Life Support for a Low-Cost Lunar Settlement: No Showstoppers

Lynn D. Harper,[1] Clive R. Neal,[2] Jane Poynter,[3] James D. Schalkwyk,[4] and Dennis Ray Wingo[5]

[1]Space Portal, NASA Ames Research Center, Moffett Field, California.
[2]Department of Civil and Environmental Engineering and Earth Sciences, University of Notre Dame, Notre Dame, Indiana.
[3]World View Enterprises, Tucson, Arizona.
[4]Deltha-Critique, NASA Ames Research Center, Moffett Field, California.
[5]Skycorp Incorporated, NASA Ames Research Park, Moffett Field, California.

ABSTRACT

In 2014, space experts were challenged to develop strategies that would enable 10 people to live for 1 year on the Moon by 2022 for a total development cost of $5B. This was to be done in a manner that would minimize resupply of consumables from Earth and lead to a permanent lunar settlement of 100 people within 10 years. To sustain small groups on the Moon within this budget, recycling life-support consumables, rather than continuously supplying them from Earth, is required. The International Space Station (ISS) provides existence proof that these technologies are currently available. On the ISS, physicochemical regeneration of air and water reduces resupply of these consumables by more than 80%, increases the resilience of missions, and enhances productivity by enabling science, technology, and commercial payloads to replace life-support consumables. A permanent settlement must also employ bioregenerative strategies where, in addition to providing food, plants also remove carbon dioxide, produce oxygen, and generate potable water from gray water. Food production is only practical if abundant sunlight (or power) provides the light necessary for photosynthesis. Thus, quasicontinuous sunlight, obtainable only near the poles, is the most important resource for meeting time and budget constraints, although regolith constituents and lunar polar hydrogen (presumably ice) deposits are also valuable assets. Although improvements are always beneficial, the technologies needed for life support for the first phase of Lunar Settlement are available now.

INTRODUCTION

In August 2014, a group of space experts, entrepreneurs, and venture capitalists met at the offices of Draper-Fischer-Jurvetson (DFJ), a venture capital firm managing a multi-billion dollar investment portfolio, to determine how to establish a permanent human settlement on the Moon. The meeting was hosted by Steve Jurvetson, one of the managing partners of DFJ, and chaired by Will Marshall, CEO of PlanetLabs. The purpose of the meeting was to determine an economically viable strategy for building a settlement of 100 people on the Moon within 15 years. The first challenge the group tackled was to determine how to build a core capability supporting 10 people on the Moon within 5 years for a cost of under 5 billion dollars. This core capability also had to provide the foundational infrastructure upon which the settlement would grow.

It became apparent early in the discussions that the strategies selected for life support would have critical impacts on the success and affordability of the enterprise. The best choices for life support depend upon several interacting variables, including number of people, duration of stay, availability of indigenous supporting resources, readiness of the physical–chemical and bioregenerative technologies for life support, ease and cost of resupply from Earth, and provisions for emergency conditions.

Life-Support Requirements

In this article, the life-support requirements for a single individual are based on an average metabolic rate of 2,700 calories/person/day and a respiratory quotient of 0.87. (The respiratory quotient is a ratio of the amount of carbon dioxide [CO_2] eliminated from the lungs divided by the amount of oxygen [O_2] consumed.[1])

Using that definition, a person requires a minimum of 15 kg of life-support consumables (air, food, and water) per day and a method to remove carbon dioxide (*e.g.*, lithium hydroxide [LiOH] canisters). Supporting a single individual without recycling would require approximately 5,475 kg/person/year, not including leakage, emergency supplies, or the resources needed for extra-vehicular activity (EVA) suits and surface activities. This, however, is an austere strategy appropriate only for short-duration missions.

For a permanent settlement to thrive, people need additional resources for cooking, cleaning, showers, toilets,

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Table 1. Life-Support Requirements Based on ISS Calculations (kg/Person-Day)[27,28]

	Minimum Sortie	Maximum Settlement for Long-Term Inhabitants
Air total	2.93	2.93
Oxygen	0.84	0.84
O_2 tankage	0.34	0.34
LiOH (including packaging)	1.75	1.75
Water total (including tankage)	9.69	28.63
Food preparation	0.40	0.91
Drinking	0.21	1.77
Shower	1.82	2.73
Dishwash	3.63	5.45
Handwash	3.63	4.54
Toilet flush	0.00	0.73
Clothes wash	0.00	12.50
Food total[29]	2.51	2.51
Food	1.83	1.83
Containment trays	0.68	0.68
Total life-support requirements (kg/person/day)	15.13	34.07

LiOH, lithium hydroxide.

fresh food growth, and other psychological and physiological support elements. Thus, over the long term, the recommended life-support strategy would be to provide at least 35 kg of air, food, carbon dioxide removal, and water per day. This would be in addition to the expendables needed to manage hygiene and biological wastes.[2] In total, this open-loop strategy requires more than 12,775 kg/person/year (*Table 1*).

Without some sort of recycling and/or use of *in situ* resources, meeting the lunar settlement goal of 100 people would require delivery of over 1 million kilograms of life-support consumables per year. The transportation costs of these materials on a continuous basis from Earth would be ruinously expensive for a nascent settlement.

Fortunately, better options exist.

METHODS: DESIGN CONSIDERATIONS

Many workable strategies for long-term occupation of the Moon have been developed since the first men landed on the lunar surface in 1969.[3,4] At the Low Cost Lunar Settlement Workshop, ideas harvested from these concepts resulted in a 4-phase development approach: Precursors, Sorties, Lunar Station, and Lunar Settlement.

Each phase supports a wide range of activities and purposes and is executed by diverse groups of developers, owners, producers, consumers, users, and customers. The meeting was organized around the premise that the lunar settlement would be funded primarily by private investors and would not rely heavily on traditional government procurements. The goal was eventually to enable a thriving settlement that would be both self-sustaining and economically viable. Nominal life-support requirements for the Precursors, Sorties, and Settlement phases are presented in *Table 1*.

FINANCIAL VIABILITY

Regardless of the life-support approach taken, the biggest contributor to the cost of establishing a permanently inhabited Lunar Station is likely to come from the transportation of supplies from Earth. Thus, a large part of making Lunar Station sustainable will involve reducing the quantity of resources needed from Earth. This article presents a survey of how the inhabitants will be able to reduce their reliance on Earth-based life-support resources, but even in the mature settlement, some resupply will still be necessary.

Launch costs are coming down. However, to maintain conservative estimates in this article, we only used the prices that were advertised publicly by launch services providers. Today, SpaceX advertises delivery of 4.85 MT to geostationary transfer orbit (GTO) for \$61.2 M, which translates to a cost of \$12 M/metric ton (MT). No attempt was made to estimate how much more it would cost to deliver cargo to the lunar surface because the deep space transportation vehicles, landers, and robotic equipment necessary to offload the cargo do not exist at this time. Nonetheless, the first step, leaving Earth, provides a starting place for comparing the costs of different life-support strategies, and current launch costs offer a reasonable benchmark (*Table 3*).

Precursors to Sorties to Station to Settlement

Precursors. The first Precursor phase deploys robots for site selection. This includes surveys of local hazards and resources, as well as terrain characterization, with the initial sites chosen from existing orbital datasets (*e.g.*, topography and imagery from the Lunar Reconnaissance Orbiter mission).[5] Assuming the site offers adequate resources (sunlight, important chemical constituents, and water) and sufficiently few terrain hazards, autonomous or teleoperated robotic site preparation would commence to enable the arrival of people. The Precursor phase ends when launch and landing sites and core infrastructure (power, habitats, life support, communications, laboratories, surface vehicles, and production equipment) are ready to support short-term human occupation.

Sorties. In the Sortie phase, people would land on the Moon and stay for periods of days, then weeks and months, to complete construction and testing of the core infrastructure. This infrastructure is called the Lunar Station. However, the evolving Lunar Station would not be continuously occupied until the end of this period. The Sortie phase ends when the Lunar Station is ready for permanent occupation of 10 people.

Settlement. The Settlement phase is divided into 2 stages of development: Lunar Station and Lunar Settlement. The Lunar Station phase culminates with permanent occupation of the Moon by 10 people for at least a year. This is an essential learning period, where the occupants and the facilities to support them are tested for productivity, reliability, performance, psychological support, and evolution based on lessons learned. Strategies, technologies, and infrastructure will be modified based on this experience and lunar resources will be used to enable growth of the population and the community's activities.

In the final Lunar Settlement phase, the population would increase by 10 persons annually until the settlement could permanently support 100 people, 10 years from the end of the Sortie phase. After that the settlement would continue for centuries. Although the settlement infrastructure will be permanent and continuously occupied, for the first decade or so it is expected that people will only visit for defined periods of time, as they do now on the International Space Station (ISS). Eventually, however, permanent occupants and their offspring could establish the first true human settlement beyond Earth.

Life-Support Strategies by Phase

There are 5 basic strategies for lunar life support: (1) open loop, (2) physicochemical life-support systems (PLSSs), (3) bioregenerative life-support system (BLSS), (4) *in situ* resource utilization (ISRU), and (5) hybrid life-support systems.

Open loop. The simplest life-support strategy is called open-loop or direct supply, where food, air (in the form of compressed gases), and water are brought from Earth. No recycling is attempted. Carbon dioxide removal is achieved using LiOH canisters. Management of biological wastes (urine, feces) is minimal, for example, bagging the waste and physically removing it from the living space. Over the long term, or in the short term with a large number of people, this is the most expensive life-support strategy that can be considered. However, it is immediately available and has an extensive heritage. Apollo missions and Space Shuttle missions used open-loop life support. As a primary life-support strategy, this approach is only suitable for the Sortie phase not only because of the expense of resupply but also because of how vulnerable lunar occupants would be to delays in delivery of life sustaining consumables from Earth.

An open-loop strategy requires each person who arrives at the lunar settlement either to carry or be preceded by enough life-support consumables to initiate their habitat and provide their individual life-support requirements. Additional life-support consumables would need to be delivered and stored to accommodate leakage, habitat initiation, EVAs, surface vehicles, and emergencies.

Even assuming just 15 kg/person/day (including packaging and emergency supplies), this strategy would require ~54,750 kg of life critical consumables to support 10 people for 1 year on the lunar surface, not including the habitat. Using today's advertised prices from SpaceX ($12.6 M/MT), the launch costs alone of transporting this quantity of life-support consumables to the Moon would cost ~$680 M/year, a substantial fraction of the 5 billion dollar budget.

Physicochemical life-support systems. PLSSs generate oxygen, remove carbon dioxide, and clean and recycle water through chemical and mechanical processes as shown in Figure 2. Food is supplied from Earth as an open-loop consumable. Biological wastes may be discarded or processed to extract carbon, hydrogen, oxygen, nitrogen, and sulfur for use in other settlement activities (*Fig. 1*). A PLSS strategy can save up to 90% of the costs of resupply over open-loop systems (*Table 2*). The ISS, which has supported more than 200 people continuously in space since November 2, 2000, is the existence proof of the effectiveness of this type of strategy in extraterrestrial locations (*Fig 1*).[6]

PLSS technologies aboard the ISS include systems to manage water reclamation, air recycling, leakages, and emergencies. All of these functions must perform within the ISS's 84 kW power budget. Life-support power requirements on the ISS average ~300 W per crew member.

Water recycling. The ISS PLSS features a water reclamation system designed to support up to 7 crew members. The

FIG. 1. Orbiting by Earth's horizon and the blackness of space, the International Space Station (ISS) is 357 feet (109 m) end-to-end and almost spans the 360-foot area of an American football field, including the end zones. With 33,023 cubic feet of pressurized volume, the space station now has more livable room than a conventional 5-bedroom house. Image Credit: NASA.

station's purification system uses a 3-step process to reclaim wastewater from urine, handwashing, oral hygiene, and humidity from cabin air. The first step filters out particles and debris. The liquid is then passed through semipermeable membranes containing substances that remove organic and inorganic impurities. Finally, a catalytic oxidation reactor removes volatile organic compounds and kills bacteria. The finished product is water pure enough to drink.[7]

The water reclamation system on the ISS comprises a urine processing assembly (UPA) and a water processing assembly (WPA) (*Fig. 3*). The UPA uses a low-pressure vacuum distillation process and a centrifuge (to compensate for low gravity in the separation of liquids and gases) to convert pretreated urine and flush water coming directly from the waste hygiene compartment into purified water. Approximately 70% of the water content from urine is recovered and recycled.[8] The WPA processes UPA distillate, condensate from the cabin air, and system wastewater. It filters out gases and solid materials before passing the water through filter beds and a high-temperature catalytic reactor assembly. The WPA produces iodinated water that is tested by onboard sensors and delivered through a potable water bus to the oxygen generation system (OGS) for oxygen production, the potable water system for crew consumption, and other systems/payloads.[9]

Air recycling. Air recycling is accomplished on the ISS using (i) an OGS, (ii) a carbon dioxide removal assembly (CDRA), (iii) a Sabatier reactor, (iv) air contamination control (ACC), and (v) temperature and humidity control (THC) (*Figs. 4, 5*).[10,11]

(i) The OGS is sized for a crew of 11. It is an electrolyzer that uses water from the WPA to produce oxygen (which is inserted into the cabin) and hydrogen (which is used in the Sabatier reactor). It provides up to 9 kg of oxygen per day during continuous operation.
(ii) The CDRA has 2 units. One is located in the U.S. Laboratory module of the ISS and the other is located in Node 3. Each unit is designed to remove carbon dioxide for 7 crew members. A limited number of LiOH

Table 2. Launch Costs: PLSS Versus Open-Loop Life Support Based on ISS

Estimates	Initial PLSS Equipment (kg/CM/year)	Lunar Crew	Total (MT/year)	Launch Costs on Falcon 9 Based on Advertised \$61.2 M for 4.85 MT to GTO (\$12.6 M/MT)
				One-time emplaced cost for 10 crew members
ISS PLSS lower estimate	1,088	10	10.8	\$136
ISS PLSS upper estimate	2,563	10	25.6	\$323
Annual consumables needed				
				Annual cost for a crew of 10 for life-support consumables
ISS annual resupply lower limit	343	10	3.4	\$43
ISS annual resupply upper limit	467	10	4.67	\$59
Open-loop lower limit	5,475	10	55	\$693
Open-loop upper limit	12,775	10	128	\$1,613

PLSS, physicochemical life-support system.

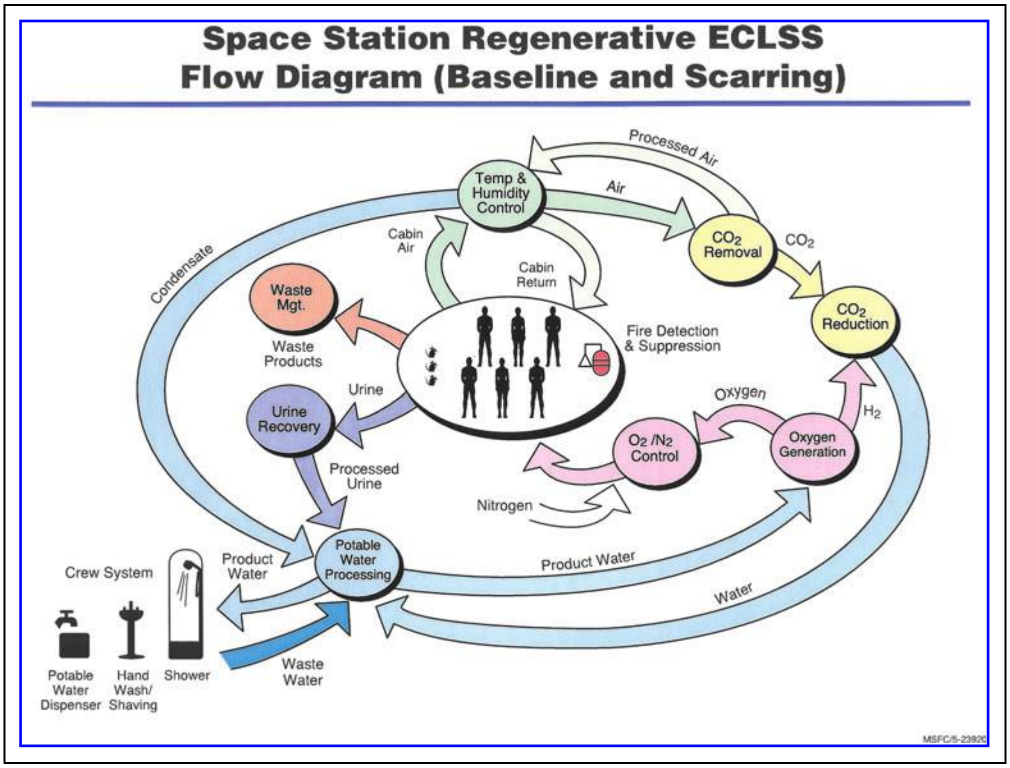

FIG. 2. This diagram from 2000 shows the flow of recyclable resources in the ISS. The Environmental Control and Life Support System (ECLSS) Group of the Flight Projects Directorate at the Marshall Space Flight Center was responsible for the regenerative ECLSS hardware as well as providing technical support for the rest of the system. The regenerative ECLSS, whose main components are the Water Recovery System (WRS) and the Oxygen Generation System (OGS), reclaims and recycles water and oxygen. The ECLSS maintains a pressurized habitation environment, provides water recovery and storage, maintains and provides fire detection/suppression, and provides breathable air and a comfortable atmosphere in which to live and work within the ISS. The ECLSS hardware is located in the Node 3 module of the ISS. Image Credit: NASA.

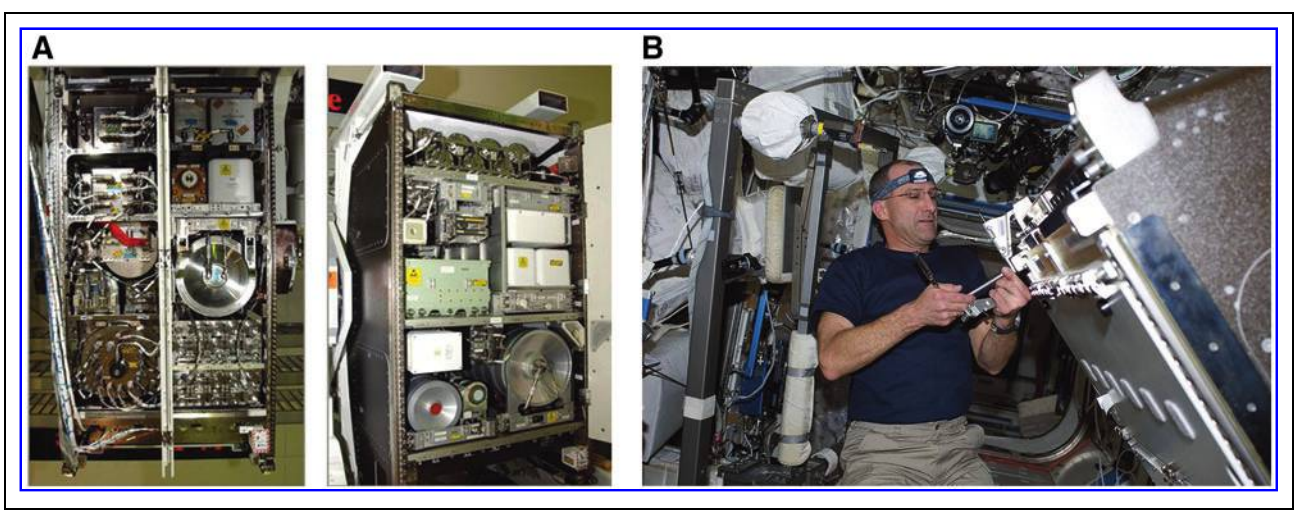

FIG. 3. (A) The ISS water recovery component of the Environmental Control and Life Support System (NASA). **(B)** NASA astronaut Don Petit installs the WRS into the Destiny Laboratory on the ISS in November 2008. Image Credit: NASA.

FIG. 4. In October 2010, aboard the ISS, NASA astronaut and Expedition 25 commander Doug Wheelock installed the Sabatier system, which extracts more water out of the ISS atmosphere. Sabatier creates water from the by-products of the station's OGS and Carbon Dioxide Removal Assembly. Image Credit: NASA.

canisters are available on-orbit to support carbon dioxide removal in case of complete CDRA failure.

(iii) The Sabatier System is a commercially operated system that uses hydrogen generated from the OGS system and carbon dioxide removed by the CDRA to produce water and methane. Water is fed to the WPA for processing and methane is currently vented overboard from the ISS. However, methane is a useful material for fuel and other chemical processes. In a Lunar Station, methane recovery would be prudent.[12]

FIG. 5. Commander Hadfield checks out Amine Swingbed (March 20, 2013)—Expedition 35 Commander Chris Hadfield in Harmony Node 2 aboard the Earth-orbiting ISS examines his work after reassembling the amine swing bed into its locker chassis. This device examines whether a vacuum-regenerated amine system can effectively remove carbon dioxide from the space station atmosphere using a smaller, more efficient vacuum regeneration system. The goal is to recover carbon dioxide from the atmosphere, and separate the dioxide from the carbon, so that the oxygen molecules can be used for crew life support. Image Credit: NASA.

(iv) There are 2 ACC units on the ISS, one located in the U.S. Laboratory and the one in Node 3. Each ACC is sized for a crew of 6. Each unit comprises a trace contaminants control assembly (TCCA) and a major constituent analyzer (MCA). The TCCA controls the concentration of trace contaminants from the cabin air using a charcoal bed to remove high-molecular-weight contaminants, a high-temperature catalytic oxidizer to remove low-molecular-weight contaminants (*e.g.*, methane, hydrogen, carbon monoxide), and an LiOH sorbing bed to remove acid by-products generated in the oxidation process. The MCA is a mass spectrometer that continuously monitors the partial pressures of oxygen, carbon dioxide, hydrogen, methane, nitrogen, and water vapor in the ISS atmosphere. Other handheld equipment is available onboard to measure specific compounds, especially those related to the presence of combustion products.

(v) THC on the ISS is achieved through the use of a fan and heat exchanger to provide fresh air to the crew members. Each module of the ISS has its own THC, sized for loads of 3–6 crew members according to location. Condensate from the THC is transferred to the WPA for processing.

Leakage and emergencies. Open-loop oxygen and nitrogen tanks are provided to compensate for leakage (overall ISS leakage is ~0.195 kg/day), losses during EVAs, and emergencies. A set of onboard sensors, including the MCA, oxygen, and nitrogen, are provided to the cabin when required through pressure regulators.

Fire detection and suppression are provided in each module of the ISS using laser-based smoke detectors. Fire suppression is performed by applying carbon dioxide from 2 portable fire extinguisher tanks provided in each module. Two portable breathing apparatuses that dispense oxygen are available in each module to support the crew during fire fighting emergencies.

Renewal/resource/input cost. PLSS requires an initial investment in equipment for recycling and an annual resupply of parts, spares, and consumables to make up for those that were not regenerated. The lower bound on a PLSS system was

Table 3. Breakeven Dates for Full or Partial Implementation of Physicochemical Recycling Systems

Component	Minimum Direct Supply vs. PLSS Regeneration Breakeven (Days)[a]	Maximum (ISS) Direct Supply vs. PLSS Regeneration Breakeven (Days)[a]
Full PLSS	199	31
Wastewater processing	93	9
Urine processing	417	94
Urine processing and oxygen generation	206	150
Carbon dioxide removal	86	86
Carbon dioxide reduction	223	78
Carbon dioxide reduction and oxygen generation	281	218
Carbon dioxide reduction for water production with a urine processor and oxygen generator	345	230

[a]Calculations refer to Table 1 and include tankage, containers, and power.
Source: Jones.[2]

calculated by Jones[2] as 1,088 kg/person and includes the power needed to run the equipment. He determined that the corresponding logistical support is 343.2 kg/person/year. This lower bound omits much of the ducting and plumbing and distributed components. If those are included, the upper bound is 2,563 kg/person and requires 467.1 kg/person/year in corresponding overall logistical support. This is a reasonable set of figures (with margin) to use for estimating life-support requirements for the initial Lunar Station.

Based on these calculations, the ISS now supports 6 crew members continuously with ~2,000 kg for the lower bound—and around 2,800 kg for the upper bound—per year of resupplied materials on top of an initial investment of between 6,528 kg (lower bound) and 15,378 kg (upper bound) for the life-support hardware.

The calculations of Jones,[2] which include equipment mass, power, parts replacement, and resupply requirements for consumables not fully recycled, indicate that investments in equipment for PLSS regeneration (oxygen, carbon dioxide, and water) will breakeven after ~180 days of continuous habitation, even with the resupply of 350–450 kg/person/year food and other consumables.

Furthermore, the phasing of the PLSS Strategy is important. For example, regenerating water may be the first PLSS element we want to implement because it is most immediately cost-effective (*Table 3*).

PLSS is likely to be the best choice for life support during the Lunar Station phase of development. For a 10-person crew for 1 year, the total nominal mass required by a PLSS would be ~11–26 MT of emplaced PLSS hardware versus 55 MT of open-loop consumables. The annual costs after the PLSS is installed are reduced to between an austere 14 MT and a more livable 30 MT/year, depending upon the amount of spares and habitability enhancements (*e.g.*, additional showers, plants that enhance food variety, but are not required for life support) included. In open-loop systems, 55 MT need to be delivered annually to support a crew of 10.

Bioregenerative life-support systems. BLSS are designed to produce food and manage waste by employing the natural processes of biological organisms. Plants, fish, animals, or microbes recycle air and water, while physical–chemical or biological processes manage waste.[13] This strategy supports growth, autonomy, and resilience to delays in resupply while also providing the psychological support and variety that a thriving settlement requires. However, the key to enabling this strategy is light for photosynthesis and the delivery of individual greenhouse modules. The practicality of BLSS is heavily dependent on either selecting a site with access to sunlight 24/7 or providing nuclear power.

BLSS also takes a significant investment in emplaced resources. For example, a Bigelow Expandable Activity Module (BEAM)—scheduled to fly on the ISS in 2015[14]—provides the approximate volume necessary to support the food energy for 2 people while removing carbon dioxide, generating oxygen, and cleaning gray water to potable standards. Fully expanded, the BEAM is ~4 m long by 3m in diameter, weighs 1,360 kg, and provides an interior volume of ~28 m^3.[15] Urban indoor farms, employing a technique known as vertical farming, provide a contemporary example of how we can implement BLSS strategies.[16]

Today, vertical farming conserves water—the most intensively used resource in conventional farming—through a closed-loop aquaponic system.[17] The waste produced by a robust fish, tilapia, provides nutrients for the plants to absorb as they clean the water, which then flows back into the tanks. This is currently being done on Earth based on principles demonstrated by NASA's controlled ecological life-support system (CELSS) in the 1990s.[18] In the 1990s, NASA's Ames Research Center and Kennedy Space Center and NASA sponsored research at the University of Utah produced world record wheat yields.[19] Using hydroponic techniques of the kind envisioned for the low-cost lunar settlement, NASA researchers in the 1990s were able to produce all of the food energy needed for a single individual within 10–20 m^3 versus 4,050 m^3 needed for field agriculture. This was done without genetic modification.[20]

However, scientists have known since the early days of the space program that low gravity affects plant metabolism in ways that have not been characterized for the 0.16g of the Moon.[20,21] Before committing to a BLSS, candidate crops need to be grown on the Moon and carefully analyzed for toxins in either off-gassed volatiles or in the edible biomass. While a potential benefit to BLSS is the production of seeds for an expanding population, it is not known whether seeds will set normally or what mutations might occur after multiple generations on the lunar surface.[22]

Nevertheless, contemporary biotech is becoming increasingly sophisticated and it is likely that we will begin to genetically engineer plants for lunar life support.

There are other organisms that offer candidates for BLSS or could be used to support other settlement enterprises. A wide range of natural and engineered organisms could help break down wastes,[23] process regolith, produce propellant, or provide novel biological materials for sale on Earth.[24]

There is an elegant symbiosis between people and plants. We exhale carbon dioxide that plants use in the presence of light to convert CO_2 to sugar and oxygen through photosynthesis. Feces provide the nitrogen and other nutrients required for plant growth. The diversity of plant life offers a wealth of flavors, nutrients, and beauty that can help people thrive in the alien environment of the Moon.

In situ resource utilization. ISRU is the strategy where critical life-support materials (light, power, nutrients, oxygen, and water) are obtained from indigenous resources. While the elements found in the lunar regolith might be important for life support—especially for the expanding population of the Settlement phase—the members of the Low Cost Lunar Settlement working group found that the single most important life-support resource indigenous on the Moon was the availability of near-constant sunlight near the lunar poles.[25] Sunlight provides enough low-cost electrical energy to accelerate implementation of PLSS and photosynthetically important light to BLSS systems through light pipes. For this reason, selecting the right site for settlement is crucial. There is strong evidence that water ice is available in permanently shadowed craters in locations near the lunar poles[26] where sunlight is also available nearly continuously. This could allow settlers to expand their living environment, amplify productivity, and increase their safety and autonomy by living off the land. However, the results from the LCROSS mission indicate that it is unlikely that the water obtained from lunar ice would be potable[25] and is likely to require more challenging processing than simple recycling within the habitat.

Hybrid life support. This life-support strategy uses all of the above at the appropriate times and in appropriate combinations to optimize livability and minimize cost. It is the strategy most likely to be followed during the Settlement phase as lunar occupants discover and learn how to extract and use indigenous resources and novel inventions tailored to the Lunar Settlement arise out of experience and practice.

OTHER CONSIDERATIONS

Although clearly essential to life support for drinking, food preparation, and hygiene, water can also be important for radiation protection, for processing regolith, for electrolyzing into oxygen and hydrogen for rocket fuel, for entertainment, and for many other industrial-class as well as homely tasks.

Bags can be filled with water and used on the outside or inside of habitats to provide necessary radiation protection and as a mechanism for storing water for emergency use.

Biological wastes, such as feces and urine, are sources of carbon, hydrogen, nitrogen, phosphorus, and sulfur, elements that would be useful for a number of settlement activities, such as fuel production and material generation. It might be more advantageous for a settlement to use human wastes for purposes other than life-support recycling.

CONCLUSION

It became clear that selecting the correct life-support strategy was critical to achieving the objectives of the low-cost lunar settlement within the time and budget constraints established. The amount, kind, and quality of life-support constituents needed for individuals to survive are different from those needed for individuals and communities to thrive and for populations to grow. In all cases, surpluses of life-support consumables are needed for emergencies—for example, until supplies can be obtained from Earth or until an evacuation of the population can be achieved. Surpluses are also needed to initiate a habitat when a new individual arrives or to handle the inevitable leaks, losses, and incomplete recycling of life-support materials.

As for financial viability, the recent developments in the emerging space sector, combined with a smart approach to life-support systems, mean that achieving permanent human habitation on the moon is a real possibility. The method—recommended above—of relying primarily on PLSS would require 11–26 MT of equipment to be delivered to Lunar Station in the first year to support a crew of 10 as well as ~14–30 MT of nonrecycled consumables. Thereafter, based on ISS data, resupplying life-support consumables would conservatively require less than 30 MT/year for a crew of 10. Launch costs are going down, but even using today's SpaceX prices of $12.6 M/MT for the Falcon 9 cargo delivery to GTO, providing a comfortable level of life-support capabilities for the first phase of Lunar settlement would cost under $350 M to launch and provide a sound basis for growth of the settlement. Development costs would be negligible because this hardware has already been tested in space for years. This is well within the target of under 5 billion dollars a year for the initial Lunar Settlement.

The most important indigenous resource for ISRU in the early stages of settlement is sunlight. Availability of near-continuous sunlight, even more than the availability of lunar water, was a game changer that enabled a thriving Lunar Settlement model. Most surprising, however, was the observation that all of the life-support technologies needed to develop a low-cost settlement on the Moon are available now and that the effectiveness of PLSS technologies has been proved in space for the past 14 years on the ISS. While more efficient technologies would certainly benefit the settlement, we have access to sufficient life-support technologies to support implementation of the first human settlement on the Moon today.

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Address correspondence to:
Lynn D. Harper
Space Portal
NASA Ames Research Center
MS 555-3
Moffett Field, CA 94035-1000

E-mail: lynn.d.harper@nasa.gov