POTENTIAL OF DERIVED LUNAR VOLATILES FOR LIFE SUPPORT

R. J. Bula, L. J. Wittenberg, T. W. Tibbitts, and G. L. Kulcinski

University of Wisconsin
Madison WI 53706

The lunar regolith contains small quantities of solar wind implanted volatile compounds that have vital, basic uses for maintaining life support systems of lunar or space settlements. Recent proposals to utilize the helium-3 isotope (He-3) derived from the lunar regolith as a fuel for fusion reactors would result in the availability of large quantities of other lunar volatile compounds. The quantities obtained would provide the annual life support replacement requirements of 1150 to 23,000 inhabitants per tonne of He-3 recovered, depending on the volatile compound. Utilization of the lunar volatile compounds for life support depends on the costs, in terms of materials and energy, associated with their extraction from the lunar regolith as compared to the delivery costs of these compounds from Earth resources. Considering today's conservative estimated transportation costs ($10,000 per kilogram) and regolith mining costs ($5 per tonne), the life support replacement requirements could be more economically supplied by recovering the lunar volatile compounds than transporting these materials from Earth resources, even before He-3 will be utilized as a fusion fuel. In addition, availability of lunar volatile compounds could have a significant cost impact on maintaining the life support systems of the space station and a Mars base.

INTRODUCTION

Efforts toward settlements on the Moon and Mars will require major technological developments in the area of life support. Two recent reports concerning future U.S. space efforts (*Paine et al.,* 1986; *Ride,* 1987) point out that the key to living and working in space is the development of reliable life support systems that are not dependent on Earth resources. A bioregenerative life support system that closes the food, water, and air loops has the potential of providing the human requirements for survival in a space environment independent of Earth resources.

The lunar regolith contains small quantities of volatile compounds implanted from the solar winds. These volatile compounds have vital, basic uses for establishing life support systems of lunar or space bases by providing (1) raw materials for food production and food processing and (2) an atmosphere in the space base structures (Fig. 1). The available carbon, as carbon dioxide, hydrogen, nitrogen, and water of the lunar volatile compounds can be combined with small amounts of other materials derived from the lunar regolith to produce food through photosynthesis and autotrophic hydrogen and nitrogen bacteria.

The cost effectiveness for using these lunar volatile compounds in a life support system has been greatly enhanced by the recent proposal to use the helium-3 isotope (He-3) derived from the lunar regolith as a fuel for fusion reactors (*Wittenberg et al.,* 1986). *Li and Wittenberg* (1991) have developed a model of He-3 mining using a relatively low heating temperature of 700°C and have calculated the amounts of volatiles that would be produced from the regolith at that temperature (Table 1). Thus, large quantitites of other lunar volatile compounds would be evolved during procurement of the He-3 (Fig. 2). The number of inhabitants supported for a year by the nitrogen, water, and carbon dioxide derived with each tonne of He-3 mined is shown in Fig. 3.

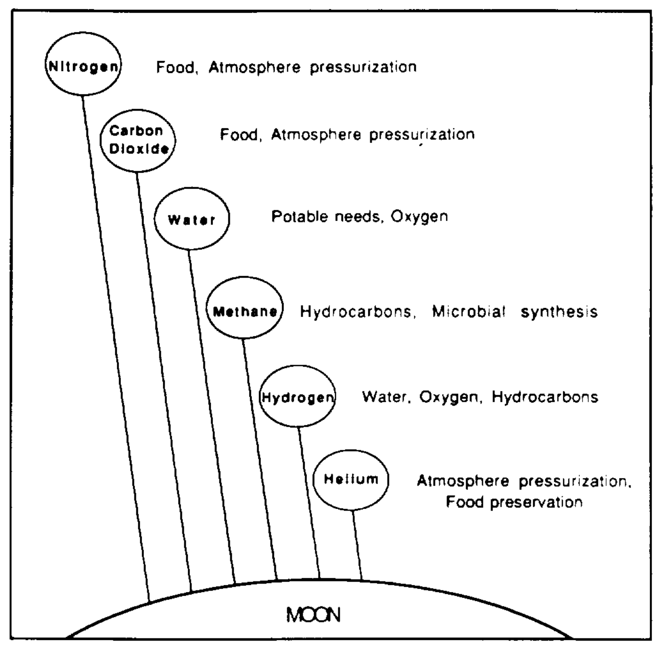

Fig. 1. Potential applications of solar wind deposited lunar volatile compounds for life support.

NITROGEN REQUIREMENT

The nitrogen derived from the lunar volatile compounds can be converted by appropriate bacteria to ammonia and then incorporated into proteins and other food materials. In addition, nitrogen will serve a very necessary role by providing the principal gas required for maintaining atmospheric pressures in the living and working areas of the lunar base and for the plant growing

TABLE 1. Estimated amounts of lunar volatile compounds released from lunar regolith heated to 700°C, volatile compound replacement requirements, and amount of regolith processing required to provide the requirements.

		Per Inhabitant	
Volatile Compound	Amount Evolved* from Regolith (g per tonne)	Volatile Requirements (g per day)	Required Regolith Processing (tonnes per day)
Nitrogen	4.0	960	240
Carbon dioxide	12.0	210	18
Water	23.0	390	17
Oxygen†	–	410	–
Methane‡	11.0	–	–
Hydrogen§	43.0	–	–
Helium¶	22.0	–	–

*From *Li and Wittenberg* (1991).
†Will be derived from electrolysis of water derived with the lunar volatiles or from reduction of lunar ilmenite.
‡Can be used as substrate for microbial synthesis of more complex carbon-containing compounds.
§Can be used to reduce ilmenite to produce water or oxygen.
¶No life support need exists, but may be used to replace a portion of the nitrogen required to maintain atmospheric pressure.

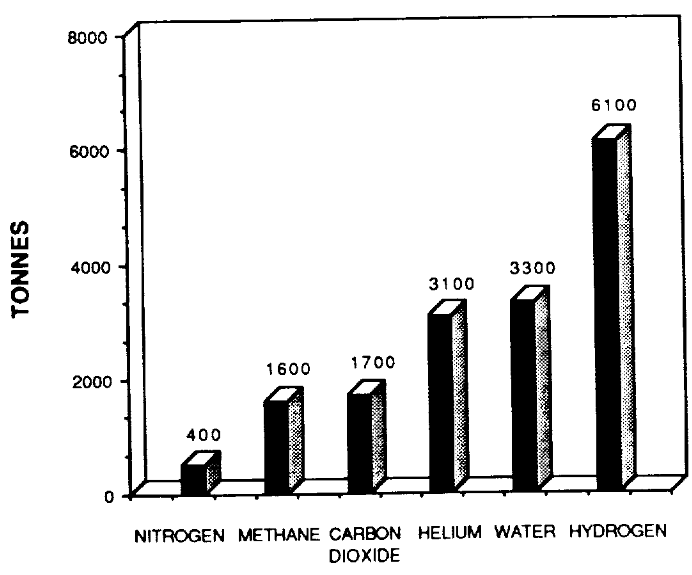

Fig. 2. Tonnes of lunar volatile compounds per tonne of He-3 recovered from the lunar regolith.

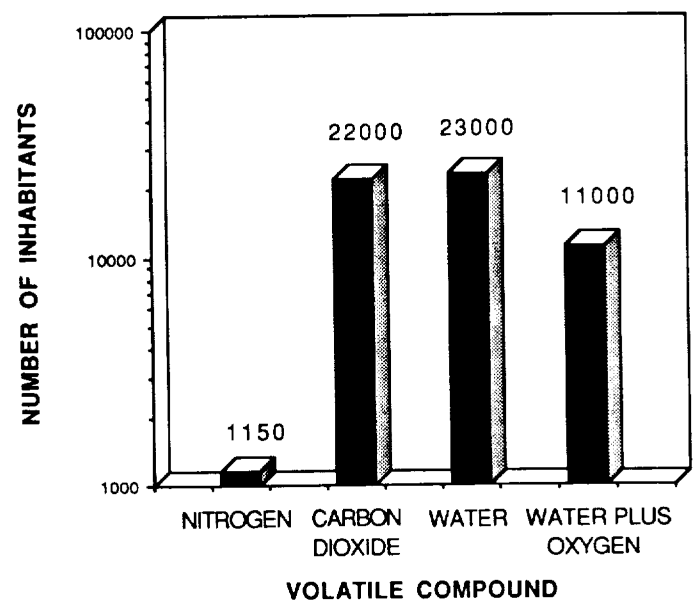

Fig. 3. Number of inhabitants supported for a year by the nitrogen, carbon dioxide, and water derived with each tonne of He-3 mined.

facilities. The requirements for initially pressurizing the space base volumes are not large, but the requirements for atmospheric pressure maintenance of these volumes would be substantial because of atmospheric leakage from the lunar structures and ingress and egress activities. The amount of nitrogen required to maintain atmospheric pressure represents over 99% of the annual nitrogen replacement requirement because only a small amount would be lost in the food production, food processing, and waste recycling operations of the life support system, even if a 10% annual loss is assumed.

The annual replacement requirement of nitrogen is based on providing a volume of 100 m^3 of living and working space per person and the volume associated with a bioregenerative life support system. If a 1.0% per day leakage rate is assumed for this volume, and an atmospheric pressure of 101 kPa is maintained, the annual per person replacement requirement of nitrogen would be 350 kg (0.96 kg per day × 365 days).

It is estimated that 400 tonnes of nitrogen will be recovered with each tonne of He-3 recovered from the regolith. This amount of nitrogen would provide the annual nitrogen replacement requirement of 1150 people. The quantities of helium recovered from the lunar regolith could be used as a partial substitution for the nitrogen in the atmosphere. This would extend the supply of nitrogen in proportion to the percentage of helium substitution possible. Research is needed to determine what percentage of nitrogen in the atmosphere can be replaced with helium.

OXYGEN REQUIREMENT

Oxygen is a critically important requirement of a life support system. Gaseous oxygen has not been found among the lunar volatile compounds; however, heating the lunar regolith to 700°C, as proposed for the extraction of He-3, does result in a portion of the hydrogen reducing the iron-oxide-bearing regolith materials to form water. The oxygen required for life support could be derived by electrolysis of the water obtained in this manner. An alternative method of obtaining the needed oxygen is by hydrogen reduction of lunar-surface ilmenite and electrolysis of the water as proposed by *Gibson and Knudsen* (1985). The primary use of oxygen produced by this or similar methods would be as a propellant. Thus, the amount involved for life support purposes would be relatively inconsequential by comparison.

Replacement requirements of oxygen are associated with atmospheric leakage and loss in the food production, food processing, and waste recycling operations. If the partial pressure of oxygen in the atmosphere is maintained at a level equivalent to the Earth's atmosphere (20.2 kPa) for the volumes described for the nitrogen requirements, the annual oxygen replacement would be 95 kg per person per year (0.26 kg per day × 365 days).

The amount of oxygen lost in the other aspects of the life support system can be estimated from data quantifying the amount of oxygen given off by plants. It is estimated that a 20-m^2 area of plants would provide the daily caloric requirements of one person (*Wheeler and Tibbitts,* 1987). A plant area of this size would give off approximately 1500 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 replacement requirement of 55 kg per person (0.15 kg per day × 365 days). Thus, considering the losses associated with atmospheric leakage and with the food and waste recycling processes, the total oxygen replacement requirement per person per year would amount to 150 kg.

CARBON DIOXIDE REQUIREMENT

Analysis of the annual carbon dioxide requirement is based on a 10% loss in the food production, food processing, and waste recycling operations because the carbon dioxide loss associated with atmospheric leakage is negligible. A 20-m^2 plant area produces approximately 2100 g of carbon dioxide per day (*Wheeler and Tibbitts,* 1987). If a 10% loss of carbon dioxide in the food production, food processing, and waste recycling operations is assumed, then 210 g per person per day would need to be replaced. This would amount to an annual carbon dioxide replacement requirement of 77 kg per person (0.21 kg per day × 365 days). It is estimated that approximately 1700 tonnes of carbon dioxide will be recovered with each tonne of He-3, thereby providing the annual estimated carbon dioxide replacement requirement of 22,000 people.

WATER REQUIREMENT

Water replacement requirements are based on estimates that a person requires approximately 3900 g of potable water per day (*NASA,* 1985). 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 amount is lost during the recycling process, then 390 g of water per person per day would need to be replaced. This indicates an annual water requirement of 142 kg per person (0.39 kg per day × 365 days).

The total annual replacement amount of water can be calculated to include the loss associated with providing the potable water and the oxygen. It is estimated that approximately 3300 tonnes of water will be recovered with each tonne of He-3 recovered. If only the replacement requirement associated with the drinking water loss is considered, the 3300 tonnes of water would provide the annual estimated water replacement requirement of 23,000 people. If the water is used to provide the replacement for both the water and oxygen loss, the 3300 tonnes of water would provide the annual replacement requirement of approximately 11,000 people.

COSTS OF LUNAR-DERIVED VOLATILE COMPOUNDS COMPARED WITH DELIVERY COSTS OF RESUPPLIES FROM EARTH RESOURCES

Utilization of the lunar volatile compounds for life support will depend on costs, in terms of materials and energy, associated with their extraction from the lunar regolith as compared to the delivery costs of these compounds from Earth resources. The value of He-3 as a fusion fuel is estimated to be at least $1,000,000 per kilogram (*Kulcinski,* 1988). Obviously, if the lunar volatile compounds used for life support are obtained as a part of the He-3 extraction process, the costs of obtaining the non-He-3 volatile compounds on the Moon would be much less than the delivery costs from Earth resources.

Today's transportation costs of Earth resources to a lunar base are optimistically estimated to be $10,000 per kilogram (*Koelle,* 1991). Considering that the annual total life support material replacement (nitrogen, carbon dioxide, oxygen, and water) is estimated at 719 kg per person, the present-day transportation costs of these life support materials would approximate $7,190,000 per person per year. The number of lunar base inhabitants has been projected to be 30 by 2010 (*Ride,* 1987). Annual transportation costs, on the basis of today's cost estimates, for replacement of life support materials for a lunar base of that size would amount to $215,700,000. It is anticipated that future transportation costs may be reduced by an order of magnitude, or to $1000 per kilogram of payload transported from the Earth to the Moon.

By comparison, the costs of recovering the lunar volatile compounds from the lunar regolith can be estimated on the basis of the amount of regolith that would have to be mined to provide the life support replacement requirements. Large-scale regolith mining costs, such as would be involved in recovering large quantities of He-3, are estimated at $5 per tonne of regolith handled (*Sviatoslavsky and Jacobs,* 1988). Mining the regolith for the sole purpose of life support replacement materials would not be considered as large-scale mining and, therefore, the per tonne mining costs could be higher than $5. Comparisons of the break-even costs of lunar regolith mining compared to transportation costs from Earth to a lunar base are shown in Fig. 4. The relationships shown in Fig. 4 are based on the assumption that 240 tonnes of regolith per inhabitant per day must be mined and processed to supply the nitrogen replacement requirement (Table 1). Mining this amount of regolith will be sufficient to supply the replacement requirements of all the other volatile compounds. At

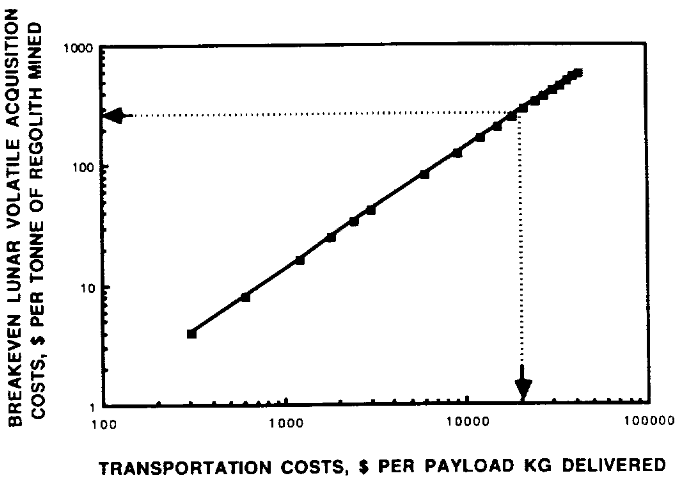

Fig. 4. Comparison of costs for supplying the life support replacement requirements from lunar regolith volatile compounds vs. transportation costs for resupply from Earth resources. The dotted lines correspond to twice the costs estimated by *Koelle* (1991).

transportation costs of $20,000 [twice the current costs estimated by *Koelle* (1991)], it would be more economical to obtain the life support replacement materials from the lunar regolith if mining costs were less than $200 per tonne. Likewise, if mining costs are less than $5 per tonne [as currently estimated by *Sviatoslavsky and Jacobs* (1988)], then transportation costs to the Moon would need to be less than $400 per kilogram to be economically competitive. These cost comparisons do not take into consideration the possibility of using helium for replacing a portion of the nitrogen used for maintaining atmospheric pressure. By using some of the available helium, the mining costs would be reduced because less regolith would need to be mined to obtain the replacement life support materials since considerably more helium than nitrogen is recovered per tonne of regolith (Table 1).

Availability of lunar volatile compounds would provide additional, distinct advantages related to life support for inhabitants of space bases. The quantities of replacement supplies available on the lunar surface would allow some relaxation of the otherwise stringent recycling requirements being projected for a space-based life support system. Some of the waste materials and other carbon-containing volatile compounds, such as methane, could be utilized by plants and microorganisms to produce complex carbon compounds. These complex carbonaceous compounds could serve as raw materials for the synthesis of other products required at a space station, such as plastics. Also, the lunar volatile compounds, or the synthesized products (food), could be exported to other space bases, such as the space station and Mars, more economically than from Earth resources. The value of the lunar volatile compounds in this context is not possible to estimate at this time; however, it is likely to be significant, particularly as the number of inhabitants at space bases increases.

It appears reasonable to conclude that the life support replacement requirements of a lunar base could be more economically supplied by recovering the lunar volatile compounds than transporting these materials from Earth resources even before He-3 will be utilized as a fusion fuel. Therefore, development of technology to recover lunar volatile compounds could be started in the next decade without waiting for the D-He-3 fusion reactors to be built on Earth. The early use of the lunar volatile compound recovery technology could reduce significantly the costs of maintaining the life support systems of the space station and of settlements on the Moon and Mars.

REFERENCES

Gibson M. A. and Knudsen C. W. (1985) Lunar oxygen production from ilmenite. In *Lunar Bases and Space Activities of the 21st Century* (W. W. Mendell, ed.), pp. 543-550. Lunar and Planetary Institute, Houston.

Koelle H. H. (1992) The influence of lunar propellant production on the cost-effectiveness of cislunar transportation systems. In *The Second Conference on Lunar Bases and Space Activities of the 21st Century*, this volume.

Kulcinski G. L. (1988) *Commercial Attractiveness of D-He^3 Fusion Reactors*. UWFDM-755, Univ. of Wisconsin, Madison. 49 pp.

Li Y. T. and Wittenberg L. J. (1992) Lunar surface mining for automated acquisition of helium 3: Methods, processes, and equipment. In *The Second Conference on Lunar Bases and Space Activities of the 21st Century*, this volume.

NASA (1985) *Engineering and Configuration of Space Stations and Platforms*, pp. 468-473. Noyes Publications, Park Ridge, NJ.

Paine T. O. et al. (1986) *Pioneering the Space Frontier. The Report of the National Commission on Space*. Bantam, New York.

Ride S. K. (1987) *Leadership and America's Future in Space: A Report to the Administrator*. U.S. Govt. Printing Office, Washington, DC. 63 pp.

Sviatoslavsky I. N. and Jacobs M. (1988) Mobile helium-3 mining system and its benefits toward lunar base self-sufficiency. In *Space Engineering, Construction, and Operation in Space* (S. W. Johnson and J. P. Wetzel, eds.), pp. 310-321. American Society of Civil Engineers, New York.

Wheeler R. M. and Tibbitts T. W. (1987) Utilization of potatoes for life support systems in space. III. Productivity of successive harvest dates under 12-hour and 24-hour photoperiods. *Am. Potato J., 64*, 311-320.

Wittenberg L. J., Santarius J. F., and Kulcinski G. L. (1986) Lunar source of ^{3}He for commercial fusion power. *Fusion Technol., 10*, 167-178.