Mining Helium-3 from the Moon – A Solution to the Earth's Energy Needs in the 21st Century

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MINING HELIUM-3 FROM THE MOON --
A SOLUTION TO THE EARTH'S ENERGY NEEDS IN THE 21st CENTURY

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ABSTRACT

The recent discovery of large amounts of helium-3, a valuable thermonuclear fuel, on the surface of the Moon has prompted engineers and scientists to examine the commercial attractiveness, thetechnological feasibility, and the environmental features of this important resource. The main feature of this fuel cycle is the low (≈ 1%) fraction of energy released in neutrons. Such low neutron fluxes result in important reductions in the amount of radioactivity, afterheat, and radiation damage in a fusion power plant. On the other hand, the high fraction of energy in charged particles and synchrotron radiation can be directly converted to electricity, resulting in very high efficiencies of electricity production (≈60-70%). It has been shown that there is 10 times more energy in He3 on the Moon than there ever was in fossil fuels (i.e., coal, oil, and gas) on the Earth. The techniques and equipment needed to extract the helium-3 have been examined and internationally acceptable mechanisms for the industrial development of this resource have been outlined. This paper expands on the financial, environmental, and technical aspects of the recovery of helium-3 for use in the 21st century.

INTRODUCTION

In a recent speech President Bush (1989), announced that he wanted the U.S. to make a long term commitment to Space and to return to the Moon, "....And this time back to stay." Such an ambitious undertaking makes it all the more urgent that *long* range planning for the inhabitation of Space be initiated. The President's announcement was made in the midst of a major worldwide environmental crisis, largely brought on by the extensive use of fossil energy. The present world average energy use rate (≈10 barrels of oil equivalent per person per year or 50 billion barrels of oil equivalent per year worldwide) has resulted in the relatively rapid depletion of valuable fossil hydrocarbons and the fouling of our air, water, and land to obtain and use those resources. Furthermore, we may be in the process of causing permanent climatic changes by expelling potential "greenhouse" gases (CO_2 and CH_4) into the Earth's atmosphere.

One obvious way to save our fossil fuels and to improve the terrestrial atmospheric environment would be to make extensive use of nuclear energy in the form of fission reactors. This has been undertaken to varying degrees in the developed countries and some 27 nations are now operating 434 nuclear fission power plants which produced ≈17% of the World's electricity in 1988 (U.S. Council for Energy Awareness, 1989). However, nuclear fission waste issues plus concern over costs and safety have effectively halted the continued development of that energy option in many countries.

Another form of nuclear energy, nuclear fusion, promises to be much more environmentally acceptable and, because of superior safety characteristics, should be free from many of the costly delays now facing the licensing of fission power plants. Unfortunately, the control of the fusion reaction in the laboratory has proved to be harder than for the fission process, but scientists are now within a year or two of the first scientific break-even experiments (Sinnis, J.S., 1989; Huguet, M., and Bertolini, E., 1989) with deuterium (D) and tritium (T) and serious planning for a 1000 megawatt facility to operate at the turn of the century is underway (Baker, C.C., et al., 1989).

It has been known for some time that an even more attractive fusion fuel cycle than the DT system exists through the combination of D and an isotope of helium, He3. The advantages of this fuel cycle will be briefly examined in the next section, but the major impediment to the development of this fuel cycle has always been the location of a large source of He3. Such a source eluded fusion scientists until 1986 when a major deposit of He3, originally discovered in lunar samples in 1970 (Pepin, R.O., et al., 1970), was "rediscovered" by the fusion program (Wittenberg, L.J., et al., 1986). Subsequent analysis of the He3 resource base (Kulcinski, G.L., and Schmitt, H.H., 1987; Cameron, E.N., April 1988; Cameron, E.N., 1988), the mining equipment needed (Sviatoslavsky, I.N., and Jacobs, M., 1988; Sviatoslavsky, I.N., 1988), and the design of D-He3 fusion power plants (Kulcinski, G.L., et al., 1989), has been augmented by legal (Bilder, Richard B., et al., 1989) and financial studies (Report of NASA Lunar Energy Enterprise Case Study Force, 1989). It is now obvious that the energy resources on the Moon are enormous (approximately 10 times the energy in all the economically recoverable fossil fuels used to date on Earth) and the possibility now exists that we can solve both our environmental and long range energy problems by extracting this valuable fuel from the Moon and bringing it to the Earth.

BACKGROUND AND STATUS OF FUSION RESEARCH

Scientists first proposed the use of thermonuclear energy for civilian applications in the 1950's. This work closely followed on the heels of the first test of the hydrogen bomb, and it was felt that commercial fusion energy would take only a few decades to perfect. Unfortunately, the difficulty of controlling plasmas (collections of charged particles and electrons) at temperatures 10 times hotter than the center of the sun proved to be much more difficult than originally anticipated. Most of the 1960's was spent developing the field of plasma physics and laying the groundwork for a theoretical understanding of plasmas. By the end of the 1960's, and with unprecedented cooperation between U.S. and Soviet scientists, it became apparent that once the plasma physics problems were solved, significant technological progress was also needed to develop a safe and clean power source. Thus, in the 1970's, a dual approach to the problem was pursued:

(1) several large plasma physics facilities were constructed to test the theories developed in the 1960's, and

(2) engineering analyses of power plant designs were initiated to ascertain the technological, economic, safety, and social implications of this new form of energy.

Both of these lines of research have been continued in the 1980's with a major milestone of energy breakeven (i.e., the point at which as much energy is emitted from the plasma as it takes to keep it hot) within our grasp as we move into the 1990's. The current plan is to construct one or more reactor-like facilities in the 1990's which will produce power in the 500 to 1000 megawatt regime and to use these facilities to test materials and power conversion schemes that are needed in the 21st century.

The worldwide fusion effort is roughly equal between four programs with the European research effort being slightly larger than that in Japan, the United States and the USSR. In the early 1980's, approximately 2 B$ per year was being spent on fusion research with the U.S. in the lead of that effort. Today, the total effort is slightly less but it is clear that the European program has taken the lead from the U.S. and that a strong challenge for 2nd is being made by the Japanese. Altogether, over 25B$, in then current dollars, has been spent on fusion research worldwide since the early 1950's.

Relevant Plasma Physics Principles of Thermonuclear Research

Since the early days of the civilian thermonuclear fusion program, scientists had always envisioned that fusing a deuterium (D) and tritium (T) atom at very high temperatures would prove to be the most favorable for the production of electricity.

$$D + T \rightarrow He4 + neutron \qquad (1)$$

Energy released,
Q = 17.6 Million Electron Volts (MeV)

There were several reasons why this choice was made, ranging from the fact that the DT cycle ignites at the lowest energy (see Figure 1) to the experience gained from the thermonuclear weapons program in breeding

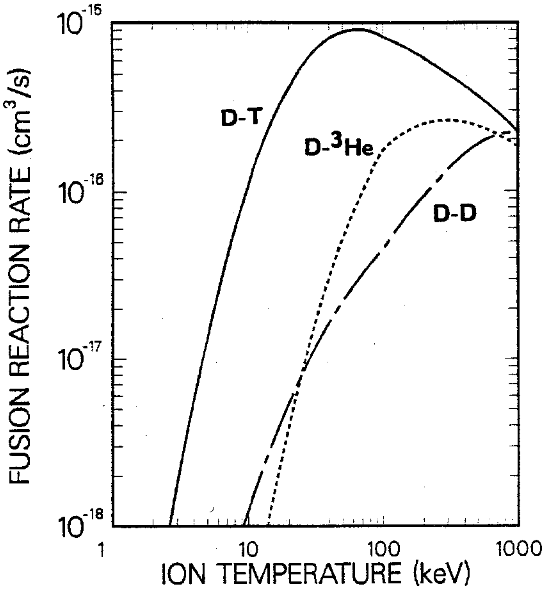

Figure 1. Major fusion fuel reactivities.

and handling tritium. Two other reactions, listed below, were also briefly considered.

$$D + D \begin{cases} \nearrow T + H \quad 50\% & Q = 4.0\ \text{MeV} \\ \searrow n + He3 \quad 50\% & Q = 3.3\ \text{MeV} \end{cases} \qquad (2)$$

$$D + He3 \dashrightarrow He4 + H \quad Q = 18.4\ \text{MeV} \qquad (3)$$

Neither of these reactions has received much attention since the 1950's, because they both require higher temperature to ignite and because there was no significant resource of He3 available on Earth.

Several things have changed since those early days of fusion research, and two of these will be considered here. First we will address the improving situation in fusion physics, and second we will examine the renewed interest in the technological and environmental advantages of the D-He3 cycle. The question of the He3 fuel supply will be addressed later.

State of Plasma Physics as it Pertains to the D-He3 Cycle

Simply stated, the objective in magnetic fusion research is to heat the confined plasma fuel to sufficiently high temperatures (T), at high enough densities (n), and for long enough times (t), to cause substantial fusion of atoms to take place. Mathematically stated for a reactor using the DT cycle, this can be stated as;

$$n\ t \geq 2 \times 10^{14}\ \text{seconds per cm}^3 \quad @\ T > 20\ \text{keV (200 million °C)}. \qquad (4)$$

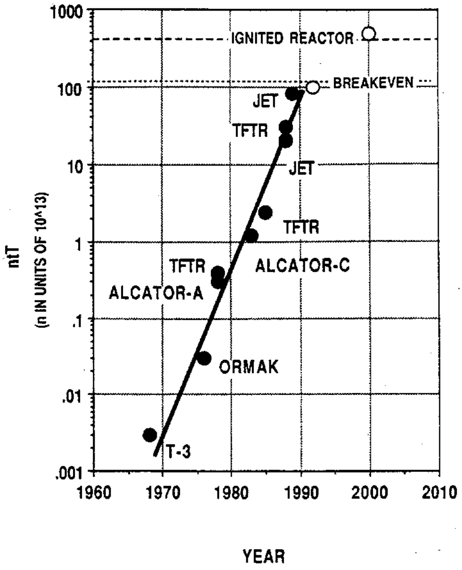

Figure 2a. Steady progress is being made toward fusion breakeven conditions.

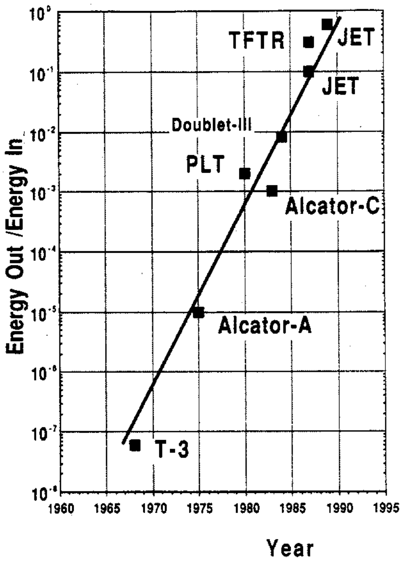

Figure 2b. Progress in fusion breakeven experiments.

Some perspective on the rate of progress in producing these conditions is given in Figure 2a where the ntT values achieved are plotted with respect to when they were first attained and in Figure 2b which shows the progress toward energy breakeven. The ntT product has been increasing at the phenomenal rate of a factor of 100 every 10 years. In fact in one parameter, namely the temperature T, scientists have actually produced 30 keV ions in TFTR plasmas at the Princeton Plasma Physics Laboratory (PPPL). This is 50% higher than needed for a DT reactor and only a factor of 2 lower than needed for a D-He3 reactor. The appropriate n,t, and T values for a D-He3 reactor are

$$nt \ge 4 \times 10^{15} \text{ seconds per cm3} \quad (5)$$
$$@\ T \cong 60 \text{ keV } (600 \text{ million } ^{\circ}\text{C}).$$

A detailed physics analysis shows that the Compact Ignition Torus (CIT) now being designed at PPPL could achieve the above temperatures in the mid to late 1990's.

While it is necessary to reach a ntT product (in units of 10^{13} keV-s per cm^3) of ~100 for breakeven in DT and a value of 400 for DT reactor operations (Figure 2b), it is necessary to achieve a ntT product of 24,000 for the D-He3 reactor. Recent analyses show that such values could be achieved by small modifications of the Next European Torus (NET) (Emmert, G.A., et al., 1988) or the International Thermonuclear Experimental Reactor (ITER) currently being designed for operations around the year 2000 (Emmert, G.A., 1989). In other words, despite the factor of 60 increase required in ntT values for a working D-He3 power plant over a DT system, several possibilities to achieve those values are available.

The surprising historical point of the previous discussion is that only a few short years ago, most scientists would have believed it impossible to produce significant D-He3 fusion power before the year 2020 or even later. However, scientists at JET have recently produced 100 kW of thermonuclear power with the D-He3 cycle (Boyd, D.A., et al., 1988) (see Figure 3) and expect that even higher levels can be achieved in the near future. The possibility that significant power could be produced with He3 before the year 2000 has opened up a whole new class of studies since 1987 and caused a complete reassessment of our long-range goals in fusion research.

TECHNOLOGICAL BENEFITS OF THE D-He3 FUEL CYCLE

One of the key features of the pure D-He3 reaction in Equation 3 is that both the fuel and the reaction products (protons and He4) are not radioactive. However, some of the deuterium ions do react with each other producing a small amount of neutrons and tritium. When the cross section and fuel mixtures are included, one can calculate how much of the average energy release is in the form of neutrons (see Figure 4). Whereas the DT cycle releases 80% of its energy in neutrons regardless of the plasma temperature (and the DD cycle releases ~50% in neutrons) one can see that operation at ~60 keV with a 3:1 ratio of He3/D, can result in release of as little as 1% of the energy in neutrons in a D-He3 plasma.

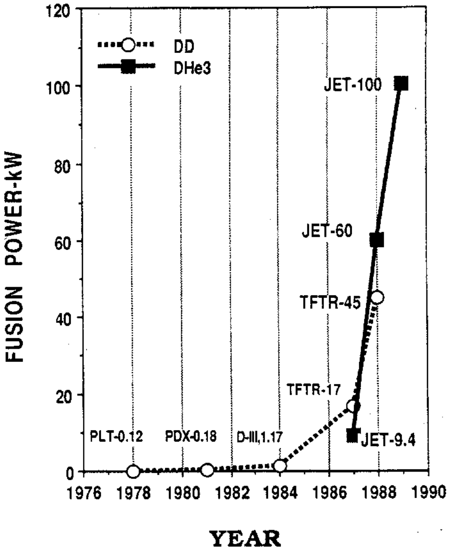

Figure 3. Actual thermonuclear power produced in fusion devices.

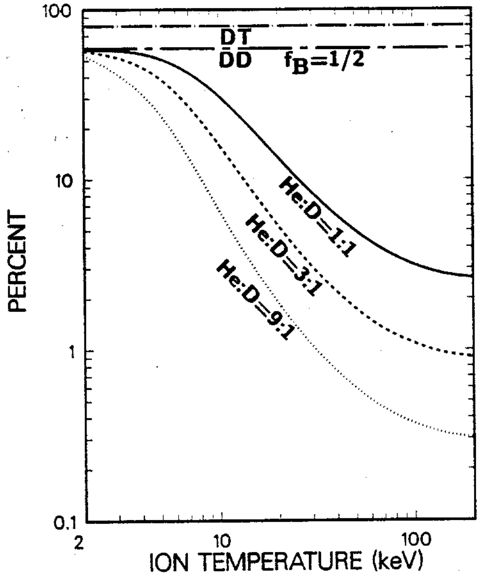

Figure 4. Percent of fusion power in neutrons (50% Tritium Burnup).

Why is this important? The radioactivity associated with, and radiation damage of reactor components, is directly proportional to the number of neutrons produced. Since the energy released per reaction from DT and D-He3 is roughly the same, then per unit of power produced, the problem associated with neutrons can be reduced by almost 2 orders of magnitude.

The main technological advantages resulting from these characteristics of the D-He3 fuel cycle, when compared to the DT cycle, are summarized as follows:

a) Increased electrical conversion efficiency.
b) Reduced radiation damage.
c) Reduced radioactive waste.
d) Increased level of safety in the event of an accident.
e) Lower cost of electricity.
f) Shorter time to commercialization.

Only a very brief comment on each of these features will be made here and the reader is referred to several recent publications for a more in-depth analysis (Kulcinski, G.L., et al., 1987; Kulcinski, G.L., and Schmitt, H.H., 1987).

Efficiency. If only ~1% of the energy is released in neutrons, then the other ~99% is released as charged particles or photons. In linear magnetic fusion devices, where most of the energy leaks from the reactor in the form of highly energetic charged particles, one can convert their kinetic energy directly to electricity via electrostatic converters at ≥ 80%. This means that overall plant efficiencies of 60 to 70% are achievable. In toroidal magnetic devices, one can convert the synchrotron radiation emanating from the electrons (frequency ~3000 gigahertz) directly to electricity at roughly the same efficiencies through the use of rectenna. Depending on how the other forms of energy emitted from the plasma are utilized, the efficiency in toroidal devices may then be in the 50-60% range.

A comparison of the maximum conversion efficiencies that might be achieved by fission or fusion devices is shown in Figure 5. The important point to note is that fusion devices may increase the efficiency of fuel usage by as much as 50 to 100% compared to fossil fuels or fission reactors. Such considerations are very important for thermal pollution in a terrestrial setting, but they are, in fact, critical to power plants that may operate in space. The rejection of heat in space is very, very costly.

Radiation Damage. When high energy neutrons, such as the 14 MeV neutrons emitted from the DT reactions, interact with structural reactor components they can greatly reduce the mechanical performance of those components as well as induce significant long-lived radioactivity. Within our present state of knowledge it is known that it will be difficult to operate a fusion reactor for more than a few years before the metallic components become so brittle that they will have to be replaced. This requires shutting the reactor down, handling highly radioactive components, exposing workers to ionizing radiation, and generating large volumes of radioactive waste. Our best estimates at this time are that 2 to 3 full power years is about the limit for present day materials. Since reactors should operate for 30 or more years, such changeouts will occur 10 or more times during the lifetime of a typical DT fusion plant.

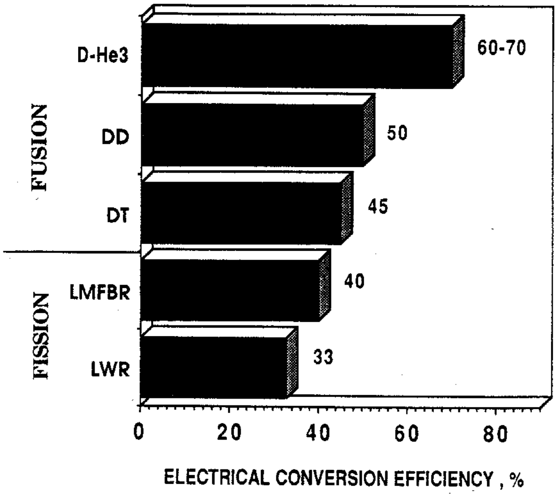

Figure 5. Comparison of nuclear energy electrical conversion efficiencies.

On the other hand, if one can reduce the neutron fraction to ~1% of the energy released in the D-He3 cycle, then the metallic components will last ~80 times longer than in a DT reactor. Such an extension is enough to completely obviate the necessity for component change due to neutron damage. This longer life and associated reduction in waste material will have profound economic and environmental benefits in a society based on the use of fusion energy.

Reduced Radioactivity. Because of the much smaller number of neutrons, the induced radioactivity in the reactor walls will also be reduced by a factor of ~80. In today's DT fusion reactor designs, special materials will have to be developed in order to avoid generating large amounts of high level wastes that must be placed in deep underground repositories. For example, conventional steels would become so radioactive and damaged in a DT reactor that as much as 10 m^3 per reactor year would have to be sequestered in one of the national deep repositories scheduled for operation near the turn of the century. On the other hand, these same materials would last the full 30 year life of a D-He3 plant and still could be disposed of as low level, class C waste buried in near-surface disposal sites. If low activation steels or other materials are developed, then such alloys, after 30 years of operation, could be buried along with medical waste in near surface class A sites. Aside from the tremendous savings in cost, one would find that wastes from a D-He3 reactor would decay to benign levels in less than 100 years instead of the 1000's of years required for current fission and fusion devices.

Safety. One of the most severe accidents that could occur in a DT fusion plant is the complete loss of coolant along with a complete breach of reactor containment. The afterheat in a DT reactor can be sufficient to release large amounts of tritium and radioisotopes from the reactor structure. At present, it is not known whether we can keep critical components from melting in a commercial DT reactor.

In a D-He3 reactor, two fundamental characteristics prevent such dire consequences from a loss of coolant. First, the afterheat (which comes directly from the neutron activation products) is so low that in the event of the most severe accident to be imagined, and if no heat leaked from the system (e.g., if the entire reactor was wrapped in a perfect, thermally insulating blanket), the maximum temperature increase in a week would be ~500°C (still 1000°C below its melting point). Secondly, the tritium inventory in a D-He3 plant can be as little as 2 grams. The complete release of this tritium in a rainstorm could still cause no more exposure to a member of the public living next to the D-He3 reactor than he or she typically receives from natural sources of radioactivity such as cosmic rays and radon gas in a year's time.

Cost of Electricity. There are features of the D-He3 fuel cycle which strongly suggest that it will provide electricity more cheaply than a DT fusion power plant. These are:

a) lower capital cost
b) lower operation and maintenance costs
c) higher efficiency
d) higher availability.

The first point is based on a comparison of two recent D-He3 reactor designs, Ra (Pepin, R.O., et al., 1970) and Apollo (Wittenberg, L.J., 1986), to 17 previous DT reactor designs, most done by the same group with the same costing philosophies. The results of this comparison are discussed elsewhere where it is shown that the capital cost of the Apollo-L D-He3 system is ~20-50% lower than comparable DT plants. The reason for this has to do with the greatly reduced balance of plant costs (i.e., that part of the power plant outside the fusion reactor), associated with conventional steam generators and turbines. It also has to do with the fact that D-He3 plants, which contain such low levels of tritium and radioactivity, could use conventional grade construction material, thus avoiding the high nuclear-grade material costs associated with fission and, probably, with DT fusion reactors.

Because of the low radioactive inventory and low level of neutron damage, there should be no required replacement of components due to neutron damage. This means that the number of plant personnel can be greatly reduced compared to a DT plant. The use of solid state electrical conversion equipment also will require less maintenance personnel.

The higher electrical efficiency will have a direct effect on the specific cost parameters. For example, the capital cost per kWe will be lower for the same thermal power, and the cost of heat rejection equipment (i.e., cooling towers) will be greatly reduced.

Finally, the ultimate cost of electricity, in mills per kWh, can be reduced if the plant stays on line for a larger fraction of its total lifetime. As stated previously, a DT power plant has to be shut down frequently to change neutron-damaged components. The duration of the down time will be adversely affected by the induced radioactivity and the problems associated with tritium contamination. It is also well known that plants which use a high-pressure steam cycle (as would a DT plant), require on average on the order of 10-15% of their total lifetime to repair steam turbines and heat exchangers. The use of solid state conversion equipment, rather than a steam cycle, should reduce that number in a D-He3 plant similar to the way solid state TV sets are more reliable than those which used vacuum tubes.

The time from now to commercialization of D-He3 fusion could be shorter than the time to commercialize the DT cycle even if it takes longer to solve the remaining physics problems associated with higher temperatures and longer confinement times. The reason for this again lies in the low fraction and low energy of neutrons released in the D-He3 cycle and the need to develop a whole new class of metals and alloys to withstand the damage associated with the 14 MeV neutrons from the DT cycle. Conservative estimates of the cost to solve this problem include a materials test facility (1-2 B$ capital plus 10-15 years operating time requiring another 1-2 B$ in operating expenses), and a completely new blanket test facility in a demonstration power plant (3-4 B$ + 10-15 years and ~5 B$ operating costs) before one could get to a commercial system. Add to this significant sum the cost of an auxiliary technology program for 20-30 years beyond the solution of the physics problems (another 10-20 $B) and we can see that an additional ~30 $B and 30 years could be required to commercialize DT fusion after the DT operation in the ITER class of fusion devices in the year 2005.

On the other hand, if the ITER could be slightly modified (for less than 10% of its present cost) to ignite D-He3, then the same reactor could also be used to generate electricity in a demonstration reactor mode by 2005-2010. Since there is no need for a materials test facility nor for the need of developing breeding blankets, a prototype D-He3 commercial plant could be operational by the year 2015-2020, a full 15-20 years sooner than possible with the DT cycle.

AVAILABILITY OF HELIUM-3

Terrestrial Resources

It was commonly believed in the fusion community that after the questions of plasma physics have been solved, the next single largest barrier to the widespread study of the D-He3 reaction would be the lack of any large identified terrestrial source of helium-3. Studies on the SOAR (Space Orbiting Advanced Reactor) concept at the University of Wisconsin (Santarius et al., 1988) in 1985 identified only small amounts of indigenous He3 on the Earth and a roughly equal-sized source from the decay of tritium ($t_{1/2}$ = 12.3 years) in the U.S. thermonuclear weapons program (see Table 1).

Table 1

AMOUNTS OF He3 THAT COULD BE AVAILABLE IN THE YEAR 2000

Source	Cumulative Amount (kg)	Production Rate After Year 2000 (kg/y)
Primordial-Earth		
• US Helium Storage	29	---
• US Natural Gas Reserves	187	---
Tritium Decay		
• US Nuclear Weapons	300	~15
• CANDU Reactors	10	~ 2
TOTAL	>500	~17

Note: 1 kg of He3 burned with 0.67 kg of deuterium yields 19 MW-y of energy

Most of the primordial He3, present at the formation of the Earth, has long since diffused out of the Earth and been lost in outer space. What is left in any retrievable form is contained in the underground natural gas reserves. Table 1 reveals that the total He3 content in the strategic He reserves stored underground amounts to only some 30 kg. If one were to process the entire United States known conventional natural gas reserves, approximately another 200 kg of He3 might be obtained.

Another source of He3 on Earth is from the decay of tritium ($t_{1/2}$ = 12.3 years). When T_2 decays, it produces a He3 atom and a beta particle. Simple calculations of the inventory of T_2 in U.S. thermonuclear weapons show that if all the He3 were collected, some 300 kg would be available by the year 2000. Presumably about the same amount of He3 would be available from the weapons stockpile of the USSR. The equilibrium production of He3 (assuming no future change in weapons stockpiles) is around 15 kg per year in each country. It may seem strange to rely on a by-product from weapons for a civilian application, but the He3 commercially available today is from just such a process. One can purchase up to 1.38 kg of He3 per year directly from the U.S. government (10,000 liters at STP), all of which comes from T_2 decay. Obviously, considerably more is available, and simple calculations of the tritium production from U.S. facilities at Savannah River indicate that tritium production could be in the 10-20 kg per year range. This would imply an "equilibrium" He3 production rate of ~10-20 kg/year minus losses in processing.

One could also get smaller amounts of He3 from the T_2 produced in the heavy water coolants of Canadian CANDU reactors. This could amount to 10 kg of He3 by the year 2000, and He3 will continue to be generated in these plants at a rate of ~2 kg per year thereafter.

It should be noted again that 1 kg of He3, when burned with 0.67 kg of D, produces approximately 19 MW-y of energy. This means that by the turn of the century, when there could be several hundred kg's of He3 at our disposal, the potential exists for several thousand MW-y of power production. The equilibrium generation rate from man-made T_2 resources alone could fuel a 300 MWe plant indefinitely if it were run 50% of the time.

Clearly, there is enough He3 to build an Experimental Test Reactor (ETR) (a few hundred MW's running 10-20% of a year) and a demonstration power plant of hundreds of MWe run for many years. This could be done without ever having to leave the earth for fuel. The real problem would come when the first large (GW$_e$ level) commercial plants could be built around the year 2015.

What and Where are the He3 Resources on the Moon?

Wittenberg et al. (1986) showed in September 1986 how the He3, first discovered on the Moon by the Apollo-11 mission, could be utilized in a fusion economy. Since that time, work at the University of Wisconsin has elaborated on the original idea. A few highlights will be summarized here.

The origin of lunar He3 is from the solar wind (i.e., the charged particles leaking from the sun and "blowing" on the rest of the bodies in the solar system). Using data which showed that the solar wind contains ~4% helium atoms and that the He3/He4 ratio is ~480 appm, it was calculated that the surface of the Moon was bombarded with over 250 million metric tonnes in 4 billion years. Furthermore, because the energy of the solar wind is low (~3 keV for the He3 ions), the ions did not penetrate very far (<0.1 micron) into the surface of the regolith particles (lunar soil). The fact that the surface of the Moon is periodically stirred, as the result of frequent meteorite impacts, results in the helium being trapped in soil particles to depths of several meters.

Analysis of Apollo and Luna regolith samples revealed that the total helium content in the Moon minerals ranges from a few to 70 wtppm (see Figure 6). The higher concentrations are associated with the regolith on the old titanium-rich basaltic Maria of the Moon, and the lower contents are associated with the Highland rocks and Basin Ejecta. Clearly the higher concentrations are in the most accessible and minable material. Using the data available, it is calculated that roughly a million metric tonnes of He3 are still trapped in the surface of the Moon (Wittenberg, 1986) (see Table 2).

<u>Table 2</u>

<u>HELIUM-3 CONTENT OF LUNAR REGOLITHS</u>

Location	% Lunar Surface	Ave. Helium Conc.wtppm	Tonnes He3
Maria	20	30	600,000
Highlands & Basin Ejecta	80	7	500,000
TOTAL			1,100,000

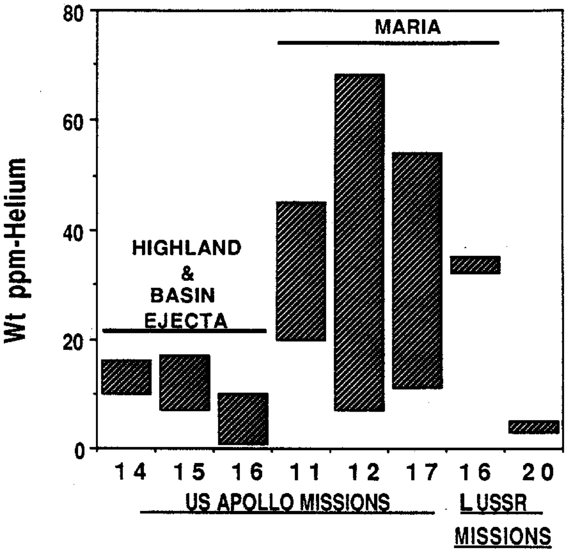

Figure 6. Measured helium content in lunar samples.

The next step is to determine the most favorable location for extracting this fuel. Cameron (1987) has shown that there is an apparent association between the helium and TiO$_2$ content in the samples. Assuming that this is generally true, he then examined the data on spectral reflectance and spectroscopy of the Moon which showed that the Sea of Tranquility (confirmed by Apollo 11 samples) and certain parts of the Oceanus Procellarium were particularly rich in TiO$_2$. It was then determined, on the basis of the large area (190,000 km^2) and past U.S. experience, that the Sea of Tranquility would be the prime target for initial investigations of lunar mining sites. This one area alone appears to contain more than 8,000 tonnes of He3 to a depth of 3 meters. Backup targets are the TiO$_2$-rich basalt regolith in the vicinity of Mare Serenitatis sampled during Apollo 17 and areas of high-Ti regolith, indicated by remote sensing, in Mare Imbrium and other mare of the lunar western hemisphere (Cameron, 1987).

How Would the He3 be Extracted?

Since the solar wind gases are weakly bound in the lunar regolith it should be relatively easy to extract them. Pepin (1970) found (Figure 7) that heating lunar regolith caused the He3 to be evolved above 200°C and by 600°C, approximately 75% of the He gas could be removed.

There are several methods by which the He could be extracted and a schematic of one approach is shown in Figure 8. In this unit, the loose regolith, to a depth of 60 cm, is scooped into the front of the robotic unit. It is then sized to particles less than 100 microns in diameter

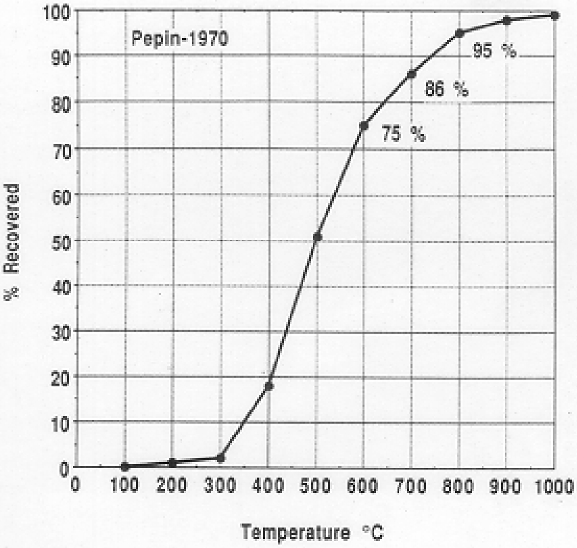

Figure 7. Evolution of helium-3 from lunar regolith.

(about 65% of the regolith) because there seems to be a higher concentration of solar gases in the smaller particles (presumably because of the high surface to volume ratio). After beneficiation, the concentrate is preheated by heat pipes (Sviatoslavsky and Jacobs, 1988) and then fed into a solar-heated reaction chamber. At this point, it is anticipated that heating to only 600 or 700°C is required, and the volatiles (H_2, He4, He3, H_2O, C compounds, N_2) are collected. The spent regolith concentrate is discharged through recuperative heat exchangers to recover 90% of its heat. The spent regolith is finally dropped off the back of the moving miner. Note that in the 1/6 gravity environment, relatively little energy is expended lifting material.

Of course, this solar energy-driven scheme would only work during the lunar day, but orbiting mirrors, nuclear reactor heat from a mobile power plant, or indirect radio frequency (RF) heating from electricity generated at a central power plant on the Moon could extend the operating

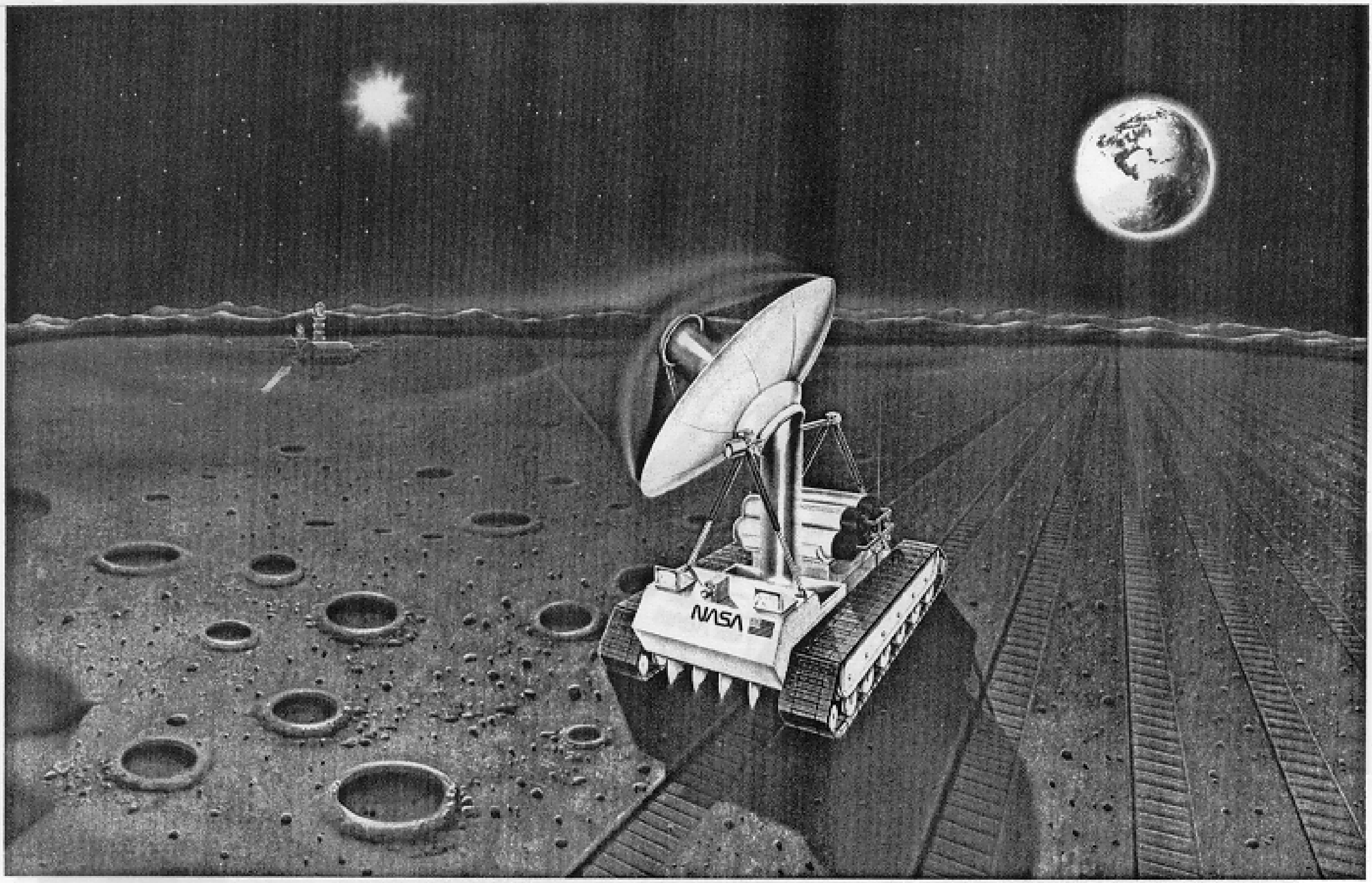

Figure 8. Schematic of a robotic lunar miner for extracting helium-3

time. Alternative schemes are being examined through parametric analyses of such variables as particle size vs. temperature vs. yield, mining depth vs. He3 concentration vs. particle size distribution, manned operation vs. robotic operations vs. maintenance costs, mechanical particle separation vs. gaseous particle separation vs. yield, solar vs. nuclear power, etc.

Once the lunar volatiles are extracted, they can be separated from the helium by isolation from the lunar surface and exposure to outer space (<5 K) during the lunar night. Everything except the helium will condense and the He3 can be later separated from the He4 by superleak techniques well established in industry (Wittenberg et al., 1986).

For every metric tonne of He3 produced, some 3100 tonnes of He4, 500 tonnes of nitrogen, over 4000 tonnes of CO and CO_2, 3300 tonnes of water, and 6100 tonnes of H_2 are produced (see Figure 9). The H_2 will be extremely beneficial on the Moon for lunar inhabitants and for propellants. Transportation of that much H_2 to the Moon, even at 1000 $/kg (less than 1/10 of present launch costs), would cost ~6 billion dollars. As noted below, the He3 itself could be worth as much as ~2 billion dollars per tonne. Of the other volatiles, the N_2 could also be used for plant growth, the carbon also for plant growth, for manufacturing or atmosphere control, and the He4 for pressurization and as a power plant working fluid. Oxygen, either from the water or carbon compounds, could be used for interior atmospheres or for fuel in rockets from the Moon.

The environmental impact to the Moon as a result of this type of volatile extraction would be minimal. For example, there would be "tracks" on the Moon and the surface would be smoothed and slightly "fluffed up" as the spent regolith is redeposited. The vacuum at the lunar surface might also be temporarily affected but, due to the low gravity level, most of the gas atoms will leave the surface of the Moon during the lunar day.

How Much is the He3 Worth?

While it is hard to anticipate the cost of energy in the future, one can anticipate what we might be willing to pay for fuel based on today's experience. First of all, it is worthwhile to get a feeling for how much energy is contained in the He3 on the Moon. If the ultimate resource base is 1 million metric tonnes, then there is some 20,000 TW-y of potential thermal energy on the Moon. This is over 10 times more energy than that contained in economically recoverable fossil fuels on earth. This amount of energy is also 100 times the energy available from economically recoverable U on earth burned in Light Water Reactors on a once through fuel cycle or roughly twice the energy available from U used in Fast Breeder Reactors.

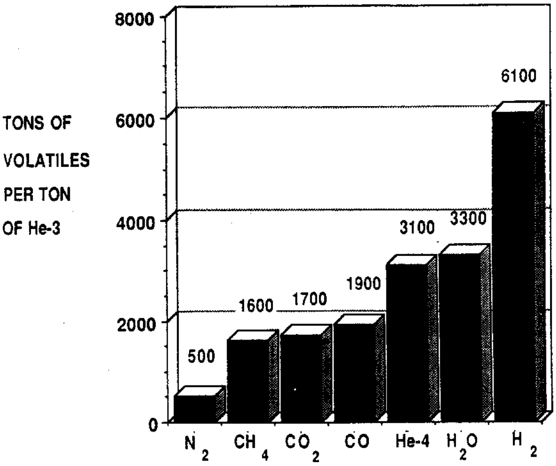

Figure 9. By-products of lunar helium-3 mining.

The second point is that only 25 tonnes of He3, burned with D_2 would provide the entire U.S. electrical consumption in 1990 (some 300,000 MWe-y). The 25 tonnes of condensed He3 could fit in the cargo bay of a spacecraft roughly the size of the U.S. shuttle.

A third point is that in 1989, the U.S. spent over 40 billion dollars for fuel (coal, oil, gas, uranium) to generate electricity. This does not include plant or distribution costs, just the expenditure for fuel. If the 25 tonnes of He3 just replaced that fuel cost (while the plant and distribution costs stayed the same) then the He3 would be worth approximately 1.6 billion dollars per tonne. At that rate, it is the only thing we know of on the Moon which appears to be economically worth bringing back to earth.

An obvious question at this point is how much does it cost to obtain He3 from the Moon? The answer to that depends on three things:

(1) Will the U.S. develop a Moon base for scientific or other mining operations without the incentive of obtaining He3?

(2) If the answer to the above question is yes, then how much will the incremental costs of mining He3 be after manned lunar bases are already in place?

(3) How will the benefits of the side products be treated? For example, will one be able to "charge" the lunar settlement for the H_2, H_2O, N_2, He, or carbon compounds extracted from the lunar regolith?

(4) Will the ultimate export of volatiles to a Mars settlement add a significant rate of return to the enterprise?

The answer to question 1) may be yes. In a 1987 report to NASA by the Ride Commission (Ride, 1987), it was stated that one of the 4 major future programs in NASA should be a return to the Moon and the establishment of a manned base early in the 21st century. Similar statements have been made in 1989 by President Bush. This recommendation was made without any reference to the He3 mining possibilities. At this time, it appears reasonable to assume that the cost of returning to the Moon will be borne by the U.S. government or by an international entity as a general investment in science.

The answer to question 2) cannot be given at this time but should be the subject of study in the near future. It appears that, based on the mobile mining concept described earlier, the equipment required to produce 25 tonnes per year could be transported to the Moon for well under 30 billion dollars (e.g., at 1000 $/kg this would allow 30,000 tonnes to be transported to the Moon). Operational costs should be well under a billion dollars per year even if no use of lunar materials is allowed. The above costs are to be compared to 500-1000 B$ in revenue from the He3 mining during the useful life of the equipment.

The possibilities of "selling" the by-products of the He3 to lunar colonies is also very intriguing. The by-products from mining just one tonne of He3 would support the annual lunar needs (properly accounting for losses through leakage and through waste recycling) of (Bula et al., 1988)

1,400 people for N_2 (food and atmosphere)
22,000 people for CO_2 used to grow food
45,000 people for H_2O.

If the cost of transporting the equipment to extract these volatiles from the lunar regolith is written off against the savings in sending up life support elements such as H_2, N_2, or carbon for manned lunar bases, then it is possible that the cost of He3 may in fact be negligible. If that were true then the cost of electricity from D-He3 fusion power plants would indeed be much cheaper than from DT systems and possibly even from fission reactors (without taking credit for all the environmental advantages of the D-He3 fuel cycle).

To answer the question posed by the title of this section, it appears that a realistic figure for the worth of He3 on the earth is ~1 or 2 billion dollars per tonne (1000 $/g). This should allow D-He3 fusion plants to be competitive with DT systems and provide adequate incentive for commercial retrieval from the Moon. This latter point was the subject of a separate study by NASA published recently (Kearney et al., 1989).

CONCLUSIONS

It has been shown that among the potential fuels for the 21st century, the D-He3 fuel cycle ranks high with respect to safety, environment and cost. The procurement of He3 from the moon is not only feasible, but could be very attractive economically. The major nations of the world cannot afford to be left out of the race to commercialize this fuel and it is expected that once the major magnetic fusion programs of the world reach energy breakeven, their attention will naturally turn to the D-He3 fuel cycle.

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