Impact of Lunar Volatiles Produced During ^{3}He Mining Activities

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January 1996

UWFDM-1001

Presented at the 34th AIAA Aerospace Sciences Meeting and Exhibit, Reno, NV, 15–18 January 1996

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Abstract

It has been known for some time that the rare isotope ^{3}He, found on the surface of the Moon, will be a valuable fusion fuel in the 21st century. However, the by-products from the lunar mining process, H_2, H_2O, ^{4}He, N_2, CO, CO_2, and CH_4, have only received cursory study to the present time. It is found in this study that the volatile by-products may even be more valuable to space travelers than the ^{3}He used in safe, clean, and economical reactors on the Earth. The fact that over 18,000 tonnes of volatiles will be evolved for every tonne of ^{3}He extracted on the Moon, and that these volatiles can be used for everything from producing power in fuel cells to life support, and rocket fuel, suggests that the development of a ^{3}He economy may be the key to establishing a permanent human presence in Space as well as a stable economy on the Earth.

Introduction

The discovery of the ^{3}He isotope on the Moon by the Apollo astronauts[1] in 1969 and the subsequent connection of that resource to the thermonuclear fusion program in 1986 by scientists at the University of Wisconsin[2] has had a profound impact on our perception of future energy reserves for the Earth.[3,4] It is now possible to anticipate the production of safe, clean, and economical electrical energy from ^{3}He fusion in the 21st century. Furthermore the ^{3}He resources on the Moon are sufficient to provide for Earth's energy demand for the next 1,000 years.[1,3,4]

It was also pointed out, in 1988,[5] that in the process of mining the valuable isotope ^{3}He, large quantities of volatiles (H_2, ^{4}He, H_2O, CH_4, CO, CO_2, and N_2) would be evolved which may be of considerable value to future generations in their exploration of Space. It is the purpose of this paper to expand on a few of the potential uses for those by-product lunar volatiles and to show that they have an economic value that might rival the use of ^{3}He in fusion reactors.

Terrestrial Need for ^{3}He

In order to estimate the magnitude of by-product lunar volatiles that might be available as a function of time, one must know the scale and time constraints placed on the demand for ^{3}He. To first order, the major requirements for the ^{3}He fuel will come from electrical power plants on Earth. Previous analyses have shown that with a vigorous (but not a crash) program, the first fusion reactors capable of efficiently burning the D-^{3}He fuel might be available by the year 2015.[6] Assuming that the penetration of fusion reactors into the future world electrical energy market is roughly the same as the previous penetration rate of fission reactors (i.e., ≈20% of the world electrical generating market captured in 25 years), one can estimate the demand for ^{3}He. In other words, the cumulative magnitude of ^{3}He required up through the middle of the next century depends on how large the world demand for electricity will be between now and the year 2050 and what fraction of that electricity will be generated by ^{3}He fusion.

Historical worldwide electrical production rates from all sources including fission reactors (1973 through 1994) are shown in Figure 1.[10] The projected demand for electricity from the present to 2010 is also included using data from the U.S. Department of Energy.[11] To complete the projection to 2050, a 1.5% growth rate in electricity demand is assumed, which is less than the average growth rate over the past 15 years.

In order to predict the amount of future electricity that may be produced by fusion, it is assumed that the rate of introduction of fusion electrical generating capacity will be equal to the historical penetration of fission technology into the electrical generation market (see Figure 2). The projected amount of fusion generated electricity up to the year 2050 (assuming a 2015 introduction date for commercial fusion reactors) is shown in Figure 3. Using the fact that 1 tonne of ^{3}He, burned with D, will produce ≈10 GWe-y,[5] the annual demand for ^{3}He is also plotted in Figure 3.

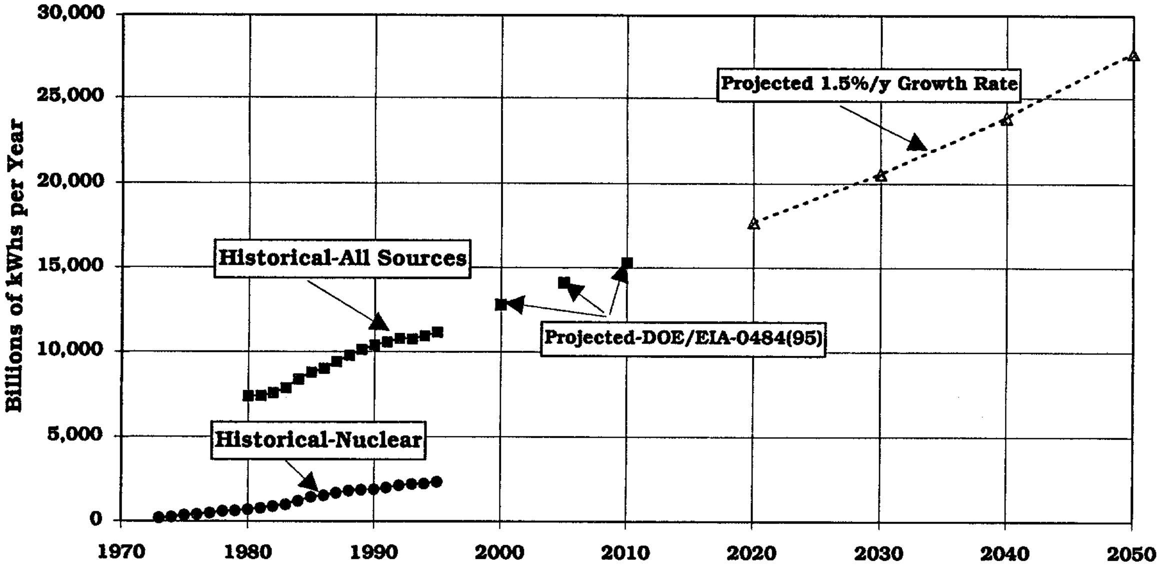


Figure 1. The total amount of electricity generated worldwide in 2050 will more than double the amount generated today.

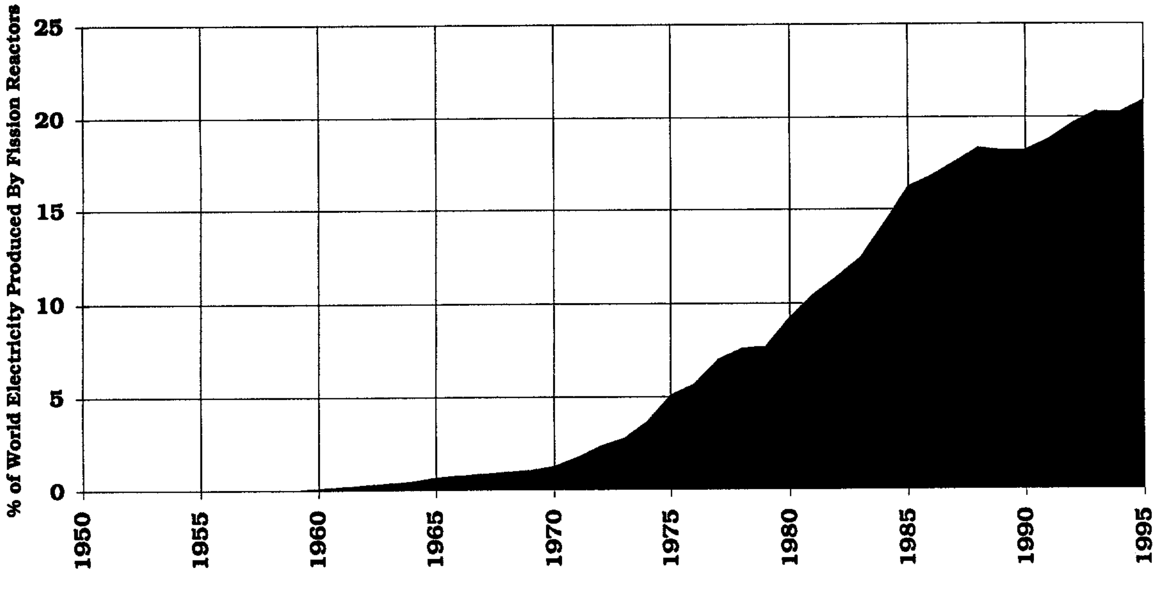


Figure 2. An increasing fraction of the world's electricity is being produced by fission power.

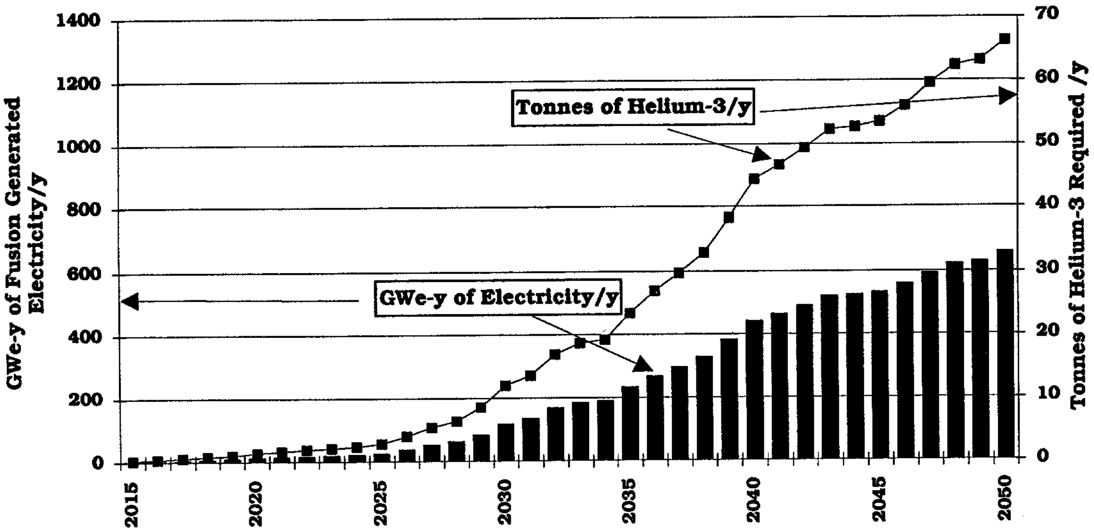


Figure 3. The annual amount of fusion generated electricity could reach ≈650 GWe-y by 2050.

Figure 4. The MARK-II Helium-3 miner.[14]

The end result of all these calculations is that the annual amount of ^{3}He required from the Moon starts from 0 in 2014, to 10 tonnes in 2029, 20 tonnes in 2034, and nearly 70 tonnes in 2050. This amount of ^{3}He will supply D-^{3}He plants producing nearly 700 GWe-y of electricity by the middle of the 21st century.

Collection of Lunar Volatiles

Several studies in the past have shown that ^{3}He (and other volatiles associated with it) can be extracted from lunar regolith by thermal desorption.[12,13] Equipment has been specially designed for this task and one such unit is described here.[14,15]

The University of Wisconsin lunar volatiles miner utilizes earthbound processes for excavating and moving the lunar regolith, but the analogy ends there. It was clear from the very beginning, that a volatiles miner had to perform many functions which are not typically found on earthbound mining machines. Furthermore, it had to be compact and relatively light, since it had to be transported to the surface of the Moon from Earth.

With these considerations in mind, the miner[14] has been designed to be a self-contained machine. It excavates the regolith, separates out the large aggregates, beneficiates out the fine particles, and heats the fine grained material up to 700°C to evolve the lunar volatiles. It then cools the regolith down to recover the energy, and finally deposits it back on the lunar surface. The evolved volatiles are compressed into cylinders and later separated at a central processing station on the Moon. The ^{3}He, in the form of liquefied gas, is then shipped to the Earth for use as a fuel in advanced fusion reactors.

Figure 4 is an artist's conception of the lunar miner designed for the tasks described above[14,15]. Excavation takes place by means of a bucket wheel excavator which executes a 120° arc ahead of the miner, opening up a trench 11 meters wide and 3 meters deep. The regolith is transported into the miner by a conveyer after which it passes through several sieves, collecting only particles larger than 200 microns. The regolith is further separated by a fluidized bed[15] such that only sub-fifty micron particles proceed to the heater. The process energy is supplied by means of a fixed 110 m diameter solar dish located on the lunar "hill" which tracks the miner and, at the same time, beams the solar energy to it. A 10 m diameter dish mounted on the miner receives the energy and concentrates it into the miner where it boils sodium in heat pipes to heat the regolith. An extremely efficient heater made entirely of heat pipes with no moving parts then heats the regolith to 700°C and a recuperator cools it back to 100°C, thus allowing 85% of the energy to be recycled. After extracting the volatiles, the miner sprays the regolith back on the lunar surface, filling the trench behind it as it moves. In the reference design, photovoltaic cells occupying a small fraction of the solar dish on the miner provide the electric power of ~200 kWe for operating the miner. This electrical power could also be provided by fuel cells as discussed later.

The miner uses 12.3 MW of process heat and can collect 33 kg per year of ^{3}He while operating during lunar days. Lunar nights are used for repair and maintenance of the miner. Table 1 gives a selected set of miner parameters.

Table 1

Selected Mark II Lunar Miner Parameters[14,15]

Annual collection rate of ^{3}He (kg)	33
Mining hours per year	3942
Excavating rate (tonnes/hr)	1258
Excavating volume (m^3/hr)	759
Depth of excavation (m)	3
Forward speed of miner (m/hr)	23
Net Processing rate (tonnes/hr)	556
Area excavated per year (km^2/y)	1.0
Thermal process energy (MW)	12.3
Heat recovery (%)	85
Estimated operating power (kW_e)	200
Total Earth mass miner (tonnes)	18

By-Products of ^{3}He Mining

It has been shown that many other volatile compounds can be evolved from the lunar regolith during the 700°C desorption process.[13,16] A summary of the data reported by Li and Wittenberg[16] is given in Table 2.

The first realization that over 18 tonnes of useful compounds would be produced for every kg of ^{3}He mined opened up a large number of options previously not available to the Space

Table 2

Gaseous By-Products of Heating Lunar Ilmenite to 700°C[13,16]

Isotope, Molecule, or Compound	kg of Volatile Component per kg of ^3He
H_2	6,100
^4He	3,100
H_2O	3,300
N_2	500
CH_4	1,600
CO	1,900
CO_2	1,700

program. Consider, for a moment, that in the year 2030, as much as 10 tonnes of ^3He might be needed to power ≈100 fusion power plants on the Earth (Figure 3). This would mean that the annual production of water might be ≈33,000 tonnes, enough to fill 4 swimming pools that are the size of a football field (100 meters long, 40 meters wide) to a depth of 2 meters! Similarly, if the 52,000 tonnes of carbon-containing gases produced in that same year were broken down into their constituents, approximately 23,000 t of oxygen, 4,000 t of hydrogen, and 25,000 t of carbon would be available. It is also not very hard to imagine uses for the additional 61,000 t of hydrogen and 31,000 of ^4He gas produced in the same year along with the 5,000 t of nitrogen.

In order to highlight the usefulness of the lunar volatile by-products, two possible applications in space will be examined here and related to the amount of human activity that could be supported in Space from the mining of ^3He for energy applications on the Earth. There are undoubtedly many more applications than the two chosen here, but they alone justify further investigation of this important resource.

Use of Hydrogen and Oxygen in Fuel Cells

One obvious use of the molecular hydrogen produced in the thermal processing of ilmenite is to combine it with oxygen in a fuel cell to make electricity and water. Unfortunately, gaseous oxygen does not exist on the lunar surface. Studies[17] have shown, however, that the mineral ilmenite ($FeTiO_3$), which exists on the lunar surface, can be reduced by excess H_2 when heated to ~1000°C, according to the reaction:

$$H_2 + FeTiO_3 = H_2O + Fe + TiO_2 .$$

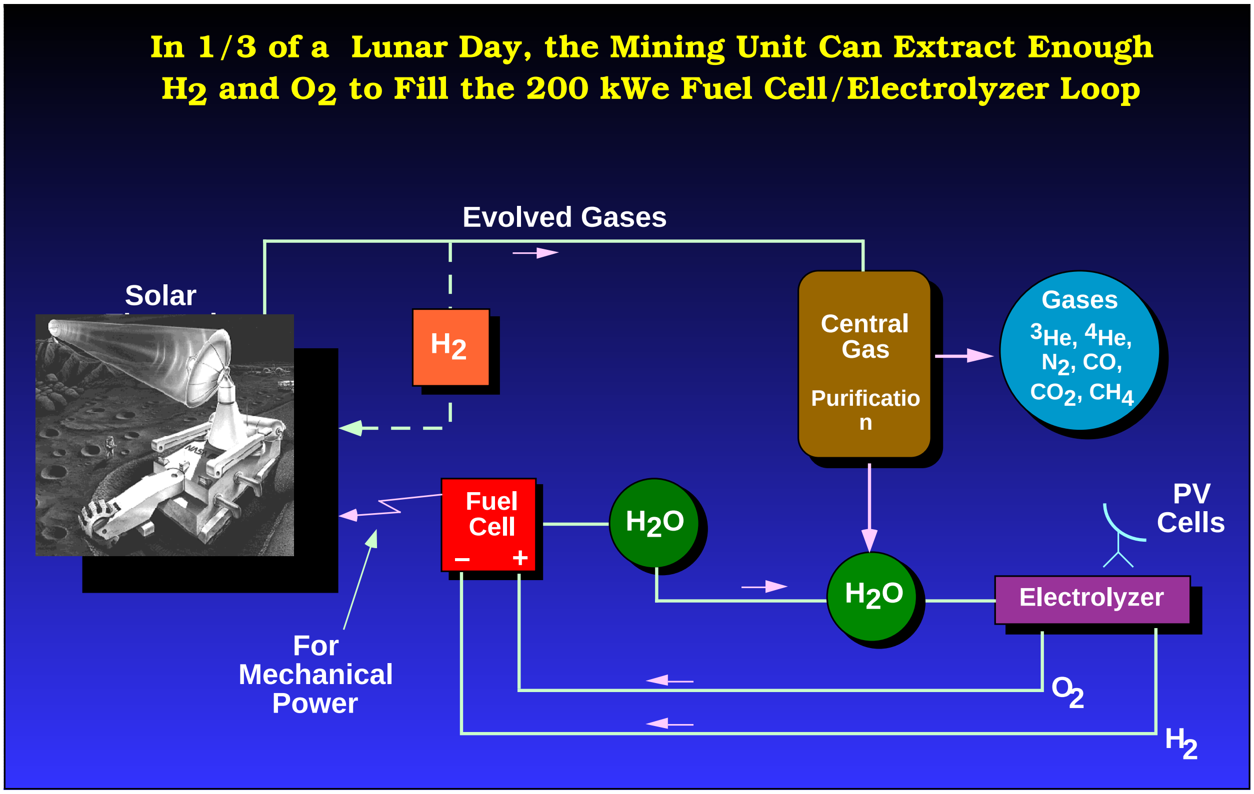
The amount of oxygen produced is ≈25% of the weight fraction of TiO_2 in the regolith. Remote sensing studies suggest that some lunar maria soils consist of ~10.5 wt% TiO_2; hence, these soils could yield ~3 wt% O_2.

Initially, electrical power from a bank of stationary solar photovoltaic cells would be used to electrolyze this water. Later, fusion reactors utilizing ^3He could provide the electricity to separate the water into its constituents. The H_2 and O_2 which is produced would be utilized in fuel cells for electrical power production. This electrical power could be used, for instance, to supply the 200 kW_e of mechanical drive power for the lunar mobile miner (see Figure 5a).

The miner processes regolith at the rate of 154 kg/s and produces H_2 gas with a yield of ~50 g/metric ton of regolith; hence the H_2 production rate is 17.4 g/s (8.72 moles/s). The presently configured miner could produce only a small amount of hydrogen from the H_2O, only 5 mole% of the total H_2 evolved. In order to increase the extraction of oxygen in the form of H_2O from the ilmenite-bearing regolith, excess H_2 at a pressure of 1 atm must be maintained in the heater unit, requiring recycling of the H_2 and some modifications to this unit (see Figure 5a).

An estimate of the oxygen yield expected can be made based upon the kinetic studies by Gibson,[18] using hydrogen reduction of an actual sample of lunar regolith. With a mean particle size of 240 µm, the reaction was essentially complete within 5 min at 1000°C. These conditions are different than those in the proposed miner heating unit in which all particles are <100 µm, with a mean size of ~30 µm, a temperature of 700°C and the residence time of only 20 s. When the experimental data are extrapolated to the conditions in the heater unit of the miner, the fractional oxygen release in the miner is predicted to be 4.3×10^{-4} of the mass of the regolith. The oxygen production rate expected, based upon the predicted oxygen release and flow rate of regolith to the heating unit, is 2.07 moles O_2/s, nearly half of the stoichiometric amount of hydrogen production needed for the formation of H_2O.

Figure 5a



In 1/3 of a Lunar Day, the Mining Unit Can Extract Enough H_2 and O_2 to Fill the 200 kWe Fuel Cell/Electrolyzer Loop

Evolved Gases

Solar

H_2

Central Gas

Purification

Gases

^3He, ^4He, N_2, CO, CO_2, CH_4

PV Cells

Fuel Cell

– +

H_2O

H_2O

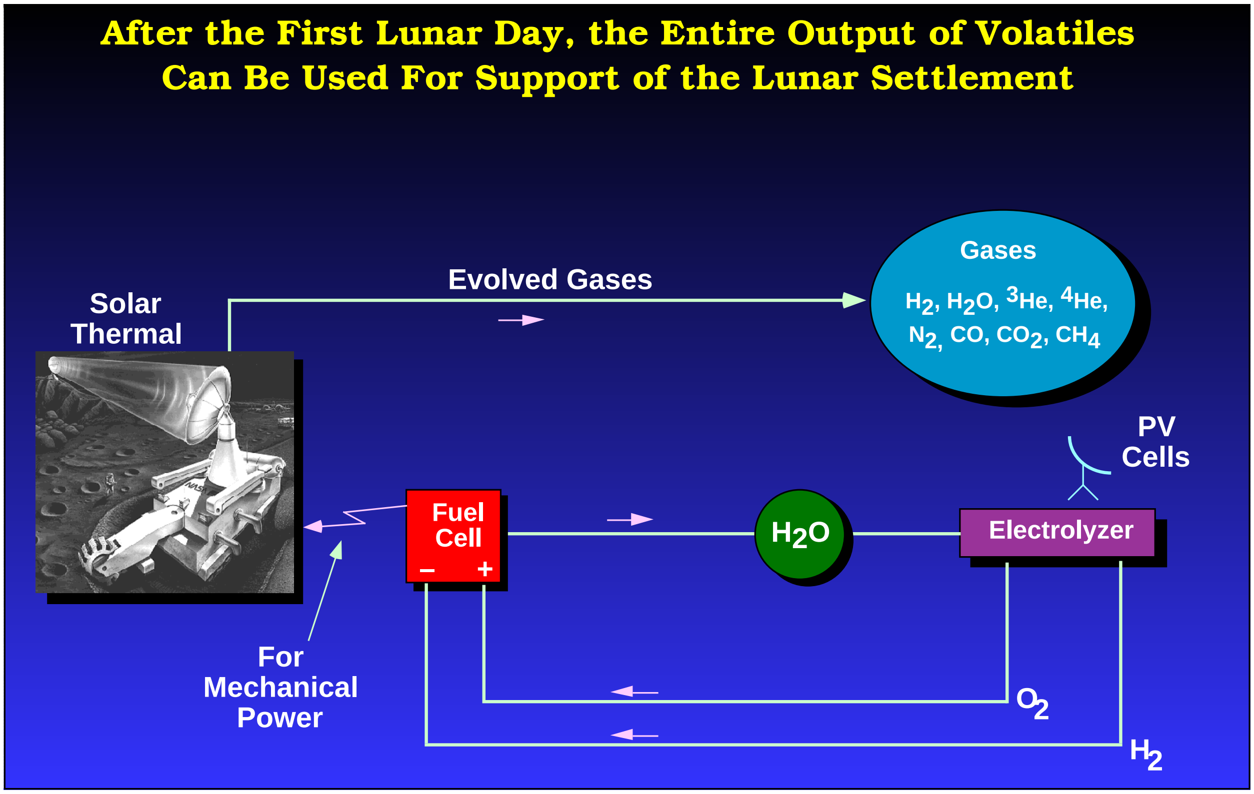
Electrolyzer

For Mechanical Power

O_2

H_2

Figure 5b



After the First Lunar Day, the Entire Output of Volatiles Can Be Used For Support of the Lunar Settlement

Evolved Gases

Solar Thermal

Gases

H_2, H_2O, ^3He, ^4He, N_2, CO, CO_2, CH_4

PV Cells

Fuel Cell

– +

H_2O

Electrolyzer

For Mechanical Power

O_2

H_2

The H_2O produced would accumulate with the other gases evolved during the heating of the regolith, which are stored in cylinders and transported to a central gas handling facility. The liquid water would be separated from the gases and electrolyzed to form H_2 and O_2 utilizing photovoltaic solar arrays during the long lunar day. The H_2 and O_2 gases would be returned to the miner to supply electrical power, via a fuel cell, to power equipment on the miner. If the 2 moles of O_2/s are reacted with 4 moles of H_2/s, the resultant power produced is 750 kW_e (750 kA @ 1 V). This is much more than the 200 kW_e needed for the mechanical operation of the miner, but only 6% as much as required for the heater unit. Because the thermal power requirement to the heater unit is so large, the fuel cell generated electrical power would be utilized only to provide mechanical power to the miner. This result means that the miner would operate only during the lunar day. Any excess H_2 and O_2 would be stored until needed for make-up. For instance, the electrical power obtained when these stored gases are utilized in a fuel cell, could be used to provide off-duty locomotion to the miner or power resistance heaters located at critical points on the miner in order to keep them warm during the long, cold nights. Alternatively, these gases could supply fuel cells on other service equipment or provide heat and lighting in habitats.

The initiation of this concept requires that some H_2 and O_2 be supplied initially to operate the miner, while additional H_2O is formed during the heating of the soil. This newly formed H_2O would be combined with that formed in the fuel cell and electrolyzed (known as the regenerative fuel cell concept); see Figure 5. Repeating the cycle increases the inventory of water and potentially the energy reserve, up to the limit of the electrolyzer. It can be shown that if each miner carries ≈23 tonnes of O_2 and H_2, enough to provide 200 kW_e for one lunar day (14 Earth days), and if an equivalent amount of H_2O is being electrolyzed during the lunar day, then a single miner will have to operate at least 7.5 earth days to provide the 23 tonnes of water (actually oxygen and hydrogen) needed to power the miner. Allowing for leakage and inefficiencies, it is reasonable to think that the first full lunar day (14 Earth days) could be devoted to making the water needed for the fuel cells, electrolyzer, and the "pipeline" between the miner and the electrolyzer base. After that time, the entire output of the miner could be used for life support or other lunar/space based activities (see Figure 5b).

Life Support

Until recently, the number of astronauts that could be permanently supported on the Moon could be counted on two hands. The main problem is the supply of food, water, and breathable air. The availability of lunar volatile by-products would drastically change that limitation. Let us consider what effect the ^{3}He mining would have on just 4 elements or compounds vital to life support:

1. Nitrogen
2. Oxygen
3. Carbon dioxide
4. Water.

Nitrogen

The nitrogen derived from the lunar volatiles can be converted, by appropriate bacteria, to ammonia and then incorporated into proteins and other food materials. It can also serve as a gas to maintain atmospheric pressures in the living and working areas of a lunar base and for the plant growing facilities. The requirements for initially pressurizing the habitats are not large, but the leakage from lunar structures due to egress and ingress activities might be substantial. The amount of nitrogen required to maintain atmospheric pressure represents over 99% of the annual nitrogen replacement because only a small amount would be lost in food production, food processing, and waste recycling even if a 10% annual loss (<0.03% per day) is assumed.

If each astronaut is allotted 100 m^3 of living, working, and bioregenerative life support space at 100 kPa (≈1 atm), then a 1% leakage per day amounts to an annual per person requirement of 350 kg of N_2 per year.[19] It will be shown later that this is much more than might be lost through the food cycle.

Oxygen

The main losses of oxygen are associated with atmospheric leakage and the loss in the food production, food processing, and waste recycling operations. If the partial pressure of oxygen in the habitat atmosphere is maintained at a level equivalent to the Earth's atmosphere (20 kPa) and

Table 3

The By-Products from Lunar ^{3}He Mining Could Play a Crucial Role in the Permanent Settlement of the Moon

	Nitrogen	Oxygen	Water	Carbon Dioxide
Annual requirement - tonne per person	0.350	0.150	0.142	0.077
Tonnes of volatile per tonne ^{3}He	500	48,800[a]	3,300	1,700
Number of people supported/y per tonne ^{3}He	1429	325,000	23,239	22,078
Tonnes of volatile produced in 2030 (12 tonne ^{3}He)	6,000	586,000	39,600	20,400
Number of inhabitants supported/y in 2030	17,140	3,900,000	278,870	265,000
a = maximum amount of oxygen produced by reacting 6,100 tonnes of H_2 with ilmenite.				

the loss rates are the same as assumed for nitrogen, then the annual oxygen replacement would be 95 kg per person per year.

The amount of oxygen lost in other aspects of the life support system can best be estimated from the amount of oxygen given off by plants. It is estimated that 20 m^2 area of plants would provide the daily caloric requirement of one person.[20] A plant area of this size would give off approximately 1,500 g of oxygen per day. If a 10% loss of this oxygen is assumed in the food production, food processing, and waste recycling operations, then 150 g of oxygen per person per day would need to be replaced. This amounts to an annual requirement of 55 kg per person. The total oxygen requirement is then 150 kg per person per year.

Carbon Dioxide

The analysis of annual CO_2 requirements is based on a 10% loss in the food production, food processing, and waste recycling operations because the CO_2 loss associated with atmospheric leakage is negligible. A 20 m^2 plant area produces approximately 2,100 g of CO_2 per day.[20] If there is a 10% loss of carbon dioxide in the food production, processing, and waste recycling operations, then 210 g per person per day would be required. This amounts to an annual requirement of 77 kg per person.

Water

The water requirements are based on estimates that a person needs approximately 3,900 g of potable water per day.[19] This does not represent the total water requirement, but rather only the amount of potable water for drinking, food preparation, and in unprepared food. If 10% of this water is lost during the recycling process, 390 g of water per person per day would need to be replaced. Thus an annual water requirement of 142 kg per person may be reasonable.

Perspective

A summary of the life support volatiles requirements is given in Table 3 along with the number of people that can be supported per tonne of ^{3}He mined and the amount that could be supported in the year 2030. It is interesting to note that in terms of lunar settlements, the number of inhabitants that can be supported annually from the by-products of ^{3}He mining in the first few years (≈1 tonne ^{3}He/y) ranges from over 1,000 (N_2 needs) to over 20,000 (water and CO_2 needs) and finally to >300,000 (O_2 requirements). Of course not all the water, N_2, CO_2, etc. would go exclusively to just life support, some would be used in the industrial and manufacturing sectors of a true lunar settlement. It is also possible that some of the excess would be sold to crews on their way to Mars, the outer Solar System, or even farther. This would make the Moon analogous to the "Hudson Bay" store of the inner Solar System.

It is also interesting to note that the cost to transport the large amounts of H_2, H_2O, N_2, CO_2, etc. to the surface of the Moon would be enormous even if the cost to land a kg of payload on the moon were to fall from its present value of >40,000 \$/kg to 1,000 \$/kg. For example, consider the situation encountered within 5 years of the first mining operations when 1 tonne of ^{3}He is produced. This will evolve over 18,000 tonnes of useful volatiles (or ≈50,000 tonnes when reacting the H_2 with ilmenite). At 1,000 \$/kg, this would require 18-50 billion \$ in transportation costs alone, a factor of 6-17 times the 3 billion \$/tonne obtained for the ^{3}He itself.

Conclusions

It has been shown that the volatile by-products from ^{3}He mining operations will be extremely valuable to the future inhabitants of the Moon. There are 18,000 tonnes of useful volatiles emitted per tonne of ^{3}He mined. These volatiles can be used for producing power in portable fuel cells, providing life support for humans through the production of suitable atmospheres, and the growing of food. Within a decade from the start of the first mining operations, it appears possible to support the annual nitrogen needs of 10,000 people or more, the water and CO_2 needs of a quarter of a million inhabitants, and the oxygen needs of over a million people. It is possible that the economic value of the lunar volatiles, evolved during the mining of ^{3}He for use in terrestrial fusion plants, will exceed that of the already valuable fusion fuel. Thus, a ^{3}He economy will not only benefit society on the Earth, but it may also be the key to establishing a permanent presence in Space with numbers of inhabitants only dreamed about to this point in time.

Acknowledgments

The authors would like to acknowledge stimulating discussions with Professors H. H. Schmitt and E. N. Cameron of the University of Wisconsin. Financial support for this work came from the David Grainger Foundation.

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