SCENARIOS FOR OPTIMIZING POTATO PRODUCTIVITY IN A LUNAR CELSS

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The use of controlled ecological life support systems (CELSS) in the development and growth of large-scale bases on the Moon will reduce the expense of supplying life support materials from Earth. Such systems would use plants to produce food and oxygen, remove carbon dioxide, and recycle water and minerals. In a lunar CELSS, several factors are likely to be limiting to plant productivity, including the availability of growing area, electrical power, and lamp/ballast weight for lighting systems. Several management scenarios are outlined in this discussion for the production of potatoes based on their response to irradiance, photoperiod, and carbon dioxide concentration. Management scenarios that use 12-hr photoperiods, high carbon dioxide concentrations, and movable lamp banks to alternately irradiate halves of the growing area appear to be the most efficient in terms of growing area, electrical power, and lamp weights. However, the optimal scenario will be dependent upon the relative "costs" of each factor.

INTRODUCTION

The establishment of bases on the surface of the Moon has been identified as one of the primary initiatives to be pursued by NASA (*Ride,* 1987). Potential economic benefits from mining the lunar surface may provide an additional impetus for establishing these bases (*Kulcinski,* 1988). As lunar outposts increase in size, the high cost of resupply from Earth will make it imperative to reduce the quantity of these resources. Controlled ecological life support systems (CELSS), systems that recycle chemical and biological resources necessary to support human life, will therefore come to play a crucial role in the long-term support of these bases (*Ride,* 1987).

Green plants (primarily various algae and higher plants) will play an integral part in a CELSS because the process of photosynthesis utilizes radiant energy (400-700 nm) to convert carbon dioxide and water into carbohydrates and oxygen. In addition to removing carbon dioxide from the atmosphere and producing food and oxygen, higher plants can purify water through the process of transpiration. The gravitational field of the Moon should be sufficient to allow the production of higher plants using systems that have been adapted from the technologies used for controlled-environment plant growth on Earth (*Bula et al.,* 1987).

Several species of higher plants have been selected for study as possible CELSS candidate crops (*Tibbitts and Alford,* 1982). One of these species is the white, or Irish potato (*Solanum tuberosum L.*). Potato exhibits several characteristics that are of value in a CELSS (*Tibbitts and Wheeler,* 1987), including high rates of productivity and a high ratio of edible to inedible biomass (high harvest index). In addition, they are a good quality food source (rich in carbohydrates with adequate protein levels), are easily stored for long periods, and can be prepared in a number of culinary forms. There is also a good information base available on potato culture, and a substantial amount of work has been done in recent years to investigate potato productivity and physiology under controlled environments. In general, high tuber yields (tubers being the edible underground portion of the potato) are promoted by short photoperiods (i.e., diurnal cycles with short days and long nights), moderate to high irradiance (1/4 to 1/2 full sunlight), cool temperatures (<20°C), and high carbon dioxide levels (e.g., 1000 ppm). Certain environmental requirements, however, can be offset or compensated for by altering other factors. For example, tubers will form without any dark periods (i.e., continuous irradiation) provided irradiance is sufficiently high and temperatures are cool (*Wheeler and Tibbitts,* 1987a; *Wheeler et al.,* 1986). Also, high carbon dioxide concentrations can partially substitute for high irradiance. When all factors are optimal, yields as high as $40\,g\,m^{-2}\,day^{-1}$ of tuber dry matter have been obtained from controlled environments (*Tibbitts et al.,* 1989). This equates to over 200 metric tons (fresh weight) per hectare, or approximately seven times the average field yield in the United States.

In contrast to most traditional agronomic systems, the goal of maximum production per unit area may not be the major concern in a CELSS. Rather, the primary goal will likely be to optimize productivity based on the relative costs of various factors. Thus, it is important to assess various ways in which the growing environment of potatoes might be manipulated to optimize production in relation to the factors that are most likely to be limiting in a lunar CELSS. These include the growing area (or volume) available, electrical power (or possible total energy) availability, and launch weight of the hardware required to support plant growth. The weight of lighting equipment is of particular significance because the cost of transporting lamps for a 30-person CELSS to the lunar surface could run into hundreds of millions of dollars (not including purchase price) at the conservatively estimated launch cost of $10,000 per kilogram (*Koelle*, 1988). Other factors that might be limiting to plant productivity include temperature and humidity control, water and nutrients to support plant growth, inert gases to maintain atmospheric pressure, and reliability and safety considerations.

BASELINE ASSUMPTIONS

To evaluate the tradeoffs between various CELSS environments in terms of growing area, energy efficiency, and initial payload weight, a "baseline" situation needs to be defined. The following assumptions will be made for the purpose of this discussion:

1. ***Potatoes will be the sole biomass producing crop.*** In reality, a true CELSS diet would consist of several different plant species, matched to provide a balanced and interesting diet (*Hoff et al.*, 1982). Eventually, various production scenarios will need to be developed that take into account the integration of the different species used for biomass production in a lunar CELSS.

2. ***Temperature and humidity control, water and nutrients, inert gases, and reliability and safety will be considered nonlimiting.*** More detailed concepts of an actual lunar CELSS are required before the impact of these factors can be evaluated.

3. ***The base will have 30 inhabitants.*** A lunar base with 30 inhabitants has been projected for the year 2010 (*Ride*, 1987). Because the caloric requirement for each inhabitant will be approximately 2800 kcal d^{-1} (*NAS*, 1980), the total needs of all the inhabitants would be on the order of 84,000 kcal d^{-1}. Potatoes provide 3.73 kcal g^{-1} of tuber dry weight (*Watt and Merril*, 1963), so 30 inhabitants would require about 22,5000 g (dry weight) of tubers per day, or about 112 kg (250 lb) of fresh tubers.

4. ***Electrical lamps will be used in a lunar CELSS.*** Although the possibility exists that direct solar radiation can be utilized for plant growth in a lunar CELSS, lamps will still be necessary to provide irradiance during the two-week-long lunar "nights." Currently, one of the most efficient irradiation sources for photosynthetic lighting is the 1000-W high-pressure sodium lamp (*Tibbitts*, 1987). The relationship between lamp input power and the photosynthetically active radiation (PAR) produced can be conservatively estimated at 1 W m^{-2} of lamp input power for each μmol sec^{-1} m^{-2} of PAR produced (The Phytofarm, DeKalb, IL, personal communication, 1987), which is approximately equivalent to a 20% conversion of electricity to PAR. The weight of a 1000-W high pressure sodium lamp (bulb, ballast, and reflector) has been estimated at 20 kg (W. W. Grainger, Inc., 1987 catalog).

5. ***Tuber productivity will follow trends shown in Fig. 1.*** Approximate tuber productivity values in response to various combinations of irradiance, photoperiod, and carbon dioxide level are shown in Fig. 1. These curves are derived from experimental data (*Wheeler and Tibbitts*, 1987a; R. M. Wheeler and T. W. Tibbitts, unpublished data, 1988), though productivity at high and low levels of irradiance are estimations based on related work and past experience.

MANAGEMENT SCENARIOS

Fixed Lamps, Low Carbon Dioxide Concentrations

The first set of scenarios involves a fixed lamp arrangement to provide irradiance at 400 and 800 μmol sec^{-1} m^{-2}, 12-hr and 24-hr photoperiods, and "Earth" ambient (350 ppm) or low carbon dioxide levels (Table 1). Those scenarios that utilize high irradiance levels (scenarios 1 and 2) require the least growing area to provide daily caloric requirements, but scenarios utilizing 12-hr photoperiods (scenarios 2 and 4) are most efficient in terms of energy required. Use of continuous, low-level irradiance (scenario 3) requires the least initial lamp weight. Although scenario 1 is the most efficient on an area basis, it is the least efficient on any energy basis and its lamp weight is high. This would be of use in situations where area is limited, but energy and lamp weight are of minimum concern. Scenarios 2 and 3 are equivalent in terms of area and energy efficiency, but the lamp weight for scenario 3 is half that for scenario 2. Scenario 3 would provide a good compromise if all three potentially limiting factors were of equal concern. Scenario 4 is most efficient in terms of energy and is moderate in terms of weight, but it requires a large growing area. This scenario would be useful if growing area were of minimum concern.

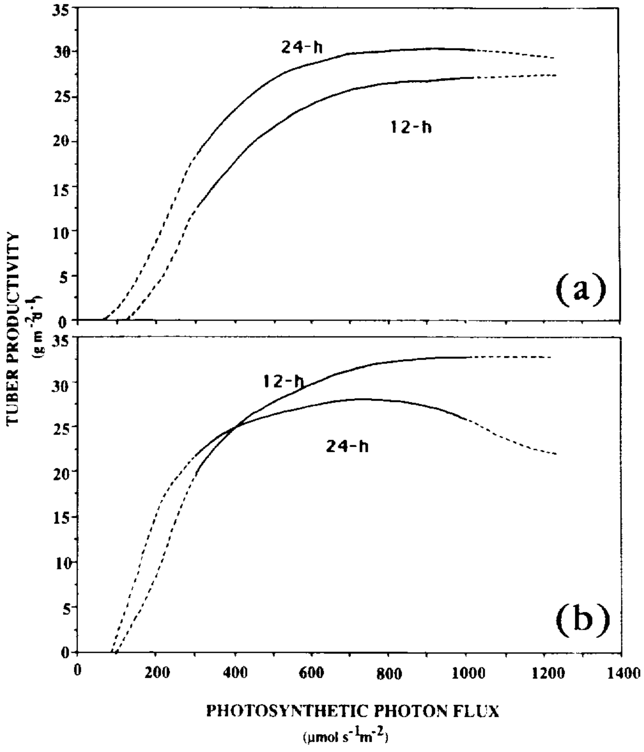

Fig. 1. Potato productivity curves for **(a)** low and **(b)** high carbon dioxide concentrations at various photosynthetic photon flux (irradiance) levels (*Wheeler and Tibbitts*, 1987a; R. M. Wheeler and T. W. Tibbitts, unpublished data, 1988). Productivities at high and low photosynthetic photon flux (broken lines) have been estimated based on related work.

Fixed Lamps, High Carbon Dioxide Concentrations

The next set of possible scenarios again assumes fixed lamps but is based on the use of carbon dioxide enrichment to increase the productivity of potato plants under the 12-hr photoperiods to levels nearly equivalent to those observed under the 24-hr photoperiods, essentially substituting for increased irradiance. However, increasing carbon dioxide concentrations has only a small effect on plants grown for 24 hr at 400 μmol sec^{-1} m^{-2}, and no effect on those grown at 800 μmol sec^{-1} m^{-2} (R. M. Wheeler and T. W. Tibbitts, unpublished data, 1988). Using carbon dioxide enrichment, scenario 6 (Table 1) now becomes the most efficient on an area basis, while scenario 8 becomes the most efficient on an energy basis. In addition, carbon dioxide enrichment results in a substantial decrease in the number of lamps required for growing plants under a 12-hr photoperiod. With the use of carbon dioxide enrichment, 12-hr photoperiods show a definite advantage in productivity efficiency compared to the use of 24-hr photoperiods regardless of radiation level. If energy, growing area, and lamp weight were of equal concern, scenario 8 would be the best selection of the scenarios thus presented, including all carbon dioxide level scenarios.

Movable Lamp Arrangement

Because the potential cost of transporting lamps to the lunar surface is so great, it might be desirable to utilize movable lamp banks (*Wheeler and Tibbitts,* 1987b). By breaking the growing area into segments, half the segments could then be irradiated during the first 12-hr period (out of 24 hr) and the other half irradiated during the second 12-hr period. This reduces the number of lamps required by half while maintaining desired productivity levels (Tables 1 and 2, scenarios 10 vs. 4 and 12 vs. 8), and allows continuous use of available power. Alternatively, lamps could be positioned twice as densely to obtain irradiance (with a 12-hr photoperiod) twice that possible by lighting the entire area with the same number of lamps over a 24-hr photoperiod (Tables 1 and 2, scenarios 9 vs. 3 and 11 vs. 7). In fact, if mobility of the lamp bank is not in itself a limiting factor and carbon dioxide can be maintained at high concentrations, it would always be better to double lamp density (~doubling PAR) over half of the growing area (Table 3, column 2 vs. column 1). If area is not as limiting as power or lamps, it would again be better to use alternate 12-hr photoperiods (with movable lamps) but with twice the planted area (Table 3, column 3 vs. column 1). This would provide a productivity level equivalent to two 12-hr yields as compared to one 24-hr yield. If potatoes can be successfully grown under an 8-hr:16-hr light:dark cycle without serious reductions in productivity, three 8-hr photoperiods during each 24 hr might provide even greater increases in growing efficiency. It is noteworthy that if lamp and ballast weights could be reduced (e.g., through the development of small, energy efficient, solid state ballasts), the initial payload weight of lamps might be removed as a primary limiting factor in a lunar CELSS. However, the equipment required to make the lamp banks movable adds an unknown increment of weight that needs to be taken into consideration.

TABLE 1. Management scenarios for optimizing production of the 22,500 g day^{-1} of potato tubers required to satisfy caloric needs for 30 inhabitants in a lunar CELSS using an arrangement of fixed lamps.

Scenario	Irradiance	Photoperiod	Area Requirement	Energy Requirement	Area Efficiency[*]	Energy Efficiency	Lighting System Weight[†]
	(μmol $sec^{-1}m^{-2}$)	(hr)	(m^2)	(kWhr d^{-1})	(g m^{-2} d^{-1})	(g $kWhr^{-1}$)	(kg)
Low Carbon Dioxide Concentration (350 ppm)							
1	800	24	776	14,900	29	1.51	12,400
2	800	12	900	8,640	25	2.60	14,400
3	400	24	938	9,005	24	2.50	7,504
4	400	12	1184	5,683	19	3.96	9,472
High Carbon Dioxide Concentration (1000 ppm)							
5	800	24	776	14,900	29	1.51	12,400
6	800	12	726	6,970	31	3.23	11,616
7	400	24	900	8,640	25	2.61	7,200
8	400	12	882	4,234	25.5	5.31	7,056

[*] Also termed productivity. Adapted from *Wheeler and Tibbitts,* 1987a and Wheeler and Tibbitts, unpublished data, 1988. Values based on the average of 2 cultivars, Denali and Norland.

[†] Including ballast, bulb, and reflector.

TABLE 2. Management scenarios for optimizing production of the 22,500 g day^{-1} of potato tubers required to satisfy caloric needs for 30 inhabitants in a lunar CELSS using an arrangement of movable lamps.

Scenario	Irradiance	Photoperiod	Area Requirement	Energy Requirement	Area Efficiency[*]	Energy Efficiency	Lighting System Weight[†]
	(μmol $sec^{-1}m^{-2}$)	(hr)	(m^2)	(kWhr d^{-1})	(g m^{-2} d^{-1})	(g $kWhr^{-1}$)	(kg)
Low Carbon Dioxide Concentration (350 ppm)							
9	800	alt. 12[‡]	900	8640	25	2.60	7200
10	400	alt. 12	1184	5683	19	3.96	4736
High Carbon Dioxide Concentrations (1000 ppm)							
11	800	alt. 12	726	6970	31	3.23	5808
12	400	alt. 12	882	4234	25.5	5.31	3528

[*] Also termed productivity. Adapted from *Wheeler and Tibbitts,* 1987a; and Wheeler and Tibbitts, unpublished data, 1988. Values based on the average of 2 cultivars, Denali and Norland.

[†] Including ballast, bulb, and reflector.

[‡] Alternate 12-hr photoperiods—half the growing area irradiated during the first 12-hr period, half irradiated during the second 12-hr period.

TABLE 3. Comparisons of fixed and movable lamp configurations based on an equal energy input.

Fixed lamp configuration		Movable lamp configurations			
1 1 × area*		2 1 × area†		3 2 × area‡	
Irradiance	Yield	Irradiance	Yield	Irradiance	Yield
(μmol sec^{-1}m^{-2})	(g m^{-2}d^{-1})	(μmol sec^{-1}m^{-2})	(g m^{-2}d^{-1})	(μmol sec^{-1}m^{-2})	(g m^{-2}d^{-1})
300	18	600	26	2 × 300	30(2 × 15)
400	25	800	28	2 × 400	44(2 × 22)
500	27	1000	29	2 × 500	50(2 × 25)
600	28	1200	30	2 × 600	52(2 × 26)

* Lamps covering entire growing area (1 × density), 24-hr photoperiod.

† Lamps covering 1/2 of the growing area (2 × density). After a 12-hr photoperiod, lamps are moved to other 1/2 of growing area for another 12-hr photoperiod.

‡ Lamps covering 1/2 of the growing area (1 × density), except growing area is *doubled* in size. Therefore, lamps are spaced identically to those in column 1, but are alternated between each half of the growing area as for column 2.

Yield data are averaged over high and low carbon dioxide concentrations and for two potato cultivars, Denali and Norland (*Wheeler and Tibbitts*, 1987a; Wheeler and Tibbitts, unpublished data, 1988).

Other Scenarios

The management scenarios above, while simplified for the purpose of discussion, provide a framework within which additional scenarios can be generated by the manipulation of various factors and then evaluated and compared. For example, some of the lamps used could be placed within the plant canopy to improve the efficiency of irradiation absorption by the plants. This might result in an increase in productivity without a corresponding increase in required power inputs. Another possibility would be to utilize the growing area more efficiently (i.e., reduce the amount of open space between plants during early growth). This could be done by using a variable spacing mechanism, but the complexity of such a system might negate any increase in area-use efficiency obtained. An alternative would be to use an intercropping management system. At the per plant spacing used to determine productivity factors in this discussion (0.2 m^2), potatoes do not form a closed canopy until five to six weeks after planting (*Tibbitts and Wheeler*, 1987). A short season crop, such as lettuce, could be planted in the culture unit between the young potato plants and harvested before the canopy closes. Again, this would increase productivity of the CELSS with minimal additional input.

CONCLUSION

The crop management scenario that is ultimately chosen for a lunar CELSS will depend upon the factor or factors that are most limiting in terms of cost. A lunar base will likely evolve and assume several configurations depending on the stage of development of the base. Therefore, biomass production in the CELSS will be a dynamic process, changing with prevailing base configurations to optimize productivity. For example, as a lunar base expands, the area available for plant growth may become less limiting, thereby favoring those management scenarios that are energy efficient at the expense of area efficiency. However, the increase in growing area might result in factors such as carbon dioxide or lamp weight becoming limiting. Likewise, development of an energy intensive industrial process (i.e., lunar oxygen processing) might require cutbacks in the power available to the plant growing unit. Such a situation would favor a mangement scenario that is very energy efficient.

In any CELSS, maximum crop yield probably will not be the main objective. Rather, obtaining efficient production based on system limitations will be the primary concern. The management scenarios discussed represent an attempt to address crop production in a lunar CELSS from a limiting factor perspective. More detailed evaluation of these and other factors will be needed in order to determine break-even points between development of a CELSS and resupply of life support requirements from Earth. Similar system analyses for all potentially useful CELSS crops will enable the integration of these crops into an overall management program for the lunar CELSS.

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POTENTIAL OF DERIVED LUNAR VOLATILES FOR LIFE SUPPORT

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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.

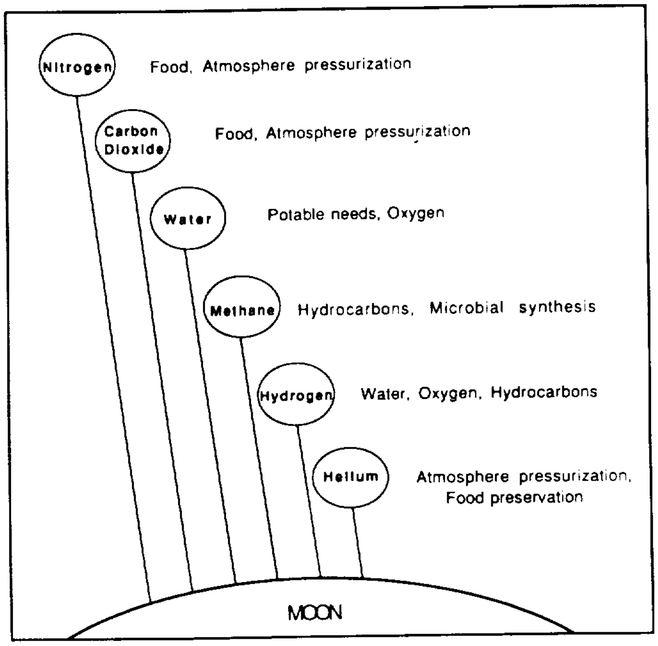

Fig. 1. Potential applications of solar wind deposited lunar volatile compounds for life support.

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.

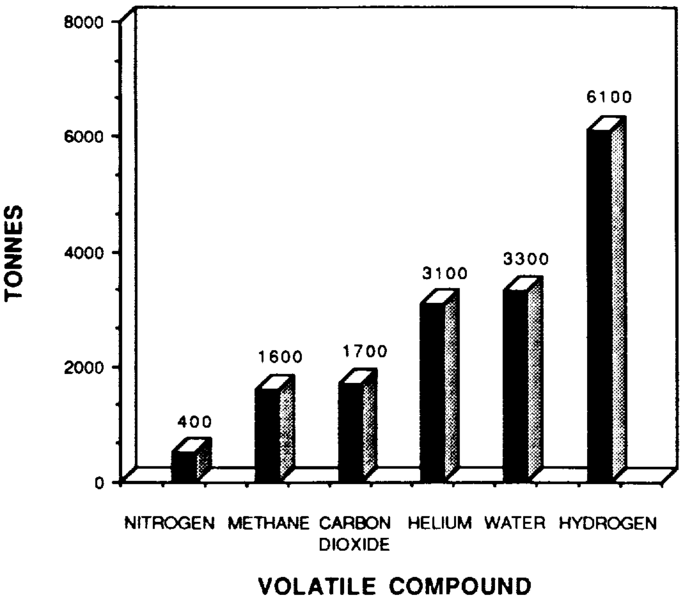

Fig. 2. Tonnes of lunar volatile compounds per tonne of He-3 recovered from the lunar regolith.

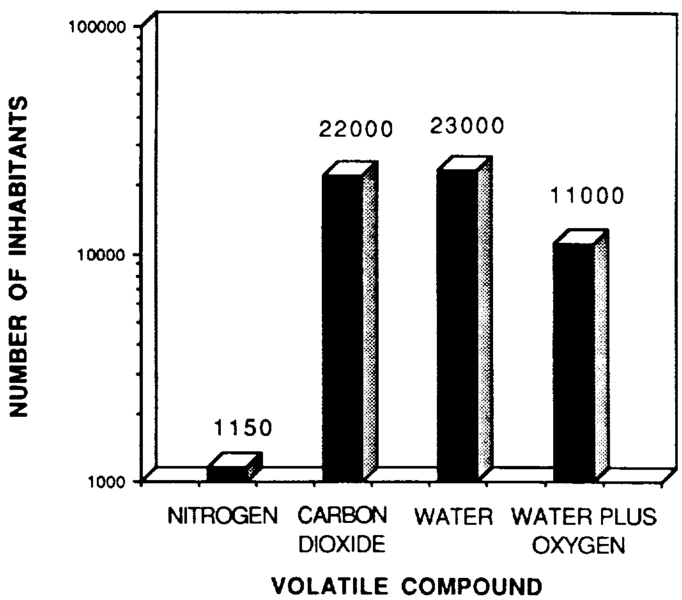

Fig. 3. Number of inhabitants supported for a year by the nitrogen, carbon dioxide, and water derived with each tonne of He-3 mined.

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

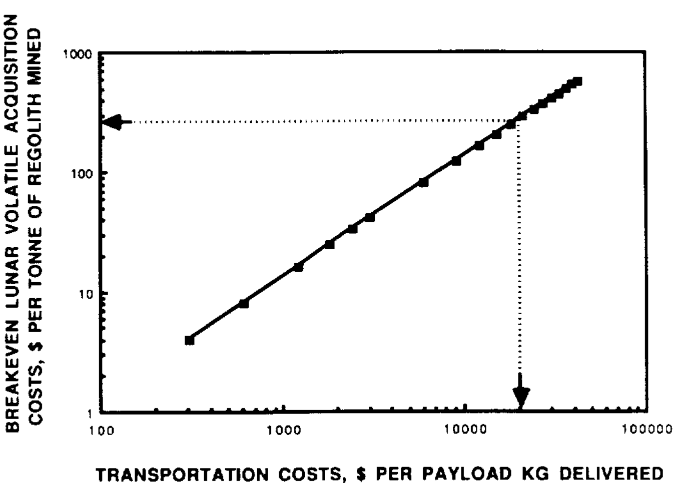

Fig. 4. Comparison of costs for supplying the life support replacement requirements from lunar regolith volatile compounds vs. transportation costs for resupply from Earth resources. The dotted lines correspond to twice the costs estimated by *Koelle* (1991).

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.

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