A Resource Assessment and Extraction of Lunar ^{3}He

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1. Introduction

The attractiveness of a D^3He fusion reactor economy has been shown in previous papers.[1-6] The main advantages of such an energy source stem from the low fraction of fusion energy released in neutrons (a few %) compared to 80% from the more "traditional" DT fuel cycle. This low neutron fraction has several important consequences:

- Greatly reduced radioactivity.
- Greatly reduced radiation damage to reactor components.
- Inherently safe reactor operation.
- Much higher overall efficiency of operation.
- Potentially lower cost of electricity.
- Shorter time to commercial electrical power plants.

There are two reasons that such a fuel cycle has not been pursued in the past:

1. the physics requirements of the D^3He cycle are more demanding than those for the DT cycle,[3] and
2. there was no known large ^3He resource available prior to 1985.[7]

The situation with the D^3He physics has greatly improved in the past 5 years with a world record 140 kW of D^3He fusion power being produced in JET[8] and plasma ion temperature of 35 keV (roughly half of what is required for a D^3He reactor plasma) produced in TFTR.[9] There has been even greater progress in the ^3He resource picture in the last 5 years. Prior to that, the only known ^3He resource accessible to us on the earth was the primordial ^3He collected in underground natural gas reserves (≈200 kg) and the ^3He from decaying tritium in thermonuclear weapons and heavy water CANDU fission plants (≈300 kg). With an energy content of ≈10 MWe-y/kg of ^3He burned this would only provide ≈5 GWe-y of fusion energy, hardly enough around which to develop an energy industry.

In 1985, scientists at the University of Wisconsin postulated that there should be a large amount of ^3He implanted in the lunar surface from the solar wind. This was confirmed by data originally collected by the U.S. Apollo and U.S.S.R. Lunakhod program.[7]

The purpose of this paper is to examine the extent of that resource and discuss methods by which it could be extracted.

2. ^{3}He Resource Estimates on the Lunar Surface

Several studies of the extent and distribution of the lunar ^{3}He resources have been made in the past few years, principally by Cameron,[10-12] Gibson,[13] and corroborated by Jordan.[14] The source of the ^{3}He comes from the solar wind which has been incident on the lunar surface for ≈4 billion years and has showered the moon with ≈500 million tonnes of ^{3}He. The low energy hydrogen and helium atoms have been implanted 100's of angstroms into the material covering the lunar surface. However, the ^{3}He has been detected to a depth of several meters because the surface has been "gardened" (i.e., the surface has been turned over and over) by the action of meteorites over the billions of years the moon has been exposed to the solar wind and debris from space.

A summary of the He content measured in lunar samples is given in Fig. 1. It can be seen that the He content is generally higher in the lunar maria (i.e., the "Seas of the Moon") than it is in the highlands and basin ejecta (mountains of the moon). The reasons for this higher retention of the helium in lunar regolith (the name given to the very fine grained material making up the maria) is unknown at this time. In any case, it is very fortunate that the helium is preferentially retained in the regolith because it has the consistency of "dust" which makes it easier to handle.

By knowing the ^{3}He/^{4}He ratio (it was essentially the same as in the solar wind, ≈480 ppm) and the relative area in maria of the moon, one can calculate the approximate amount of ^{3}He present on the lunar surface. Table 1 shows that this is in the neighborhood of 1,000,000 tonnes divided roughly equally between the maria and the highlands.

Just how much energy is there in the lunar ^{3}He? Some perspective on the number can be obtained by noting that it would take only 25 tonnes of ^{3}He, combined with deuterium, to provide the ≈250 GW_e-y of electrical energy consumed in the U.S. in 1991. Furthermore, that 25 tonnes when liquified, would fit in the cargo bay of just one present U.S. shuttle craft. Another comparison is that the 6×10^{23} joules of potential thermal energy in the ^{3}He atoms is ≈10 times the energy in all the economical fossil fuels left on the earth.

Fig. 1. All the samples returned from the moon that were tested for helium revealed ^{3}He and ^{4}He at approximately the solar wind ratio.

Table 1

Lunar ^{3}He Reserves Calculated From U.S. Apollo and Soviet LUNA Missions

Location	% Lunar Surface	Average He Conc. wtppm	Tonnes ^{3}He
Maria	20	30	600,000
Highlands and Basin Ejecta	80	7	500,000
Total			1,100,000

3. Distribution of the ^{3}He on the Moon

Cameron[10] noticed that there was an important relationship between the amount of He in lunar material and the TiO_2 content (Fig. 2). If that relationship is consistent around the lunar surface, then it should be easier to know where the first mining sites should be located. Such an analysis reveals that we should concentrate on the maria of the moon. As an example, Cameron[13] has examined the Mare Tranquillitatis from UV/IR spectral photographs. Such diagnostics reveal the TiO_2 distribution and by using the correlation in Fig. 2, he was able to estimate that there is over 15,000 tonnes of ^{3}He in Mare Tranquillitatis alone. At the present U.S. electrical consumption rate, this Mare alone would provide over 600 years of our needs.

Fig. 2. There is a reasonable correlation between TiO_2 and He content in lunar samples.[10]

4. Extraction of the Lunar ^{3}He

The basis for the extraction of ^{3}He from lunar regolith was discovered over 20 years ago by Pepin.[15] In the process of studying the samples from Apollo 11, he found that heating the lunar regolith to temperatures of ≈700°C would cause ≈85% of the ^{3}He to be evolved (Fig. 3). In an interesting side note, Pepin was studying the Apollo samples in a purely scientific manner and had no idea of the value associated with ^{3}He in fusion. This information was in the scientific literature for more than 15 years before fusion scientists at the University of Wisconsin "rediscovered" it.

Knowing that the ^{3}He could be extracted by heating the regolith allowed other scientists at Wisconsin to design equipment capable of operating in the lunar environment. Sviatoslavsky and co-workers[16-18] designed lunar mining equipment (see Fig. 4) that is capable of collecting the loose regolith, separating the material to grains less than 50 microns in diameter, and heating the regolith to ≈700°C using the indigenous energy source, the sun. Once the solar wind volatiles have been evolved and collected in gas tanks, the warm spent regolith is passed through a

Fig. 3. Early experiments by Pepin(15) revealed the temperatures required to evolve ^{3}He.

Fig. 4. The Lunar Volatiles Miner designed at the University of Wisconsin makes use of the "local" energy supply.[18]

regenerative heat exchanger to heat the incoming, colder regolith. The spent regolith is then returned to the lunar surface thus avoiding the transport of large amounts of lunar material around the lunar surface.

5. Important By-Products from Lunar ^{3}He Mining

In addition to the important ^{3}He isotope, several other elements and compounds are released from the lunar regolith during the heating process. For every tonne of ^{3}He collected large amounts of valuable gases will also be produced[19] (see Fig. 5). The water comes from the reaction of the implanted hydrogen and the oxygen in the lunar regolith (≈50% by weight).

Fig. 5. The volatiles associated with ^{3}He extraction can have an enormous effect on the ability of society to support a human occupied base on the moon.

The H_2 is removed first though a heated permeable Pd membrane. Next, the mixture of gases is allowed to cool during the (14 earth day) lunar night by radiation to outer space. This will bring the temperature down to ≈50°K where all the gases except the He will be either liquified or solidified. The separation of ^{3}He from ^{4}He takes place using "superleak"[7] techniques at very low temperatures (<4°K). The low temperatures are provided by cryogenerators run by batteries charged by solar energy during the 14 earth day lunar day. The important feature of this process is that most of the energy required to extract and separate the ^{3}He is provided by the sun and the "coldness" of outer space. Hence the energy payback from this scheme will be very favorable.

It should be obvious that the lunar volatile by-products will be extremely valuable to the development of bases on the moon and even Mars. The 18,200 tonnes of gases generated per tonne of ^{3}He can be used for propellant, growing of food, life support, atmosphere control, pressurization, etc. To transport that much mass to the Moon, even at one tenth the launch costs of today (≈$10,000/kg), would cost 18 $B! And that is only if one tonne of ^{3}He is produced. Clearly, the benefits of the other lunar volatiles will be of equal or higher value than the ^{3}He itself.

6. Energy Payback For Lunar ^{3}He Mining

An estimate of the energy payback ratio for mining ^{3}He can be made by knowing the mass of mining, processing, and associated personnel related equipment required to produce a kg of ^{3}He.[20,21] Figure 6 shows the mass required and coupling this with the energy involved in transportation,[20] results in 2085 GJ per kg of ^{3}He delivered to the earth. Since the fusion of 1 kg of ^{3}He with D produces ≈600,000 GJ of energy, we conclude that the energy payback is ≈300 to 1. When the construction of the power plant is included, this ratio drops to ≈80 to 1.[21]

Fig. 6. The mass required to mine ^{3}He on the moon is dominated by the mass of the miner.[20,21]

7. Economic Value of ^{3}He

The value of an energy resource is not always based on a straight substitution for other forms of energy. Factors such as waste disposal, safety, dependability, etc., can also have a major impact. However, at this point in time we can make some rough estimates of the economic value of ^{3}He based on historical energy prices. For example, the U.S. spent ≈50 \$B for fuels alone to make electricity in 1990. If 25 tonnes of ^{3}He will produce the same amount of electricity, then one might conclude that ^{3}He was worth ≈2 \$B/tonne. This assumes that the cost of the facilities to make the electricity from either fuel is the same.

Another estimate could be made by considering the allowable contribution to the cost of electricity, or mills/kWh for the fuel. If we assume that the fusion fuel can contribute ≈10 mills/kWh, then the ^{3}He is worth ≈1 \$B/tonne. Note that coal contributes ≈18 mills/kWh in the U.S. and the fission fuel cycle contributes ≈10 mills/kWh.

One might also compare the energy in ^{3}He to oil. At 1 \$B/tonne for ^{3}He, this would make ^{3}He equivalent to oil at 7 \$/barrel or coal at 15 \$/tonne. Both of these values are far below the current cost of oil (20 \$/barrel) and coal (20 \$/tonne) indicating that ^{3}He is worth more than 1 billion dollars/tonne.

A recent NASA sponsored study[22] showed that even at 1 billion dollars/tonne, the rate of return on investment for the research, development, collection, and delivery of ^{3}He is >20% even without use of the valuable by-products. Work by Ott[23] shows that government investment in this technology would justify the 15 to 20% rate of return.

The conclusion is that the value of ^{3}He is at least 1 billion dollars/tonne on the earth and that such a value should be sufficient to stimulate investment if 10's of tonnes were to be needed per year.

8. Other Considerations

The legal regimes for mining ^{3}He have been investigated by Bilder et al.[24] and the conclusion of that study was that the present international treaty structure is sufficient to insure that ^{3}He could be commercialized. A proposal for an international company called INTERLUNE was made and possible internationalization mechanisms outlined.[25] The problem is not one of politics as much as one of technology.

The question of the net environmental impact to the moon and the earth has been examined by Cameron et al.[22] The conclusion from that study was that the detrimental effects to the moon would be very small and that the beneficial effects to the earth would be large. The main concern on the moon was the potential for spoiling the vacuum around the moon and for changing the reflectance of the area mined. Both problems seem to be easily solved or of little consequence in the long run.

9. Timing

There are two technologies to consider in this case: the commercialization of D^3He fusion reactors, and the establishment of lunar bases for the mining equipment. Figure 7 presents one possible scenario for the simultaneous development of both technologies. The present world fusion program is on the verge of achieving the first breakeven experiments with DT and getting ready for the construction of a 1000 MW reactor called ITER.[26] It is expected that ITER will operate shortly after the turn of the century. With minor modifications of ITER, it is possible that we could approach the ignition point in D^3He early in its operating sequence.[27] Assuming that a successful reactor grade plasma can be produced in ITER, it could then be shut down, refitted with power reactor components, and restarted as a demonstration power plant by 2010. Meanwhile, the design of a commercial power plant could be conducted so that as soon as successful operation of the demo plant was achieved, construction could begin on the commercial unit. In this case, one might have commercial electricity by the year 2015. All of this development could be accomplished with the ^3He presently on the earth.

The timetable for the return to the moon is probably a bit more certain than the fusion schedule. After robotic missions in the 1990's, it is anticipated that humans will again be on the moon by the first decade of the 21st century. It will probably take 5 years or so to establish a permanent base and thereafter small, mobile miners can be utilized to demonstrate the volatile collection process. By the year 2015, 100 kg quantities of ^3He could be returned to the earth and industrial sized miners could be in place to increase the output to the tonne/y level. The generation of valuable by-products could be used to finance the operation.

Fig. 7. The schedules for the commercialization of fusion and the return to the moon are compatible with the use of lunar ^{3}He.

10. Conclusion

For the first time in human history, we have found a portable energy source in space that could satisfy the energy needs of the earth for 100's of years to come. It could do this while greatly improving our environment and in a manner which is both safe and efficient. The problem that lies before use is to, on the one hand, demonstrate that a D^{3}He plasma can be produced and controlled in an economical manner, while at the same time, demonstrate that ^{3}He can be obtained in a dependable, and economical fashion. This will require the efforts of both the energy and space communities in parallel. The successful use of lunar resources may open a whole new era of international collaboration and could replace the intense military competition which has prevailed for the past 4 decades.

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