important to mention the sources of energy or methods or energy transfer that may one day become the source of the moon base energy source, or even the energy source of the earth as fossil fuels diminish.

7.1 Nuclear Fusion

Researchers believe that in the future, nuclear fusion will be a viable replacement for current day nonrenewable energy sources such as fossil fuels. As it was discussed earlier nuclear fission is a process in which energy is produced through the breakdown of atoms. Nuclear fusion, on the other hand, is a process in which energy is formed by the combining of atomic structures. In nuclear fusion systems, energy can be either absorbed or released, depending on the relative size of the product to the reactants. It has been established that if the product of a nuclear fusion reaction has a nucleus with a higher mass than that of iron then the reaction will absorb energy. In contrast, if a reaction yields a product with a nucleus mass that is smaller than that of iron then the reaction will release energy. Therefore, studies are being undertaken in order to utilize the combining of light elements to produce large amounts of energy.

At this time, there has yet to be a nuclear fusion reactor model to be tested and to operate properly. One major problem is that it is necessary to provide a great deal of energy to the system before any reaction can begin. This energy is needed in order to heat the system of reactants to where there is enough energy to overcome the repulsive electrostatic force between two positively charged reactants. Due to this need for an energy input, there have been no successful systems that have been able to create an output of energy that far exceeded the necessary energy input. Scientists refer to a factor of “Q” (wikipedia_Fusion, 2005) which is a ratio of the amount of energy output to the amount of energy input. At this time, few systems have been able to surpass the level of Q=1, but in order for a system to be economically viable, the Q value must reach levels closer to Q=20, where the energy output is twenty times greater than the required energy input.

The fuel needed in order for a nuclear fusion reaction to produce energy is a fuel consisting of elements and isotopes with small masses. Therefore, the most abundant fuel for nuclear fusion is Hydrogen’s three isotopes: deuterium, tritium, and protium. Hydrogen’s low mass and low nucleic charge allow for Hydrogen to bond with other atoms at low temperatures as the atoms do not need to be at extremely high temperatures to overcome the repulsive electrostatic force between particles in order to combine. Other isotopes with light masses are also common in nuclear fusion reactions, such as isotopes of lithium and boron as well as the ^{3}He isotope. The ^{3}He isotope would be an exceptional candidate for nuclear fusion if it were available, but the only known sources of ^{3}He are extraterrestrial. A common product for nuclear fusion reactions is Helium, because of its extremely low mass per nucleon within the atom. Table 7 shows a list of the most common nuclear fusion reactions. The energies in parentheses are the amounts of exothermic energy that the reactions release. Following the list is an illustrative representation of a nuclear fusion reaction between deuterium and tritium, producing Helium, a free neutron, and releasing energy, as shown in Figure 10.

(1)	D	+ T	→	^{4}He (3.5 MeV)	+	n	(14.1 MeV)	
(2)	D	+ D	→	T (1.01 MeV)	+	p	(3.02 MeV)	
(3)			→	^{3}He (0.82 MeV)	+	n	(2.45 MeV)	
(4)	D	+ ^{3}He	→	^{4}He (3.6 MeV)	+	p	(14.7 MeV)	
(5)	T	+ T	→	^{4}He	+ 2	n	+ 11.3 MeV	
(6)	^{3}He	+ ^{3}He	→	^{4}He	+ 2	p	+ 12.9 MeV	
(7)	^{3}He	+ T	→	^{4}He	+	p		+ n + 12.1 MeV
(8)			→	^{4}He (4.8 MeV)	+	D	(9.5 MeV)	
(9)			→	^{4}He (0.5 MeV)	+	n	(1.9 MeV)	+ p (11.9 MeV)
(10)	D	+ ^{6}Li	→ 2	^{4}He + 22.4 MeV				
(11)	p	+ ^{6}Li	→	^{4}He (1.7 MeV)	+	^{3}He (2.3 MeV)		
(12)	^{3}He	+ ^{6}Li	→ 2	^{4}He	+	p	+ 16.9 MeV	
(13)	p	+ ^{11}B	→ 3	^{4}He + 8.7 MeV				

Table 7: List of common nuclear fusion reactions. (wikipedia_Fusion, 2005)

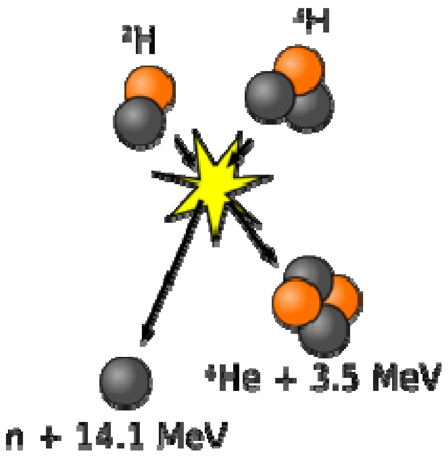


Figure 10: D-T nuclear fusion reaction
(wikipedia_Fusion, 2005)

Nuclear Fusion Reactor

The nuclear fusion reactor much resembles the nuclear fission reactor in that they each have 2 main compartments, one being the nuclear plant and the other is the electricity production portion. Like fission reactors, the electricity produced in a nuclear fission reactor is produced through the use of steam to turn turbines linked to an electrical generator. The main differences in the reactors come with the nuclear portion. Nuclear fusion's "nuclear island has a plasma chamber with an associated vacuum system, surrounded by a plasma-facing components (first wall and divertor) maintaining the vacuum boundary and absorbing the thermal radiation coming from the plasma, surrounded in turn by a blanket where the neutrons are absorbed to breed tritium and heat a working fluid that transfers the power to the balance of plant" (wikipedia_Fusion, 2005). Figure 11 is a split image of a nuclear fusion reactor with the right side showing the plasma during a shot.

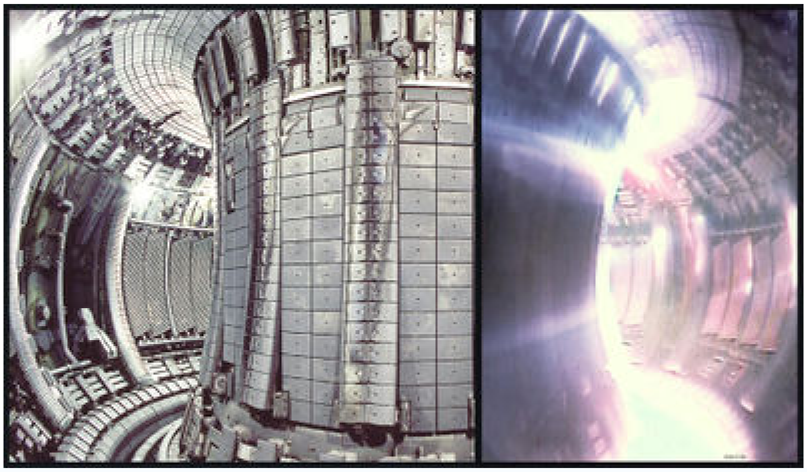


Figure 11: Nuclear Fusion Reactor; A split image of the largest tokamak in the world, the JET, showing hot plasma in the right image during a shot.
(wikipedia_Fusion, 2005)

In today's research, a major concern is the choice of materials in the construction of the reactor. This is a difficult task due to the radioactivity that the materials must handle. As the materials are bombarded with neutrons the materials become radioactive and begin to deteriorate. There are efforts to construct a material that will prevent such breakdown of the structure.

There are several key advantages to nuclear fusion over nuclear fission. The main advantage is that the radioactive waste from fusion typically has a half-life of a decade or two while fission waste can have a half-life of thousands of years. This significant decrease in half-life allows for the radioactivity to die out in a relatively short period of time, allowing for safer disposal of the material. Another great advantage of the fusion reactor over the fission reactor is the overall safety. A fission reactor normally contains a supply of reactant that may last a year or more while the fusion reactor currently only holds enough reactant to undergo a reaction for a minute. Therefore, the possibility of a catastrophic accident is far less.

Even though the technology of Nuclear Fusion has yet to be successful, it is strongly believed that by the time the lunar base is in its beginning stages, a productive nuclear fusion reactor will have been developed. It is believed that nuclear fusion reactors will be smaller, therefore easier to transport to a lunar base.

7.2 Microwave Beam Energy Transmission

A current vision for the energy stability of the earth in the future is a process called microwave beam energy transmission. This process entails collecting solar, or other types of energy, on the lunar surface with the use of microwave transmitters. Once the energy is collected it would be beamed back to receivers on the earth in microwaves. "As part of the Lunar Solar Power System, beams of microwaves from the moon are directed to receiving antennas on Earth called rectennas" (space.com, 2005).

There are several issues that arise from this new technology. The first major issue is the cost of transporting all of the solar arrays from the earth to the moon in order to set up the large "solar farms"(space.com, 2005). Through thorough examination of the "hundreds of pounds of lunar soil" (space.com,2005) brought back during the Apollo missions, it is believed that the lunar soil contains the majority of the materials needed in order to produce solar panels on the lunar surface. “Lunar material contains quantities of silicon, oxygen, and metals; such as iron and aluminum” (space.com, 2005). Therefore, special equipment can be shipped to the lunar surface to collect lunar soil and produce the solar panels on the moon; greatly reducing the cost of transport of materials from the earth to the moon.

The second issue is that at the lunar equator, where the solar sites, such as in Figure 12, are planned, there is a lunar day that lasts for 14 days that is followed by a lunar night of the same length. The problem with this lunar night is that there would be no sunlight for this extended period, thus no energy production or beaming of energy to the earth. The solution to this issue is to produce more than one solar site. If there are two solar sites constructed approximately 180 degrees around the equator from each other then there would always be at least one sight in sunlight. Also, it is believed that solar sails could be used in order to reflect sunlight from areas of light to areas of dark on the lunar surface. Other than bringing sunlight to dark areas, the sails could also just increase the amount of sunlight going to a particular site, in turn increasing the amount of energy production.

The third issue that must be considered is the rotation of the earth relative to that of the moon. Due to the two rotations the microwave transmitters on the lunar surface would not constantly be in line with the receiving antennas stationed on the earth. The solution to this problem is the orbiting of “orbital redirector or reflectors” (tipmagazine.com, 2002) that would have the purpose of changing the direction of the beam sent from the moon. Therefore, a microwave energy beam from the moon could be redirected to any antenna on the earth at any point in time with the series of reflectors orbiting the earth.

Figure 12: Representation of possible lunar solar site. (dailykos.com, 2005)

Therefore, in the future, a lunar base may provide more than just a stepping-stone to the outer solar system. Researcher, David "Criswell estimates that in 2050, a population of about 10 billion would require about 20 terawatts of power. The moon receives more than 13,000 terawatts of solar power and harnessing just one percent could satisfy Earth's power needs" (dailykos.com, 2005). With the additional energy of lunar solar sites, it is apparent that the future stability of earth's energy resources may be in less jeopardy, granting that the construction and commercialization of solar sites is complete before the elimination of all carbon-based, non-renewable energy sources.

Appendix

Alternative Energy Sources

The purpose of this section is to provide a brief overview of some of the other energy sources that are used on earth that were researched in preparation of this report. Due to the differences between the earth and lunar environments and also the format of the future lunar base, it became apparent that some of the relatively common sources of energy on the earth would not apply at all to a lunar base. Because of this fact, after minimal research, a number of the energy sources that were originally going to be considered were ultimately removed from the main structure of the analysis. Within this section, the energy sources of wind energy and bioenergy are considered.

Wind Energy

On earth, wind energy is becoming an increasingly popular energy source as the need for a renewable energy source grows as the supply of fossil fuels diminishes. Energy is produced from wind power through the use of a wind turbine. The purpose of the wind turbine is to convert the force of the wind into a source of electrical energy. As the wind turns the turbine, an internal shaft connected to an electrical generator turns. Therefore, the wind power is first converted into mechanical energy with the spinning of the turbines and the shaft and ultimately the mechanical energy is then converted into electrical energy within the generator unit.

In areas on the earth where wind can be considered in plentiful supply, wind power provides a great source of renewable energy, but if the wind is not nearly constant or not nearly strong enough then the source of wind will not be sufficient enough for the production of electrical energy. As time passes there is an increasing number of considerations for what are called “wind farms” where great numbers of wind turbines would be constructed either in wide open fields or even in an area of open water, such as an ocean.

The problem with considering wind energy as a viable option for an energy source for the future lunar base has a great deal to do with the moon’s lack of an atmosphere. The issue that arises with the lack of atmosphere is that without an atmosphere there will be no significant weather patterns, hence no significant winds. Without a significant source of wind power the wind turbines would obviously be ineffective.

It was also considered that it may be possible to use the power of the solar winds to propel the wind turbines and convert the power of the solar winds into electrical energy. The use of the solar winds was first considered once the velocity of the solar winds was found to be approximately 400Km/s (Stern, 2004). With such a high velocity one would believe that the source of wind power would be more than significant, but the deciding factor is not the velocity of the wind in this case, but rather it is the density of the wind. Due to the fact that the solar wind is comprised almost entirely of charged particles, the density of the wind is extremely low, approximately six ions per cubic centimeter (Stern, 2004). The low density of the wind will negate its high velocity because without a dense enough force the particles of the wind will pass through the turbine and exert little or no force on the turbine. Due to the above reasons, further discussion of the possibility of using wind energy will be excluded from the analysis of energy sources to follow later in the report.

Figure 13 : Platte River Wind Turbines; The Platte River Power Authority wind site in Medicine Bow, Wyoming, which supplies energy to Tri-State Generation & Transmission Association and the municipal utilities of Fort Collins, Longmont, Loveland, and Aspen. *(Hall, 1998)*

Bio Energy

Bioenergy is the production of energy through the burning of bio fuels. Biofuel is the form of biomass that is used in the production of both electrical and thermal energy. Biofuel is used in the production of energy as it is burned in order to produce thermal energy in local areas as well as the production of electricity to be used outside of the localized area. The burning of biofuel produces energy as the release of chemical energy occurs.

Biomass used as biofuel consists of substances and materials on earth that would go to waste otherwise if they were not utilized for the production of energy. Examples of biomass that would be used for biofuel would be household wastes, agricultural waste, sewerage, and dried plants.. There are also crops grown for the sole purpose of using them for biofuel such as a grass species named Miscanthus and switchgrass; each growing to full volumes, making it economical to farm them for the production of biofuel. Biomass is also an indirect form of solar energy because in some way or another, all biomass utilized solar energy in stages of production through photosynthesis.

In this current age of technology, bioenergy provides nearly 15% of the world's energy consumption. Though this energy is used for a great deal of energy, this form is primarily only used in developing countries where the inhabitants have no better options. The problems with bioenergy are based around its pollution. The burning of biofuels still pollutes the atmosphere as toxic gases are released. One extraordinarily dangerous form of biofuel is animal dung which releases a toxic gas as it is burned. Studies have shown that the burning of dung may have lead to the deaths of 1.5 million people in the past. This problem exists due to poor designs of systems in developing countries as these designs allowed fumes to be released into the homes.

In analyzing the potential for bioenergy, it is apparent that bioenergy may be a feasible option for secondary energy sources within a lunar habitat, but it certainly would not suffice as a primary source. It would be possible to utilize bioenergy in order to power one segment of a lunar base. Therefore, bioenergy will not be considered in the primary analysis of the feasible energy sources for the lunar base. The use of bioenergy would not nearly be viable unless the lunar base grew to a substantially larger facility producing a larger amount of biowaste.

Group Dynamics

In this project, as with most projects in life, we had to work as a group to achieve a common goal. By working in a group, we were able to accomplish something that would have been far more difficult and time consuming for an individual. Working in a group, while being beneficial, does have setbacks. Different people have different opinions, as well as different approaches to tasks and objectives. Because of the different approaches, group members generally take on different roles. Typically one person takes on a leadership type role, and tries to motivate and direct the group to project completion. The other group members tend to fall in line behind the leader. There are really no typical other roles that evolve in a group, other than in every group a leader will emerge. Because each person is different, compromises must be reached in order to promote and maintain group integrity. Through compromise, even the most diverse group can come together to produce a quality result.

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Chapter 4: Evaluation Criteria

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Chapter 5: Analysis of Energy Options

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