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HARVESTING HELIUM-3 FROM THE MOON

An Interactive Qualifying Project Report

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by

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Abstract

The world is approaching an energy crisis, and it is critical to focus on an alternate long term energy source. Given the current urge to explore space and expand humanity's outreach, harvesting the energetically rich Helium-3 from the Moon's surface is an ideal, yet challenging, objective which is amply motivated by current energy economic realities. He-3 can be used in a nuclear fusion reactor to generate enormous energy outputs with negligible waste. In this project, we study the scientific breakthroughs required in space and fusion technologies to successfully harvest He-3 from the Moon. Additionally, a multitude of interests expressed on a global scale in lunar He-3 are examined and assessed based on a legal space framework, and socio-economic political scenarios are developed that would result from the aforementioned space venture.

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1. Introduction

The energy scenario today is governed by uncertainty and fear. Energy demand is expected to increase eight fold by 2020 due to an increase in population and energy requirements, especially on the part of China and India. Alongside an increase in energy demand, oil production is expected to peak within the next decade and, according to conservative estimates, may be exhausted by the middle of the 21st century. Against this reality, alternative energy sources are not only an "alternative," but rather a necessity. It is with this necessity in mind that exploration of He-3 fusion as a potential energy substitute or a complement to other energy sources is being investigated.

He-3 is a heavy isotope of noble gas helium and is present everywhere in the universe in varying amounts. The Earth's supply of He-3 is negligible, but the mineral was found in abundant quantities in soil samples taken from the lunar regolith in 1972 in the exploratory mission, Apollo 17, led by NASA. Since then, there has been considerable interest among physicists, geologists, social scientists and economists in extracting and using the He-3 available in the Moon. The major arguments for the exploration of He-3 are as follows: firstly, it has a high energy density when combined with deuterium in a fusion reaction, hence only small amounts of He-3 are required to supply the same amount of energy as large volumes of oil. Secondly, the low radioactive waste emission and the safety of a He-3 fusion reaction are very attractive attributes when compared to the high safety risks inherent in fission reactors used in nuclear power plants today. Furthermore, He-3 provides us with the opportunity of exploring and settling a permanent base on the Moon, which would give us a solid base for further space exploration.

This Interactive Qualifying Project will explore and evaluate the technical feasibility of extracting He-3 on the Moon, transporting it back to Earth and reacting it with Deuterium in a fusion reactor. We will present the legal framework under which a He-3 mining venture could be conducted, as well as investigate the international interest of a He-3 mining and exploration venture as posed by the governments of Europe, the United States, India and China. We will also analyze the commercial viability of using He-3 as an energy source. In addition, we will present possible scenarios that could follow from introducing He-3 into our current economy.

Although the physical and technical constraints inherent in the project are immense and may not be achievable within the span of the next twenty years, the need to explore alternative energy resources, like He-3, is powerfully relevant today and will only become more relevant in the future. We believe that a colossal change in our society and ideology will follow from a change in energy regime. It is important to anticipate this change to prepare us for the future. In fact, even if the scenarios that we developed and explored never actually consolidate, the exercise of posing them is not in vain.

2. Current and Alternative Energy Sources

In order to explore the He-3 venue, it is important to learn what other energy sources can offer, that is, their advantages, disadvantages and if they will be able to fulfill the energy needs of our planet. Although there are numerous energy sources, we will explore only four: hydrogen energy, fossil fuels, nuclear energy, and solar energy.

2.1 Hydrogen Energy

Much interest and controversy have been devoted by the prospect of a “Hydrogen Economy,” a term concocted by General Motors in the 1970 (Rifkin, 2002) to describe what they believed was the future of motor vehicles and the energy system. Hydrogen has been effectively marketed as the energy of the future due to the element’s wide availability (though not in pure form) and the prospect of no waste generation if hydrogen is produced by electrolysis. In fact, Iceland has already committed to a hydrogen governed economy by undertaking a venture to completely eliminate its dependence on fossil fuels by 2020 and running their whole energy infrastructure based on hydrogen. They also plan to export the excess hydrogen they produce, thus becoming the world’s first hydrogen economy and hydrogen exporter. The hydrogen enterprise is a joint venture between government and private sectors and enjoys high approval from the population at large. Moreover, the promise of a hydrogen economy has sparked the interest of many nations and governments. In 2002 the European Union (EU) made known its plan to become the world’s first “fully integrated, renewable based hydrogen superpower of the 21st century” (Rifkin, 2002). To support this effort, the EU has projected to invest more than 2.3 billion pounds on renewable energy by 2006; the focus would be hydrogen energy. Not to be outrun, in his 2003 State of the Union address, President George Bush announced that his administration would pursue a hydrogen future. The urge to explore an alternative energy route is not without reason. The hydrogen future, thus presented, looks bright and promising; however, this is a simplification.

Global hydrogen production in 2001 was 400 billion metric tons, which amounts to 10% of the global fossil fuel production (Rifkin, 2002). Nonetheless, most of the hydrogen currently produced is obtained via fuel gas reforming

$$CH_4 + H_2O \Leftrightarrow CO + 3H_2 \qquad (2.1)$$

followed by a gas shift reaction,

$$CO + H_2O \rightarrow CO_2 + H_2 \qquad (2.2)$$

Electrolysis of water to obtain hydrogen, which has been widely advertised as being completely waste-free, comprises only 4% of the total hydrogen production. The reason for such a small contribution to the total is the fact that electrolysis of water is a high expenditure energetic process; in fact it is four times as expensive as the production of hydrogen through reforming of natural gas. Production of hydrogen from natural gas is not a sustainable process, since the production of natural gas is expected to peak alongside petroleum in the early to middle part of the 21st century. A most important annotation is that hydrogen, unlike fossil fuels *is an energy carrier rather than an energy source*; that is hydrogen must be generated via an endothermic process. In the absence of fossil fuels to power the electrolysis of water, nuclear energy is most likely to be employed as opposed to “green” alternatives because of its much higher energy yield. Once produced by an endothermic process, hydrogen could be used in various small scale applications ranging from motor vehicles in a fuel cell cars, and small electronic devices. Fuel cell output can be scaled for almost any application if the hydrogen fed to them is pure enough and given that the supply of precious metals needed in manufacturing fuel cells does not sabotage the process.

Although nuclear energy has been posed as the most likely alternative for hydrogen production, as of 1995 a solar powered hydrogen producing facility was established in El Segundo, California (Rifkin, 2002) producing between 1,500 to 2,000scf of H_2 per day. Wind energy is another alternative to produce hydrogen. In fact it is one of the most cost efficient forms of renewable energy (Rifkin, 2002). According to Rifkin's calculations a three bladed propeller with a diameter of 50 meters operating where wind speeds are in average 7.5m/s, can produce 250kW of electricity. The cost of generating electricity from wind energy has dropped from 40 cents to less than 4 cents in 20 years and is expected to drop even further in coming years. Surprisingly, estimates predict that wind energy can provide 10% of the electricity supply by 2020.

Hydrogen is definitely an interesting alternative and a very relevant topic. A vast amount of research is being devoted both to sustainable hydrogen production and its use in fuel cells. In fact, major energy companies are investing large amounts of money in research and development as well as governments and academia. Nonetheless, hydrogen is not the energy solution as it has deceivingly been promoted. Its propagated use would require an energy source which could be in the form of nuclear or "green energy" alternatives. The benefits of hydrogen are widely exalted in terms of the political freedom that it allows countries, since hydrogen, if extracted from water, is available in vast quantities at almost any location. Hence, it's appealing nickname "the democratic fuel."

2.2 Fossil Fuel Reserves

Fossil fuels such as oil, coal and natural gas are vital fuels that have accelerated the technological development of the world. They have provided us with industrial power to make almost everything ranging from food, medicines, and chemicals to powering transportation, electricity and the running of industries. A constant supply of energy from these resources is necessary to keep these processes going. But glancing at the world's consumption of oil in a day brings us to the real truth that one day we might run out of these precious fuels.

To stress the importance of using alternate sources of energy, we looked into the oil reserves that are remaining on the Earth and the amount that the world consumes.

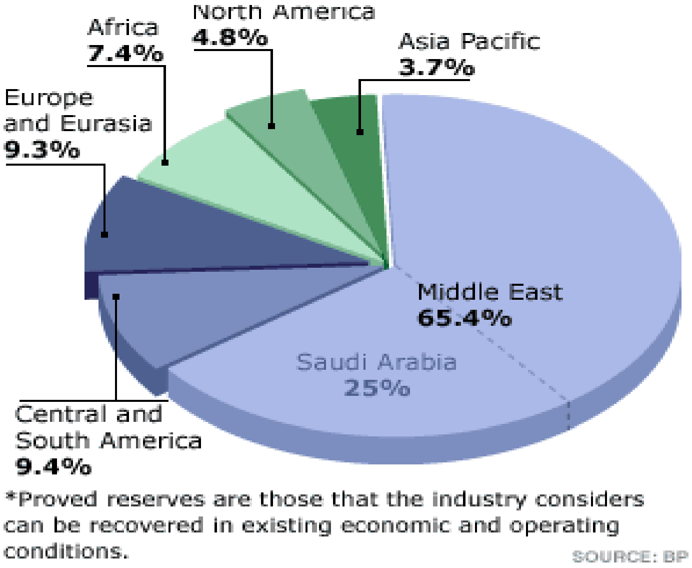


Figure 1: Proved Reserves in the World (Ibrahim, 2005)

Table 1: World Proven Crude Oil Reserves by country 2000-2004 (million of barrels) (Ibrahim, 2005)

REGION	**2000**	**2001**	**2002**	**2003**	**2004**
North America	26,900.9	27,101.1	27,167.0	27,200.0	26,191.0
Latin America	22,202.6	124,593.0	117,529.0	117,045.2	118,952.2
Eastern Europe	79,558.7	81,431.4	87,408.5	90,433.5	91,467.5
Western Europe	19,250.6	19,410.3	18,403.5	18,037.6	17,391.6
Middle East	694,578.9	698,638.3	730,102.3	735,083.3	739,135.6
Africa	92,415.2	95,876.5	103,859.3	111,205.2	111,645.6
Asia and Pacific	39,477.5	39,711.9	39,836.5	39,416.7	39,229.7
World Total	1,074,384.4	1,086,762.6	1,124,306.1	1,138,421.5	1,144,013.1

The total oil reserves that were present in the world at the end of 2004 were 1,144,013.1 million barrels. In 2000, according to the reference case of OPEC's World Energy Model (OWEM), the world consumed almost 76 million barrels a day. Thus as the world’s economic growth continually increases, the crude oil demand will also rise to 90.6m b/d in 2010 and 103.2m b/d by 2020 (Ibrahim, 2005). The International Energy

Agency states that at the end of 2030 the world might use approximately 120m b/d to satisfy the energy needs of the energy hungry world.

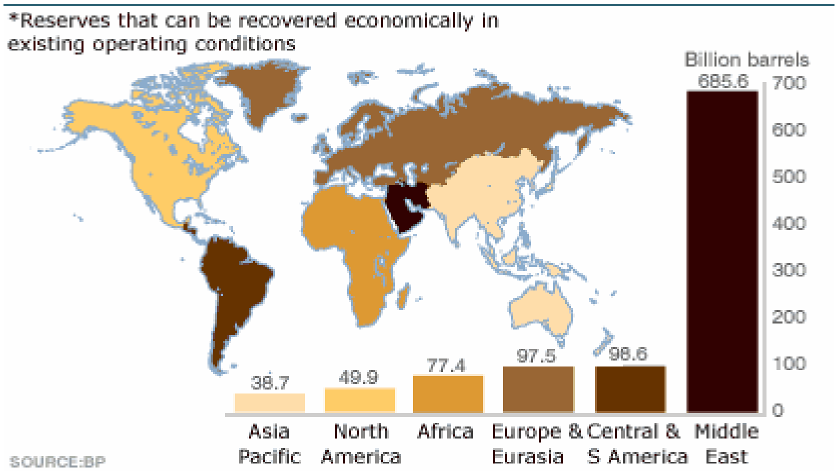


Figure 2: World Oil Reserves till 2002 (Kirby, 2004)

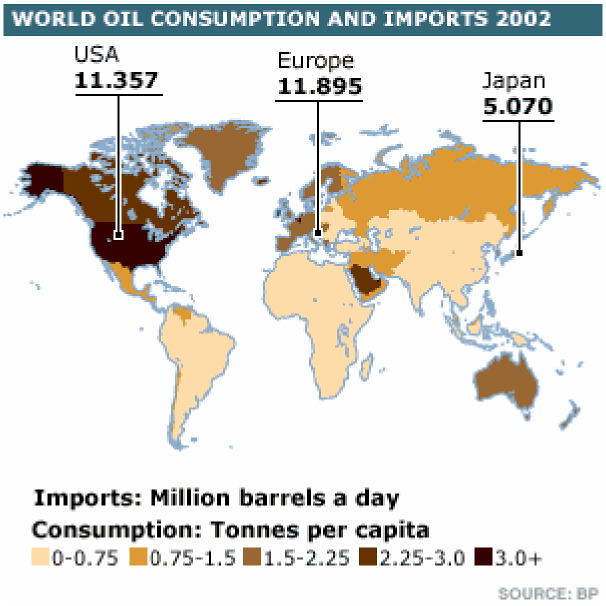


Figure 3: World Oil Consumption and Imports till 2002 (Kirby, 2004)

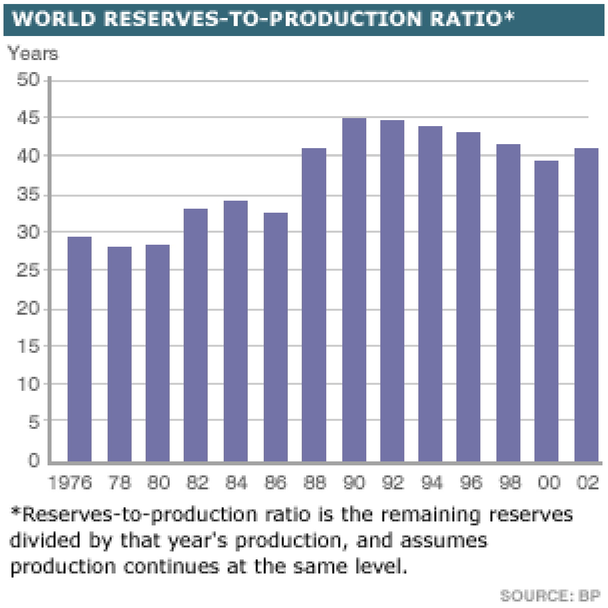


Figure 4: How ling will Oil last for? (Kirby, 2004)

According to Figure 4, there are 40 years of proven reserves at the moment. With the present rate of fossil fuel consumption, we are surely going to run out of these valuable reserves one day. In future years, as the population of the world increases to about 10 million, oil consumption will sky rocket to the consumption of 10 to 150 billion barrels of oil per day.

Almost all industrial processes depend on oil. Some of them even need oil as a raw material for the production of items such as chemicals. We should be saving these resources so that they can be used to produce these items even in the future. Alternate renewable sources of energy should be used even now, wherever possible, so that we can save the fossil fuels for any irreplaceable processes. Thus utilizing renewable sources of energy such as wind, water, solar energy and biomass or relying on nuclear energy to provide the majority of the energy can help reduce our dependence on fossil fuels.

Furthermore, with the environmental pollution that fossil fuel cause, many countries prefer to use renewable sources of energy.

2.3 Nuclear Energy on Earth

Nuclear energy is another source of energy, and is being used currently in many parts of the world. In a nuclear power plant, the process of fission generates a large amount of heat energy, which is then converted into electric energy. The fission process consists of bombarding Uranium, which is a radioactive material and also the primary fuel, with neutrons that split uranium atoms (fission) and release a large amount of energy in the form of heat and high energy neutrons. The fission of one uranium atom releases three more neutrons that further split three more uranium atoms, and this causes nine neutrons to be released. In this manner a chain of fission processes takes place, called a chain reaction, which releases a tremendous amount of energy that can be useful for us. A controlled chain reaction is used to heat coolants (like water), which are later used to turn turbines to generate electricity. In this manner, the process of generating electricity by a nuclear power plant is similar to the process used by a conventional power plant that used fossil fuels to heat coolants. Both release heat in different ways, but capture heat to generate electricity in similar ways. This implies, however, that the process of converting heat energy to electricity has large losses associated with it, due to limited efficiencies of turbines and other mechanical machinery.

Nuclear energy can be considered to be relatively environmentally friendly and clean. As compared to fossil fuel energy, nuclear energy pollutes the environment less as it does not emit any harmful gases or waste products into the environment. The waste from a nuclear plant includes used up uranium derivatives and neutron emissions which, being radioactive, can be easily controlled and isolated from being emitted into the environment. The Nuclear Energy Institute (NEI) in Washington D.C. considers nuclear energy to be very economical because it is very dependable, consistent and efficient, which enables it to be cost-effective. There are a total of 442 nuclear power plants in the world in 31 countries, which are supplying 16 percent of the world's electricity. There are about 24 new nuclear power plants currently being built in 9 different countries (NEI, 2006). Nuclear fuel is also very abundant, and very efficient. One pellet of uranium (about 1 cm in diameter) is equivalent to 17,000 cubic feet of natural gas, 1,780 pounds of coal, or about 149 gallons of oil (NEI, 2006). As mentioned by the Nuclear Energy Institute, "Countries generating the largest percentage of their electricity from nuclear energy were: Lithuania, 79.9 percent; France, 77.7 percent; Slovakia, 57.4 percent; Belgium 55.5 percent; Sweden, 50 percent; Ukraine, 45.9 percent; Slovenia, 40.4 percent; Republic of Korea, 40 percent; Switzerland 39.7 percent; Bulgaria, 37.7 percent; and Armenia, 35.5 percent." Also from NEI, "To produce one Watt of electricity, it takes 1.0 lbs. of coal/kWh from coal plants using steam turbines, 0.48 lbs. of natural gas from natural gas using steam turbines, 0.37 lbs. of natural gas/kWh using combined cycle technology, 0.58 lbs. of Heavy Oil/kWh using steam turbines, and .0000008 lbs. of Uranium enriched at 4% U235 and 96% U238 for use in a commercial nuclear reactor."

Nuclear Energy is definitely a strong competitor against fossil fuels today, and a powerful competitor against natural renewable resources. As the fossil fuel reserves in the world are coming to a fast end, it is crucial to understand the need for alternative resources of energy, for commercial use as well as daily household use. Nuclear energy is definitely appealing due to its advanced technological development and implementation, the high energy output and the relatively low level of emissions. Its major disadvantages are the risk of nuclear weapon proliferation and the generation of dangerous and costly radioactive waste and the associated cost of disposing of them.

2.4 Solar Energy

Solar power energy, one of the most reliable sources of alternate energy, is a method of harnessing energy from the sun. It has been present in many traditional building methods for centuries, but has become of increasing interest in developed countries as the environmental costs and limited supply of other power sources such as fossil fuels are decreasing. It is already in widespread use where other power supplies are absent, such as in remote locations and in space. Direct conversion of solar energy to electricity through photocells have many applications in space and remote locations where other sources of electrical power are either not cost competitive or have political drawbacks. Commercial and residential solar photoelectric arrays feed power into base load grids (Schmitt, 2006). Solar energy can also be used to produce electricity by the use of solar towers that collects solar energy from a large field of mirrors. The heat collected is focused on a single broiler thermal system which is then utilized to produce electricity.

Deployment of solar power to power plants and houses depends largely upon local conditions and requirements of the country that is utilizing it. But as all industrialized nations share a need for electricity, it is clear that solar power will increasingly be used to supply an alternative or complementary source of electricity. Several experimental photovoltaic (PV) power plants of 300 to 600 kW capacities ere connected to electricity grids in Europe and the USA as of 2005, there is a list of technical conditions that factor into the economic feasibility of going solar: the amount of sunlight that the area receives; the purchase cost of the system; the ability of the system's owner to sell power back to the electric grid; and most importantly, the competing power prices from the local utility (Wikipedia).

However without the benefit of taxpayer subsidies and efficient energy storage systems, the collection of solar energy to use as heat or to provide electricity has found no broad commercial niche. Many thermal conversion issues related to exposure to natural environmental conditions (extreme cold, heat, dust and moisture) have to be solved before broad-scale commercial applications of using solar energy is considered as a reliable energy source (Schmitt, 2006).

2.5 He-3: A Useful Fuel from the Moon

Helium-3 has been recognized as a useful energy source because it can be used in a nuclear fusion reaction to generate vast amounts of energy. The abundant He-3 in the Moon needs to be mined and extracted before using it. There is about one million metric tons of He-3 in the lunar regolith that has been deposited over time due to solar winds (Lewis, 1990). The production of 1kg of He-3 would require the mining of about 120,000 metric tons of the lunar soil (Lewis, 1990). Other valuable elements like He-4, nitrogen, carbon monoxide, carbon dioxide and hydrogen could also be extracted that are of commercial value. The hydrogen can be used to generate electricity in fuel cells, which can be used to sustain the working of various machines and modules on the Moon. Furthermore, by combining with oxygen found in lunar rocks the hydrogen could also be used to make water, and also as rocket propellant. The nitrogen could be used to grow plants in pressurized greenhouses, the carbon could be used in manufacturing, and the He-4 could be used as a 'power plant working fluid' and for pressurization (Lewis, 1990).

The idea of mining and getting the He-3 to Earth is very attractive, as has been recognized by the scientists at the University of Wisconsin, because of its efficiency and potential. He-3 is considered to have a value of about $1 billion a ton on Earth, and its energy potential is considered to be 10 times more than what is contained in all the known recoverable fossil fuels on Earth, and about twice that is contained in the uranium which is used in fast breeder reactors (Lewis, 1990). Another fascinating estimation is that 25 metric tons of He-3 reacted with deuterium would have provided all the electricity used in the United States in 1986.

The following is an example of how advantageous it is to use He-3 as a fuel source compared to fossil fuels like oil: One ton of He-3 burned with 0.67 ton of Deuterium can produce 10,00MWof energy. If the same amount of energy were to be produced from oil it would require 130,000,000 barrels of oil. At 20$ per barrel, this would cost $2.6 Billion totally. Thus the energy from one ton of Helium is worth ~ 2.6 billion dollars (Kulcinski, 2004).

25 metric tons of He-3 would fit into the cargo bay of a space transport the size of a shuttle (Lewis, 1990). This information was estimated around the 1990s and the feasibility of mining and transporting the He-3 to Earth was very positive.

One of the possible uses of He-3 does not even massive scale energy production, but instead makes use of the relative portability of inertial electrostatic confinement reactors (IEC), which will be described in greater detail in a later section of this document. The deuterium He-3 reaction could be profitable even if it does not yet reach break even energy potential, that is, even if does not produce as much power as is required to begin and sustain the reaction. One of the fields of interest is medical imaging. In this application, Deuterium and He-3 are reacted to form protons which are then used in the conversion of stable isotopes of various gases to positron emission tomography (PET) images, which are used in medical imaging.

2.5.1 He-3 Formation

A rare isotope of the noble gas Helium, He-3 is believed to have been formed by three principal mechanisms. The first dates back to the dawn of the universe approximately 15 billion years ago when the Big-Bang explosion gave rise to Deuterium and Hydrogen which further reacted leading to the formation of He-4 and He-3. The ratio of He-3 to He-4 in those early minutes of the universe is believed to have been ~ 140 x 10 $^{-6}$. Another source of He-3 is nucleosynthesis, the process by which elements of formed by nuclear reactions. Two reactions are of interest

$$d + p = {}^{3}He + \gamma \qquad (2.5.1)$$

$$2{}^{3}He = {}^{4}He + 2p \qquad (2.5.2)$$

Where d denotes deuterium and γ is a gamma ray.

Moreover, He-3 also exists in solar winds. These are geomagnetic fluxes (Wisconsin) emanating from the Sun’s core and striking the heliosphere. The highly charged and accelerated particles contained a He-3/He-4 ratio of 480 ppm, much higher than that detected elsewhere. Because of the absence of an electromagnetic field surrounding the Moon, the solar winds could penetrate and deposit the isotope on the Moon’s soil, known as the regolith. Earth’s electromagnetic field, however, prevents the entrance of solar winds due to their charged nature, and thus the He-3 content of this planet is extremely low and the little there is attributed mainly to the Big Bang formation.

Table 2: Earthly He-3 Resources Estimate in Tons (Kulcinski, 2004)

	Proved	Probably	Possible	Speculative
Atmosphere	4000	-	-	-
Oceans	13			
Coastal Natural Gas (US.A)	0.23	0.18	0.20	0.0
Subduction Zone Natural Gas	0.03	-	1000	25000
Mantle Gas	-	-	-	10^6-10^7
Total	4 x 10^3	0.18	10^3	10^6-10^7

He-3 content on Earth is inadequate as a long term fusion fuel; however, some of this He-3 can and has been used (Kulcinski, 2004) to demonstrate the viability of a fusion reaction based of the isotope.

2.5.2 Energetics of He-3

He-3 is especially promising as a fusion fuel due to the low levels of radioactive waste produced by its reaction with deuterium and also because of the impressively high efficiencies. 99% of the energy is released as charged particles, thus being converted immediately into electricity. In contrast, other nuclear reactions in which energy is derived from the heat produced by the reaction are less efficient because of mechanical constraints in efficiencies.

Nuclear fission reactions have provided the world with enormous amounts of energy. It involves the splitting of atoms to produce energy.

$$^{235}U + {}^{0}n = \text{two fission products} + 2.5\ {}^{0}n\ (1\text{MeV}) \qquad (2.5.3)$$

But the main draw back of deriving energy from this process is the disposal of its radioactive waste. The main nuclear fuel used to produce energy is ^{235}U which releases high energy neutrons that are the main culprits of radioactive nuclear waste. These high energy neutrons can also lead to the decay of the power plant reactor's core**.** There is also the fear that nuclear reactors can malfunction, thereby releasing the hazardous nuclear radionuclides into the environment. Even though the nuclear energy industry in the United States is quite safe, events of nuclear reactor breakdown in places like Chernobyl, in the former Soviet Union, have made people skeptical about relying heavily on the nuclear fission reactions. Proliferation of nuclear wastes is also a major concern after 9/11/01 because theses wastes can be used in nuclear weapons program (Hurtack, 2004).

Fusion reactions use isotopes of hydrogen to produce energy. The most well known isotopes used for this reaction are deuterium and a tritium, which are fused to produce 1 ^{0}n (14.1MeV) and ^{4}He (3.5MeV).

$$^{2}H + {}^{3}H = {}^{0}n\ (14.1\ \text{MeV}) + {}^{4}He\ (3.5\ \text{MeV}) \qquad (2.5.4)$$

Another way of using fusion reaction to produce energy is by the following set of reactions.

$$^{2}H + {}^{2}H = {}^{0}n\ (2.5\ \text{MeV}) + {}^{3}He\ (0.8\text{MeV}) \quad (50\%) \qquad (2.5.5)$$

$$^{2}H + {}^{2}H = {}^{1}H\ (3\ \text{MeV}) + {}^{3}H\ (1\text{MeV}) \quad (50\%) \qquad (2.5.6)$$

Reactions 2.5.5 and 2.5.6 are equally probable in a fusion reactor employing deuterium as the initial fuel.

All the isotopes involved in the previous reactions are called first generation fuels. Fusion reactions that do not involve the production of neutrons directly are called second generation fuels, as shown in the reaction below:

$$^{2}H + ^{3}He = \text{Proton (14.7 MeV)} + ^{4}He \text{ (3.7MeV)} \qquad (2.5.7)$$

Some of the deuterium atoms (^{2}H) can also react with each other to produce neutrons by 2.2.5. Thus even second generation fusion reaction fuels produce radioactive wastes, but they have shorter half life than the radioactive wastes produced during nuclear fission reactions.

Third generation fuels, are the fuels involved in the fusion reactions that do not produce any neutrons. An example of a third generation reaction is the fusion of two He-3 nuclei.

$$^{3}He + ^{3}He = \text{2 Protons} + ^{4}He \qquad \text{(Total energy =12.9 MeV)} \qquad (2.5.8)$$

This reaction produces no neutrons and also its reactants are not radioactive. Hence, this reaction is an ideal reaction to produce energy in terms of radioactive disposal (Kulcinski et al, 2000).

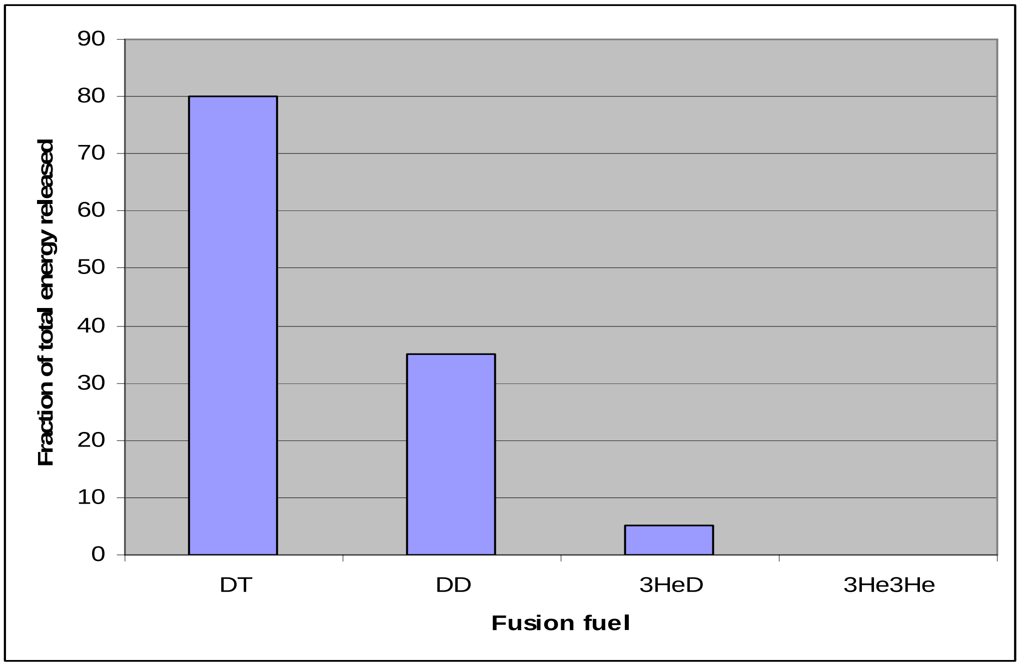


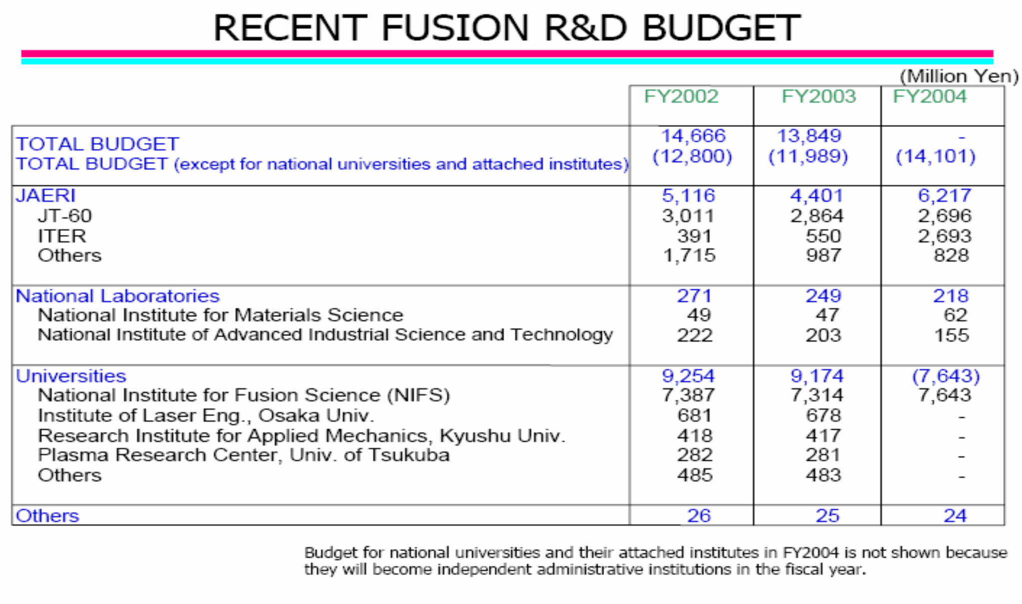
Figure 5 : Fraction of the Total Amount of Energy Released by Neutrons (Kulcinski et al, 2000)

Figure 5 shows the energy released from neutrons from the four fusion fuels: 80% in DT, 35% in DD, 5% in D^{3}He and 0% in ^{3}He-^{3}He reactions. Since the amount of radioactivity and radiation damage is directly proportional to the number of neutrons, we can see why third generation fuels such as ^{3}He-^{3}He should be utilized. Furthermore there is also the problem of disposing of the radioactive wastes produced by the neutrons in the first and second generation nuclear fusion fuels. The cost of storing these radioactive wastes in disposal areas such as the Yucca Mountains is 50 times more expensive than the first and second generation wastes of fusion reactions. Thus by using He-3, which leaves behind no radioactive wastes, we can save costs arising from any radioactive disposal issues (Hurtack, 2004).

The energy density of He-3 is such that, following the progressive theory of Rifkin, it would certainly revolutionize the world's socioeconomic order. As stated before, 28 metric tones of the fuel would be sufficient to power the whole United States for a complete year. Despite the cost of He 3 projected as US$1 billion per ton, the energy output of the reaction is comparable to an oil barrel selling for US$7 (Chowdhuri, 2003).

2.5.3 Fusion Reactor

Table 3: Fusion R&D budgets



RECENT FUSION R&D BUDGET

(Million Yen)

	FY2002	FY2003	FY2004
TOTAL BUDGET	14,666	13,849	-
TOTAL BUDGET (except for national universities and attached institutes)	(12,800)	(11,989)	(14,101)
JAERI	5,116	4,401	6,217
JT-60	3,011	2,864	2,696
ITER	391	550	2,693
Others	1,715	987	828
National Laboratories	271	249	218
National Institute for Materials Science	49	47	62
National Institute of Advanced Industrial Science and Technology	222	203	155
Universities	9,254	9,174	(7,643)
National Institute for Fusion Science (NIFS)	7,387	7,314	7,643
Institute of Laser Eng., Osaka Univ.	681	678	-
Research Institute for Applied Mechanics, Kyushu Univ.	418	417	-
Plasma Research Center, Univ. of Tsukuba	282	281	-
Others	485	483	-
Others	26	25	24

Budget for national universities and their attached institutes in FY2004 is not shown because they will become independent administrative institutions in the fiscal year.

For a long time, a fusion reaction had been considered almost impossible. Regardless of its benefits, a nuclear reaction was very hard to achieve because of the thermodynamics governing the reaction and the high energy expenditure associated with beginning and maintaining a fusion reaction. Nonetheless, work performed in the $10-billion International Thermonuclear Experimental Reactor (ITER), at the University of Wisconsin, Princeton University and elsewhere offered an encouraging perspective for fusion reactors. Table 3 offers an overview of recent budgets devoted to research in fusion R&D in three sectors: international cooperation, academic research and national laboratories. Although this paper will not explore the physics of nuclear fusion in depth, we will seek to provide a brief overview of the fusion reactor's mechanism.

Nuclear fusion development began in the mid twentieth century. During the 1960's Dr. R.L Hirsch and Dr. G.A. Meeks performed a successful ion gun driven Inertial Electrostatic Confinement (IEC) experiment. An IEC experiment is when an electric field accelerates charged particles radially inward in a spherical or cylindrical geometry. In the experiment, an ion gun served to fuse a Deuterium-Tritium (D-T) fuel mixture generating 10^{10} neutrons/s. The rate of neutron production is an indicative of the rate of reaction and hence the energy generated.

There are two types of fusion reactors. The first uses inertial confinement fusion, (ICF). ICF employs laser beams to symmetrically compress deuterium and tritium pellets. Magnetic confinement fusion, MCF, is the other primary approach and a very promising one for commercial power production (Schmitt, 2006). In MCF magnetic fields are used to confine the plasmas and accelerate the ions in the fusion reaction. The toroidal, high intensity reactors are referred to as Tokamaks and the magnets employed in these devices reach intensities of 15-20 Tesla. The magnetized-target fusion reactor (MTF) is a particular type of MCF reactor. MTF employs a conducting liner to implode a magnetized plasmoid. That is, it would use magnetic lines to channel, accelerate and collide charged particles. A third option is gravitational implosion, which occurs due to the high gravitational forces in the sun and other stars; this, however, is implausible on Earth. Figure 6 shows the three reactor designs mentioned.

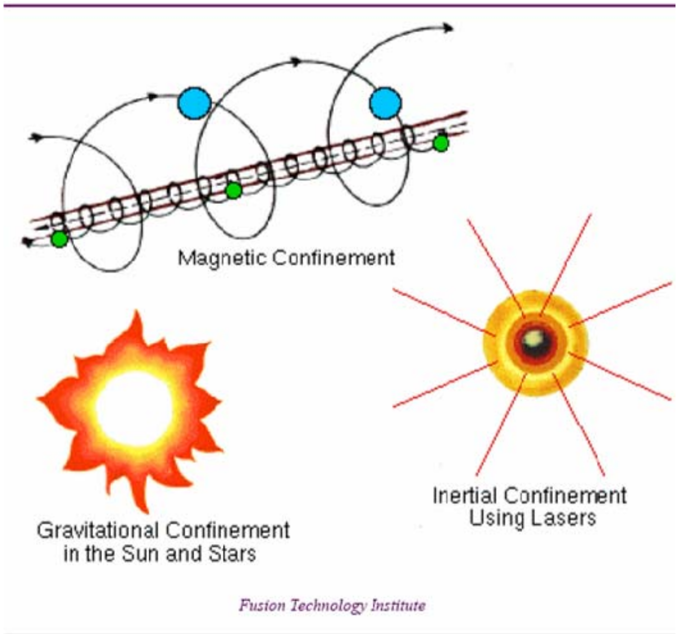


Figure 6: Types of Fusion Reaction Mechanisms (Kulcinski, 2004)

Modern fusion reactors are comprised of an inner spherical cathode biased toward a high negative charge. The fuel gas (consider tritium and deuterium for reference) enters the chamber while a constant pressure is maintained. Positive ions are generated by the voltage in the anode, these ions are magnetically accelerated toward the inner grid at velocities (and hence energies) that allow for fusion. The ions collide with other ions and neutral molecules or with the grids after which the particle detectors monitor the extent and the rate of reaction. The design of these reactors is referred to as plasma a design. Plasma is a "quasineutral gas of charged and neutral particles" exhibiting collective behavior. It can be thought of as a fourth state of matter.

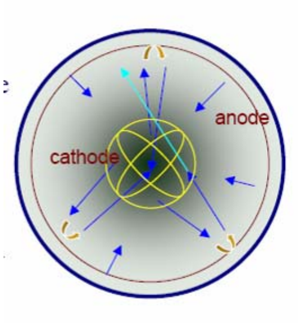


Figure 7: Schematic Design of Tokamak Reactor (FTI, 2004)

From its early ion gun beginnings, the fusion reaction rates have come a long way. In January 2004, a plasma reactor operating with a D-T fuel mixture reached a max voltage of 180 kV from an initial voltage of 80 kV in January 2001, showing the rapid progress achieved. Moreover, the neutrons production rate of a D-T continuously increased reaching a maximum of 1.8 x 10 ^{8} neutrons/s.

A milestone work was completed at Princeton's Plasma Physics Laboratory, using a now famous reactor known as the Tokamak Fusion Test Reactor (TFTR). This reactor achieved a temperature of 510 million degrees Celsius, which is a temperature of 30 times that of the center of the Sun. In addition, by November 1994 the TFTR reached an all the time maximum power emission of 10.7 million watts which is enough to power 300 American household year round. This is no doubt a promising perspective for nuclear fusion and has given ground to vigorous investigation in other types of reactor designs.

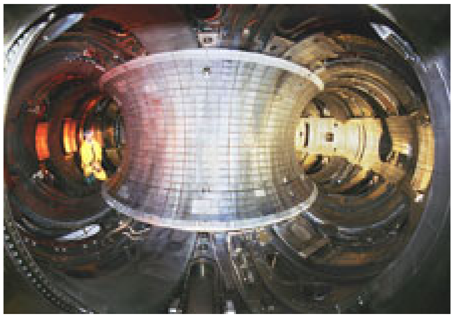


Figure 8: Inside the Tokamak Reactor (Demeo, 2005)

Although deuterium-tritium is the most advanced fuel in terms of research interest and completed milestones, it has serious disadvantages that limit its use as a commercial fusion source. Firstly, tritium is radioactive; hence the costs of waste handling are significant and may yield the reactor incompetent against similar risks in fission reactors, seeing that the latter are already fully developed. Secondly, energy from D-T reaction comes in the forms of neutral particles, which limit energy conversion to electricity to the mechanical limit of 40%, which is a result of the steam cycle employed for electricity generation. Moreover, the kinetic energy of the neutrons in the reactor becomes thermal energy when the particles collide with the reactor walls. These collisions bring about two adverse effects; they progressively exacerbate the reactor's wall materials, thus constant replacement and maintenance of the reactor is required. Also, and most importantly, the metallic wall of the reactor, once bombarded with neutrons, becomes highly radioactive as a consequence of transmutations induced by neutron collisions. In fact, the volume of radioactive material per kW-h of D-T power is greater than that in existing fission power reactors (Schmitt, 2006). Moreover, tritium confinement is a critical issue in D-T fusion reactors.

The Fusion Technology Institute at the University of Wisconsin has invested more than $43 million dollars in developing a better tritium confinement reactor with enhanced nuclear materials, and has also devoted considerable resources to the development of a Deuterium Helium-3 reactor. Although the He-3-D reaction has not reached the energy output levels reported by the FTRT, the IEC reactor in the University of Wisconsin at Madison reached a steady state D-He-3 of 5 x 10^7 protons/s at 115 kV and 60 mA, which is an impressive milestone. However, no fusion reaction to date has achieved energy break even, defined as the ratio of energy output by the reaction to the energy input required to start and maintain the reaction. The greatest ratio achieved by the IEC reactor is 0.65 (Schmitt, 2006).

The theoretical advantages of a D-He-3 reaction are significant. Two of the most prominent advantages were already mentioned. Because the D-He-3 reaction releases less radioactive particles than does the D-T analog, the magnetic shielding on the reactor can be permanent as it is not damaged by the impact of these particles; furthermore, the D-He-3 reaction offers enhanced ease of radioactive waste disposal. In fact, the reactor walls need not be replaced during the first 40-50 years of operation and once they are replaced they can be disposed of as low radioactive wastes, comparable to those of nuclear medicine (Schmitt, 2006). A third and very important advantage is that the D-He-3 second generation reaction produces two charged particles directly. The production of charged particles implies that direct conversion of fusion energy to electricity is possible, whereas the production of energy in the form of neutrons and alpha particles offers no such choice. Figure 9 presents a comparative perspective of electricity conversion efficiencies of several energy generating reactions. Although neutron production in the D-He-3 reactor also occurs as a consequence of the collision of two deuterium ions, neutron production is only 1% of that in the D-T reactor.

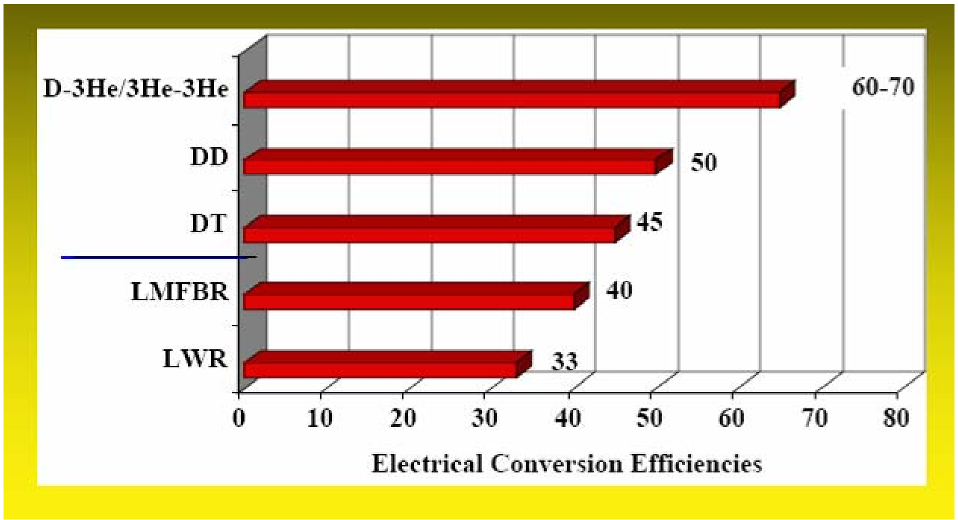


Figure 9: Electricity Conversion Efficiencies for Different Fusion Reactions (Kulcinski, 2004)

Also, the He-3 deuterium reactor would be ideal for powering spacecraft because the reactor needed is not as massive as other power sources. The lesser mass is a consequence of the smaller need for massive radioactive shielding materials. The lighter mass contributes to a very attractive thrust to drive ratio that translates to large engineering efficiency, which is critical to fast interstellar transport and cargo transport.

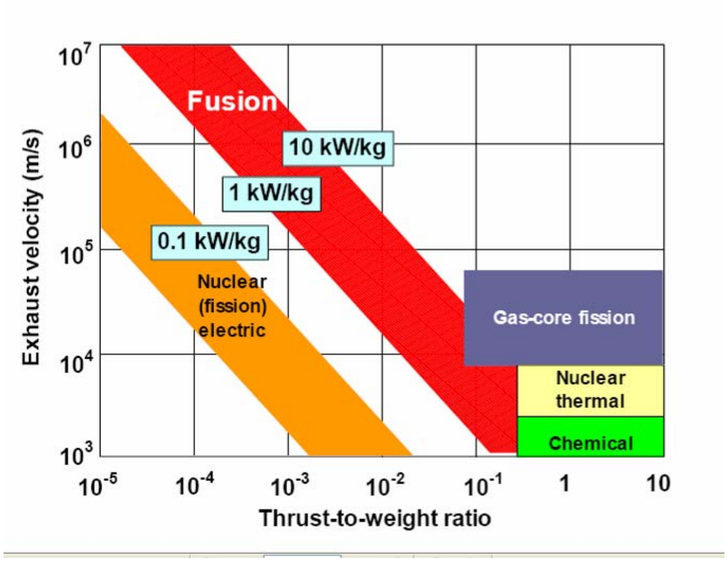


Figure 10: Thrust to Weight Ratio for Different Fuel Reactions in Powering Spacecraft (Kulcinski, 2004)

As shown in Figure 10, fusion has the greatest engineering efficiency. A boom in space exploration will undoubtedly increase the interest in the D-He-3 reaction making scientific advances in fusion technology more rapid. Figure 11 offers a comparison of the various fusion reactors as evaluated in the base of neutron generation.

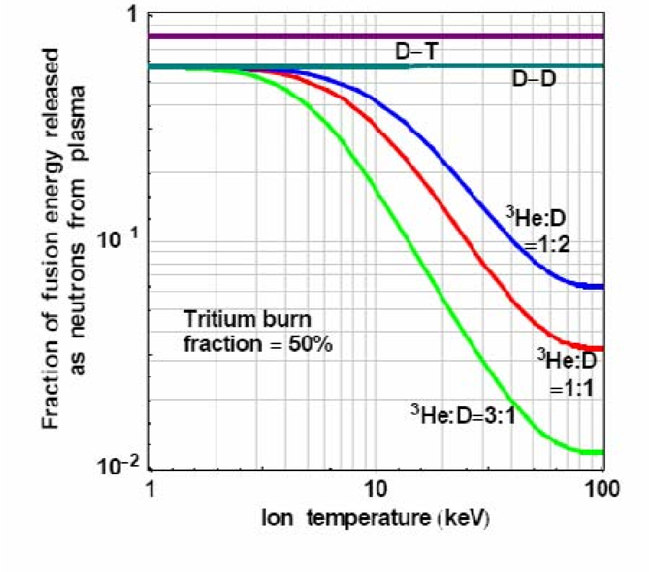


Figure 11: Neutron Generation of Three Different Fusion Reactions (Kulcinski, 2004)

Dr. Kulcinski and his team have successfully maintained a steady state D-He-3 reaction at a rate of 2.6 million reactions per second. According to Kulcinski this success serves as “a proof of principle, but is still a long way from producing electricity or making a power source out of it.” Nonetheless, his team is actively working toward this goal.

One of the greatest detriments of fusion reactions at this stage is the fact that none has become reached the break-even energy limit; that is, none has produced more energy than that required to start the reaction. The energy expenditure comes in the form of the immensely high vacuum and temperature requirements to operate the reactor. In addition, unlike nuclear fission where a chain mechanism allows for the continuous production of power, nuclear fusion relies on a continuous energy supply to ionize the fuel and accelerate the ions.

More recently, space enthusiasts have proposed a design for He-3 reactor that would operate in space. This reactor would use giant laser crystals that would be grown in the microgravity environment of outer space. The advantage of growing these crystals in outer space is that it allows for the growth of large crystals, which is not possible on Earth because the gravitational forces would make the crystal collapse under its own weight. Although an amateur conception, the physics of such device are conceivable. A sketch of the fusion reactor is presented in Figure 12.

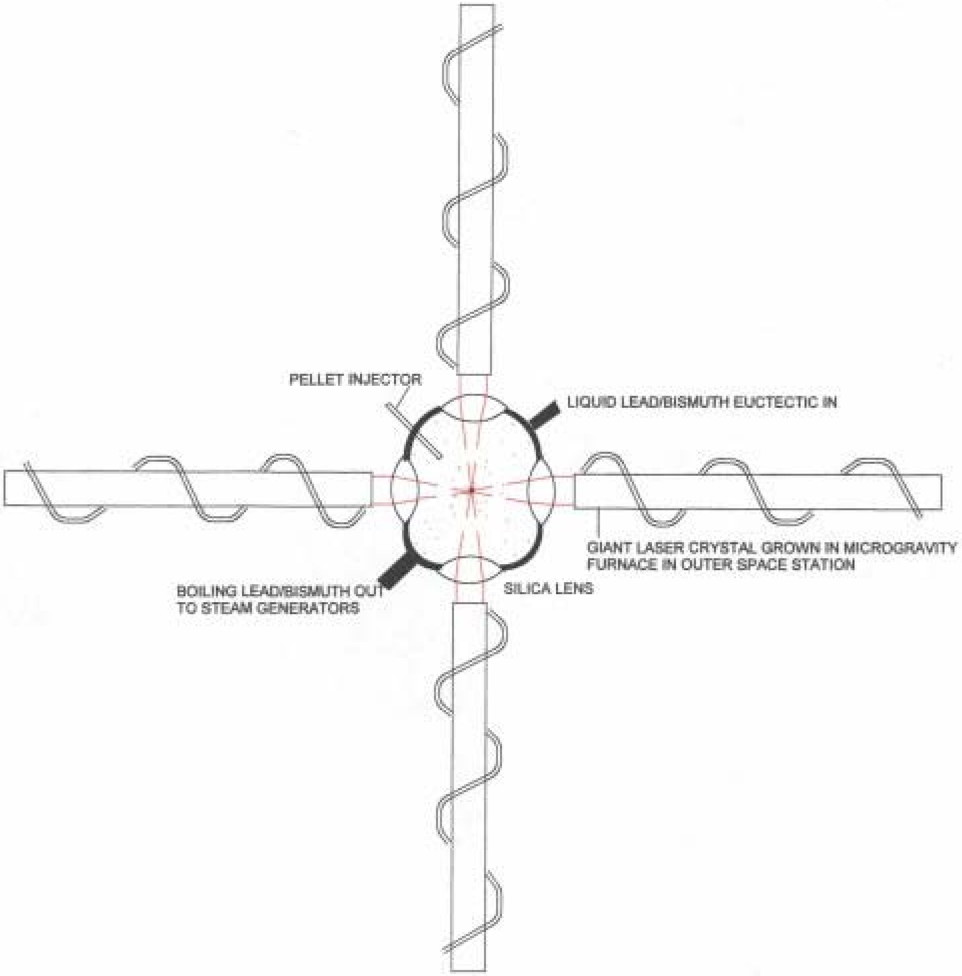


Figure 12: Artists Conception of Space He-3 Reactor (Dietzler, 2006)

3. Technical

The Manned exploration to the Moon in 1972 yielded unexpected results. After the catastrophic failure of Apollo 13 in 1962, Apollo 17 became NASA's last manned lunar mission of the past century. This mission differed from the previous missions in that it was a scientific endeavor, for which geologist Harrison H. Schmitt was chosen in addition to a group of space experts. On his return from the mission, Mr. Schmitt brought with him 244 pounds of Moon rocks for geological examination. It was only 13 years after his arrival that studies of the lunar specimens at the University of Wisconsin showed that lunar soil had significant amounts of the scarce isotope of Helium, He-3.

3.1 Geology of the Moon

Whether or not the task to mine He-3 on the Moon is successful depends in a great measure on the He-3 concentration in the lunar soil. To examine this issue we will present an overview of lunar geology.

The geological composition of the Moon closely resembles that of Earth, which is a consequence of the fact that the Moon is believed to have been formed by the same nebula that gave rise to our planet. The presence of essential elements such as iron, titanium, silicon and oxygen has been detected on the Moon; furthermore, titanium oxygen and iron form the mineral Ilmenite, the presence of which has been found to be an indicative of the presence of He-3. It has also been stated that approximately 46% (Rosensweig, 1999) of the Moon's surface is oxygen in the form of oxides. Hydrogen constitutes only 0.01 percent, however. Frequent meteor impacts on the Moon made lunar geology different from that of Earth which has suffered a smaller density of meteor impacts. The upper layer of the Moon is a layer of topsoil known as the regolith. This layer is rich in the debris from meteor crashes known as ejecta.

The absence of both a strong electromagnetic field and an atmosphere and the frequent impact of celestial bodies have given the Moon’s soil particular characteristics, and it is precisely this peculiarity that allows for the significant presence Helium-3 on the Moon. He-3 content in the lunar regolith is a function of many variables:

1. Exposure of the lunar latitude and longitude to solar wind flux.
2. Temperature profiles of the regolith according to their location.
3. Interaction of the Moon with the Earth’s magnetosphere.
4. Number of meteorites colliding with the upper surface.
5. Redeposition of volatiles on the regolith, once they have been disturbed by thermal cycling and meteor impacts.

This list can be further expanded and puts in evidence the difficulty of estimating He-3 content from a remote location. Nonetheless, an empirical correlation that links the presence and concentration of Ilmenite to He-3 has proven very effective. From soil samples brought by the Apollo mission, it was found that the concentration of He-3 in Ilmenite rich soil sample 10084,47 was two to three times that of the bulk sample. Similarly, the He-3 content of the ilmenite rich portion of sample 75081,72 was four times the bulk. It has been proposed that the closed packed hexagonal structure of ilmenite better confines He-3 as compared to silicates and prevents it from escaping during thermal cycling. This does not mean, however, that Ti depleted portions of the Moon are necessarily free of He-3. The advantage of the correlation is that titanium content can be monitored by remote spectrometric analysis, whereas He-3 cannot be tracked remotely.

The Moon consists of two basic types of terrain, the basaltic mare and the highlands. The basaltic mares are characteristic for their dark coloration, which corresponds to high iron and titanium contents. These areas constitute roughly 17% of the Moon. It has also been shown that He-3 is uniformly deposited in the titanium rich areas at a depth of approximately 3 meters. The Ti rich regions constitute nearly 50% of the Maria or basaltic mare, and from this the estimate of He-3 content in these areas is of 1 million tones.

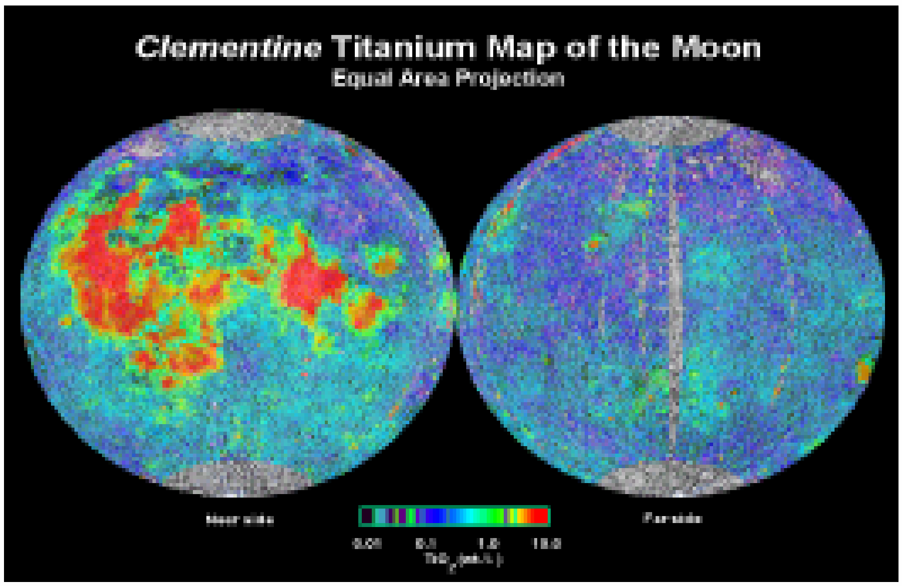
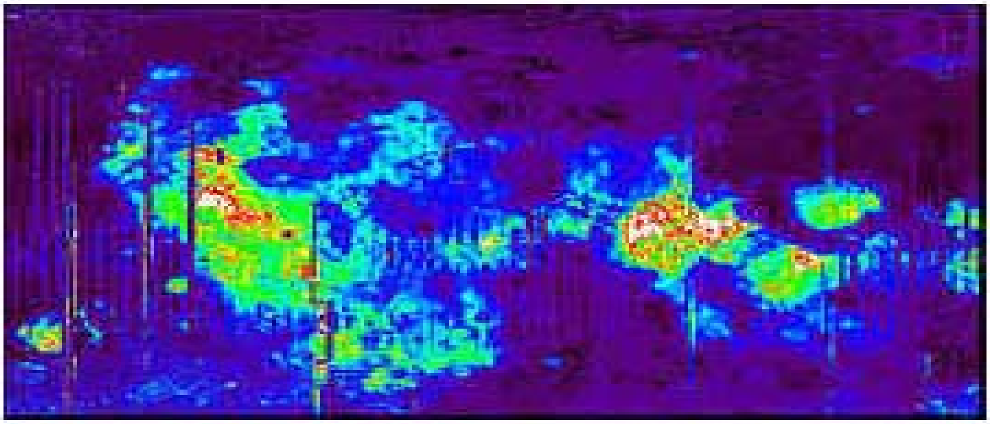


Figure 13: Illmenite Distribution on the Moon (Stube, 2003)

The lunar highlands are brightly colored areas of higher elevation. They constitute the remaining 83% of the lunar surface; however, they have much lower titanium content. In addition, the lunar highlands are brightly colored denoting the presence of forms of iron oxide. Although the lunar Highlands are said to contain much lower He-3 content than the Mare Tranquillitatis or Basaltic Mare, it has also been proposed that because the regolith layer in these areas is 5 meters in depth it is possible that He-3 is deposited at greater depths, which lends itself to a generous estimate of He-3 as being an additional million tones (Stube, 2006) for a total of two million tones. Figure 13 shows the titanium distribution in the Moon. These types of mappings are the ones used in determining He-3 content.

Another factor that weighs heavily on He-3 content is the particle size distribution of the regolith. The smaller the particle size, the higher the He-3 content, such correlation can be expected since finer particles have higher surface area and consequently higher exposure to solar winds, which is the primary mechanism of He-3 deposition.

Harrison Schmitt, who visited the Moon with Apollo 17, estimates that the He-3 reserves in the Moon's regolith would dwarf the energetic potential of uranium as a fuel for fusion reactions. According to him, 17 square kilometers of the Moon's surface could provide sufficient electricity to power a city of 10 million people for a complete year, but also acknowledges that the technology required for the enterprise will not be available for the next 15 years.

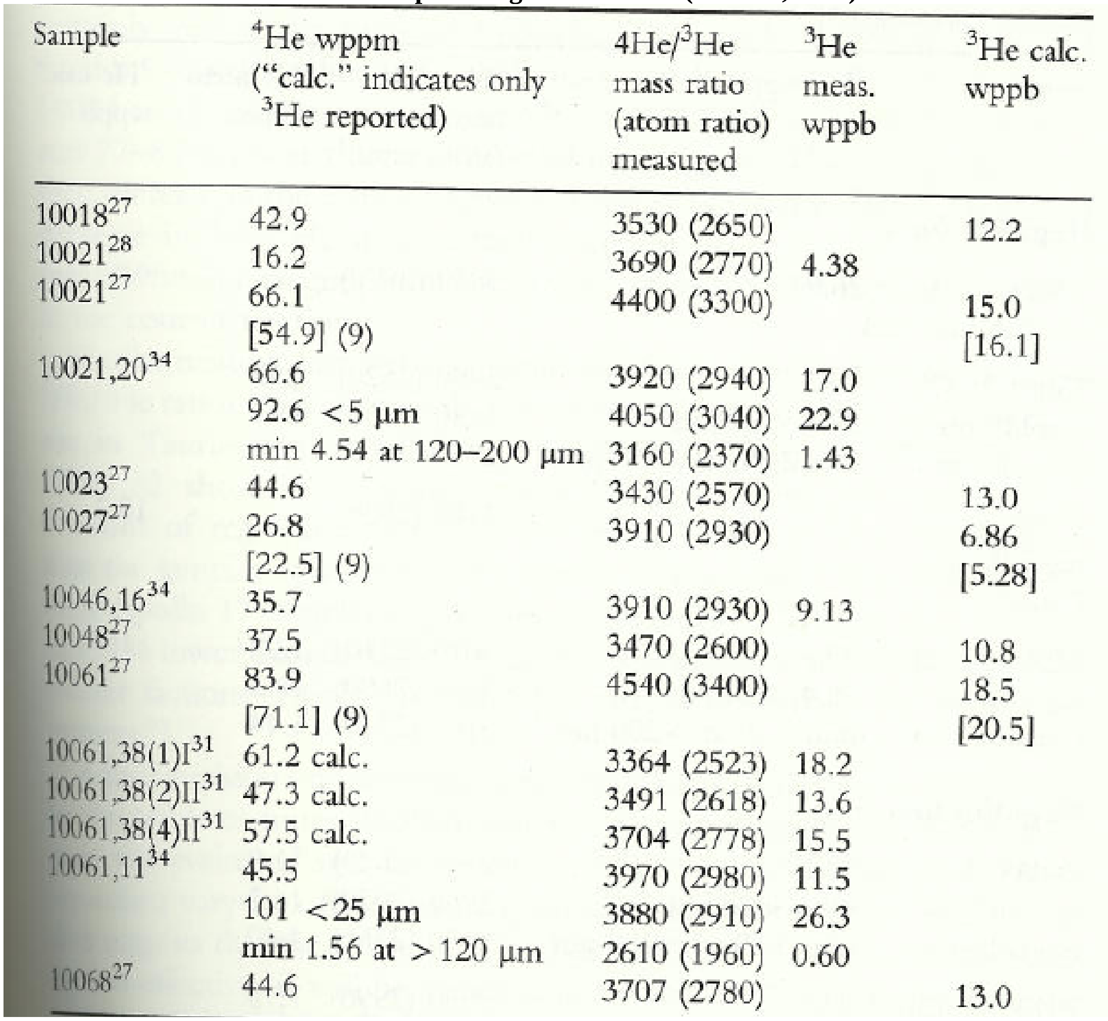


Map 2: The red indicates an abundance of Helium-3 on the Lunar Surface. [10]

Figure 14: Abundance of Helium-3 on the Moon (Stube, 2003)

The Late professor Eugene Cameron, a noted geologist, provided some estimates of He-3 content on Mare Tranquillitatis in 1980 using spectroscopic data of titanium concentration. An economic geologist, Dr. Cameron rated the areas based on the availability and ease of mining He-3 from them. According to his study, the premium areas add to 84,000 km^2 and those of medium grade were an additional 195,000 km^2. These figures are for Mare Tranquillitatis *only*. The highest grade areas alone would yield 2500 tons of He-3. According to the prospective price of steam coal in 2015, those 2500 tons would be valued at $3.5 trillion. Dr. Cameron estimated that the concentration of He-3 in the regolith's upper 6 meters would be at least 20 wpps, which classifies this He-3 as recoverable by financial standards. Table 4 summarizes the He-3 concentration in a number of regolith samples taken by Apollo in the 1970's.

Table 4: Helium Concentration in Apollo Regolith Breccias (Schmitt, 2006)



Sample	^{4}He wppm (“calc.” indicates only ^{3}He reported)	4He/^{3}He mass ratio (atom ratio) measured	^{3}He meas. wppb	^{3}He calc. wppb
10018[27]	42.9	3530 (2650)		12.2
10021[28]	16.2	3690 (2770)	4.38	
10021[27]	66.1	4400 (3300)		15.0
	[54.9] (9)			[16.1]
10021,20[34]	66.6	3920 (2940)	17.0	
	92.6 <5 µm	4050 (3040)	22.9	
	min 4.54 at 120–200 µm	3160 (2370)	1.43	
10023[27]	44.6	3430 (2570)		13.0
10027[27]	26.8	3910 (2930)		6.86
	[22.5] (9)			[5.28]
10046,16[34]	35.7	3910 (2930)	9.13	
10048[27]	37.5	3470 (2600)		10.8
10061[27]	83.9	4540 (3400)		18.5
	[71.1] (9)			[20.5]
10061,38(1)I[31]	61.2 calc.	3364 (2523)	18.2	
10061,38(2)II[31]	47.3 calc.	3491 (2618)	13.6	
10061,38(4)II[31]	57.5 calc.	3704 (2778)	15.5	
10061,11[34]	45.5	3970 (2980)	11.5	
	101 <25 µm	3880 (2910)	26.3	
	min 1.56 at >120 µm	2610 (1960)	0.60	
10068[27]	44.6	3707 (2780)		13.0

Geological estimates of He-3 content are a determining factor on deciding whether to engage in the venture at all. Preliminary data seems to suggest that there is enough He-3 content to satisfy growing energy requirements and offers a stable financial pillar upon which to support investigation and development.

3.2 Mining the Moon

In order to start mining He-3 from the Moon, along with other minerals present in the regolith, it is first important to develop an infrastructure that can support such activities on the lunar surface. It is rational that before humans can start excavating the lunar surface, they should develop a lunar base with sufficient self-sustaining power, and technology to transport cargo to and from Earth.

3.2.1 Mining Scenarios

In this section, a few mining scenarios will be discussed as presented by various researchers and scientists. Igor N. Sviatoslavsky of the Fusion Technology Institute and the Wisconsin Center of Space Automation and Robotics and Mark Jacobs of the Astronautics Corporation of America presented a scenario in the 1988 Space Conference for the American Institute of Aeronautics and Astronautics (Lewis, 1990). The researchers introduced the idea of an automated mobile lunar machine that would excavate the regolith to a depth of 3 meters. It would collect the excavated regolith and separate particles 50 micrometers in size electrostatically because these particles contain the highest helium content. The remaining soil is dumped back on the lunar surface. These particles would be heated to 600-700 degrees Celsius to boil off the trapped gases, which are collected and compressed into cylinders. The cooled particles are also dumped back on the surface. The heat required to heat the particles is sourced from the sun using ‘solar disks’ about 110 meters in size, which concentrate the heat in an oven.

Figure 15: Solar Powered Lunar Mining Rover (Kulcinski, 2000)

Igor N. Sviatoslavsky, of the Fusion Technology Institute, has already designed a mobile miner which he has named the Mark II Miner. The design parameters for this miner are given in Table 5.

Table 5: Design Parameters for the Mark II Miner (reprinted from Schmitt, 2006)

PARAMETER	VALUE
Annual collection rate of He-3 at 10 ppb	33 kg
Mining hours per year	3942 hr/yr
Excavation Rate	1258 tons/yr
Depth of excavation	3 m
Forward speed of miner	23 m/hr
Area excavated per year	1 km^2 / yr
Processing rate	556 tons/yr
Lunar process energy (82 GJ/g with solar thermal energy)	12.3 MW
Heat recovery	85%
Estimated operating electrical power	200 kW

The collected and compressed gases are sent from the mobile miner to a condensing station by automated ground service vehicles. The gases, consisting of hydrogen, nitrogen, oxygen, carbon dioxide and helium, are cooled to about 55 degrees Kelvin in radiators and collected in liquid form. The helium is further cooled in a 'cryogenerator' to about 1.5 degrees Kelvin to separate the He-3 isotope from the He-4 isotope. This condensation would allow the He-3 to be extracted as it drains off separately. Also, the 'waste' products of this condensation, like oxygen, nitrogen, water, methane and hydrogen, are crucial for life support purposes on the lunar base that would exist. Refining the mixture of gases is a complex process requiring several consecutive steps. The first consists of separating hydrogen which is done by passage of the hot volatiles through a heated niobium window. Secondly, the raffinate is sequentially cooled to liquefy water, carbon compounds and nitrogen compounds by difference in boiling points. The liquid are transported to an intermediate storage area. Oxygen, probably the most important byproduct, is obtained by splitting water into hydrogen and oxygen using electrolysis (Schmitt, 2006). He-3 is separated from He-4 by a superleak membrane process.

The scientists also calculated some numbers and figures for this fascinating mobile miner machinery. It would collect 33 kilograms of He-3 a year, which means that it would excavate and mine about 1280 tons of regolith an hour (of which 566 tons would be processed). The power consumption of this miner would be 30 kilowatts, according to scaling measurements of a similar miner on Earth. The miner would weigh 18 tons, and would mine the regolith 3 meters deep and 11 meters wide at a speed of 25 meters an hour. Heating the regolith to the required temperatures is the most energetically costly step. There are many proposed methods for accomplishing this. The preferred method is microwave radiation. Microwave radiation requires a source of electricity, which has severe associated efficiency losses; to counteract such losses, however, microwave radiation is very efficient since it takes advantage of microwave coupling with the nanophase iron particles that are known to be finely distributed in the regolith (Schmitt, 2006). Choosing microwave radiation does not solve the energy source problem because an energy source would be needed to generate electricity. The favored method seems to be solar energy, given the competitive advantage offered by the long lunar days. Solar energy could be coupled with hydrogen and oxygen in large fuel cells to produce electricity, in the process water is generated as by product. Alternatively, nuclear fusion would provide both thermal and electrical energy for heating the regolith. With nuclear fission heating can be done directly or through microwave radiation. Fusion energy from He-3 seems to be an obvious candidate, but because a fusion reactor would operate for a He-3 and deuterium fuel and due to the low deuterium content on the Moon, this is an unlikely alternative when weighted against fission energy. Fusion would imply transporting deuterium from the Earth to the Moon which is a venture in itself.

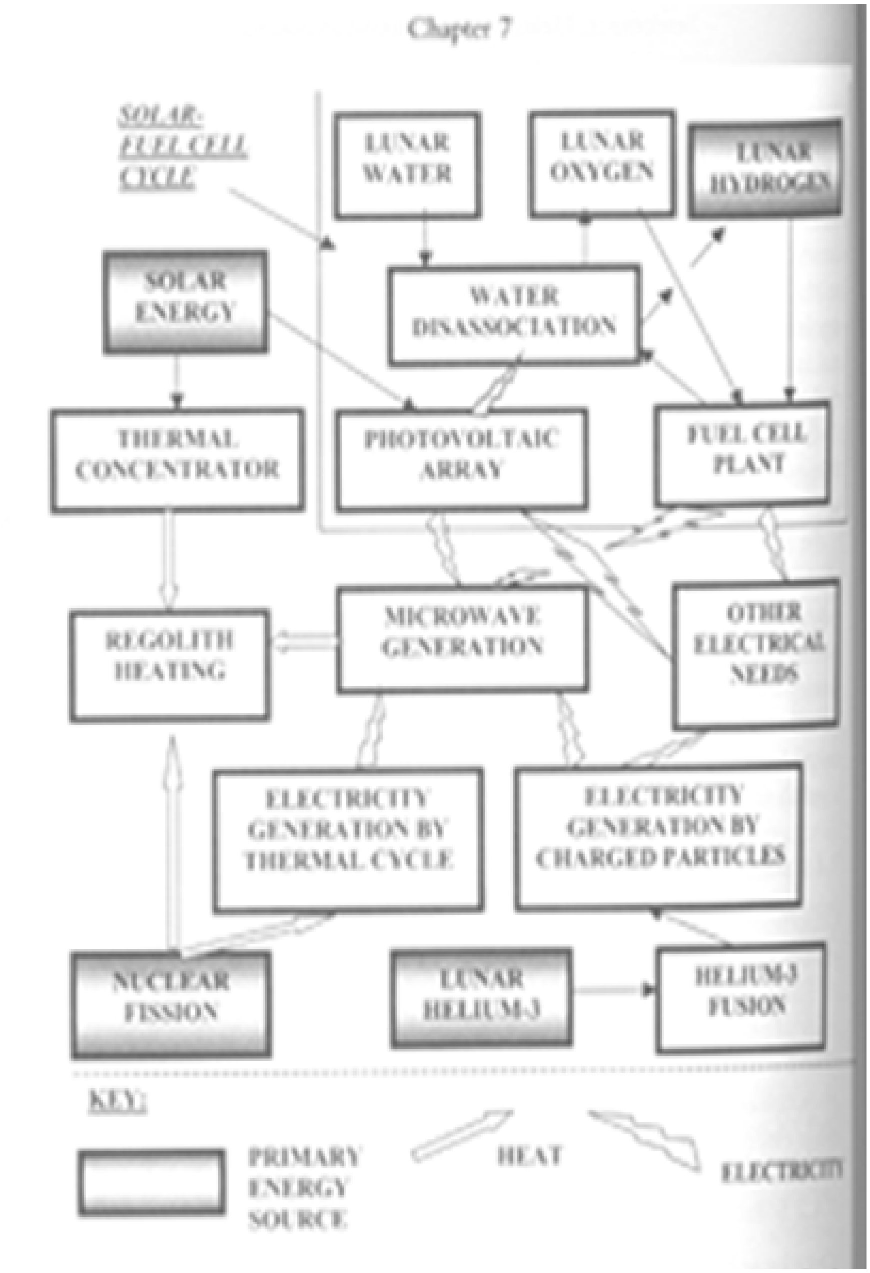


Figure 16: Schematic Flow Diagram Illustration Options for Producing Thermal and Electrical Power for Lunar Operation (Schmitt, 2006)

Kraftt A. Ehricke (1917-1984), who was a leading engineer and theoretician of modern space travel, suggested many different scenarios and visions for a lunar base. As discussed by Lewis (Lewis, 1990), Ehricke even suggested an alternate process of obtaining He-3 from the Moon. As Lewis explains, Ehricke described a process in 1984 of obtaining He-3 from the decay of excess tritium produced by the deuterium-tritium reaction in nuclear fusion plants, which would be built on the Moon where there would be no public concern about radiation. He-3 as a byproduct could be shipped to the Earth for radiation-free power from He-3-D fusion reactors (as discussed before). This is a very interesting option, which also produces He-3 from the nuclear reaction and not mining. But the feasibility of this vision seems to be less than the mining scenario. In both cases, first there has to be a lunar base established on the Moon. The development of a mining station is not farfetched, since the principles that apply are basically the same as those of mining operations on Earth, and the technology would need only slight modifications to deal with the harsh lunar environment. It is an engineering task, and its possibilities are finite. Also, a mining station would be less risky than a nuclear fusion plant as it relies mainly on mechanical and chemical risks, and not 'nuclear risks' that are definitely worse. Therefore, if we focus strictly on He-3 mining operations, the mining technique is better than He-3 being obtained primarily from a nuclear plant. Of course, the He-3 from the nuclear reactor can also be used as a side-resource, but definitely the nuclear plant would primarily exist for providing the needed power for the lunar bases and mining operations.

3.2.2 Mining Feasibility

The soil on the Moon is very different that the soil found on Earth. According to a study done by E. R. Podenieks and W. W. Roepke from the U. S. Department of the Interior, Bureau of Mines (Lewis, 1989), the surface friction and rock strength are higher in 'hard vacuum' on the Moon than on Earth. This is because of lack of moisture and stronger adhesion forces in vacuum, which result in chip formation and clogging during drilling. Even though He-3 is present mainly in the regolith in a range of approximately 3 meters, special attention has to be paid to the mining process. For example, the astronauts on Apollo 15 experienced drilling problems as the drill stem in their jackhammer broke at a depth of about 4 feet (Lewis, 1989). Furthermore, the researchers reported that friction in the lunar regolith may be 60 times more than frictional forces on terrestrial soil.

Keeping the soil properties in mind, a mining method needs to be developed that minimizes friction. Some mining techniques investigated by the Bureau of Mines are using gaseous lubricants, blasting techniques designed for lunar surfaces and using electrothermal (lasers) techniques to break rock. A combination of these techniques would be the ideal approach to lunar soil mining. A lunar mining team would be composed of engineers and scientists who must be very familiar and experienced in mining techniques unique to lunar soil (Roepke et al, 1985). There are two main mining strategies that could be applied. The "rectilinear strategy" is based on the customary mineral mining performed on Earth and envisions the use of rectangular mining blocks inserted between crater ejecta. Mining would take place back and forth and parallel to these blocks (Schmitt, 2006). Mining cuts would be 11 meters wide by 3 meters deep. Rectilinear mining would result in the mining of 28-57 % of the total mining area of Mare Tranquillitatis. The extracted volatiles would be stored in large pressure tanks which would in turn be transported to a central refining facility.

Spiral mining, on the other hand, is analogous to open pit mining. In this mining approach the mineral processing unit lies at the end of a telescopic arm attached to a large and self sufficient mobiles central station. The central station would be comprised of refining, power, control and mobility facilities in addition to habitation compartments. It would move periodically once the miner has mined the immediate periphery of about one to two kilometers. The period required to mine this volume of regolith is approximately two to six years according to conservative estimates (Schmitt, 2006). For many practical considerations, spiral mining is favored over rectilinear mining by many studies. The reasons for this preference are a reduced exposure risk for manned crews, since all components are confined in a central space, ease of automation by use of telerobotic operations and finally avoiding costly transportation within the Moon.

3.2.3 Lunar Mining Base and Transportation

A lunar base and transportation between the Earth and the Moon is necessary to carry out the daily routines of space mining and other features. In the paper, Strategies for a Permanent Lunar Base (Duke et al, 1985) from the NASA/Johnson Space Center in Huston, Texas, the authors discuss some interesting visions of a lunar base. There are two options for transport: to liquefy He-3 and carry it in liquid form or to transport it as a gas. The first is advantageous in terms of volume and hence the size of the boosters; however, the higher costs of liquefying and the complexity of the spacecraft needed to maintain the products in liquid form will most certainly offset the higher cost of bigger equipment for transporting it as a gas. Hence, in this study we will assume that He-3 will be transported in gaseous form. First of all, due to the Moon's weaker gravitational field and the absence of an atmosphere, the forces required for liftoff from Moon would be much less compared to liftoff from Earth. Most of the payload while liftoff from Earth is about 50% fuel that is required to reach escape velocity and arrive at the Lower Earth Orbit, LEO. The same shuttle, if lifted off from the Moon, can carry about 50% more cargo instead of fuel. A favorable propulsion system would be a hydrogen-oxygen based system. There is abundant oxygen present on the Moon, which can easily be extracted from the soil. The problem exists in the fact that there is not enough hydrogen present on the Moon. This can be overcome by carrying hydrogen to the Moon, while transporting cargo, and using it with lunar derived oxygen in the propulsion system. This would make it easier to transport life-sustaining commodities to the Moon, and exchange cargo on the way back.

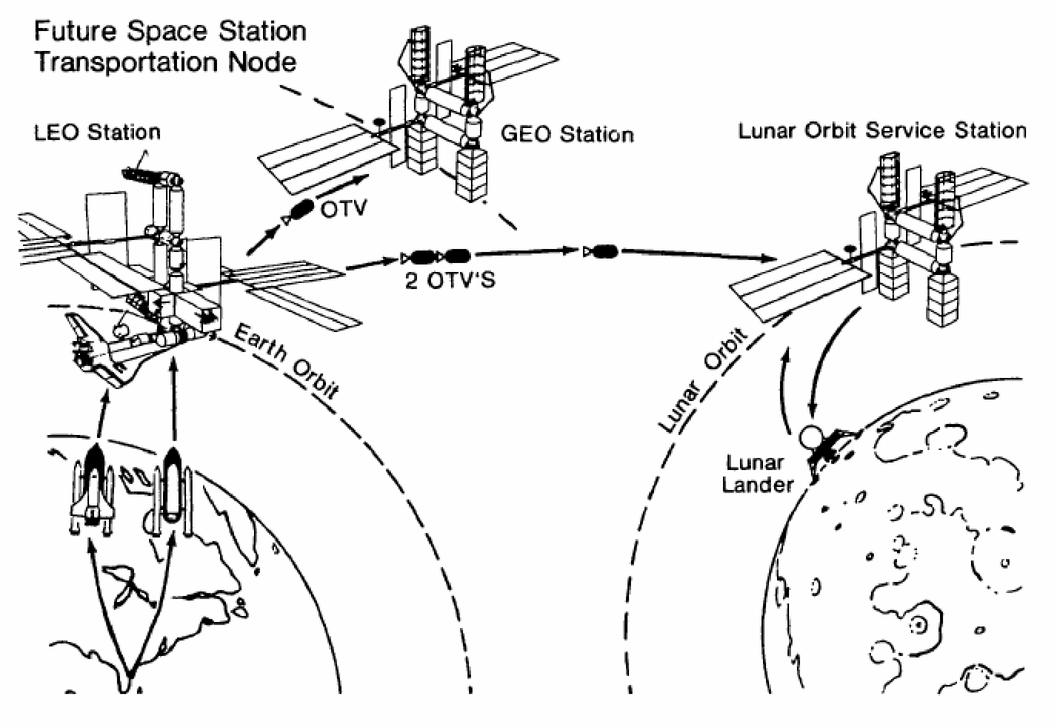


Figure 17: Transport between Earth and the Moon (Duke et al, 1985)

One proposed idea explained by Duke et al is that there would be a low-Earth orbit (LEO) space station, and a lunar orbit space station (as seen in Figure17). Space shuttles from Earth with cargo would rendezvous with the LEO station, and Orbital Transfer Vehicles (OTV) would be used to transfer the payload from the LEO station to the lunar station. Then, a Lunar Lander, which would only travel between the lunar station and the lunar surface, would transfer cargo to and from the Moon. In the same way, the OTVs would return with cargo from the lunar station to the LEO station. The cargo would then be brought to Earth using conventional space shuttles or a similar vehicle. This scenario would keep a flow in transported cargo (and hydrogen necessary for propulsion with lunar oxygen) and there would be no need for a new space shuttle to be launched every time to send cargo to the Moon, which would also waste a lot of fuel and efficiency. Duke et al also mention that it would be indispensable to have international cooperation and participation in the planning stages, in science and technology development, and in operations at the lunar base (Duke et al, 1985).

There are several other transportation techniques that have been envisioned by many scientists. Some fuel systems that have been introduced in this paper and could be used for propulsion include nuclear fission and fusion. One possible space fuel would be He-3, which is very clean and can provide high thrust (as discussed before). The drawback of this fuel is the high temperature fusion reactions require, and the very high cost of building such reactors to be compatible with the size of the vehicle.

In order to save on astrofuel, a long-term idea has been proposed which involves the use of carbon-nanotubes in a 'space elevator.' This elevator would be a carbon-nanotube based 'cable' that would extend from the Earth's surface to LEO, and would be in geostationary orbit. An article from NASA's website states that, "A space elevator is essentially a long cable extending from our planet's surface into space with its center of mass at geostationary Earth orbit (GEO), 35,786 km in altitude. Electromagnetic vehicles traveling along the cable could serve as a mass transportation system for moving people, payloads, and power between Earth and space" (Price, 2002). This approach would allow transfer of cargo to LEO as the 'space ships' or 'cargo carriers' use the elevator to climb and descent. This would be a good way to transport cargo without manned spacecrafts.

However, this technology is far from fully developed, and may take many decades and a lot of money till it is possible.

Another approach being tested by NASA is the use of ‘Magnetic Levitation’ described in the NASA website and shown in Figure 18.

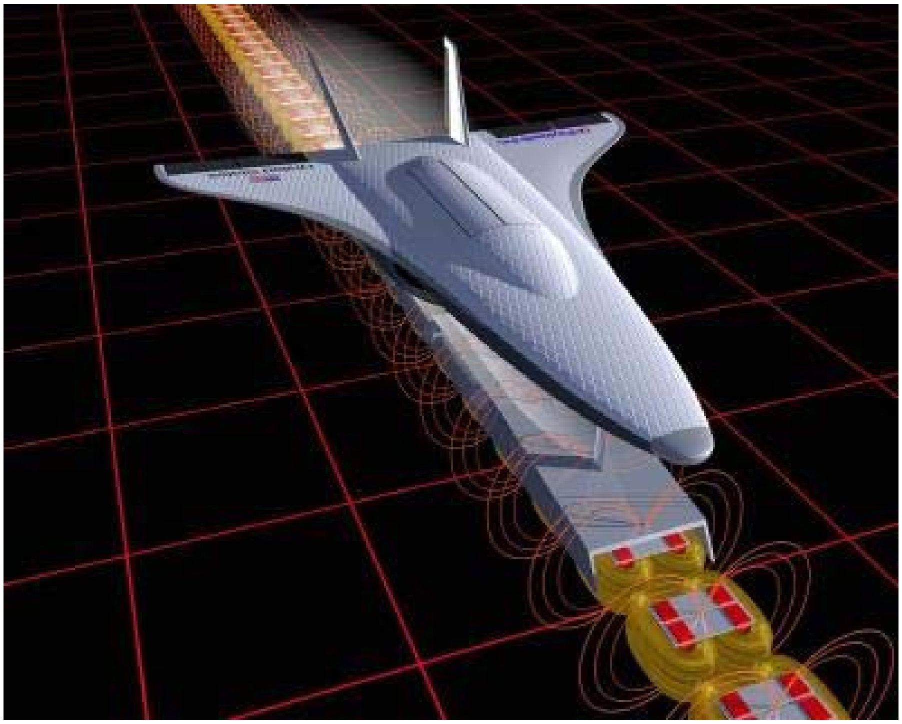


Figure 18: Computer Model of Magnetic Levitation (NASA, 1999)

Magnetic levitation involves the use of magnetic fields to accelerate a spacecraft along a path, and then releasing it at the end to fly upwards. After the launch, the spacecraft would use its own thrust to continue. This approach would significantly reduce fuel consumption.

The building of a lunar base would consist of constructing pressurized chambers that would be shielded from solar winds, and would be able to sustain human survival. Also, a mining station would need to be setup that would process and package He-3 for transport. Another idea for a lunar mining station is ‘spiral mining’ (Mineral Science

Technology), which would consist of a mobile miner, similar to the one discussed earlier, that would be attached to a central station with a telescoping arm. The spiral mobile miner would get its electrical power from the central station, and the extracted materials would be transported continuously to the central station. The central station would then be used as a reservoir for mined materials. For example, the liquefied He-3 could be packed in the central station and be transported to a launch station, where the Lunar Lander would transport the cargo to a lunar orbital station, as discussed above, and then be transported via OTVs.

4. Legal and Political Framework

4.1 Moon Treaty

The 1979 Moon Treaty-"The Agreement Governing the Activities of States on the Moon and Other Celestial Bodies" was a treaty developed by the United Nations to set the limits for the future regulation, exploitation, and exploration of the Moon. The basic purpose of this Treaty was to ensure that any wealth obtained from the Moon was to be distributed to all the nations of the world. Article 4 (2) of the Treaty states that,

> "*The exploration and use of the Moon shall be the province of all mankind and shall be carried out for the benefit and in the interests of all countries, irrespective of their degree of economic or scientific development. Due regard shall be paid to the interests of present and future generations as well as to the need to promote higher standards of living and conditions of economic and social progress and development in accordance with the Charter of the United Nations*." (Office for Outer Space Affairs, 1967)

The phrase "the Moon shall be the province of all mankind" has created controversy among nations. This is because the way the sentence is phrased sounds like it means that all the resources of space belong to all nations and the use or extraction by one nation is against this treaty. On the other hand, it actually meant to say that no single country could claim outer space or other celestial bodies as colonies, but it permits the use of the resources (Graham, 1995). Due to this misinterpretation of the Treaty many nations haven't signed it yet.

The fact that the wealth obtained from the Moon has to be shared with all the nations of the world equally does not give the private-sector a chance of developing their own lunar economic development business. The ethical issues arise when profits are earned by these businesses and supporters of the "Moon as the province of mankind" principle demand distribution of the benefits and profits from commercial lunar development (Livingston, 2000).

According to the Moon Treaty, an international agency is to be created which will be responsible for and capable of distributing lunar resources equitably. However, political and economic tensions might rise between developing nations and developed nations making any attempt to enforce the "Moon as the province of mankind" principle a questionable proposition. Even if an international organization could be created to distribute benefits equally and fairly among nations, no private investor would be willing to invest capital on the Moon if it would obtain no return on its investment. In reality, "the Moon as the province of mankind" principle is a serious hurdle for the private sector in creating lunar-based businesses (Livingston, 2000). Thus, it's up to governmental organizations of nations to develop any interests they have on the Moon.

As of now, the Treaty has not been accepted by all the members of the UN. The nations that have ratified them are Australia, Austria, Chile, Mexico, Morocco, the Netherlands, Pakistan, Philippines, and Uruguay. In addition, the agreement has been signed, but not ratified, by five countries: France, Guatemala, India, Peru, and Romania.[3] Article 11 of the Treaty states that,

> *"Neither the surface nor the subsurface of the Moon, nor any part thereof or natural resources in place, shall become property of any State, international*

> *intergovernmental or non- governmental organization, national organization or non-governmental entity or of any natural person. The placement of personnel, space vehicles, equipment, facilities, stations and installations on or below the surface of the Moon, including structures connected with its surface or subsurface, shall not create a right of ownership over the surface or the subsurface of the Moon or any areas thereof…"* (Graham, 1995)

It is interesting to note that the nations that have ratified the Treaty have no ongoing lunar exploration activities and that the current main players in the Moon race, the United States, China and Russia which have ongoing lunar projects, have not signed and ratified the treaty. Although it bans appropriation of lunar territory, the Space Treaty does contemplate the use of lunar material for scientific purposes and for technological development. The Space Law consultant Amanda Lee More, says that the principle of non-appropriation is "sufficiently normative in character so as to be considered a valid principle of international law both in treaty and costume

4.2 International Interest in He-3

The abundance of He-3 on the Moon has stirred the competitive interests of countries such as the United States, Russia, China and India. The United States leads the research in He-3. The Fusion Institute of Technology in Wisconsin, Madison performs most of the He-3 research to develop the necessary technology and means to extract He-3 from the Moon. The Center for Space Automation and Robotics department at the University of Wisconsin in Madison was the first to envision the idea of mining Astrofuel from the Moon in 1986. The center, one of 16 NASA funded facilities for the commercial development of space, is positioned to manage the project because of the university's already existing fusion, space and life support research program (Chowdhuri, 2003).

On January 14, 2004 U.S. President Bush announced a new vision for NASA that incorporated a human return to the Moon by 2020(Cramer, 2004). In his message he also wished that the private sector take a leading role in developing human expansion into space. The President's Commission on Implementation of U.S. Space Exploration Policy subsequently recommended that NASA encourage private space-related initiatives. “I believe in going a step further. I believe that if government efforts lag, private enterprise should take the lead in settling space”, he stated (Schmitt, 2004).

However, a loophole in the UN Outer Space Treaty has given advantages to individuals and companies to hold Mineral Rights on the Moon, Mars and other celestial bodies. It stipulated that no government can own extraterrestrial property. However it neglected to mention individuals and corporations. Taking undue advantage of this error, Dennis Hope, a Lunar Entrepreneur has claimed to have started a Lunar Embassy, which sells plots on the Moon and other celestial bodies. There is also a Lunar Settlement Initiative that provides a framework for private development of the Moon.

Another individual, Dr. Resnick (former NASA scientist and current consultant to NASA) states "Space law does not allow countries to have land ownership on planets and Moons in the solar system but it does allow for the Mineral Rights to be obtained by individuals and companies. The countries party to the Space Treaty Act have agreed that none of them has either jurisdiction or ownership of any extraterrestrial body, nor samples.” He found this ambiguity in the Space Law 25 years ago that allowed him ownership of all planetary bodies outside the "Third Planet from the Sun” submitted the document to the World Court at The Hague, and to the United Nations in New York City. For more than years no one has ever disputed Dr. Resnick's claimed ownership. This loophole in space law has been a growing concern to scientists; however, most were unaware that Dr. Resnick had foreseen some of these issues long ago when he obtained ownership of the mineral rights (Cramer, 2004).

As a result of these settlements which are not really valid, many private entrepreneurs have started to own land on the Moon. Growing concern from scientists that these rights may be held hostage have been alleviated by a three man North American team; Dr. Joseph Resnick, Dr. Timothy R. O'Neill and Guy Cramer (ROC-Resnick/O'Neill/Cramer team) who have acquired the mineral rights for 95% of the side of the Moon that faces Earth, the polar regions and 50% of the far side of the Moon. They set aside 8.9 million acres around the Apollo 11 Lunar landing site and designated it as a "World Heritage Site". The ROC team announced that it was holding more than 75% of the Lunar Mineral rights to allow for the extraction of Helium-3 and other minerals for the advancement of Space Exploration Earth and Space Sciences and safer more efficient energy production. With the mineral rights secured, the ROC team wants to administer the extraction process of He-3 and other minerals for any robotic or human ventures to obtain these materials to ensure the Moon is not stripped off all its valuables (Cramer, 2004).

4.3 Energy Treaties

Recognizing the political and economic impact energy can have, many different attempts at regulating or establishing a comprehensive energy treaty have been made. A most recent one took place in Beijing where the International Renewable Energy

Conference condemned the action of many nations that claim to be working toward an international energy agreement, while sustaining practices domestically that drift far from that focus.

Politically committing to an energy agreement is a delicate issue because of the implications in national industrial development that it can carry. Nonetheless, vigorous action has taken place in the last years favoring the formation of an organized international committee for renewable energy. In fact, the World Energy Assembly took place in 2005, and its intent was to establish a formal law binding agreement to which industrialized nations would subscribe.

The Kyoto Protocol in 1997 established a milestone in emission regulations, which are directly tied with hydrocarbon energy. In this agreement national emission levels for a series of nations were established; these would contribute to a 20% decline in major polluting gases emission such as CO_2, FCH and NO_2 by the year 2010. Hence, Kyoto established incentives for developed countries to seek alternative energy sources, so as to comply with the proscribed emission levels. A major drawback, however, was that within the treaty, the level cuts were negotiable and could be traded within the "emission trading regime," which allows mechanisms known as Joint Implementation via which financing alternative projects is equivalent to an actual emission reduction. Moreover, the United States, the most important emission country by volume, failed to ratify the treaty in 2001. President Bush stated in his State of the Union Address that,

> *"This is a challenge that requires a 100 percent effort; ours, and the rest of the World's. The world's second-largest emitter of greenhouse gases is China. Yet, China was entirely exempted from the requirements of the Kyoto Protocol. India and Germany are among*

> *the top emitters. Yet, India was also exempt from Kyoto. . . . America's unwillingness to embrace a flawed treaty should not be read by our friends and allies as any abdication of responsibility. To the contrary, my administration is committed to a leadership role on the issue of climate change. . . . . Our approach must be consistent with the long-term goal of stabilizing greenhouse gas concentrations in the atmosphere."*

The history of the Kyoto Protocol, its good intentions and its failure, provide an interesting basis upon which to analyze what could occur in the future if He-3 is used extensively as an energy source.

4.4 Principles and Treaties Directing Space Exploration and Exploitation

Acknowledging the need of nuclear fuel in space missions, the United Nations has assembled a number of regulatory treaties. Among the most relevant is ARES_47_68 which treats the issue of nuclear in space use directly.

Paragraph 2 of the aforementioned treaty establishes that nuclear reactors may be operated on interplanetary missions if operated at sufficiently high orbits. The former are defined as orbits whose lifetime is sufficient to allow for the "decay of fission products to approximately the activity of the actinides". This particular portion is, however, irrelevant as concerned with nuclear fusion, which is basically radiation free. The treaty limits the use of nuclear reactors to those fueled by uranium 253; a consideration made almost entirely in anticipation of radioactive waste emission. This limitation shows the potential advantage of using He-3 to power space flight, since its use results in much lower radiation emissions, if any at all.

Another particularly relevant aspect of this treaty is encompassed in Principle 8 which addresses the responsibility of states, assigning full responsibility and liability of a nuclear incident in outer space to the "launching state" defined as the nation whose vehicle and or ground of launching is involved. Particularly it establishes that:

"The compensation that such States shall be liable to pay under the aforesaid Convention for damage shall be determined in accordance with international law and the principles of justice and equity, in order to provide such reparation in respect of the damage as will restore the personal, natural or juridical, state or international organization on whose behalf a claim is presented to the condition which would have existed if the damage had not occurred." 85th plenary meeting 14 December 1992.

This treaty establishes a premise upon which to consider what may happen legally in the case that nuclear reactor facilities, such as plasma reactors for the fusion of He-3 and H^2 , were established on the Moon or other celestial bodies and in the case that their failure generated damage.

"The Declaration on International Cooperation in the Exploration and Use of Outer Space for the Benefit and in the Interest of All States, Taking into Particular Account the Needs of Developing Countries" established that,

"exploration and use of outer space, including the Moon and other celestial bodies, shall be carried out for the benefit and in the interest of all countries irrespective of their degree of economic or scientific development, and shall be the province of all mankind."

The terms used throughout the treaty are vague, though well intentioned. It establishes, for example, that "states are free to determine all aspects of their participation in international cooperation in the exploration and use of outer space on an equitable and mutually acceptable basis.” What is equitable and acceptable is subject to the agreement of the parties and realistically can be established either by free will or by some sort of economic or political coercion. This, however, is a rather pessimistic interpretation and it is also possible that equitable is applied in a broader sense implying the distribution of the source (in this case energy) based on the pressing needs of developing countries, the needs for sustainability and development of under-developed countries and the needs of industrial countries. How to define these needs is a controversial issue that deserves its own individual analysis and will not be considered in depth in this paper. Such a humanitarian approach would be desirable in the framework of a world developing in unison, but would require much philosophical change from the current market-based view.

Joined international treaties have established some important considerations regarding the use and exploration of space resources; they will be reproduced below.

1. Promoting the development of space science and technology and its applications.
2. Fostering the development of relevant and appropriate space capabilities in interested States.
3. Facilitating the exchange of expertise and technology among States on a mutually acceptable basis.

Many space advocates insist that private commercial participation for He-3 exploitation is vital and unavoidable. In fact, former senator Harrison Schmitt, openly advises against the United States ratifying the Moon Treaty, in which ownership of celestial bodies is prohibited. He insists that only if He-3 is developed commercially as regulated by the rules of an open market will it be a viable source of energy.

> *As lunar resources are important to the future of humankind, both in space and on Earth, entrepreneurs in the United States and elsewhere will need to see to it that the so-called Agreement* [The Moon Treaty] *disappears from further consideration.* (Schmitt, 2006).

A formal mining framework for celestial bodies has not been recognized internationally, and there is certainly not one in effect; however, the underlying concepts could resemble those rights of other mineral rights agreement. One vision considers the exploration of He-3 as a building block to permanent settlement on the Moon. In this vision mineral are granted similarly to the way in which mineral right including petroleum are granted on Earth. It recognizes private ownership, but places demands upon production to retain the right of exploitation, and places and emphasis on how lunar settlers have a priority over mining privileges. An outline of this vision is the following:

1. The land will only be granted if the requesting party demonstrates sound financial status and technical capacity to develop the terrain and extract minerals within 20 years.
2. The areas to be exploited must be specified in detail and can not exceed a certain maximum.
3. No land can be grant if it has been previously granted to another entity.
4. Granted property can be sold or traded and partitioned; however the new owner must comply with the original terms and duration of the agreement.
5. Grants can be revoked if:
    a. Production of resources or provision of services has not begun within 20 years of the grant.

b. Willful failure to adhere to applicable provisions of the Outer Space Treaty of 1967.
c. Adherence to an open market trade for the products; except when precluded by national boycotts and embargos.

This vision embodies a commercial approach to He-3 development and as can be seen largely simulates the actual code. Other approaches favor the development of the lunar resources via a “commons” approach; this latter approach, however, is not favored by entrepreneurs.

5. Economic Study and Financial Analysis

As illustrated in Table 6 by the priorities of each particular enterprise are similar but differ on rating. Like any commercial enterprise, He-3 harvesting must be evaluated based on financial viability criteria. Useful indicators for this analysis are capital cost as required for minimum total start-up capital including R&D; operating costs and long term profitability criteria. Operating costs for this type of venture would be relatively small compared to capital investment, but are not negligible and could exceed capital costs in the long run. Given the lucrative nature of energy enterprises and the energy density of He-3 as a fusion source, demand is most likely not an issue once the technology is available, and commercialization follows almost immediately from feasibility, i.e. the highest cost and risk are engrained in start-up. A good measurement of financial viability is maximum return on investment described as the ratio of project lifetime net gains vs. total capital investment. For such an analysis the most important parameter is the projected lifetime of the project. To answer this question we must revert to estimates of He-3 reserves in the Moon as given in the technical section.

With a conservative Lunar He-3 content estimate of 1 billion metric tons, and taking under consideration the expanding energy consumption, Lunar He-3 is expected to last 300 years. Such an enormous time frame brings with it some additional considerations, such as the possibility of dramatic breakthroughs; however, for a financial assessment, no such breakthroughs will be contemplated and instead only a net present value (NPV)[1] analysis will be conducted.

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[1] NPV is defined as the sum of cumulative cashflows through the project lifetime.

Let us first examine the costs intrinsic in the mining operation. Namely we will consider the energy requirements of each operation, which will provide a good understanding of operating costs. The first major cost is the cost of transporting all necessary mining and processing equipment for He-3 extraction from the Earth to the Moon. A second major cost factor is the maintenance of a small Moon base devoted solely to the sustenance of the personnel required for the extraction process. Thirdly, the mobile miner for He-3 extraction will consume large amounts of energy. Fourth, the separation and condensation modules for other gases will be endothermic modules. Lastly, the isotopic separation of He-3 from a mixture containing He-4 as well will consume large amounts of energy.

The University of Wisconsin has conducted a detailed cost analysis based on the mass of earthly material required for each kilogram of He-3 produced. According to their estimates 51 kg of mining material will need to be transported for each kg of He-3 extracted. The ensuing energy cost is 100 GJ of energy using today's transportation facilities, but it has been estimated that it could be reduced as low as 30 GJ/kg using technology currently under development. This energy requirement can be seen as a capital cost, since the expected lifetime of the investment is 20 years. Similar analysis was performed and a total cost estimate of 1753 GJ/ kg He-3 was found. Considering the energy potential of 1 kg of He-3 of 300,000 GJ, then the expected payback is quite high. The Solar System Exploration Committee of the NASA Advisory Council reported that the mining of He-3 from the Moon would yield an energy payback ratio of 250 as compared to 20 for Uranium light water reactor and 16 for coal (Lewis, 1990).

A profitability analysis, however, must be much more rigorous than the payback calculation entails; in fact, we need to examine the susceptibility of the project to changing variables. Again, such a study has been performed at length and the results of it will be summarized here. Basically, extraction of He-3 and its use in a plasma reactor for electricity generation can be viewed as an energy operation analogous to those that oil firms currently conduct. The up-field operation is comprised of He-3 mining and extraction, followed by He-3 separation and transportation. Similar to the case of crude petroleum entering a refinery to be processed to the high-value-added product gasoline, the gaseous mixture obtained from mining must be rigorously separated for the production of pure He-3. The requirements for production of the mining endeavor, will be set by demand; however, annual mining objectives of 100 kg He-3 year have been posted as the benchmark for commercial development. The value of the lunar miner processor and the associated refining facilities needed for this capacity was estimated (Schmitt, 2006) to be $1 billion with additional annual inputs of $200 million as comprised by operating costs.

Once obtained in a pure form, He-3 is then reacted with Deuterium to produce electricity, much like natural gas is transported in the pipelines to continue with the analogy, and the electricity sold as a utility. Hence the whole enterprise comprises two separate organizations: upstream and downstream. The downstream operation, that is the sale of electricity, is sensitive to the market price of He-3, while the upstream operation's profitability is more likely affected by capital and operating costs. It was determined from this study that the utility service provider would be most sensitive to He-3 prices and that a maximum profit would occur at a He-3 selling price of USR$1000/g. Costing of He-3 in the market will, of course, be a function of demand, cost of production, availability and many other variables. A rough estimate of the market cost of He-3 comes from comparing its energy potential with the presumed price of steam coal in 2010-2015. Steam coal was chosen for comparison because it presents a realistic competitor for He-3 through the 21st century. Based on a selling price of US$2.50/ million BTU of steam coal, it has been estimated that the price of He-3 would be roughly *$1.4 million/1 kg.*

5.1 Prospects of a He-3 Mining and Commercialization

The prospect of He-3 harvesting, mining and commercialization depends largely on the agents that will be involved in the trade as depicted in Table 6. Again there are several likely possibilities.

1. A single government or nation will pursue the trade (National Monopoly)
2. The trade will be pursued by a joint governmental international enterprise (A body similar to the UN).
3. It will be pursued by a group of developed nations acting in behalf of these countries. (G-8 approach)
4. It will be a commercial enterprise financed partially by private organizations.
5. It will be a commercial enterprise financed exclusively by private organizations.

The priorities of each of the options above will differ. For convenience a table is presented below:

Table 6: Priorities according to exploring organism

Priority number	***All US government/private partnership***	***International***	***Multilateral (INTELSAT)***	***All Private***
1	US political environment	Space law environment	Promoting use voting system	Financial and technical feasibility
2	Space law environment	Managerial Control	Space environment Managerial control	Return on investment
3	Managerial control	Contract dispersion	Financial and technical feasibility Return on investment	Managerial Freedom
4	Financial and technical feasibility Budgetary commitment	US political environment Budgetary commitment	Technical feasibility	US political environment
5	Technical feasibility	Technical feasibility	US political environment	Regulatory environment
6	Regulatory environment	Financial feasibility	Budgetary commitment	Space Law Environment

The fact that the Moon treaty does not prohibit commercial exploitation of lunar resources suggests that the administrating body for lunar exploitation could resemble the Intelsat. Carrying the analogy further, Schmitt went as far as proposing to name the body Interlune. Interlune would be composed of a board of governors, a board of users and investors, and a director general. Its objective would be to provide international management of a lunar base in a cooperative basis. Management would emphasize the benefit of all member states, users and investors. However, at the time the lunar treaty was being ratified, many US senators expressed their concern that the Moon treaty could "inhibit or even prohibit industry from developing or exploiting extraterrestrial material" (Lewis, 1990).

One very close analog to the Moon's territorial claim issue, is the case of Antarctica. Initially the continent was claimed by seven nations including Argentina, Chile, the Soviet Union, Australia, New Zealand, Norway and France. The Untied States also maintained a Little America base, though made no former claim. In spite of what seemed to be destined to become a multilateral conflict over a potentially rich land, the countries agreed to conduct the International Geophysical Year, in which they cooperated on scientific exploration of Antarctica. Following this year, the Antarctic Treaty was negotiated and signed by Argentina, Australia, Belgium, Chile, France, Japan, New Zealand, Norway, the Union of South Africa, the Soviet Union, the United Kingdom and the United states. The treaty succeeded in setting apart the continent for the benefit of science. The continent was established free of nuclear testing, military bases and frontiers and open to all human beings who desire to go there. The success of the Antarctic treaty sets an encouraging precedent for space exploration.

Many hold the view that the government's role in space exploration should be limited to providing the infrastructure needed for exploration and playing a regulatory role. These advocates of privatization argue that successful enterprises like the 1860's transcontinental railroad system in the US would not have been achieved if they were not fueled by private capital. However, they are also careful to note that government should verify that private ownership of resources in space does not lead to consumer abuse.

In spite of the tremendous economic potential of harvesting He-3 even at a modest selling price, many skeptics like the regular columnist for the Space Review, Sam Dinkin assert that "Even if He-3 can be harvested it would offer no return on investment." This view is held by many skeptics who see the possibility of a successful nuclear reactor as far fetched.

Important consultants in the field of project management and enterprise success have catalogued the issues that would be involved with a He-3 mining venture according to many relevant categories. They have developed a list of external issues and given them weighs based on the importance that each has for each of the possible entrepreneurs. Table 7 reproduces a table assembled by Harrison Schmitt (Schmitt, 2006).

Table 7: Ranking of External Issues According to Entrepreneur Choice (Schmitt, 2006)

External Issue	Weigh	All US-government	Multilateral Model	Intelsat Model (Interlune)	Private/Govt partnership	Private/ Govtfunded RTD&E	All private
Net environmental protection	3	24	3	15	24	30	30
Potential for technology spinoff	1	1	2	5	7	6	**10**
Economic benefit	2	10	2	6	14	16	20
World benefit	3	3	3	24	3	3	30
Potential for space settlement	2	2	2	10	9	14	20
External issues total		40	12	60	57	69	110

The weighs and the criteria for evaluation used in Table 7 depict Dr. Schmitt's principles and values and hence represent only one point of view. Though it is possible that Dr. Schmitt has in fact gathered data from the corresponding sectors, this is not evident from his text. Regardless of the weighing distribution and the total that Dr. Schmitt arrives to, the issues he presents are relevant and should be evaluated in depth for any commercial enterprise of the size of lunar He-3 mining. For example, the ability of private sectors to successfully introduce new technology into an existing market place gives the private sector a competitive advantage in development. However, the private sector has a very significant obstacle to overcome, capital investment. Unlike the government sector that has the power and resources to engage in monumental enterprises through specialized agencies, the private sector is subject to larger financial liability and is more reluctant to invest in risky ventures. Nonetheless, the potential for a technology spinoff, given a weighting of 1 under Schmitt's scheme, is a valuable asset for risk taking entrepreneurs. Because the strengths of the private sector do not overlap with the strengths of the government sector, and in fact these two sectors complement each other in terms of capital and efficiency, a joined private-government initiative would be very likely. Such an initiative is not without precedents; technology spinoffs of the Apollo missions led to a huge boom in the aeronautics industry to the point that NASA now flies aircraft manufactured by components made in commercial industries.

One of the large hindrances that the government and even international initiatives face is that they must respond to the public about their decisions and are thus subject to monumental political pressure. Financing would be compromised for a long term venture, since it would be subject to the approval ratings of the current governments, the political choices of leaders and the whole weight of bureaucracy. These indirect links would endanger the long term sustainability of the project if financed uniquely by the government.

The efficacy of the private sector to turn projects into revenues is a big asset that seems to favor the private approach over the others. Schmitt (pg. 165) argues that the likelihood of success is, without competition, higher if the all private approach is adopted. Nonetheless, an all private approach implies that the energy generated would be governed by market rules, which tend to favor the industrialized nations as they have greater acquisition power. This result is in direct opposition to the principles of the Space Treaty, which indicates that all celestial resources should benefit the whole of mankind. In spite of this, it can be argued that even developing nations would have access to technology if they were to purchase it through debt financing. Debt financing, however, is a risky business and can prove catastrophic for the future liquidity of the country as a whole, which is the current case of many Latin and African nations.

The energy portion of the project is perhaps the most complicated from a commercial and technical perspective. Apart from the engineering difficulty of attaining a steady state fusion reaction, power ownership and distribution are delicate issues, which have even become hot political subjects. Whether energy should be a national asset or if it can be privately owned is an ongoing debate and will certainly come back again if and when He-3 fusion makes it to the market place.

As it is evident from the previous discussion, the choice of initiative is a major issue that He-3 harvesting must face. Furthermore, the final initiative chosen will largely determine whether He-3 is commercially viable and will also play a significant role on larger global problems such as income distribution and comparative competitive advantages of one nation or region over others. In the end, the very choice of initiative will undermine the judgment of whether He-3 harvesting and fusion were a benign choice for the future of humanity or a grave mistake.

The profitability analysis presented is included with the purpose of exemplifying the commercial and financial viability of the enterprise. Asserting these, we can proceed to analyze the impact of such an enterprise on many areas of our societal structure

5.2 Social and Economic Impact of He-3

Energy is the most important driving force for powering industrial nations. In fact, a measure of a country's industrialization is its annual energy consumption. Fossil fuels like coal, petroleum and natural gas are the chief means by which most nations get their energy. Because of the world's increasing standards of living and its increased dependence on oil, fossil fuel amounts might not last longer than a few decades. Also with the world's population expanding to almost 12 billion by the year 2050, our oil demand will also increase drastically. Oil has become a key issue in the political and economic affairs of many nations especially after the United States second war with Iraq. In such cases of crisis, *the development of He-3 will alleviate the dependency on crude oil.* Fossil fuels also release a lot of harmful greenhouse gases into the atmosphere that have detrimental effects on the atmosphere, whereas the usage of He-3 fusion technology will be a great substitute to the fossil fuels as it doesn't release any harmful byproducts. In addition to the non- polluting properties of He-3 fusion on Earth, the mining of He-3 from the Moon will not contaminate the Moon as the gases that are released during the extraction process (water and oxygen) aren't harmful, and instead could be used for sustaining a lunar colony as outlined in the technical section.

The United States leads the research in He-3. In 2004, President Bush released his new vision of space exploration. He wants to complete the International Space Station by the year 2010. The completion of this project will greatly increase the working research on the lunar mining of He-3 as the astronauts can experiment on different techniques to extract He-3 from the Moon's regolith. The International Space stations could be used a trade center for the distribution of He-3 for world wide distribution. Another goal of the current White House administration is that NASA returns to the Moon by 2015 and to have a permanent living settlement for astronauts by 2020. President Bush has allocated 12 million dollars to the Moon Development Initiative. This initiative would help tremendously in the progress in the He-3 research if a permanent colony is established on the Moon (Hurtack, 2004).

The developed world would no longer have to depend on the Middle East , where the most of the world's fossil fuel reserves are located, for its energy supply. American scientists have already declared that the Moon could be the Persian Gulf of the present century. *Two liters of He-3 would do the work of more than 1,000 tons of coal* (Chowdhuri, 2004).

He-3 also has long term and short term benefits for society. In the near term applications, it can help in medical research. A useful product of He-3 fusion reactions is the production of isotopes that are very useful in the biomedical field. Positron Emission Tomography (PET) is one such field. This process uses the isotopes from He-3 fusion reaction like He-4 in its working. He-4 has a much longer half-life and it can be stored for a much longer periods of time compared to other isotopes. By using He-3 isotopes we can reduce the radioactive exposure to patients compared to the regular isotopes that are used in PET that emit radioactive waves (Hurtack, 2004).

It can also be used for environmental restoration, detection of chemical and radioactive wastes, cancer therapy and defense. For intermediate term applications, it can be used for the destruction of toxic fissile materials, to harness space power and to supply energy to remote energy stations. In the long term it can have applications in propulsion technology, hydrogen production, synthetic fuel applications, base load electrical power plants and small electrical power plants (Kulcinski, 2001). The advantage of initially using He-3 fusion for non-energy applications is that the cost base is different for specialized applications and He-3 can be competitive in the short run. This would then open the ground for further cost reduction and prepare He-3 fusion to enter the energy marketplace at competitive prices.

6. International Lunar Exploration

6.1 History

The Moon race began in 1959 when Russia launched Luna 1, the first artificial spacecraft that passed within 5995 km from the Moon's surface. As mentioned in the detailed timeline presented in NASA's webpage, Luna 2 (Russia's second launch to the Moon) was the first space craft to land on the Moon's surface on September 12, 1959. Later in October 1959, Russia launched yet another spacecraft, Luna 3, which was the first probe to successfully return pictures of the Moon to Earth. USA launched Pioneer 4, which was the first American spacecraft to flyby the Moon, soon after the Launch of Luna 1. Between 1959 and 1956, both USA and Russia launched numerous missions to the Moon which consisted of flybys and impacts (not landing) on the lunar surface. The race to explore Moon and to land on Moon was on full force as Russia and USA tried to be the first to land on the Moon.

On Jan 31, 1966 Russia finally became the first to finally land a spacecraft, Luna 9, on the lunar surface and transmit photographic data (NASA timeline). Again, soon after Luna 9, USA successfully landed Surveyor 1 on the Moon that also transmitted data. It also demonstrated that USA had the technology required for such missions, and that such missions would provide useful information for their planned missions of sending Man to the Moon. As can be examined from these missions, the next big milestone in space exploration was landing Man on the Moon, which had always been the goal since the beginning of the Moon missions. Both countries were motivated and deeply involved in preparing for a man landing on the Moon. Earlier in 1961, President John F. Kennedy had already announced to the nation "a goal of sending an American safely to the Moon and back before the end of the decade." Also, Russia was doing well as it had already started preparing for human travel to the Moon by placing a 175 cm tall, 70 kg mannequin containing radiation detectors on a designed pilot's seat with attached sensors to measure radiation effects" (NASA, 2005). On July 20th, 1969 history was made as USA became the first country to safely land two astronauts on the Moon and return them safely to Earth. The race to reach the Moon was in part fueled by the imbalance of power and prestige between USA and Russia during the Cold War era. Rodger D. Launius makes a very interesting statement in his book Frontiers of Space Exploration saying,

> *"had the balance of power and prestige between the US and the Soviet Union remained stable in the spring of 1961, it is quite possible that Kennedy would never have advanced his Moon program and the directions of American space efforts might have taken a radically different course"* (Launius, 1998).

The drive to explore the Moon has influenced many countries other than USA and Russia. Even though, USA and Russia have been the major explorers of the lunar surface, Japan and the European Space Agency (ESA) have also been interested in Moon missions. In 1990 ISAS, a Japanese Space Agency devoted to space science, launched Hiten 1, which orbited the Moon and primarily tested the technologies for future Moon missions (NASA timeline). Also, just recently in 2003, ESA launched SMART 1, which was also an orbiter to test future technologies for Moon missions (NASA timeline). In this way, it can be easily seen that the countries capable of launching orbiters and probes to the Moon have already started to develop their technologies for future Moon missions that might even lead to landing more people on the lunar surface.

6.2 Current Lunar Exploratory Ventures

In order to get a better understanding of what could happen in the immediate future in terms of space exploration, we assessed the level of development and the current initiatives of some important space faring nations.

6.2.1 United States

After the initial zeal that characterized lunar exploration in the 1960s and 1970's, NASA's interest in developing lunar colonies and further advancing lunar exploration faded, to the frustration of many space enthusiasts. The Apollo missions were abandoned and space exploration directed its focus elsewhere. It was not until the 1980's that NASA expressed interest in the Moon once more. In 1984 a conference on "Lunar bases and Space Activities of the 21st Century" took place at the National Academy of Sciences. The focus of this conference was how to establish a permanent base on the Moon. Lowman, a prominent geologist at NASA, reported that the feasibility of establishing a lunar base was scientifically verified based on the reports from the Apollo missions; however, he made clear, that did not imply that the feasibility of an autonomous lunar colony was proven. The reasons for establishing a lunar base can be follow two main trends. One advocates that a lunar base would serve as a stepping stone for further exploration into outer space. The other perceives a lunar colony as a haven to save our civilization from mass extinction if a meteor were to strike Earth.

To attest of NASA growing interest on He-3, Professor Kulcinski, the director of the Fusion Technology Institute at the University of Wisconsin has recently been appointed to NASA's Advisory Council. Kulcinski is widely recognized as an authority in He-3 fusion research.

Although the Unites States is the most advanced nation in He-3 fusion reaction, this prominence was achieved entirely through the input and work of the FTI in Wisconsin. In spite of the mesmerizing advances that the research group headed by Kulcinski has achieved, Federal funding for He-3 fusion R&D is less than a million dollars. One of the main reasons for this lack of interest is that development of a fusion reactor that produces more energy than it consumes is projected to occur within 10 to 20 years and for a commercial enterprise, this time frame appears too far into the future. Funding for a He-3 reactor is sparked by two main agents: NASA and the DOE. NASA's main interest is to successfully mine and return He-3 from the Moon to Earth. The DOE is commissioned with the building and maintenance of a He-3 reactor. Kulcinski has been quoted saying that,

> *"Part of the problem, is a lack of trust between NASA and the DOE. DOE doesn't trust NASA to get access to helium-3 in a reasonable amount of time. NASA doesn't trust DOE to fund and get a helium-3 reactor working if they commit the resources to get the helium-3"* (Hedman, 2006).

Interest in Lunar exploration has sparked once more and the United States has announced that it intends to repeat a manned lunar landing before 2018. One of the main interests of the future landing would be to explore and develop He-3 mining.

6.2.2 Russia

One of the reason's for Russia resurgent interest in the Moon after the space race in the 1950's and 1960's is because of the He-3 deposits on the Moon. Russia's aerospace corporation Energiya, has shown interests in developing energy from He-3 on the Moon. Energiya President Nikolai Sevastyanov stated that, *"This is the thermonuclear energy of the future, a new environmentally clean fuel that cannot be produced on Earth; we are talking about the industrial exploration of the Moon for He-3 production."*

He further stated that the advantages of mining He-3 would justify the expenses of manned space exploration. Russian experts have also designed a nuclear engine that can be used as a lunar cargo vehicle. These vehicles could be used to carry equipment for mining and delivering He-3.

Mr. Galimov, a scientist at the Institute of Geochemistry and Analytical Chemistry of the Russian Academy of Sciences believes that Russia can compete with the United States in the race for the Moon again. He believes that Russia can afford an economically profitable and inexpensive project to mine He-3 on the Moon and will cost only about “a mere $25-30 millions to extract He-3 by warming lunar soil and scraping it from the surface of the Moon with the help of lunar bulldozers” (Radyuhin, 2004).

6.2.3 China

China’s interest in becoming a nuclear power coincides with its interest and prowess in becoming a space explorer. In what is a significant indicative of its determination, China held the first international conference on Cold Fusion of the 21st century. China’s incursion into manned space flight began in 1999 with the launch of the first space vehicle capable of transporting people into outer space.

Chinese officials have voiced their government’s interest in space race explicitly. Luo Gen, the foreign affairs director of the China National Space Administration declared that: “the Chinese government will attach more attention to the development and application of space science and technology and speed up the development of the space industry."

The Chinese National Space Administration says that "China carries out its space activities for the purpose of satisfying the fundamental demands of its modernization drive;" however, it is vague as to which projects this "modernization drive" is going to encompass.

The most relevant mission for further space exploration and especially in regard to mining operations is the manned space missions. China's manned space program began in 1992 and within seven years it launched its first vehicle able to transport human beings the Shenzhou was launched and successfully recovered in November 1999. The Chinese objectives for the upcoming 20 or more years would be to explore and utilize space resources to meet a wide range of "economic construction, state security, science and technology development and social progress, and contribute to the strengthening of the comprehensive national strength."

With regards to He-3 China has explicitly stated that one of the objectives of the manned Moon landing projected for 2017 is to "provide the most reliable report on helium-3 to mankind." China is now designing a rocket with a transport capacity of 25 tons, which might lead one to believe that it is preparing for a He-3 harvesting and transportation venture.

Nonetheless China also recognizes the need for international cooperation and claims to "support activities involving the peaceful use of outer space, and maintains that international space cooperation shall be promoted and strengthened on the basis of equality and mutual benefit, mutual complementarity and common development."

Furthermore, China seems to be committed to the principle of developing space technology and utilizing space resources for the development and benefit of all of mankind. In fact, China's has participated in join space ventures with other nations. With Germany it developed the satellite Sinosat-1 and it is working with Brazil is developing Earth resources satellite.

6.2.4 India

India, one of the fastest developing nations after China, depends heavily on oil, coal and natural gas for its technological advancement. Currently India's oil consumption is around 84 million tons per year compared to its production of 33 million tones. In addition, its GDP growth of 6 per cent will enhance the oil consumption to almost 275 million tones by the year 2020. India also has natural gas reserves of about 660 billion cubic meters. But with the present rate of development, India will have to import about 25.5 billion cubic meters of natural gas by 2010. India also produces a good amount of coal. It currently has 443 million tons of coal reserves. It is the most abundant available fossil fuel in India and provides a substantial part of energy needs. It is used for power generation, to supply energy to industry as well as for domestic needs. India is highly dependent on coal for meeting its commercial energy requirements. The coal based electricity generation capacity was 51000 MW in 1995. This is expected to go up to 140000 MW by 2009-10. However, at present, the country faces an energy shortage of about 15% and peaking shortage of 30%.

Furthermore, the Indian population has already crossed one billion and is growing at a steady rate. The energy sources on the other hand have been decreasing at a much greater pace. The reserves in India will not be able to sustain the increasing population.

Thus, India will not be completely self- sufficient in the energy sector and will need an alternative energy source to sustain their development. In the future, Indian dependence on energy source will increase rapidly and thus Indian scientists and energy security analysts are currently analyzing He-3 as a potential source of energy.

But with India's many development challenges many skeptics of India's space program are wondering why India is showing so much interest in exploring space. When India first detonated a nuclear device in 1974, the US and European nations imposed widespread sanctions to restrict India's access to technologies that could be used to make a nuclear missile. This provided India with the opportunity to develop a rocket program and forced the Indian Space Research Organization (ISRO) to reinvent technologies it could no longer buy. In the long run this has given India an advantage over other countries with aspirations to reach space. Its space program is quite self-sufficient and aims to be completely independent of foreign support. India's political leaders say the country cannot afford 'not' to have a space program. Indira Gandhi, the late prime minister of India, believed it was not only important for science, but also vital to India's development. Currently, India is eyeing the abundant He-3 reserves on the Moon. Indian President Abdul Kalam is aware of the fact that the Moon contains huge reserves of He-3.

> *"One can generate a large amount of fusion-type energy from helium. We have to develop complex fusion technology to use He-3"* (Ananthaswamy, 2005).

The Indian Space Research organization (ISRO) has planned a lunar orbit mission under the Chandraayan-1 Mission. The main objective of the mission being to search for He-3 deposits on the Moon. The mission which is scheduled to launch in 2008 has almost everything prepared. The space craft and the launch vehicle are already ready and currently they are working on fabricating the payload. During its mission the Chandraayan-1 will obtain high resolution geological, mineralogical and topographical maps of the Moon’s surface (Jayaraman, 2005).

6.2.5 Europe

Europe has made considerable progress in developing a framework in which individual European countries can integrate their various space programs towards a common goal as seen in the governance the European Space Agency (ESA). Through ESA, each country is able to contribute financially to embark on projects that would be too costly for the member country’s economy to support on its own. One of the objectives of the ESA is to look into the prospects of lunar exploration, development and utilization. They are stressing on the fact that in order to witness any breakthroughs in space explorations, the European governments should focus on creating technologies that are needed for conducting scientific studies on the Moon, from the Moon and on the Moon. The geophysical characterization of the interior of the Moon and the return of samples from the Moon are important near-future mission objectives, and opportunities for higher resolution chemical and mineralogical mapping from orbit should be pursued.

6.3 Future Collaboration

Mike Griffin, the eleventh Administrator of NASA is aware of the need to have international cooperation in developing future space projects. In an interview with the Center of International and Strategic Studies, he emphasized the need for the various governments to coordinate their scientific endeavors to explore the Moon. He also recognized that it should be the role of governments to lay down the infrastructure needed for a long-term, sustainable presence on the lunar surface and that it will be the role of the commercial sector to leap in and take advantage of that infrastructure and develop services along this infrastructure (Zelnio, 2005).

<u>International Cooperation frameworks according to Mike Griffins:</u>

1. <u>Coordination framework</u>- In this kind of framework individual countries will work on their own to develop specific space programs but will coordinate with other nations if any technical and scientific help is needed. This model of cooperation is appealing as each country can manage their own resources independently. The disadvantage of this framework is that sometimes there might be an overlap in the efforts pursued by other countries, causing work to be duplicated.
2. <u>Augmentation framework</u>- In this kind of framework, one prime country will work in developing a specific space program while the other countries will help in enhancing the project of the prime country. The major disadvantage of this kind of framework is that the prime country will have to meet most of the needs of managing the financial expenses.
3. <u>Interdependence Framework</u>- This is when countries cooperate in any important and functional parts of the project, but each country will still control their respective part of the project.
4. <u>Integration framework</u>- This is a full cooperation with shared and joint research and development with a pooling of resources. This framework distributes the financial costs, and utilizes the industries of multiple nations while still maintaining a single entity that controls the critical path.

From his four proposed frameworks, Mr. Griffin came to the conclusion that in order to better coordinate the cooperation between international nations, a two phase agreement has to be used. In the first phase, all nations should coordinate to send robotic space crafts to the Moon for a survey of the geological resources. The second phase would be an effort to develop a lunar base on the Moon.

<u>A brief description of Mike Griffin's proposed phases:</u>

1. Phase 1-CLES

   In this phase a committee of Lunar Exploration Satellites would be formed which is similar to the CEOS. Its main task would be to coordinate the development of all space craft development programs and robotic lunar missions that are underway. In addition to these responsibilities, this committee would also have the task of centralizing and distributing all scientific data from these missions to the public.

2. Phase 2- ILDA- International Lunar Development Agency

   A new international space agency should be developed for managing the efforts for developing a lunar base on the Moon. The ILDA will consist of four main divisions; the Administrative Office, The Lunar Base Development division, the Lunar Transportation Development division, the Lunar Sciences division and the Commercial Development division that will have specific tasks.

The creation of ILDA will thus provide a framework to all the countries of the world to satisfy their lunar ambitions. Its structure is such that it will be able to sustain continued operations on the Moon over the future. (Zelnio, 2005).

7. Possible Scenarios

At this point it is useful to envision a series of possible scenarios for the harvesting of He-3 and its use as a fuel source and present possible results from them.

7.1 Scenario 1

A first scenario envisions the successful establishment of a manned base on the Moon exclusively for the harvesting of He-3 and control of a fusion reaction involving primarily He-3 and Deuterium. The energy generated in the reaction is converted directly into electricity which is subsequently used in the electrolysis of water to produce H_2 which is an energy carrier rather than an energy source. Hydrogen is then used in fuel cells for the generation of electricity on Earth. The precious metals needed for manufacturing the fuel cells could be harnessed from the Moon, where they are a factor of times more abundant than on Earth (Wingo, 2003). The question that naturally arises is how the energy (in the form of purified H_2) is distributed on Earth. Will the Unites States, as the producer and most likely pioneer in the trade, have exclusive rights for the trade and distribution of H_2 or would the fuel be distributed equitably among all nations? It has been argued before that H_2 is the first truly democratic energy (Rifkin, 2001); however the energy required to produce it makes it necessarily undemocratic, since only those with enough capital to invest in *energy sources* can produce H_2 at a competitive cost.

Although this is a possible scenario politically it is technically very unlikely, since it would require transportation of H_2 back to Earth and also possibly transportation of Deuterium to the Moon to be used in the fusion reaction with He-3.

7.2 Scenario 2

A second scenario proposed by Lunar advocates including Dennis Wingo the author of “Moonrush,” (Wingo, 2003) advocates placing the He-3 fusion reactor on the Moon and returning power obtained from the reaction as microwaves or in the form of platinum group metals. That is, to use the He-3 harvested on the Moon to provide energy for mining of platinum metals on the Moon. These metals would then be sold in Earth mainly for the production of fuel cells. The idea of irradiating energy from the Moon to Earth is embraced also by some solar energy enthusiasts, who envision a large transmitting and receiving infrastructure to collect solar energy on the Moon using GaAs solar cells and irradiate it to Earth where recipient stations would be located. This scenario is schematically shown in Figure 16.

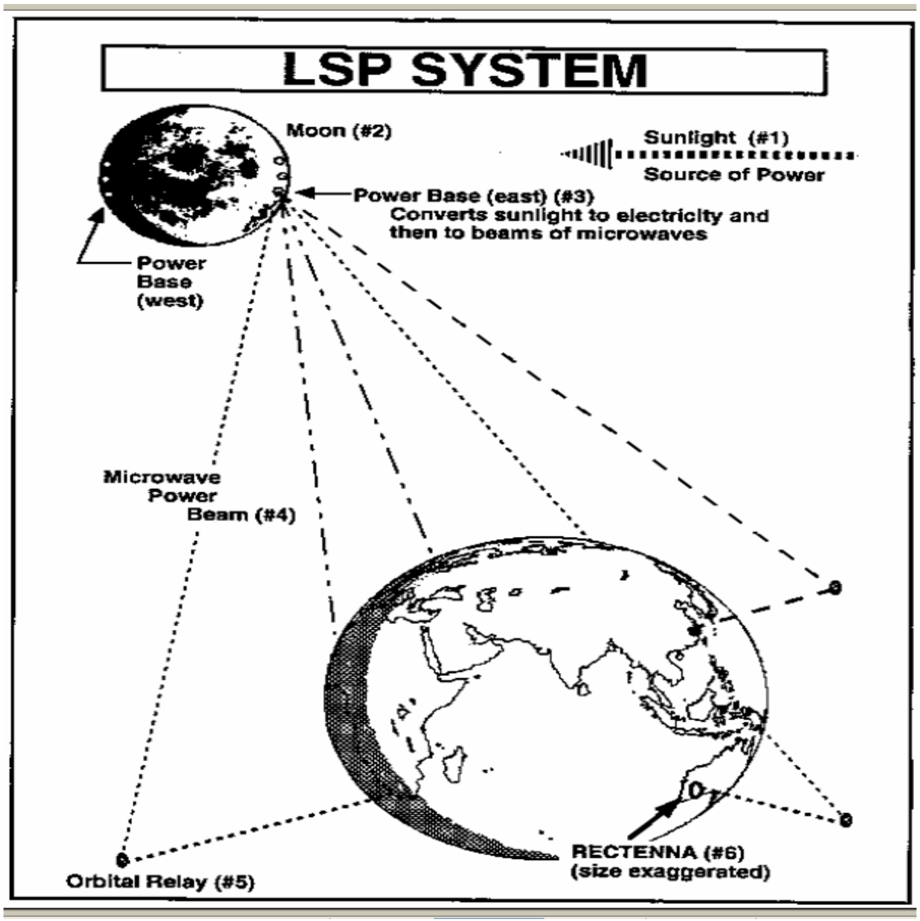


Figure 16: Lunar Solar Power Scheme (G.L Kulcinski, FTI, 2001)

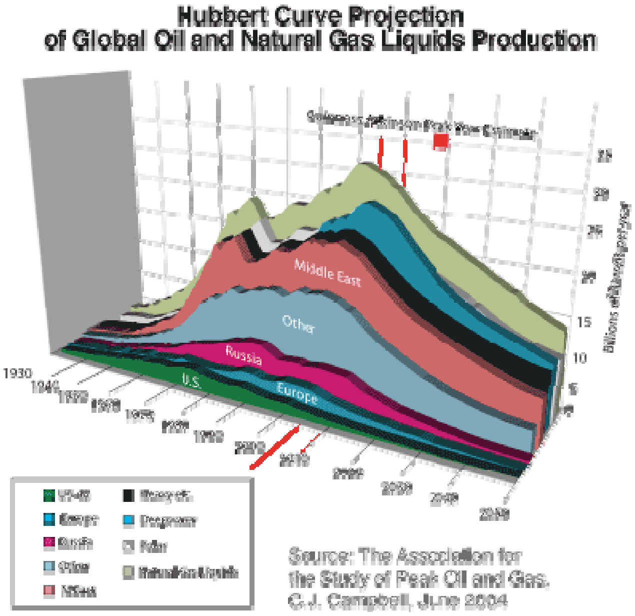
Allegedly, beaming energy to Earth would potentially benefit underdeveloped countries where an electricity distributing infrastructure is impossible due to geographic limitation. African countries are the primary example. Beaming technology would provide electricity to remote locations, where it is much needed.

7.3 Scenario 3

A more likely scenario from a technical standpoint, however, is to bring He-3 from the Moon to Earth to be reacted in the plasma reactors. This would allow use of the existing gridlines for delivering electricity and would eliminate the production of H_2 as an intermediate agent. This scenario presupposes that the He-3-Deuterium reactor is fully developed, which even according to experts in the field (see interview with Dr. Kulcinski) is a long term venture. Because the reactor is most highly developed in the United States, it would seem this country has an initial advantage. If we suppose that He-3 would become the primary energy source to power the United States and that it would become so before the end of the fuel era, this would imply that the fossil fuel prices would plummet since the primary consumer would be out of the game. This would allow developing nations to purchase larger amounts of oil which could lead to their faster development. Under this scenario India and China would again be the dominating economies within the developing countries, since they have the resources to purchase the largest amounts in a fuel market governed entirely by demand and supply dynamics. These nations also have the greatest projected need for fuel. On the other hand, if China and India develop their own He-3-Deuterium reactors, they would enter in direct competition with the US for He-3. In what manner this competition will be carried out depends largely on how closely these countries abide to international treaties and on how much they are willing to cooperate with one another.

7.4 Scenario 4

Like hydrogen, He-3 has the potential of becoming the first truly democratic fuel. If extraterrestrial resources are not to be appropriated by any nation, as outlined in the Space treaty, then He-3, wherever it is found, rightfully belongs to *all* of humanity. The question of propriety is a fundamental one. Although the land, call it lunar regolith or the soil from other planets, legally has no one owner, the extraction, compression and reaction of He-3 to produce energy is immensely costly. It has been proposed that the cost of non-renewable resources, of which He-3 is an a typical type, follows a Hubbert bell curve (Figure 17) in which the price is initially very high due to the difficulties of extraction, then plummets when and rises once more once processing the scarcer fuel becomes more difficult.



Source: The Association for the Study of Peak Oil and Gas. C.J. Campbell, June 2004

Figure 17: Hubbert Curve (Campbell, 2004)

The peculiarity of He-3 is that the resources in space are practically unlimited for a human lifespan. Thus a surge in cost is not expected to occur, at least not within what in human time standards is considered relevant (>1000 years). Because of the costs inherent in producing energy from He-3, He-3 would become a consumer good, much like energy derived from petroleum is a consumer good, and would potentially be sold as such. In fact, the cost of initially producing He-3 will most likely only be undertaken if whoever ventures into it is guaranteed exclusive rights over exploitation at least until it obtains profit from its investment. This kind of situation is analogous to the pharmaceutical industry, in which the expenses of R&D for drug development are compensated by giving the company exclusive rights over selling the product for a number of years.

In any case, the burgeoning of a He-3 focused economy, whether only in the US or worldwide, will carry with it the creation of a whole new industry, creating a number of technology jobs. Furthermore, the creation of an inhabited lunar base to mine He-3 will lead to a whole new branch of space products, services and daily commodities that would be tailored for lunar use.

7.5 Scenario 5

In the case that He-3 reaches Earth when fossil fuels are completely exhausted, the scenario might be completely different. It is very likely that the countries with nuclear programs will have developed a large dependence on fission energy. For example, India and China already have ongoing projects to harvest Uranium for use in their nuclear power plants. Europe has an organized and well regulated nuclear industry and it is very likely that in the near future it will greatly increase its dependence on nuclear energy. The question then is: will Europe, China and India continue to pursue He-3 fusion reactors or will they simply abandon the project to focus on fission? It is possible that many economies will revert to alternative energy sources *on Earth* like wind, hydroelectric and solar energy to supplement their energy needs. If this is the case, we might be exposed to a very different world, in which countries are not competing directly for a single energy source, but instead where each country develops its own autonomous energy infrastructure. Under this scheme Latin American countries, for example, would come to rely heavily on hydroelectric and solar power, which conform better with the natural conditions; whereas countries in the former Soviet Union might adopt a more nuclear oriented program, given the Uranium resources available and their technical background on nuclear fission Fuel cells and the hydrogen economy would also become important players and hydrogen energy would predominate in countries where enough infrastructures are developed for implementing it.

What approach Europe undertakes depends largely on the success and future of the European Union. Will they issue a joined initiative, or will each nation autonomously determine its energy path? It is very unlikely, however, that the United States be the only country to develop or show interest in He-3 (Kulcinski, 2006). In fact, if the trend we have observed in the past prevails, many other countries will follow the United States' lead.

Another pertinent question is whether the US will use He-3 to power its economy on Earth or if it will use it as an astrofuel for further space exploration. The answer to this question depends largely on whether NASA is the agency directing He-3 mining on the Moon or whether it is a private enterprise. NASA has voiced its objective of using resources on space almost uniquely for space exploration and expansion, but private enterprises would most likely want to seek profits on Earth before they embark into a long and very uncertain space exploration.

7.6 Scenario 6

An additional scenario envisions an active competition for lunar He-3. Under this scenario we would be faced with a global space race, in which many nations compete amongst each other to establish the most effective lunar base for He-3 extraction. Hopefully, the memory of the former space race would stimulate mutual cooperation. Also, other countries would voice their right to obtain some kind of retribution for the use of lunar resources, since it has been established in the Moon Treaty that the Moon is the heritage of all mankind and not only the minority of mankind that can actually reach it.

Regardless of the scenario, mining He-3 will open a huge resource and base for space science. It is a medical challenge to evaluate and mitigate the impact of reduced gravity in the human body. In fact, a return to the Moon and a lunar settlement for any reason would lower the cost of a number of ancillary activities such as space tourism and recreation, which will transform near space from the "final frontier" to a "just across the boarder frontier."

One of the most dramatic impacts of He-3 mining and commercialization might not be directly linked to its use as an energy source, but rather to the role that a permanent lunar colony can play on the mindsets of people on Earth. Just like the gold from the Americas was not the prime revolutionary agent for change in medieval times, but rather the newfound knowledge that the world was larger than the "old world", human settlement in space will open the mindsets of many, who will learn to perceive the near universe as part of our immediate environment.

The Apollo missions have already had tremendous effects on science and technology and these were limited in extent and duration. The technical infrastructure that needs to be developed for a permanent mining mission is astounding and will result in a number of new jobs in the technical field. The offer and demand dynamics will respond to a shift in interest of young people to more scientifically oriented careers, especially in those countries with active resources dedicated to space exploration. However, we may also expect a renaissance of philosophy and the humanities, which would bloom as a response to the new horizons that space exploration opens. The questions of what is our role in the universe and what the limits to humanity are will be more relevant than ever before.

The question then becomes: how does exploring space change life on Earth? The answer is most probably “in more ways than we can foresee.” The palpable is, of course, the technological drive that will accompany space missions. The new scientific horizons will open branches of science that are either unknown or that had remained practically stagnant for the last couple of decades. Fusion technology will revive quantum electrodynamics, for example, and space flight will appeal again to classical mechanics in a powerful way.

7.7 Scenario 7

Another palpable effect of He-3 on Earth would be the political change that the end of the oil monopoly over energy production will bring about. The present tension between Middle Eastern, oil rich nations and western nations might subside once the exclusive power that Middle Eastern countries exert in determining oil production quotas and prices is no longer as critical for global energy production. It is the view of many political analysts today that the Intifadas and the fundamentalist movement that we are experiencing today is in part fueled by the economic boom that oil producing nations are undergoing as a result of high oil prices (Rifkin, 2002). Whether this view holds or not, the situation in the Middle East is prone to change dramatically at the end of the oil age. For once, economies that depend on oil revenue will be forced to diversify their income sources. Such change will bring about revolutionary movements that may very well change the structure of society. Will this result in an even more unequal distribution of power and resources between developing nations and developed nations? Again the answer to this question resides largely upon which nations will have cheap access to energy sources and which are dependent upon others for their energy income. It is here that adherence to the UN treaty prescribing that all space resources should be used for the advancement of mankind is critical. A possible scenario that might follow from this principle would be that a few nations would directly harvest, transport and exploit He-3. For the mining privileges on the Moon, which is noted as belonging to all of mankind, these nations would be obliged to pay either royalties to all nations, or distribute electricity to other nations as a form of payment. This is a positive yet not ideal scenario. It is positive in that under-developed nations would obtain electricity directly and from it could develop industry. Nonetheless, industrialization and economic growth necessitates much more than electricity. It needs international investment and commitment, which might or might not be linked to He-3 or other alternative energy sources.

The impalpable effects of He-3 are difficult to anticipate, but they are most likely concerned with the dramatic change in perspective that access to space might bestow upon humans. For the entire history of mankind, the cosmos has always been the source of many romantic visions. In fact the very beginning of science fiction focused much of its interest on space exploration and human expansion into space. The 21st century promises to be the time when these dreams and idealizations will cease to be just that, dreams. Instead, the 21st century might just be the century when humans dive irreversibly into outer space. Many claim that the most powerful reason to explore the stars is to prevent humanity's extinction. The quest for Helium-3 in addition to precious metals for fuel cells can be the catalyst for expansion. A change in energy regime has never been deliberate; instead, changes in energy regime have come about as a result of desperate need for energy sources when the dominating source is rapidly waning. Well, the present energy crisis can prove to be the necessary crisis to spark change not only in energy regime, but most prominently, a change in the history of mankind.

Another possible side consequence of He-3 harvesting would be the beginning of a truly global mindset. Exploring space further may result in making us increasingly aware that we exist together in a single planet, which is but one of millions of planets. This realization might blur political and national boundaries. Visions of this type are best embedded in the context of space travel and may not pertain to He-3 directly and will hence not be explored further.

In this section we presented a number of scenarios that could follow directly and indirectly from He-3 exploration. Although exhaustive, this list is by no means complete and many discussions and reflections can follow from it.

8. Interview

To obtain a more professional and experienced view about our project we interviewed three knowledgeable people who are aware of the potential of utilizing He-3 as an energy source. The following are the questions that were posed to them:-

1. *What do you think are the major obstacles in the following steps in harvesting He-3? And do you think that they can be overcome in the next 20 years?*
    - *Mining*
    - *Transportation*
    - *He-3 –D reaction*
    - *Production of energy*

2. *What impact do you think a He-3 mining venture will have on future space development and exploration?*
3. *Do you think a fusion reactor can compete with a fission reactor?*
4. *What impact do you think it will have on the future energy crisis?*
5. *Do you think the US will be the only player in the He-3 race? Which other countries do you think might be involved in the He-3 race?*
6. *Do you think pursuing He-3 as an alternate energy source is relevant or should we look at any other source?*
7. *What breakthroughs will need to occur to make He-3 more feasible?*
8. *What do you think is the level of NASA's interest in He-3 mining?*
9. *In how many years do you think this project will be possible?*
10. *What is your overall impression of this project? Are you optimistic or pessimistic?*

8.1 Interview with Professor Gerald Kulcinski

We interviewed Professor Gerald L. Kulcinski, the Director of Fusion Institute of Technology at University of Wisconsin, Madison. He is an expert in the field of lunar Helium-3 mining and his specific interests lie in using advanced fuels such as D-He-3 to generate electricity. The following interview is transcribed from a phone conversation held with him.

From a technical standpoint, we asked Mr. Kulcinski what he thought were the major technical obstacles that are needed to be overcome for harvesting He-3 and developing it as an energy source. We also asked what time frame he thought was needed to overcome these obstacles.

Kulcinski: "In order of difficulty the list is: developing a fusion power plant, the mining operation, transportation and energy distribution. The level of difficulty is due to the nature of the difficulty. The fusion power plant faces an important scientific obstacle; the mining operation is subject to engineering obstacles that can be overcome. Transportation faces cost issues more than technical issues and the distribution of energy is not even an obstacle. The time frame at which the fusion power plant is developed which is the critical difficulty will be overcome depending on the level of research. At the ongoing rate there is no firm time frame, though I can assign a period of more than twenty years. If there is reasonable effort then it could be shortened to a 10 to 20 year time frame.

When I talk about investment and effort I don't only mean in my project, but rather the global perspective. There are $2 billion invested world wide, only a fraction of which are devoted to substantial research.

Major obstacles in fusion plant design are associated with the difficulty of obtaining break even energy levels. No one has been able to demonstrate break even. No t even Europe, where there is a huge, 10-20 billion, initiative to develop a steady deuterium-tritium reactor. However, the problem of the deuterium-tritium reactor is the radioactive waste produced and the issue of tritium confinement, both of which represent monumental obstacles in themselves.

There are also political obstacles. There is no trust between NASA and DOE in each other's ability to develop their respective technologies. The ability exists within each organization, but there is no coordinated program to join their individual efforts."

We also asked Dr. Kulcinski what the impact of lunar exploration based on He-3 harvesting could be on the future of space development and exploration. This is what he answered:

> *"The impact will be huge on the prospect of people living on the Moon. Mining He-3 produces great amounts of extremely valuable byproducts. The same technology that is required for He-3 extraction yields these byproducts. Sustainable lunar settlement will happen even before electricity is extracted from He-3.*
>
> *Another immense impact is the prospect of nuclear power without nuclear waste. This eliminates the need for storage facilities and it allows nuclear plants to be located in accessible locations, since the waste produced will be industrial rather than radioactive waste. These two latter issues will probably create the biggest impact. Nuclear power without nuclear waste will certainly happen, if not in this generation in the one following it. Even a D-T reaction brings safety benefits as compared to fission."*

When asked if nuclear fusion could commercially compete with fission, Dr. Kulcinski provided his impression:

> *"The competitive advantage of fusion vs. fission is in terms of waste generation and safety. Economically there is no competition. I don't think that even the D-T reaction can ever economically compete with nuclear fission, unless a huge penalty is assigned to fission reactions on the grounds of radioactive waste production. Many people say that the advantage is that nuclear fusion will abolish the risk of nuclear proliferation because a nuclear bomb cannot be made from the material. This is not true. The D-T produces huge amounts of fissionable material. Another advantage that*

> *looks good on paper is the short half life of radioactive waste produced by fusion compared to fission. However, in terms of a human lifespan a difference of 100 -1000 years lifetime is not relevant. I don't see fusion competing economically unless a breakthrough occurs."*

Dr. Kulcinski's opinion on the impact that the entrance of He-3 into the energy market would have on the future of the energy crisis was very thorough and seasoned.

> *"The impact here is huge. He-3 could potentially eliminate the energy crisis altogether. Only 10 tons of He-3 can replace ¼ of the energy that other energy sources provide for the United States. 40 tons would be sufficient to supply 100% of the US's annual energy requirement. Of course, this is not desirable because you don't want to have all the eggs in one basket. If you take a look at the volume of He-3 on the Moon, which runs in the order of 100,000 to millions of tons, the energy crisis could be removed altogether. It completely removes the issue of running out of clean energy. Now if there is a way of carrying out the He-3- He-3 at a reasonable cost, then we would have neutron less energy, which is completely clean. If you then need fluid energy to operate, you could use a combination of fusion and hydrogen."*

Working in the United States and with a leading global advantage on nuclear fusion, Dr. Kulcinski could give us a good idea of whether the United States have a one man show in developing He-3.

> *"Oh, no. Definitely not. I know that China, Russia and maybe even Japan have current projects. The media has given China a lot of press and we know the Russians*

> *have a project. I am not sure the Japanese do. So the US is not alone. In fact, there is a finite possibility that the US will not be the first to develop the technology."*

We proceeded by asking Dr. Kulcinski if he believed that it was relevant under the current world reality to pursue He-3 for energy when there were other local energy sources that could be developed. He have us his impression.

> *"It depends on the time scale that you are looking at. If you are looking for a solution in the next 10 years, then He-3 is not the solution. This was the case even for nuclear fission. The Manhattan Project was not relevant for a ten year timeframe. It is a problem of the generation, really. So, if you are considering the near term only, He-3 is not relevant. I think fission energy can bridge the gap between the current energy regime and fusion, though."*

On a more political note, we asked Dr. Kulcinski if he thought NASA was interested in pursuing He-3 exploration. His response was concise but enlightening.

> *"At this point it is not very interested. If they knew that a fusion power plant could run, then the level of interest would rise. The problem is that NASA does not trust the DOE to do so."*

Aware of the attention given to hydrogen, solar and wind energy recently by the media, we asked Dr. Kulcinski when he though He-3 would catch the public's eye and become the type of topic discussed at coffee shops.

> *"This is a process. Right now we are working on using fusion for PET. Alternative applications will catch the public's eye. They will make a commercial impact, in a scenario where break even does not even matter. The issue in nuclear medicine is how to produce radioisotopes at a reasonable cost, and in this window fusion can*

> *compete. If these applications become commercial then He-3 will be brought to the public. The next step is to demonstrate a steady He-3-He-3 device, at which my students are working. After this is achieved, we have the problem of scaling and this will surely catch the public eye. The next big step is, of course, break even. After that everything follows."*

Interested in the international spectrum of He-3, we asked Dr. Kulcinski whether his team was cooperating with other groups around the world and if he obtained his funds from a government organization such as the Department of Energy, DOE.

> *"First of all the DOE gives my group no money. We are funded by private investments of people who have made their fortunes elsewhere and see fusion as a promising technology. We have collaboration with the Japanese on the fusion side. It is low level collaboration, though, but very open."*

Finally, we were interested in Dr. Kulcinski's overall impression of the project of He-3 harvesting and nuclear fusion. He reassured us saying:

> *"I am pretty optimistic. Now this doesn't mean that I think it can be done within the next ten years. Students can see the benefits. We have a group of talented and enthusiastic students working on a steady He-3- He-3 device as part of their thesis. It may not happen in my lifetime and it is certainly a long term venture, but I can't say I am pessimistic, no."*

8.2 Interview with Ryan Caron

Ryan Caron, the President of American Institute of Aeronautics and Aerospace (AIAA) at WPI believes that mining of He-3 will be one of the major obstacles in harvesting He-3 from the Moon. As the ratio of the He-3 to the regolith soil is not ideal, the mining yield will not be very productive. But he thinks that this can be task can be managed if the proper mining hardware is developed. Also as the extraction technique will be very energy intensive, he believes that solar concentrators will have to be used. In order for the mining equipment to function in solar power, he says that they would have to be mobile at 23kph. He also stated that if the collector is separate from the oven, then the collector would have to be twice as fast. According to Ryan, transportation of He-3 will also present some obstacles. The LEO and GEO stations will not be feasible as return velocities from lunar trajectories are too high to be easily maintained in stable orbit, he said. Converting He-3 into a liquid form at low temperatures would be difficult to maintain. And utilizing it in a gaseous form will also be hard as high pressure tanks would have to be used. For the volume required per return flight to be economically feasible, small inflatable reentry craft about 1-2m in diameter should be tested and developed.

He believes that the He-3-D fusion reaction to produce energy which is currently possible but not sustainable has certain difficulties that need to be overcome. As the reaction needs a large vacuum, a space environment will be better for performing the reaction than if done on Earth, he stated. It would also be necessary to maintain a magnetic confinement and to make sure that the neutrons that are produced during this reaction are degraded. Regarding the transmission of the energy derived from He-3 on Earth, he believes that transmission through microwaves will be inefficient and so a little regional power infrastructure would be necessary. The energy can also be transported by other means such as “platinum metal mining’. And if this coupled with microwave power for electrolysis, then a hydrogen economy can be maintained.

When asked about his opinion about the impact he thinks that He-3 will have on future space development and exploration, he stated the space flights and space services will have to be economical to allow the development of tourism, technology test flights and satellite servicing. Mining of He-3 will also bring about hostility among international nations and the problem of getting rid of the orbital debris. If these problems are solved, he believes that He-3 development would 'go through the roof' in translunar space. When asked if a fusion reactor could compete with a fission reactor, he said that benefits of fusion over fission are a no-contest. Once fusion becomes economical, fission will be obsolete except in harnessing space power and rocket propulsion applications. He is of the opinion that the future energy crisis can be solved if the energy of He-3 can be efficiently brought back to Earth. And he thinks that this venture will require substantial investment in terms of infrastructure on the lunar surface.

According to Ryan all nations can play a role in developing a He-3 economy. The space fairing nations will be the main players, while countries in Africa can promote the microwave beaming technology and the industrial nations can develop the new fusion reactors. When asked about his view if any other alternate sources should be pursued other than He-3, he stated that a diverse infrastructure is a strong energy infrastructure; other alternate sources will find their niche markets where they are ideally suited. The breakthroughs that he thought was necessary in order for He-3 to be a more feasible energy source were microwave beamers, a way of maintaining vacuum and a method of maintaining field efficiency. When asked if he thinks NASA has any interest in mining He-3 from the Moon, he replied that NASA will only test any supporting technologies that would be helpful for mining He-3 as He-3 is an undemonstrated technology that is still in its infancy. Finally when asked about his overall impression about this project and the time he thinks that this project might take time to be developed, he was cautiously optimistic and hopeful that this project might compete with other energy sources like fission in the future years.

8.3 Interview with David Dietzler

We asked Mr. David Dietzler, who is a founding member of the St. Louis Chapter of the Moon Society, many questions that were focused toward the feasibility of mining He-3 from the Moon, and the social implications it may have. The information presented below faithfully represents his ideas and thoughts.

We first asked him about his views on the technologies that are required to mine He-3, and the breakthroughs needed to transport and use He-3 as a fuel source. Mr. Dietzler has a vision of using Artificial Intelligence (AI) and tele-operated automated machines, that is, machines that can be operated from the Earth. By keeping the current technological developments in mind, he believes that a nuclear powered miner, similar to the mobile miner discussed earlier, can be made within the next 20 years, given that there would be an interest to develop it. Dr. Kulcinski, of the University of Wisconsin, has preliminary designs of a miner called Mark II that weighs about 18 tons and can harvest abut 33 kg of He-3 per year (We have discussed the parameters of the Mark II Miner in Table 5). In addition, there would be many lunar robots that would assist in daily mining processes and jobs, which are relatively cheap to build these days. He also calculated that approximately 737 Mark II miners would be needed on the Moon to obtain 25 metric tons of He-3 per year, which would be enough to provide power to the United States for one year at current consumption rates. This would require 13,636 tons of machines, which is a massive amount.

The next topic stressed by Mr. Dietzler was the transport technologies and the cost of transportation. It would take a lot of money and resources to physically transport the immense weight of the miner to the Moon; for example, it would cost about $18 billion to transport all the 737 Mark II miners on the Moon. The alternate suggested by Mr. Dietzler was to build the miners on the Moon by using local resources like silicon, iron, titanium, aluminum, magnesium, sodium, chromium and manganese in the regolith. These parts could be made by 3D laser manufacturing, and could be assembled using tele-operated robots on the lunar surface. He envisions that the miner, and parts, would be build using lunar resources, which would all be derived while mining for He-3. Of course, there would be a need to first send a small number of miners that would initiate the manufacturing process. Mr. Dietzler further mentions that, “From a million tons of regolith at 100% recovery we would get about 40 tons of hydrogen, about 25 tons of helium 4, 200 tons of carbon, 100 tons of nitrogen and 500 tons of sulfur. Other machines, like magma electrolysis units, could yield oxygen, ferrosilicon and ceramic bricks. Hydrogen, oxygen and sulfur could be combined to make sulfuric acid for aluminum extraction. Hydrogen, carbon and nitrogen could be combined to make plastics. Hydrogen, carbon, silicon and oxygen could be used to make silicates. Carbon could be combined with iron to make steel. Just one ton of carbon would be needed to make about 300 tons of mild (sic) steel. Hydrogen, recycled, would also be used to extract titanium.” It can be seen that the process of manufacturing the miners on the Moon would be the major challenge. The transportation of the resources to LEO could be sent to the Moon using inexpensive rockets. He mentions an idea that the Government could offer a substantial tax break to companies that would spend their resources in sending payloads to LEO. Another idea could be that private industries would develop cheaper kerosene and liquid oxygen based rockets to transport payloads to LEO. But another difficulty that needs to be overcome is the transport of payloads beyond LEO and to the Moon. The use of ion drives has been suggested, which use very little fuel as compared to chemical based rockets. But Mr. Dietzler believes that this technology would take about 20 more years to fully develop. Some other technologies mentioned are laser or microwave sail crafts that are used to 'propel' payload from LEO to lower orbit (LO) by Earth controlled stations. The use of a space elevator is also mentioned by Mr. Dietzler as a way to transport cargo from the lunar lower orbit to the surface. There has been much debate and research about developing such technology, and there needs to be more research before we can use them.

Another breakthrough that needs to be achieved, as Mr. Dietzler explained, is the He-3-Deuterium fusion reactor. The Deuterium-Tritium fusion reaction that is planned by the International Thermonuclear Experimental Reactor project will cost about $10 billion, and the first plasma would be generated by 2016. Mr. Dietzler mentions that experts believe that the first commercial fusion will only be achieved by 2050 (refer to interview with Kulcinski). He also believes that the He-3 fusion reactor will only be made possible by the later part of the 21st century. This means that lunar He-3 will have no commercial value until about the next 50 years. Overall, Mr. Dietzler believes in using relatively cheap rockets to land a "seed" of artificial intelligence and ground tele-operated robots, which would mine valuable lunar metals and minerals, make more machines on the

Moon, and then launch the materials into space. This would require more robots, and only a few humans in space. He feels that this is important to do now, until the technology and realization of He-3 fusion comes by after about 50 years. After there are enough technological breakthroughs, Mr. Dietzler believes that there should not be many more barriers in using He-3 as a fuel source.

For the topic of a He-3 mining venture, Mr. Dietzler has some interesting views. He believes that by the end of this century we might be on the Moon and using lunar resources to build on the Moon, and that there could also be space tourism. In this case, He-3 would expand the horizon for further lunar activities and uses. And if we use this He-3 from the Moon as the primary source for energy on the Moon, it would last for about 200 years. But we would also use terrestrial energy sources like biofuels, hydroelectric and geothermal sources, which would make the He-3, last even longer. Mr. Dietzler makes another interesting point that after we mine He-3 successfully from the Moon, we could use He-3 power fusion rockets to travel to other planets, like Uranus, and mine even more He-3. He believes that mining on the Moon would just be a start towards more future mining explorations.

Next, we asked if Mr. Dietzler thought that the fusion reactor could ever compete with the fission reactor. His answer was based on current fusion reactor advancements and the potential of the fission reactors being used today. Due to the great technological advancements in economical fission reactors like the helium gas cooled pebble bed reactor that cannot melt down, and the fact that we still have not built a fusion reactor, Mr. Dietzler believes that at present fission beats fusion. An advantage highlighted by him is that the fusion reactors would produce less or almost no waste. This is beneficial because waste management in nuclear plants is a very critical and expensive issue. He also believes that people would be willing to pay more for electricity from fusion to prevent the transport of dangerous waste throughout the country. Also, he mentions that a fusion reactor, unlike a fission reactor, can be built in a city and the heat generated can be used to heat buildings in the winter, thereby improving the economic viability of a fusion reactor.

When asked about the upcoming energy crisis on the Earth, Mr. Dietzler believes that it would be defeated by discovering more oil and natural gas in deeper parts of the ocean and even in the sea floor. He envisions that energy would be conserved by the use of hybrid cars, and other renewable sources like solar energy. Afterwards, he mentions that by the time He-3 is utilized, the energy crisis would be overcome, and later the superior He-3 fusion technology would replace conventional energy sources. Furthermore, Mr. Dietzler believes that there would be a global interest in the use of He-3 as countries like US, the European Union, Japan, Russia and China would be interested. Also, Moon mining would be a private venture as companies see more advantage in lunar resources rather that the diminishing terrestrial resources. He mentions that, "the race for He-3 will involve giant international energy conglomerates." Also, since He-3 mining still needs a lot of technological developments, we should focus more on near term energy sources like fission and biofuels, and focus on He-3 as a long term goal as He-3 fusion requires very extreme and harsh temperatures and conditions, which have not been reached yet.

Mr. Dietzler's overall impression is that it would take about 50 years to accomplish the mining process if we start today, and that currently there is no interest to start now. He believes that NASA does not consider He-3 mining currently viable. He is largely optimistic about the topic of He-3 mining from the Moon because of current advancements in technology like materials, ion drives, compact space nuclear power supplies, artificial intelligence, robotics, and low cost rockets.

9. Conclusion

The potential of He-3 as a major energy source is immense and its development and adoption will bring powerful changes to the very spinal chord of a petroleum-based and Earth based society.

Through this project we have offered a comprehensive understanding of the technical difficulties engrained in the acquisition and processing of He-3 for energy production. Furthermore, we have presented and analyzed the legal obstacles and the framework that would direct an expedition to the Moon posing multiple scenarios for He-3 harvesting including private development, international cooperative development, single government development and a combination of these. The interest and initiatives of a number of space-faring nations in developing lunar resources was also presented, exhibiting the relevance of He-3 in international politics and science today. Moreover, the commercial viability of the project was put into perspective through a rough overview of the advantages, difficulties and costs of the project. Finally, multiple scenarios for developing He-3 were analyzed evaluating their impact on society on multiple levels including political power distribution, economic distribution, scientific breakthroughs, birth of new industries, the growth of global inequality and the changes in conceptual paradigms that space exploration will certainly bring.

The possibility of using He-3 as an energy source for the future is definitely a reliable option after looking into the energetics and economics of developing a He-3 economy on Earth. Even though there are many obstacles in this task, with the current research devoted to He-3 fusion technology, He-3 can be a useful energy source in the future years. The scenarios that were discussed in this paper can be realized if government and private enterprises highlight this venture as important for confronting the ongoing energy crisis. The public should also be made aware of the sources that exist to alleviate our ongoing energy crisis, and He-3 should be highlighted as one such option. He-3 certainly is a powerful option that allows us to overcome the current crises and brings with it many added benefits if used in a judicial and humanitarian manner. International interest in developing a He-3 economy should be of prime importance so that the countries of the world can work jointly in this venture. Though we recognize that the spectrum of the project is vast and that what we have posed as "ideal" scenarios are far too ideal to be conceivable, like many space enthusiasts, we are dreamers. But dreamers were exactly what were needed to land Man on the Moon and it is our chance to do so again, and this time in a more lasting manner.

10. Future Work

Our study does not end with the culmination of this project. In fact, this report opens grounds for a variety of topics ranging from Earth politics to space settlement. The different ground, upon which He-3 touches, is a measure of the magnitude of its impact in the future of global development. Although we have briefly discussed all of the points listed below, there is ample space for developing each topic further. The following is a list of topics that could lead to new in-depth studies.

1. Comparison study between the politics of the fossil fuel energy regime and a He-3/ fusion energy regime.
2. If He-3 is not used, are the energy sources available on Earth sufficient to sustain our current population and industrial growth?
3. Analyze the impact of a He-3 energy route on the development of different countries. Compare its impact on underdeveloped, developing and developed nations using specific nations for comparison purposes.
4. Analyze whether the drawbacks of nuclear fission are strong enough to impede its rise as a major energy source.
    a. Possibility of nuclear weapon proliferation.
    b. Radioactive waste.
5. Mining the Moon for precious metals and other precious resources.
6. A comprehensive inventory of lunar resources.
7. Impact of a lunar colony on the sociopolitical map of the world.
8. Will He-3 accelerate the development of space exploration?
9. Legal aspects of use of space resources. What are the perspectives?
10. Medical applications of nuclear fusion.
11. International cooperation in space exploration.
    a. Who are the players?
    b. What are the principles governing use of space resources?
12. Preparing for a space race.
    a. Professional technical preparation. Are we prepared for a space endeavor?
    b. Careers in natural sciences, space engineering and mathematics.

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