Design of a Controlled Ecological Life Support System

Regenerative technologies are necessary for implementation in a lunar base CELSS

Steven H. Schwartzkopf

As we approach the beginning of the twenty-first century, the United States moves closer to a new era in space exploration. This new era promises interplanetary transportation and the establishment of outposts on other planets. Success in this exploration depends on many different technologies: some already mature, some currently under development, and others still early in the conceptual stages. Particularly crucial are the technologies that support human life.

Currently, spacecraft life support systems rely on open-loop (nonrecycling) technologies. These are simple and sufficiently reliable for human space-flight missions of relatively short duration, small crew sizes, and limited power availability. Life support technologies for the coming era of exploration, however, must address a different set of requirements. Longer-duration missions, larger crew sizes, and changes in crew complement during the mission will require maximizing crew safety by increasing the degree of self-sufficiency of the life support system, minimizing the economic costs associated with resupply and the accompanying complexity of logistics, and maintaining a familiar, Earthlike living environment to promote human productivity and psychological well-being.

Steven H. Schwartzkopf is leader of the Advanced Life Support Project at Lockheed Missiles and Space Co., Inc., Sunnyvale, CA 94088.

Substantial work should be directed at more efficient food production

This article outlines issues involved in designing a life support system for this new era of exploration. It describes a conceptual design for a controlled ecological life support system that was developed for a lunar base.

The need to recycle

A human requires substantial amounts of consumable materials to sustain life (Table 1). Including oxygen, food, and the water required for food preparation, showers, personal hygiene, and clothes washing, it takes more than 8000 kg to support one person for a year (without recycling). This total does not include the mass of packaging materials or any structural support required to restrain the consumables during launch. In addition, the values presented in Table 1 are estimates for a 70-kilogram person and may increase with changes in factors such as the individual's level of activity and diet (Calloway 1975).

If these consumable materials must all be provided by resupply flights from Earth, a substantial logistics infrastructure is required. In addition, the cost of launching the current Space Shuttle to low Earth orbit is estimated at $11,000 per kg (Bozich 1991). The cost of launching material from Earth to a base on the moon or Mars would be even greater. Consequently, supplying all these consumables from Earth is an extremely expensive proposition. As a result, the development of technologies that recycle wastes and regenerate consumables is both logistically and economically essential.

For what length mission is it economically beneficial to recycle? Myers (1963) developed a method of determining breakeven points (Figure 1). Full recycling would pay off only on long missions, but water recycling and atmosphere regeneration would be worthwhile on shorter missions also.

Available technology and system design

The five basic functions required of any regenerative life support system are atmosphere regeneration, water purification, waste processing, food production, and food processing. The two families of technology available to provide these basic functions of human life support are physicochemical and bioregenerative. Physicochemical technologies include mechanical devices such as fans, pumps, and filters, as well as complete physical or chemical reactors (e.g., incinerators and distillation columns). These technologies tend to be fast acting but are single function and frequently require large amounts of power. Bioregenerative technologies use biological reactors incorporating bacteria, algae, or higher plants to fulfill specific life support functions. They are often characterized by slow reaction rates but are multifunctional and can usually operate with little electrical power.

Although it is conceptually possible to design a life support system based exclusively on either family of technology, analysis indicates that the best design combines the two. By carefully selecting and combining technologies with offsetting advantages and disadvantages, it is possible to develop a hybrid design that offers significant improvement over purely physicochemical or purely bioregenerative systems.

One method of combining these technologies is through the development of a controlled ecological life support system. Such a system combines biological functions such as photosynthesis for CO_2 removal and food and oxygen production, with physicochemical functions such as gas separation and the condensation and collection of water vapor on a cooling coil.

Methods for designing and developing a controlled ecological life support system fall into two categories (Taub 1974). The first category, which may be termed holistic, emphasizes a natural evolutionary development of the bioregenerative technologies (Cooke et al. 1968, Odum 1963). In this method, a variety of living organisms are placed into association with one another inside a closed environment. Through the evolutionary process, the living components of this microcosm (including the crew) mutually adjust to one another. In theory, this adjustment process produces a stable, homeostatic ecosystem at an equilibrium point maintained by internal ecological control mechanisms. A recent example of this approach is Biosphere 2, constructed in the Arizona desert by Space Biospheres Ventures (Augustine 1991, Turner 1989).

The major problem with the holistic approach lies in the designer's inability to direct the outcome of the evolutionary process. There is, for example, no guarantee that human beings would be one of the extant components of such a system once it reached equilibrium. There is also no guarantee that the equilibrium system would include species that were either practical or desirable in a life support context. As a consequence, making use of the holistic approach is a gamble. To maximize the probability of success, it is necessary to maximize the number of trial associations, thus increasing development costs.

In contrast, the alternative reductionist approach emphasizes dividing the system into subsystems for which external, mechanical control mechanisms can be developed (Jones 1975, Krauss 1979, Oswald et al. 1965). These external controls are then applied only when the intrinsic ecological control mechanisms are incapable of sustaining the stability of the life support system. After the development of these external control mechanisms, the subsystems are combined and integrated to produce a functional life support system that includes both internal ecological homeostatic mechanisms and external mechanical controls.

Table 1. Nominal life-support consumables required for a human being (after Modell and Spurlock 1979).

Consumable	Mass (kg/year)
Food (dry mass)	219
Oxygen	329
Drinking water	657
Sanitary water	840
Domestic water	6132

The major advantages of this approach are that it is more cost- and time-efficient than the holistic ap-

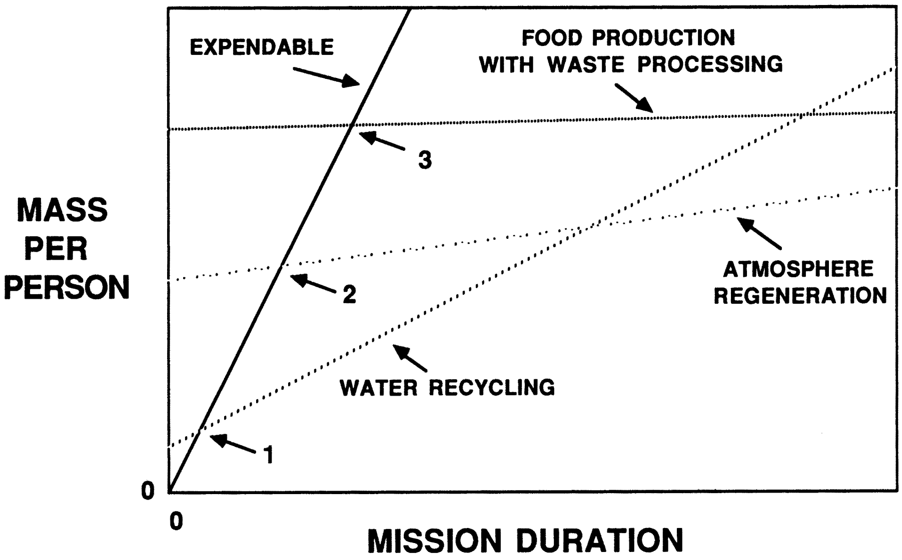


Figure 1. Graphical method for determining the mission durations at which recycling is economically beneficial (after Myers 1963). The mass of consumables plus life support hardware required to maintain one person have been plotted as a function of mission duration (line labeled "expendable"). The y-intercept of this line is the launch mass and is equal to zero at a mission duration of zero (i.e., at launch) for a scenario in which all consumables must be resupplied and no recycling is used. The line has a slope equal to the resupply mass required to support a person over whatever time unit is used to measure the mission duration. To recycle water, regenerative hardware is required. This addition increases the launch mass of the life support system. The need for resupply of consumables is decreased, however, and the slope of the line labeled "water recycling" is therefore decreased. The breakeven point for water recycling is the mission duration at which these two lines cross (labeled "1"). At any mission duration greater than this breakeven point, the total mass required to sustain a person is decreased over a resupply scenario by recycling water. This savings in mass equates directly to an economic savings, because the cost to launch a kilogram of material is approximately constant for a specific launch vehicle. A similar determination can be made by adding the hardware required to regenerate atmosphere (the line labeled "atmosphere regeneration") and that required to produce food and recycle wastes (the line labeled "food production with waste processing"). As increased regenerative capability is added to the life support system, the launch mass increases, but the requirement for resupply of consumables is reduced. Finally, when the water, atmosphere, food, and waste loops are all closed through recycling, the slope of the resupply line approaches zero. The efficiency of recycling dictates how closely the slope approaches zero.

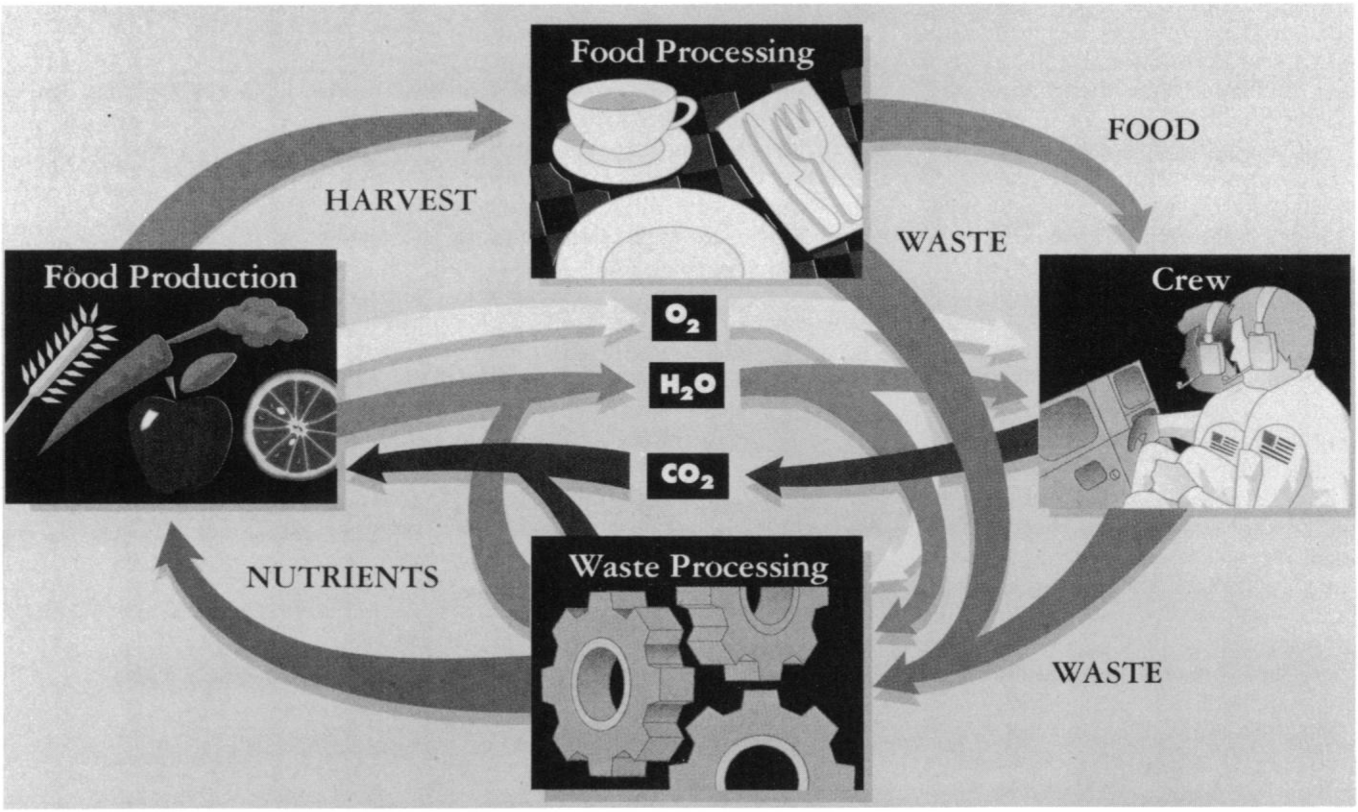


Figure 2. Generic diagram of a CELSS, illustrating primary mass flows among subsystems.

proach and that it produces a system with well-defined, controllable subsystems. The disadvantage is that this approach does not automatically incorporate any capability for establishing natural, ecological control mechanisms in the life support system. Such an omission could lead to problems of incompatibility between system components, or to less-reliable, less-efficient systems to support human life. By careful evaluation and selection of physicochemical and bioregenerative subsystem components, however, it is possible to use this approach to design a life support system that incorporates the benefits of stabilizing, internal ecological control mechanisms while simultaneously maintaining the timeliness and cost-effectiveness of the reductionist approach.

A generalized schematic of a controlled ecological life support system (CELSS) is presented in Figure 2. This figure illustrates the fundamental flows of life support materials through the system. In this example, crop plants are used to produce food for the crew. In addition to serving as the food production subsystem, the plants take up CO_2 produced by the crew, produce oxygen for the crew to breathe and for oxidation of waste materials, and produce water vapor that can be condensed and collected to supply the crew's drinking and hygiene water. In the food-processing subsystem, the foodstuffs produced by the crop plants are converted into a form palatable to the crew. Urine and feces, miscellaneous solid wastes (e.g., tissues, wipes, and writing paper), and waste biomass from the food-processing subsystem are oxidized in the waste-processing subsystem to supply the crop plants with inorganic nutrients and CO_2. Any pure water produced as a byproduct of the waste processor is supplied to the crew or recirculated through the waste-processing subsystem.

Conceptual design of a lunar base system

The objective of the lunar base controlled ecological life support system (LCELSS) study was to develop a conceptual design of a life support system to accommodate a crew that would grow from an initial size of 4 to a total of 100 people at base maturity. Several different preliminary designs were evaluated during the initial part of the study. Based on a series of detailed analyses and tradeoff studies, one of these preliminary designs was selected for the development of a detailed conceptual design (Lockheed 1991; Figure 3).

Food production. One of the key differences between physicochemical and bioregenerative systems is the means of producing food. On current missions, spacecraft crews consume foods stored aboard their spacecraft. Although physicochemical methods of synthesizing carbohydrate, fat, and protein foodstuffs have been developed (Berman and Murashige 1973, Shapira 1967), these methods typically have not produced foodstuffs of acceptable quality. In fact, consumption of many of these synthetic foodstuffs produces undesirable side effects such as nausea and diarrhea (Berman and Murashige 1973). Additionally, many of these syntheses require feedstocks of such high purity that they would be difficult to obtain from life support system waste materials.

The first studies aimed at developing bioregenerative technologies for food production for space use were initiated in the 1960s. The earliest research on food production focused on the use of algae (e.g., *Chlorella*) and small vascular plants of the family Lemnaceae (Miller and Ward 1966, Ward et al. 1963). In both cases, however, the biomass produced was generally found to be physiologically unacceptable as a human foodstuff.

In the past decade, attention has been focused more strongly on the incorporation of crop plants into the design of life support systems. Higher plants present an almost ideal solution to the problem of designing a food production system for space use. Human crews are accustomed to consuming these materials, and so there are no physiological or psychological barriers. Current estimates of the amount of growing area required to feed one person range from 20 to 30 m^2, depending on the species of plants grown. For example, Hoff et al. (1982), proposed a mixture of ten species (soybean, peanut, wheat, rice, potato, carrot, chard, cabbage, lettuce, and tomato) that satisfies all human nutritional requirements and would require approximately 24 m^2 of growing area per person.

Animals may also play a part in food production systems for advanced missions. Previously, the primary objection to their use has been the ecological inefficiency that occurs when moving food energy between trophic levels. As an example, only approximately 10% of the food provided to cattle is converted into edible biomass (Table 2). Thus, it would make more sense, energetically speaking, to feed plant materials to the human crew directly rather than giving them to an animal and then using part of the animal for human food. This concept neglects the idea of using plant parts that humans would not normally consume as animal food. For example, fish and chickens can use such materials as foodstuffs. In addition, several animal species have conversion efficiencies considerably above the 10% value typical of beef cattle (Table 2). Thus, if the proper species are selected, animals can play a substantial role in the food production subsystem.

In the LCELSS conceptual design, two components were selected to produce food: a crop growth unit and an aquaculture unit to grow the fish *Tilapia*. The plant-growth unit was designed to include wheat, soybean, peanut, lettuce, tomato, and carrot. The use of *Tilapia* aquaculture was envisioned as a means of producing a small amount of animal protein for crew consumption. With this set of plant species, supplemented by approximately 50 gm per person per day of *Tilapia* meat and some multiple vitamins, a nutritionally adequate diet can be produced.

To accommodate the increase in crew size from 4 to 100, a series of three plant-growth unit designs was developed. Cross-sections and fundamental design parameters of these three units are given in Figure 4. All of these designs incorporate hydroponic plant-growth techniques. The first de-

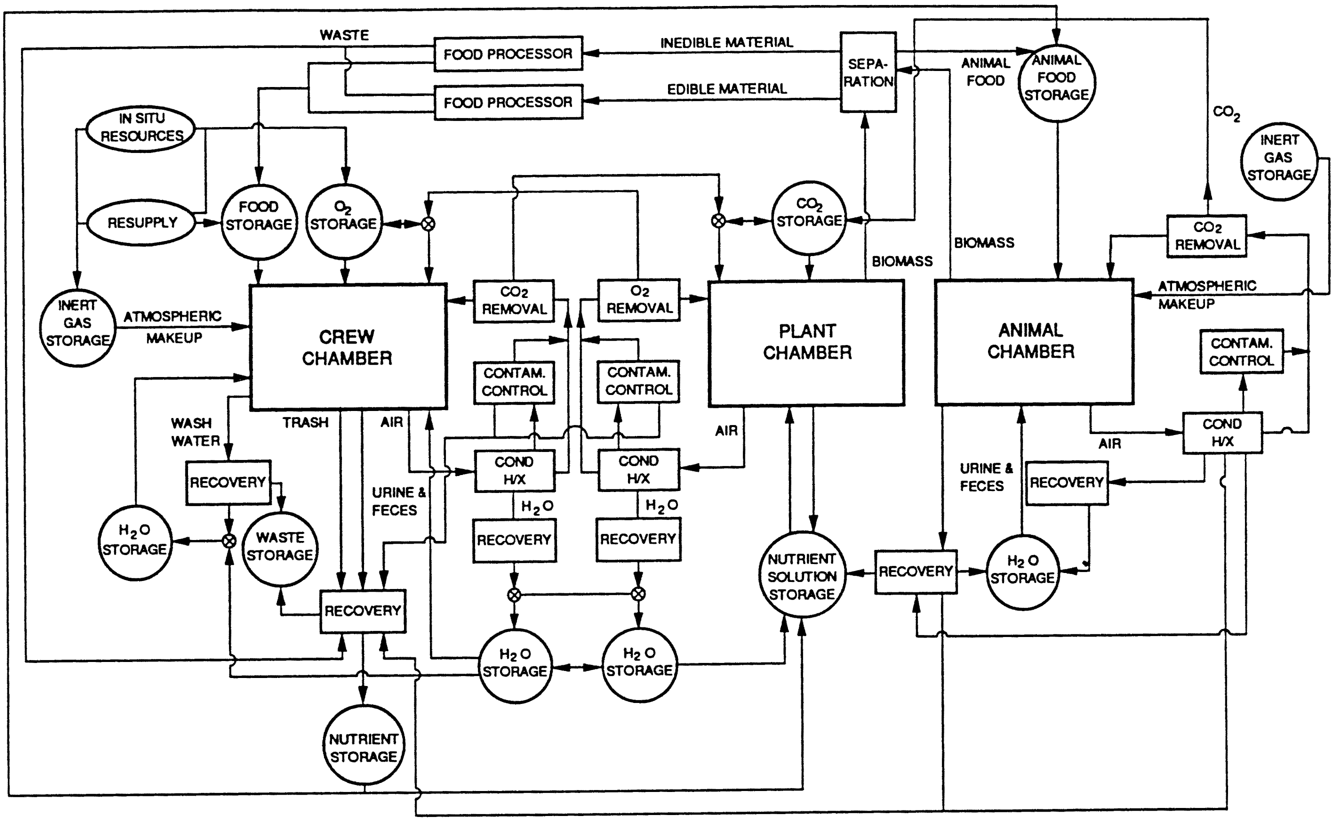
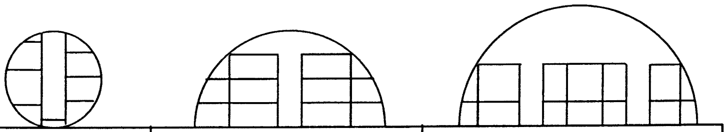


Figure 3. Functional block diagram of the LCELSS conceptual design.



Design Concept / Design Parameter	Space Station Freedom Module	Hybrid - Inflatable with Rigid Backbone	Inflatable
Dimensions	4 m dia x 11.4 m long	8 m wide x 11.4 m long	10 m wide x 60 m long
Growing Area	100 m^2	224 m^2	528 m^2
Mass	12,322 kg	17,999 kg	43,480 kg
Power Maximum Minimum	 69 kw 9 kw	 153 kw 19 kw	 360 kw 43 kw
Volume	143 m^3	287 m^3	2,356 m^3

Figure 4. Cross-sectional diagrams and design parameters of the LCELSS plant growth unit designs.

sign uses a metal pressure hull based on a Space Station *Freedom* module, and it provides approximately 100 m^2 of growing area. This unit (Figure 5) would have both an artificial lighting system and a sunlight collection and distribution system to support photosynthesis.

The second design is a hybrid inflatable/rigid backbone structure with approximately 224 m^2 of growing area. This design uses an aluminum backbone and airlock with the major utility runs premounted, with a tough, polyurethane-coated nylon material as the shell.

The third concept is a large, inflatable unit with approximately 528 m^2 of plant growing area. This design, excluding the airlocks, would be fabricated from polyurethane-coated nylon material. To begin operations, the two inflatable structures require the addition of atmosphere once they are positioned on the moon. These units could make use of direct sunlight during lunar day, either by incorporating a sunlight collection system, like the one pictured in Figure 5, or by direct illumination through the wall. This type of inflatable technology, rather than a hard shell, provides a significant reduction in launch mass. It appears feasible using advanced materials and technologies available today.

To handle the growth in crew size, different combinations of these three plant growth unit designs can be used. For a crew of 4, one of the Space Station *Freedom*–based modules is sufficient. As the crew grows to 30, another Space Station *Freedom* module and three of the hybrid units must be added. Finally, to meet the life support needs of a crew of 100, three of the large inflatable units must be added.

One of the primary drawbacks to the use of higher plants in food production is the need for lighting to support photosynthesis. If artificial lighting is used for the plants, each square meter of growing area will require 0.5 to 1.0 kW of electrical energy to produce the minimal acceptable photosynthetically active radiation (PAR) levels of 300–600 µmol/m^{-2}/s^{-1}, using metal halide or high-pressure sodium lamps. The electrical power required for illumination can be reduced by using natural sunlight during the lunar day and low-intensity artificial lighting (approximately 10–15% of full Earth sunlight intensity) supplemented by higher atmospheric CO_2 concentrations during the lunar night. The LCELSS study identified two feasible methods for using sunlight: one employing direct transmission through the semitransparent, greenhouselike, inflatable structures and the other using sunlight collectors and light conduits as distributors for opaque-walled plant growth units.

Food processing. LCELSS food processing technologies would make the biologically produced materials suitable for human consumption. These technologies may be grouped into two general categories: processing of materials normally edible by humans and conversion of normally inedible materials into edible form. Figure 6 summarizes one plan for coordinating these processes. In this plan, edible materials may be eaten directly after washing, cooked for immediate consumption or for storage and later consumption, or processed to remove a specific component (either to enhance digestibility or to obtain a component for specific uses).

This plan also illustrates how normally inedible materials can be extracted or treated to produce compounds (e.g., carbohydrate, protein, or oil) for human consumption or processed to produce feedstocks for animal consumption. One example of this application is alfalfa, which produces high-protein-content vegetable material. Alfalfa protein content can reach 15–20% by dry mass, whereas wheat is usually 10–15% dry mass protein (Martin et al. 1976). In addi-

Table 2. Efficiency characteristics of various animal species (after Phillips et al. 1978).

Animal or product	Feed conversion efficiency (kg feed/kg gain)	Harvest index*	Production efficiency (kg feed/kg edible mass)
Beef	5.9 ± 0.5	49	10.2
Swine	2.5 ± 0.5	45	5.6
Lamb	4.0 ± 0.5	23	17.4
Rabbit	3.0 ± 0.5	47	6.4
Broiler chicken	2.0 ± 0.2	59	3.1
Eggs	2.8 ± 0.2	90	3.1
Milk	3.0 (dry wt basis)	100	3.0
Shrimp	2.5 ± 0.5	56	4.5
Prawns	2.0 ± 0.2	45	4.4
Catfish	1.5 ± 0.2	60	2.5
Grass carp	1.5 ± 0.2	60	2.5
Tilapia	1.5 ± 0.2	60	2.5

*Harvest index = (edible biomass/total biomass) × 100.

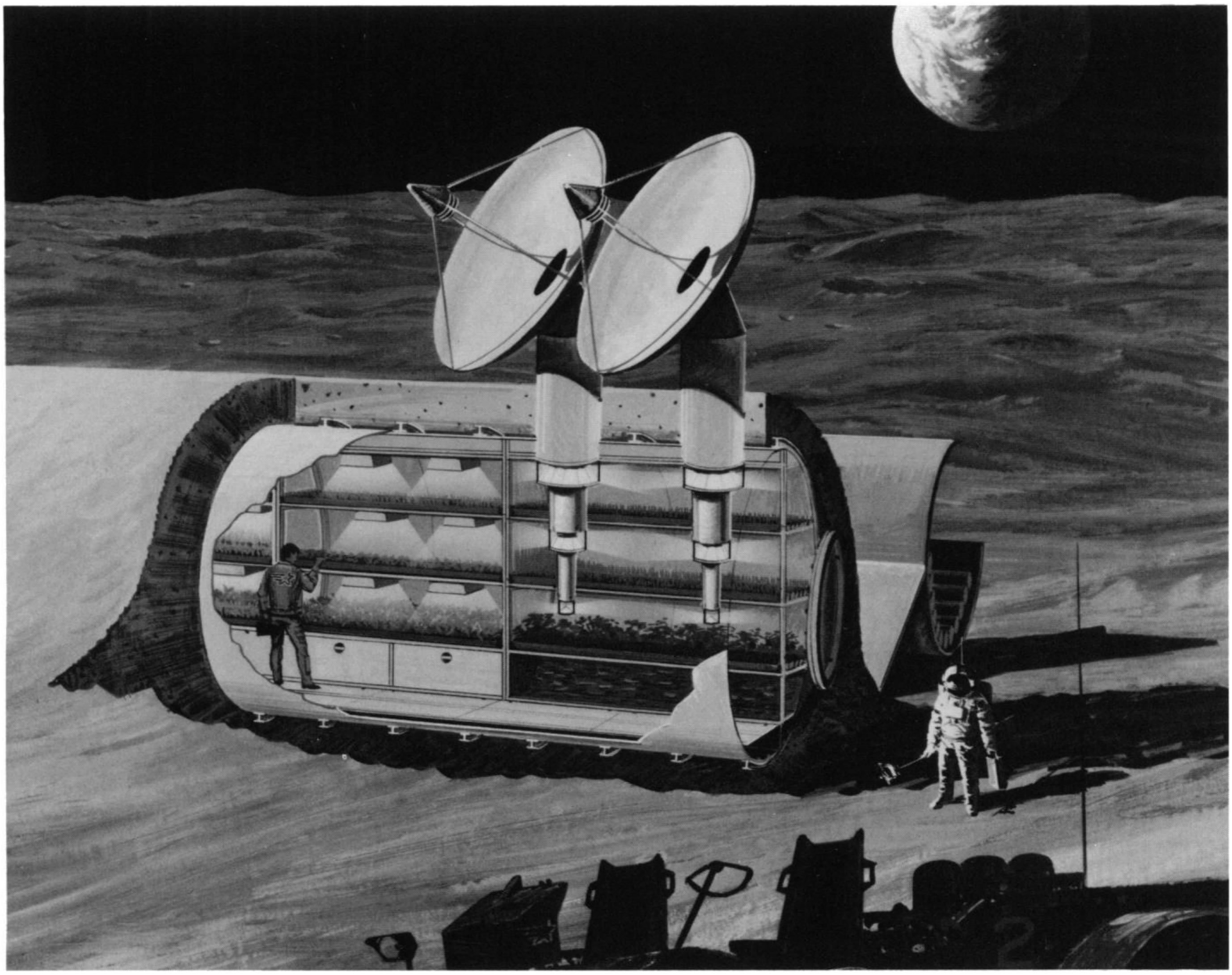


Figure 5. Artist's concept of a Space Station *Freedom* module–based plant growth unit.

tion, alfalfa produces as much as 60% more biomass per unit area than does wheat (Martin et al. 1976). Thus, if the hardware required to extract protein from alfalfa biomass and convert it to human food is included, the potential generation of protein per unit of growing area would be more than twice that of wheat.

For the LCELSS design, however, food processing hardware was minimized to decrease launch mass, and operations such as preparation of grain for milling or fish meat for cooking were assumed to be manual. It was also decided that the human-inedible plant material would be fed to the *Tilapia*. This material could be fed directly or after drying and grinding into smaller pieces.

Atmosphere regeneration. The major operations performed in atmosphere regeneration are the removal of CO_2 and gaseous trace contaminants and the supply of oxygen. Traditionally, physicochemical technologies have been designed to treat removal of CO_2 (Noyes 1987) and the supply of oxygen as separate operations (e.g., Bosch or Sabatier reactors for CO_2 removal and water electrolysis to provide oxygen).

The LCELSS conceptual design for atmospheric revitalization subsystem uses higher plants for all CO_2 reduction and oxygen production. The atmospheres of the crew, plant, and animal chambers are isolated from one another by separate physicochemical CO_2 and oxygen removal systems (liquid scrubber/stripper/concentrators). This atmospheric isolation provides for independent control of the respiratory gas concentrations in the different chambers and helps to prevent potential contamination. Temperature and humidity control are handled by standard condensing heat exchangers. Trace contaminant control is handled by modified Space Station *Freedom* hardware. The trace contaminant control system must be regenerated periodically by applying heat and vacuum to the adsorbent beds. The effluent material would be captured and stored as waste or processed by the waste processing system.

Water purification. The water available for recycling comes from three primary sources: humidity conden-

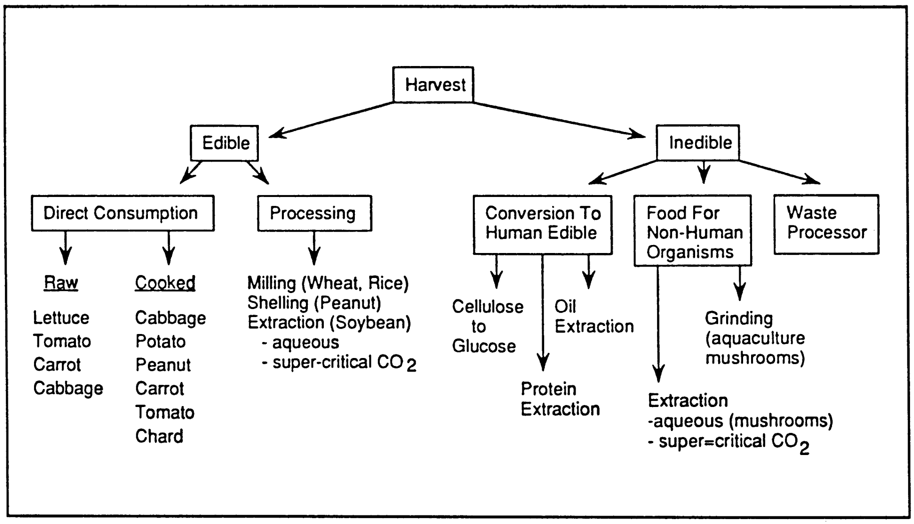


Figure 6. Food processing subsystem flow chart.

sate, wash water, and urine. In addition, water from fuel cells or from physicochemical CO_2 reduction can also be recycled when it is available (Cullingford and Novara 1988). A number of physicochemical technologies have been developed for water recycling. These technologies include simple distillation, filtration (e.g., reverse osmosis and multifiltration) and phase change processes (e.g., vapor compression distillation; Friedman et al. 1992).

Water reclamation by higher plants is the primary method of purification in the LCELSS conceptual design. Plants supply essentially pure water through the transpiration process. Typically, plants transpire between 200 and 1000 liters of water for each kilogram of dry biomass they produce (Martin et al. 1976). Thus, water processing with higher plants involves using mixtures of gray and black water, then condensing and collecting their transpiration water on a condensing heat exchanger.

In the conceptual design, drinking and food-preparation water are obtained by polishing condensate collected from the crew chamber or cabin to remove trace organic chemicals. Because the volume of condensate water is not sufficient to fill the need for drinking and food preparation, the LCELSS design provides for the required makeup by recovering condensate from the plant growth chamber and purifying it with the same systems. Hygiene and clothes wash water are taken from the plant condensate collection and treated by ultraviolet light polishing to remove bacteria and degrade trace organic compounds. The remainder of the condensate from the plant chamber and aquaculture unit is recycled by return to the hydroponic nutrient solution or by addition to the aquaculture system to make up for evaporative losses.

Waste processing. Historically, the short duration of missions has provided little impetus for waste processing. On most flights, feces and solid wastes were simply stored for return to Earth. Several physicochemical technologies have been investigated for processing and recycling solid wastes. They include dry oxidation (incineration), wet oxidation, and supercritical wet oxidation. These high-energy methods generally convert organic waste materials into inorganic salts, water, and gases.

One of the most promising technologies for CELSS application, low-pressure wet oxidation, is typically carried out at conditions below 230° C and below 3460 kPa (500 psi). The process breaks down organic material through a combination of hydrolysis and oxidation. Because low-molecular-weight compounds such as acetic acid tend to be refractory to the process, low-power wet-oxidation processes lead to lower oxidation efficiency. The result is a breakdown of solids and reduced oxidation demand, with a product liquor containing a mixture of inorganic salts and soluble low-molecular-weight organics that are refractory to the process.[1]

Bioregenerative technologies for waste processing include bacterial reactors and combination higher plant–bacterial systems. Bacterial reactors, both aerobic and anaerobic, have an extensive history of application in domestic sewage treatment plants. Aerobic systems typically require higher energy inputs to maintain oxygenation (e.g., aerating pumps and mixers). Anaerobic systems require little energy, but they have slow process rates, and the anaerobic bacteria are more susceptible to changes in environmental conditions (Wolverton et al. 1983). Combining higher plants with anaerobic bacterial systems provides several distinct advantages.

Table 3. Elemental composition of lunar regolith (after Phinney et al. 1977).

Element (%)	Mare High Ti A-11	Mare High Ti A-17	Mare Low Ti A-12	Mare Low Ti A-15	Mare Low Ti L-16	Basin Ejecta A-14	Basin Ejecta A-15	Basin Ejecta A-17
Al	7.29	5.80	7.25	5.46	8.21	9.21	9.28	10.90
Ca	8.66	7.59	7.54	6.96	8.63	7.71	6.27	9.19
Cr	0.21	0.31	0.24	0.36	0.20	0.15	0.19	0.18
Fe	12.20	13.60	12.00	15.30	12.70	10.30	9.00	6.68
K	0.12	0.06	0.22	0.08	0.08	0.46	0.14	0.13
Mg	4.93	5.80	5.98	6.81	5.30	5.71	6.28	6.21
Mn	0.16	0.19	0.17	0.19	0.16	0.11	0.12	0.08
Na	0.33	0.26	0.36	0.23	0.27	0.52	0.31	0.30
O	41.60	39.70	42.30	41.30	41.60	43.80	43.8	42.20
P	0.05	0.03	0.14	0.05	0.06	0.22	0.07	0.06
S	0.12	0.13	0.10	0.06	0.21	0.08	0.08	0.06
Si	19.80	18.60	21.60	21.5	20.50	22.40	21.70	21.00
Ti	4.60	5.65	1.84	2.11	2.11	1.02	0.79	0.97

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[1] R. A. Lamparter, 1991, personal communication. NASA Ames Research Center, Tucson, AZ.

Most significant is the capability for increasing the removal of NH$_3^-$ and NO$_3^-$ nitrogen over that obtained with bacterial systems without plants (Wolverton et al. 1983). However, such systems are less efficient in removing carbonaceous compounds than are plant-free bacterial systems.

The waste processor used in the LCELSS conceptual design was a low-pressure wet oxidation system. This system receives all solid waste materials not fed to the aquaculture unit. These solid wastes include metabolic wastes produced by crew, animal, and plant physiological activities and the nonmetabolic waste materials such as those derived from packaging materials and daily crew activities. The wet oxidation unit degrades these materials and then supplies the effluent to the plant growth chamber for addition to the hydroponic nutrient solution, where the effluent materials are further processed by bacteria and the plants.

Table 4. Elemental composition of plant and human tissue (after Epstein 1972).

Element	*Zea mays*	Man	Sucrose	Fat	Protein
O	44.43	14.62	51.42	11.33	24
C	43.57	55.99	42.10	76.54	52
H	6.24	7.46	6.48	12.13	7
N	1.46	9.33			16
Si	1.17	0.005			
K	0.92	1.09			
Ca	0.23	4.67			
P	0.20	3.11			
Mg	0.18	0.16			
S	0.17	0.78			1
Cl	0.14	0.47			
Al	0.11	–			
Fe	0.08	0.012			
Mn	0.04	–			
Na	–	0.47			
Zn	–	0.01			
Rb	–	0.005			

Table 5. Detailed LCELSS mass estimates for three different crew sizes.

	Estimated mass by crew size (kg)		
Subsystem/component	4	30	100
Plant growth unit(s)	12,322	78,641	209,081
Solid waste processing	63	273	808
Atmosphere regeneration	271	1169	3016
Water purification	31	233	778
Aquaculture (*Tilapia*)	1366	10,169	33,695
Food processing	26	52	122
Inflation gas	N/A	1446	12,014
90-day food reserve	565	4239	14,130
30-day oxygen reserve	394	2952	9840
Totals	15,038	99,174	283,484

In situ resource utilization

Although not technically a part of the life support system, an area that may significantly affect the ultimate design and operation of a lunar base life support system is in situ resource utilization (ISRU). One of the significant design advantages resulting from establishing a base on the lunar surface involves the availability of in situ resources. Table 3 summarizes the elemental composition determined for regolith samples obtained from the Apollo and Luna missions. Table 4 summarizes the elemental composition by percent of a typical plant (corn), a human, carbohydrate (sucrose), fat, and protein. From the plant composition values presented, more than 95% of plant biomass is composed of oxygen, carbon, hydrogen, and nitrogen. More than 87% of human biomass is composed of these same four elements. Thus, on a mass basis, these four elements are the most important to LCELSS implementation. Of the four, only oxygen is present in lunar regolith in large amounts.

The extraction of oxygen from regolith must be the initial target for ISRU technology development. Although trace amounts of carbon, hydrogen, and nitrogen may be extracted from lunar regolith, these elements will have to be supplied from Earth initially. As capabilities for resource extraction develop, however, there will be less need to rely on supplying even these constituents from Earth.

The LCELSS conceptual design includes two methods by which oxygen can be added. First, oxygen can be directly added to the crew atmosphere as required. Second, the atmosphere control subsystem includes an oxygen storage buffer to which oxygen from ISRU could be added. The conceptual design assumed that, at worst, the oxygen would be isolated by the same kind of component used to isolate oxygen from the plant growth unit. At best, the oxygen stream from the ISRU technology would be filtered to remove particulates and then added to the crew chamber or buffer. Both interfaces are simple and direct and neither involves any unique or specific hardware.

Because carbon, hydrogen, and nitrogen are available in regolith at much lower concentrations, the implementation of ISRU technology for their extraction is a lower priority than that for oxygen. The addition of nitrogen to the LCELSS would be as straightforward as the addition of oxygen and should require no unique hardware. Carbon and hydrogen addition would be easiest as CO$_2$ and water, respectively. Specific hardware would be required to oxidize either element before adding it to the LCELSS; however, addition of the compounds themselves presents no problems because storage buffers for both water and CO$_2$ exist in the conceptual design.

Table 6. Estimated LCELSS power requirement for three different crew sizes.

	LCELSS power requirement (kW)	
Crew size	Lunar night maximum power	Lunar day minimum power
4	72	12
30	617	94
100	1700	226

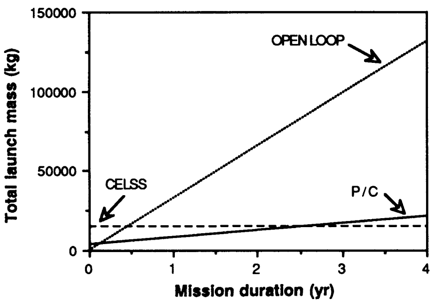

Figure 7. Cumulative launch mass of open loop, partially closed (P/C) and closed-loop (CELSS) life support systems for a four-person lunar base as a function of mission duration.

A greater challenge for ISRU, is the recovery of plant macro- and micronutrient elements from regolith. The interfacing requirements for this type of technology are difficult to derive, because the form of the elements after extraction determine the method of addition to the LCELSS.

LCELSS design characteristics and breakeven analysis

The estimated masses of the LCELSS to support crew sizes of 4, 30, and 100 are given in Table 5. The plant-growth units constitute the largest subsystem in all three cases. In the 4-person crew, the plant-growth unit accounts for approximately 82% of the total life support system mass, whereas for the 30- and 100-person crew sizes, the plant growth subsystems account for 79% and 74%, respectively, of the total mass. This percentage decrease is due to the addition of the larger, but lighter, plant-growth unit designs as the base nears maturity. The second largest subsystem is the aquaculture unit, which comprises 9–12% of the total life support system mass.

The food and oxygen reserves were calculated for different time intervals. Food was calculated on a 90-day basis, because any problem with the food production system might take up to one full crop cycle (expected to be 60–90 days) to return to equilibrium. Oxygen production, in contrast, was calculated to be adequate to support the crew's requirement approximately 30 days after starting a new crop.

Estimates of the electrical power required to operate the life support system for these three crew sizes is given in Table 6. The maximal power values would be required only during lunar night, when the plants would be provided with PAR by artificial lights. The use of sunlight to supply PAR for the plants dramatically decreases the total power requirement for the life support system.

To calculate the potential mass savings that an LCELSS would produce, a breakeven analysis was performed using the life support mass estimates for a four-person crew. Figure 7 illustrates the cumulative mass of life support materials required by four people as a function of time, if no recycling is used. If equipment to recycle air and water is added, the initial launch mass increases, but the cumulative amount of life-sustaining materials launched during the mission is lower. The breakeven point of one month shows that the total mass of a longer mission will be lower for a partially recycling system than for 100% resupply from Earth. By the same token, if a completely recycling system for atmosphere, water, food, and waste is transported to the moon, the breakeven points are five months relative to the 100% resupply and 2.5 years relative to the partial recycling (air and water only) system. Thus, in terms of the cumulative launch mass savings, a completely recycling LCELSS makes sense for any mission of 2.5 years duration or longer.

Conclusions

The focus of the LCELSS study was the development of a conceptual design for a safe, reliable, recycling life support system based on hybrid physicochemical/bioregenerative technologies. The study concluded that implementation of a CELSS approach for a lunar base is not only feasible but eminently practical. On a cumulative launch mass basis, a 4-person controlled ecological life support system would pay for itself in approximately 2.6 years, when compared with a physicochemical life support system with food resupply. For crew sizes of 30 and 100, the breakeven points are even lower (2.1 and 1.7 years, respectively).

Two other conclusions are particularly important with regard to the orientation of future studies, research, and technology development. First, the LCELSS mass estimates indicate that a primary design objective in implementing this kind of system must be to minimize the mass and power requirements of the food production plant growth units, which far overshadow those of the other life support subsystems. As a result, substantial work should be directed at identifying ways to produce food more efficiently. It is particularly important that technologies chosen for the other subsystems be integrated with the most efficient food production methods.

Second, this study illustrates that existing or near-term technologies are adequate to implement an LCELSS; no new technologies are required. There are, however, several areas in which new materials and technologies could be used to more efficiently implement an LCELSS (e.g., by decreasing mass or power requirement or by increasing recycling efficiency). These areas should be addressed through research and development.

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