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Paper Session II-C - Life Support Options and Costs

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Introduction

The Moon is a hostile place. As shown Table 1, it has no atmosphere and temperatures range from as cold as liquid oxygen during the long lunar night to as hot as boiling water during the equally long day. Ionizing radiation varies from moderately high to rapidly lethal. Meteoroids strike with explosive force. The ubiquitous dust is abrasive, particularly in vacuum. Some of the hazards have been exaggerated: for example, human bodies exposed to a vacuum do not explode as the blood boils, but they do require protection from the environment.

Table 1. Hazards

Hazard	Concern
Vacuum: 7.5×10^{-15} atmospheres ambient pressure	Effect on equipment; e.g. vacuum welding of metals, abrasion. May be detrimental to the crew.
Meteoroids: about 10^{-5}/sq ft/yr	Effects impacts on crew or equipment.
Solar and cosmic radiation: 10^{-3} to 10^{4} MeV/nucleon 1 to 10^{8} N/cm^2/s	Major concern during solar flare. Mostly for crew. Some concern for sensitive equipment.
Dust: includes fine glassy particles	Abrasive, will clog equipment. Inhalation by crew, possibly some pathogenic effects.
Thermal extremes: - 280°F to +200°F	Crew exposure, effect of extremes and cycling on equipment.

In addition to protection from the environment, the human body requires a range of commodities to survive. The equipment for life support must be complex to meet all the needs for human survival and yet still be reliable. Although some of the requirements for sustaining life are available on the Moon, none are easily acquired. Consequently, life support commodities must be either carried there or collected locally despite the difficulty of doing this.

Life Support Requirements and Mission Duration

The requirements for life support commodities are modest for short stays. As shown in Table 2, for Apollo-type missions with stay times from 21 to 75 hours, life support requirements total about 13 pounds of consumables a day. This will be about 16 pounds including containment and packaging. This is only about 100 pounds for an Apollo 17 type mission of 2 people for 3 days (excluding contingency). EVA will increase the requirement, through use of water for evaporative cooling and gas lost during airlock operations (or cabin venting). This would increase the mass by at least 6 lb/day to about 120 pounds. This is still a reasonably small amount to carry to the Moon.

Table 2. Availability of Life Support Commodities

Commodity	Requirement
Pressure	2.8 psia (100% oxygen)
Carbon dioxide removal	2.9 lb/man-days
Oxygen	2 lb/man-days
Water	0.8 gal/man-days potable, 7 gal/man-days total
Food	1.5 lb/man-days food (dry weight)
Waste disposal	2.6 lb/man-days (typical)

As the mission duration increases, the crew will need more elaborate hygiene facilities and better packaging, plus about 50 lb/day of water for hygiene and other domestic uses. This will rapidly become excessive, bringing the total to about 80 pounds a day, or 13 tons a year. Crew size is also likely to increase as mission duration increases. A 45-day 4-man Lunar campsite would require about 5 tons of life support consumables. As a comparison, this is about equal to the total mass of a loaded Apollo Lunar module.

With longer missions, the consumables mass increases proportionally. At some point, it will become cheaper to regenerate consumables than deliver them from the Earth. This will involve trading off delivered mass for increased power and cooling, and possibly manpower. Regeneration will require more equipment to perform the processing, energy for driving the exothermic chemical reactions, heat rejection to dispose of the waste heat produced by inefficiencies in operating the equipment, spare parts, filters, seals, and other items as well as maintenance.

A further possibility would be to mine the life-support consumables from the Moon. This is certainly possible for oxygen, which is ubiquitous and comprises about half of the crust. However, oxygen extraction from rock is something we have never done on a large scale even on the Earth. The equipment would have to be designed, built, tested, and operated. Oxygen for life support may well become available eventually as a by-product from production for rocket propellant. However, this will be unlikely for several decades.

Other life-support consumables are less readily available. Water has not been detected with certainty on the Moon, although Clementine did find evidence that there was trapped ice in the south polar depression. Hydrogen, nitrogen, and carbon are almost non-existent, being only known at part-per-million concentrations in the regolith. The richest source of these elements we know of at this time is crew wastes, bringing us back to regeneration. However, crew wastes other than metabolic wastes may also be useful. Paper and plastic products are ubiquitous in our society and will certainly be used on the Moon. They can provide life suppport feedstuffs, as well as reducing the need for waste disposal.

Infrastructure Costs

Any infrastructure available for life support on the Moon will have to be either carried there or built there. As shown in Table 3, current estimates for cost of mass delivery to the Moon vary widely, with a median of about $14,000 per pound. If we assume that the cost is proportional to the energy required, this is consistent with a cost to low Earth orbit (LEO) of about $5,000 per pound. This is rather lower than the cost of delivery by the National Space Transportation System (NSTS), but is not as optimistic as early estimates for Delta Clipper of about $300 per pound. It does appear to be easily achievable with the next generation of launch vehicle. Energy costs for launch to LEO would only be about $5per pound. These costs are extremely high compared to delivery anywhere on the Earth. Even delivery to the South Pole is only about $2 per pound.

Table 3. Delivery Costs

Basis	Cost, per lb	Source
Antarctic supply	$2	Phil Sadler, NRC
Moon: median cost of 7 studies	$14,000	Reference /2/
NSTS - marginal cost - average cost - all ops costs - total costs	 $900 $8,200 $20,000 $32,000	from sci.space FAQ
Energy cost to LEO	$5	from sci.space
Energy cost to the Moon	$14	Calculated

Other infrastructure costs which must be considered include costs of providing pressurized volume, electrical power, heat rejection (particularly during the Lunar day), and manpower. For trade studies, these can all be converted into equivalent mass, as discussed in Reference 2. This allows objective comparison of different options. Values currently used are shown in Table 4.

Table 4 Cost Factor Equivalencies

Cost Factor	Equivalency	Rationale
Volume	14 lb/ft^2	bare SSF module
Energy	110 kWh/lb 170 kWh/lb 1,800 kWh/lb	photovoltaic solar dynamic nuclear
Cooling	5,700 MJ/kg	daytime requirement
Manpower	1.8 mh/kg	from previous study

A wide variety of concepts have been developed for pressurized habitats on the Moon, including Apollo-type capsules, space station modules, pressurized flexible structures, natural caves or lava structures, and structures formed or built out of locally processed locally available materials. For short stays, the crew will probably stay in the vehicle, as on Apollo. For longer stays with small crews, prefabricated structures are still likely to be used. Before Skylab, a wide range of options was assessed, but the uncertainties of on-site construction and checkout and the high cost of labor in space drove the Skylab program to use a vehicle that was built and checked-out on the ground. This will be even more true for short missions to the Moon.

Long missions, especially with large crews, will probably use some local construction, particularly if natural features lend themselves to use. However, so long as the labor force is supported from the Earth, rather by a local economy, it seems that construction will be largely limited to assembly of prefabricated units shipped from Earth, where the cost of even aerospace labor will be several orders of magnitude lower than crew time on the Moon. Even at $2 per pound for delivery of materials to Antarctica, much of the building there uses prefabrication. On the Moon, naturally available materials could certainly be used for shielding the habitat. Reference 6 describes particle penetration as up to 30 feet of regolith, but most particles would be stopped by 3 to 6 feet. Use of regolith for shielding would reduce the delivered mass, but would require large earth-moving equipment.

Electrical power will be required for all functions on the Moon, including life support. The power could come from solar energy, either photovoltaic or dynamic systems, during the Lunar day. However, the Lunar night is about 15 terrestrial days long. Power storage for such a long period of time will increase the cost of solar power tremendously. There are a few locations on the Moon - near the poles - where almost continuous light is available (Reference 3), however, these locations may be less than desirable for other reasons. Nuclear power would not require so much energy storage, and thus is very attractive. Regolith could also be used for shielding nuclear reactors.

Heat rejection can be a problem, particularly during the Lunar day. The effective sink temperature varies according to the radiator configuration, but is high. Life support waste heat tends to be close to the effective sink temperature, requiring use of a heat pump to reject heat. Regolith is a good insulator, so it is impractical to dump heat to the regolith.

Regenerative Options

Life support consumables can be regenerated in a variety of ways, but most of these ways have been classified as either physico-chemical (PC) or biological. PC approaches have been developed for water and air regeneration, but not for food.

Water comprises 87% of the life support consumables for a Lunar mission. It is easily regenerated, but hard to find on the Moon. Thus, large-scale Lunar colonies will certainly regenerate water. Payback times for regeneration of water are on the order of a week. A further 10% of mass delivery could be saved by regenerating oxygen from carbon dioxide. The break-even time is somewhat longer than for water regeneration, but significant savings are still possible.

The remaining 3% is the mass of food. The only alternatives to delivery from Earth are growing plants on the Moon and chemical synthesis of food. Lunar agriculture is being investigated at NASA centers including Kennedy Space Center, Ames Research Center, and Johnson Space Center. Food production will also inherently regenerate adequate quantities of other life support . Early systems will probably still import some foods from Earth, such as meat, spices, and specialty items. As Lunar exploitation expands from an initial base towards colonization, the degree of mass closure will increase, driven by economic pressure.

Trade Study Methodology and Results

Life support options require different amounts of the different kinds of support. To avoid disagreements over which type of support is most important, an equivalent mass (EM) trade study methodology was developed a few years ago that enables us to make objective assessments. An equivalency was determined for each of the resources, converting everything into mass units. Equivalencies currently used are shown in Table 4.

Using this approach, PC and bioregenerative scenarios have been developed and the EM calculated for a 4-man 10-year Lunar base. The results for the lowest EM PC scenario are shown in Table 5.

Table 5. Physico-chemical Life Support System Mass

	Equivalent Mass (kg)					
	Mass	Volume	Energy	Cooling	Man-power	Total
Air	536	37	469	108	289	1,439
Water	502	141	403	93	289	1,428
Food	14,900	1,030	3,540	814	23	20,300
Total						23,100

Theoretically, food could be produced biochemically. This has never been done on a practical scale and the cost would be prohibitive at this time. In the future, we may be able to generate complex organic compounds in an electrochemical cell or other PC system, and build up the compounds into palatable food. However, the only practical approach at present is to use biological systems.

Various scenarios can be developed, from use of microscopic algae or photosynthetic bacteria to normal crop plants. While the Moon is an unlikely place to do so, there is also a possibility of using chemosynthetic bacteria. On Earth, for example, chemosynthesis provides the driving energy for the ecosystems near volcanic vents on the ocean floor. However, only crop plants would provide a normal diet without extensive processing. There are additional benefits from using more conventional bioregenerative approaches, both dietary and psychological.

The optimum degree of complexity of a bioregenerative system is an issue which remains to be resolved. The simplest bioregenerative system that could be developed would be based on a single crop. However, this would require dietary supplements from Earth both for balancing the diet and to improve the variety of food. More complex systems would require a greater development effort, but would be more acceptable to the crew. Adding animal components would increase the variety even more, allowing the system to be self-sufficient, but would not be cost-effective for missions shorter than several decades and with large crews.

Plants are inefficient users of light. Even under good growing conditions, they only extract about 10% of the energy of the incident light. Thus, large quantities of light are required for life support. If this is obtained artificially, there is a large heat load, especially as lamps are at best about 30% efficient. Equivalent mass is then driven by power consumption, both for lighting and because of the resulting heat rejection.

Equivalent mass for a bioregenerative life support system is shown for different power systems in Table 6. For the scenario studied, solar electrical power does not provide a benefit over PC systems except at the poles. As 10 years is close to the probable system life of any of these systems, the picture will probably not change much for longer missions. (This is true, of course, only for the Moon, where there is a large penalty for storing solar electrical power.) The last case shown, using sunlight directly when it is available, is interesting. Direct use of sunlight is a benefit because heat from the lamps does not have to be rejected during the lunar day, when the heat rejection penalty is high. Some electrical lighting options, such as fiber optics, could also avoid heat rejection penalties.

Table 4. CELSS System Equivalent Masses

		Mass (kg)	Volume (m^3)	Energy (MWh)	Cooling (GJ)	M/P (mh)	Total EM
		4,657	73	8,520	30,700	8,000	(kg)
E	SPV	4,657	5,037	40,600	3,500	4444	58,000
M	SD	4,657	5,037	23,000	3,500	4444	41,000
k	nuclear	4,657	5,037	2,190	3,500	4444	20,000
g	nuc/sun	4,657	5,037	1,312	850	4444	17,000

All of these options assume that about 25% of the crew time is spent operating the life support system. This can be reduced by an order of magnitude by physical automation (robotics). However, the cost of robotics performance has not yet been estimated. An initial design for a robot for the CELSS Breadbaord Facility (from the University of Central Florida project critical design review) was about 100 kg. Thus, the mass of the robot is probably not a major issue. However, the design could be a significant additional cost.

Using this approach, we have looked at a number of options. Bioregenerative life support is cost-effective for long-duration missions. With longer durations and larger crews, more complex systems could be used to gain additional benefits. However, the real breakthrough will occur when manpower becomes less of an issue and a local economic system develops. At that point, it would perhaps be better to regard the base as a colony.

References

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