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# Life Support and Self-Sufficiency in Space Communities

Karl R. Johansson

The development of a controlled ecological life support system (CELSS) is necessary to enable the extended presence of humans in space, as on the Moon or on another planetary body. Over a long period, the provision of oxygen, water, and food, and protection from such inimical agents as radiation and temperature extremes, while maintaining the psychological health of the subjects, becomes prohibitively expensive if all supplies must be brought from Earth. Thus, some kind of a regenerative life support system within an enclosure or habitat must be established, thereby cutting the umbilicus to Mother Earth, but not irreversibly. This protective enclosure will enable the survival and growth of an assemblage of terrestrial species of microorganisms, plants, and animals. I envision that the nonterrestrial ecosystem will evolve through the sequential introduction of terrestrial and local materials, together with the appropriate living forms.

## Lunar Characteristics

The principal constraints on life on the Moon are (1) a hard vacuum;
(2) apparent lack of water;
(3) lack of free oxygen, (4) paucity of hydrogen, carbon, and nitrogen;
(5) intense radiation, periodically augmented by solar flares;
(6) wide temperature fluctuations at extremes harmful to life;
(7) a 2-week diurnal rhythm; and
(8) gravity only 1/6 that on Earth.

***17th-Century Vision of Life on the Moon***

*In this fanciful picture of life on the Moon by a 17th-century artist, none of the constraints we now know of are in evidence. The atmospheric pressure appears to be just right for bird flight. Water is plentiful. The cloud of smoke testifies to the presence of carbon and oxygen. The hydrogen and nitrogen needed to sustain plant and animal life are apparent in the lush growth, including the pumpkin-like abodes for the human inhabitants and the cloth flags (or is it the wash?) hung out on poles and limbs. These inhabitants seem to need no heavy clothing to protect them against hazardous radiation or temperature extremes. Though there may be a long night ahead, this scene seems set in the middle of a long, lazy day. And gravity, though not strong enough to pull a "pumpkin" off a tree, is sufficient to hold the people to the floor of their barge, bridge, or balcony.*

*Artist: Filippo Morghen*

*Source of illustration: Library of Congress, Rare Book Division*

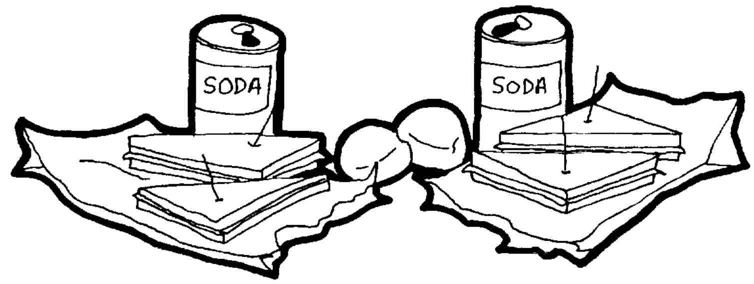
*Taken from Davis Thomas, ed., 1970,* Moon: Man's Greatest Adventure *(New York: Harry N. Abrams, Inc.), p. 69.*

## Chemistry and Nutrition

Lunar regolith as a cover for the habitat would shield the ecosystem from radiation and from both high and low temperatures. The enclosure would need to be airtight to contain a life-sustaining atmosphere of $O_2$, $CO_2$, $N_2$, and $H_2O$ vapor. Presumably oxygen would be provided through the reductive processing of oxide ores. From a hydrogen reduction process, the product water could be used. With the establishment in the enclosure of photosynthesis by eucaryotes (algae and higher plants), reliance on ore processing for life-support oxygen would diminish, although that capacity should remain in place as a backup. Additional water, as needed, would continue to be provided externally, although the amounts would be small because, in a properly functioning CELSS, all water is recycled and appropriately treated to render it potable (free of infectious or toxic agents).

The lunar regolith could also provide elements implanted there by the solar wind. These elements include hydrogen and carbon, which could be used to manufacture water and carbon dioxide, and gaseous nitrogen (see box). However, the levels of these elements are low (100-150 ppm), and thus their recovery may prove to be uneconomical. In that case, they would have to be transported from Earth until the CELSS matured. Even then, more oxygen, carbon, and nitrogen would need to be introduced into the system periodically as the human and domestic animal population of the habitat increased or as the recycling process became imbalanced. As with oxygen, tanks of compressed carbon dioxide and nitrogen should be on hand to cope with such perturbations. Both air and water would need to be biologically and chemically monitored.

The Moon contains all of the "trace elements" known to be necessary for life; e.g., magnesium, manganese, cobalt, tin, iron, selenium, zinc, vanadium, and tungsten. The trace elements are absolutely critical to all species of life, largely as cofactors or catalysts in the enzymatic machinery. While their diminution would slow down the ecosystem, a sudden flush of certain trace elements known to be toxic above certain concentrations would be detrimental to some of the component species. I hope that the microbial flora which becomes established in the ecosystem will be able to minimize the extent of fluctuation of the trace elements through its collective adsorptive and metabolic functions. This issue will need to be considered in the selection of the microbial species for introduction into the CELSS.




***Lunar Lunch***

*The Moon has been underrated as a source of hydrogen, carbon, nitrogen, and other elements essential to support life. Each cubic meter of typical lunar soil contains the chemical equivalent of lunch for two—two large cheese sandwiches, two 12-oz. sodas (sweetened with sugar), and two plums, with substantial carbon and nitrogen left over.*

*Although no free water has been found on the Moon, its elemental constituents are abundant there. One constituent, oxygen, is the most abundant element on the Moon; some 45 percent of the mass of lunar surface rocks and soils is oxygen. The other constituent, hydrogen, is so scarce in the lunar interior that we cannot claim to have measured any in erupted lavas. Nevertheless, thanks to implantation of ions from the solar wind into the grains of soil on the lunar surface, there is enough hydrogen in a cubic meter of typical lunar regolith to yield more than 1-1/2 pints of water.*

*Similarly, carbon and nitrogen have also been implanted from the solar wind. The amount of nitrogen in a cubic meter of lunar regolith is similar to the amount of hydrogen—about 100 grams, or 3 percent of the nitrogen in a human body. The amount of carbon is twice that; the carbon beneath each square meter of the lunar surface is some 35 percent of the amount found tied up in living organisms per square meter of the Earth's surface.*

*All of these elements except oxygen can be extracted from the lunar soil simply by heating it to a high temperature (> 1200°C for carbon and nitrogen), and some oxygen comes off with the hydrogen. Thus, the problem of accessibility of hydrogen, carbon, and nitrogen reduces to one of the economics of heating substantial quantities of lunar soil, capturing the evolved gases, and separating the different gaseous components from each other. Although water could no doubt be extracted from martian soil at a much lower temperature and organic compounds could probably be extracted at a somewhat lower temperature from an asteroid that proved to be of carbonaceous chondrite composition, the Moon is much closer than Mars and its composition is much better known than that of any asteroid.*

*Collection of even a small fraction of the Moon's budget of hydrogen, carbon nitrogen, phosphorus, sulfur, and other elements essential to life into a suitable environment on the Moon would support a substantial biosphere.*

*Taken from Larry A. Haskin, 1990, Water and Cheese From the Lunar Desert: Abundances and Accessibility of H, C, and N on the Moon, in* The 2nd Conference on Lunar Bases and Space Activities of the 21st Century *(in press), ed. W. W. Mendell (Houston: Lunar & Planetary Inst.).*

### Radiation

The surface of the Moon receives from the Sun lethal levels of high-energy electromagnetic radiation, frequently exacerbated by solar flares of varying duration. Without appropriate protection, no living creature, from microbe to man, could survive the onslaught of this radiation. It has been estimated that approximately 2 meters of regolith will absorb this radiation, thereby protecting the human and nonhuman occupants.

Just how much radiation will penetrate various protective shields still needs to be determined. Undoubtedly, radiation-induced mutations will occur; some will be lethal; others may be incapacitating; and still others may result in mutants better able to cope with the lunar environment than the parental organisms. Of particular concern is the likelihood of mutation among many of the microorganisms constituting the ecosystem, thereby endangering the cycling of the critical elements in the lunar CELSS.

### Temperature

With proper attire, humans can withstand, at least for short periods, temperature extremes as high as 50°C and as low as -90°C. The extremes on the Moon exceed these limits by a wide margin. Moreover, other species within the CELSS module would be either killed or suppressed by such extreme temperatures. Obviously, the temperature of a CELSS must be maintained within a moderate range, such as 15 to 45°C, to enable the growth and reproduction of living forms. While many types of psychrophilic and thermophilic microorganisms abound on Earth, their introduction into the CELSS would be useless because neither the food crops to be grown therein nor the human beings harvesting those crops can withstand the temperatures they require.

Regulation of the temperature within a CELSS must take into account radiant energy from the Sun and the release of energy from biological and mechanical activity within the confines of the habitat. The former can be minimized by the protective blanket of regolith required for radiation protection. Efflux of heat from the interior of the habitat may require provision of active or radiative cooling.

## Energy for Life

All living forms require an adequate food supply and a source of energy. Among animals and humans, energy is derived from the metabolism of various organic constituents of the diet; e.g., carbohydrates, lipids, proteins, and other nutrients. While many microorganisms gain energy (and carbon) from the oxidation of organic compounds, including methane, many also derive energy from the oxidation of reduced inorganic compounds; e.g., sulfides, ammonia, nitrites, $Fe^{++}$, and hydrogen. Photosynthetic forms of life (some bacteria, the algae, and the higher plants) can convert photons of energy into chemical bond energy with the photolysis of water and the evolution of molecular oxygen. The energy thus realized is used in the synthesis of carbohydrate (from carbon dioxide and water), which the plants can further metabolize to meet their needs or which can be eaten by animals and humans to supply their energy needs.

It is clear that the requirements for food and energy are interrelated and that the various metabolic processes in the complex food chain affect the availability of nutrients to all the species. Light is a particularly important source of energy because the process of photosynthesis must go on in order for molecular oxygen, required by all but the anaerobic forms of life (principally bacteria), to be regenerated from water. It will probably be necessary, however, to regulate the light synchrony if crop production is to be successful, because 2 weeks of dark and 2 of light will not enable normal plant growth, though special strains might be developed. At the poles, perpetual sunlight could probably be obtained on selected mountains, thus enabling an Earth-like photocycle to be created by periodic blocking of the sunlight (see fig. 5). Elsewhere, artificial light will have to be used to break up the 2-week night.

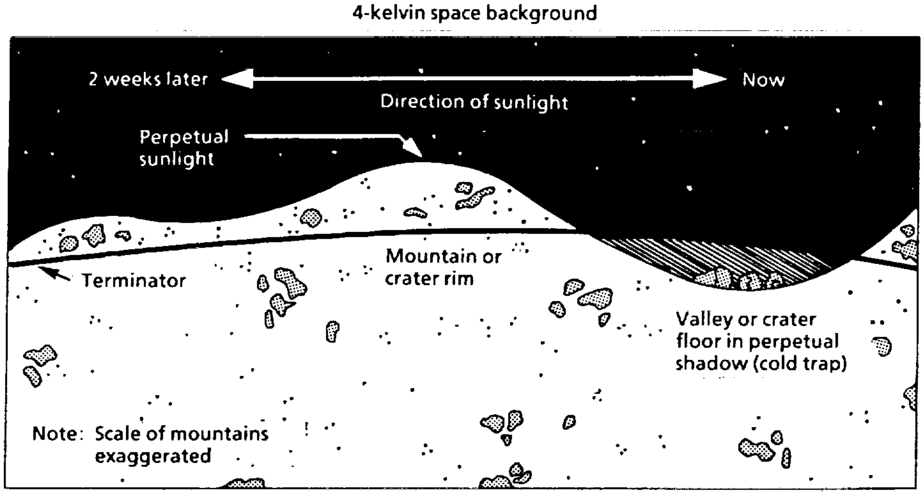
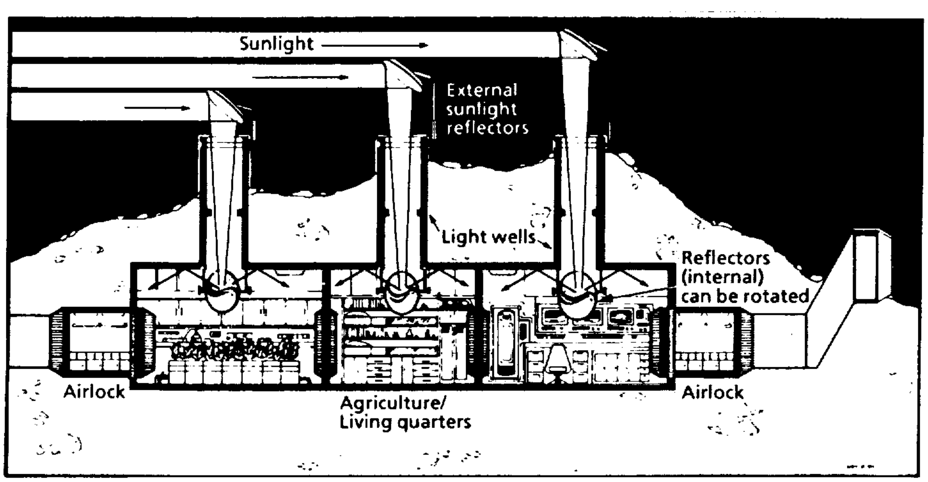



Figure 5

**a. Lunar Polar Illumination**

*The Moon's diurnal cycle of 14 Earth days of sunlight followed by 14 Earth days of darkness could be a problem for siting a lunar base dependent on solar energy or cryogenic storage. A site that might obviate this problem would be at one of the lunar poles. At a pole, high points, such as mountain tops or crater rims, are almost always in the sunlight and low areas, such as valleys or crater floors, are almost always in the shade. The Sun as seen by an observer at the pole would not set but simply move slowly around the horizon. Thus, a lunar base at a polar location could obtain solar energy continuously by using mirrors or collectors that slowly rotated to follow the Sun. And cryogens, such as liquid oxygen, could be stored in shaded areas with their constant cold temperatures.*




**b. Polar Lunar Base Module**

*Light could be provided to a lunar base module located at the north (or south) pole by means of rotating mirrors mounted on top of light wells. As the mirrors tracked the Sun, they would reflect sunlight down the light wells into the living quarters, workshops, and agricultural areas. Mirrors at the bottom of the light wells could be used to redirect the sunlight or turn it off.*

## Gravity

Investigations of the effects of reduced gravity (0.167 $g$ on the Moon) on human physiology and performance and on fundamental life processes in general are being supported and conducted by NASA. Astronauts from the Apollo and other short-term space missions have experienced the well-known, and reversible, vestibular effect (motion sickness) and cephalic shift of body fluids (facial puffiness, head congestion, orthostatic intolerance, and diminution of leg girth). (See figure 6.) Longer-term weightlessness, as experienced by the Skylab astronauts and the Salyut cosmonauts, is more complex, resulting in cardiovascular impairment, atrophy of muscle, reduction in bone mass through osteoporosis (loss of calcium), hematologic changes (leading to immunosuppression and diminished red blood cell mass), neuroendocrine perturbations, and other pathophysiological changes. Some of these effects may be minimized by routine exercise, and apparently all are reversible, in time, upon return to 1 $g$. The response of plants, microorganisms, and "lower forms" of animal life to micro- or zero gravity has been investigated on Skylab, on Space Shuttle missions (see fig. 7), and in simulations on Earth, during parabolic flight of aircraft or in a "clinostat." Unless humans and other life forms can adapt to zero $g$, or to low $g$ as on the Moon or Mars, it may be necessary to provide rotating habitats to achieve the desired gravitational force, as many authorities have long proposed.

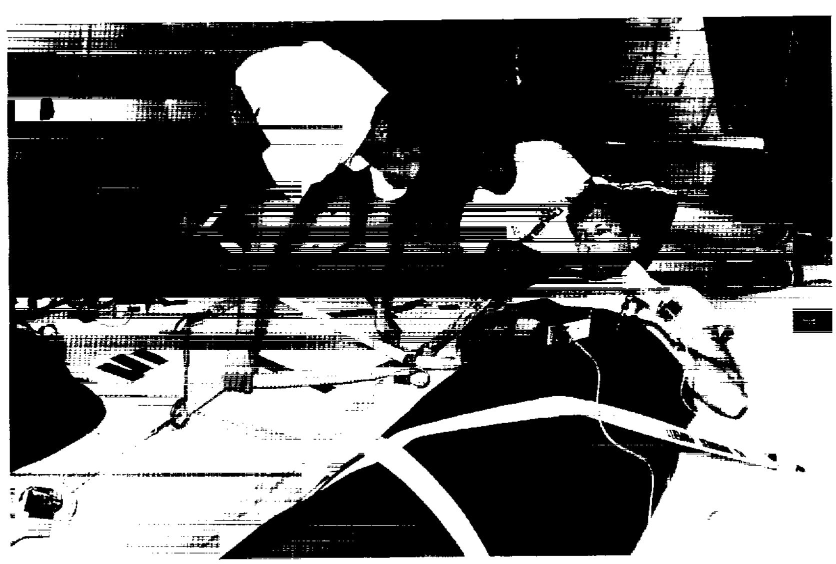


*Figure 6*

***Lower Body Negative Pressure Device***

*Principal Investigator John Charles tries out the lower body negative pressure device on a parabolic flight of the KC-135, while its designer, Barry Levitan, looks on from behind him, with project engineer Pat Hite on the side. This accordion-like collapsible version of a device used on Skylab creates a vacuum that pulls the subject's blood into the lower half of the body, just as if the person had suddenly stood up. Its purpose is to prepare the astronaut for return from weightlessness to Earth's gravity and keep that person from blacking out. Mission Specialists Bonnie Dunbar and David Low tested the lower body negative pressure device, which was fabricated at the Johnson Space Center, on Space Shuttle flight 32, January 9-20, 1990.*

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*Figure 7*

***Seedlings Grown on Spacelab 1***

*These seedlings of* Helianthus annuus *(dwarf sunflowers) were planted by Payload Specialist Ulf Merbold for Heflex, the Helianthus Flight Experiment, conducted in Spacelab 1. Upon being removed from the gravity-inducing centrifuge on which they had sprouted and being placed in microgravity, these seedlings continued to circumnutate, thus proving that Charles Darwin was right in thinking that this spiral growth process is intrinsic to plants, not a response to gravity. The curvature of the seedlings is their response to gravity upon return to Earth at the end of Space Shuttle flight 9, November 28-December 8, 1983.*

*Heflex is part of an ongoing study of plant response, which will continue in IML-1, the International Microgravity Lab, to be flown on the Space Shuttle in 1991. In two experiments in the part of IML-1 called the Gravitational Plant Physiology Facility, scientists will try to determine the threshold at which oat seedlings can detect gravity and the threshold at which wheat seedlings respond to blue light in the absence of gravity.*

*Photo: David K. Chapman, Co-Investigator*

## Selection of Species for an Ecosystem

The greatest challenge in the ultimate establishment of a true space habitat is the creation of a functioning, reliable ecosystem, free, insofar as possible, of pathogens, noxious plants, venomous insects, etc. Moreover, the integrity of a working ecosystem would need to be preserved and its functions monitored regularly.

While it is easy to propose the inclusion of particular species of bacteria, fungi, algae, and higher plants, each of which performs a particular biochemical function in the recycling of nutrients, no rationale exists by which one can predict which particular combination of species would be compatible under the conditions extant in the lunar environment. Considerably more research must be done on closed and semi-closed ecosystems before the organisms for a lunar CELSS are selected (see fig. 8). Conceivably, any number of combinations of species may be found to work well. One point must be stressed: More than one species of organism must be selected to carry out each particular function. Thus, several species of photosynthetic, nitrogen-fixing, nitrifying, or sulfur-oxidizing bacteria must be included. Likewise, a number of species of algae and higher plants, each with the common characteristic of being photosynthetic, must be introduced into the community. Such redundancy, which exists to a vast degree on Earth, provides a kind of buffer in case some of the species lose their niches in the ecosystem and die.

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*Figure 8*

***Zeoponics Plant Growth Chamber at NASA's Johnson Space Center***

*In this step toward a controlled ecological life support system (CELSS) for a lunar base, plants are being grown in varying mixtures of zeolite and quartz sand. (Zeolite is an aluminosilicate mineral that is able to freely exchange constituent ions with other ions in solution without any apparent change in its mineral structure.) Wheat plants (soft red winter wheat, Coker 68-15) have shown the most favorable response in zeoponics systems consisting of 25 to 75 percent zeolite compared to other zeolite treatments and a commercial potting soil. This research is being conducted by Doug Ming and Don Henninger.*

## Some Special Aspects of Life in the CELSS

In the first place, the smaller the CELSS, the more magnified becomes any biological, chemical, or physical aberration. No doubt human occupants of the first CELSS module would need more help from the outside at the beginning than they would later on, when numerous connected modules were in place.

The dieback of some support species may well occur from time to time. This would need to be monitored, so that appropriate measures could be taken to reintroduce another strain of the lost species or to introduce an entirely different species with comparable biochemical properties. Reasons for loss of a species in an artificial ecosystem include (1) mutation, (2) temporary tie-up of a critical nutrient, (3) a flush of toxic ions or compounds, (4) malfunction of the temperature control system, (5) a sudden shift in the synchrony of food cycling, and (6) infection or toxemia. The last reason may be particularly troublesome since it will not be possible to assure the exclusion of infectious or toxic microorganisms from the habitat. Many members of the body's normal microflora are opportunistic and can, under certain circumstances, cause disease. Also, plant diseases may emerge if care is not exercised in the initial entry of seeds or of other materials which may contain plant pathogens.

Any animals (e.g., chickens, goats, dwarf pigs) ultimately selected for the space habitat should have been raised in a pathogen-free environment on Earth and tested thoroughly for the presence of any microbial pathogens before their introduction. Gnotobiotic ("germ-free," devoid of a microflora) animals, however, should not be considered because upon exposure to the nonsterile environment of the CELSS they would undoubtedly die of overwhelming infections; such animals have very immature immune systems.

Humans chosen to occupy the CELSS should be protected against certain infectious diseases (e.g., poliomyelitis, measles, whooping cough, and typhoid fever) and bacterial toxemias (e.g., tetanus, diphtheria, and perhaps botulism) by the administration of appropriate vaccines and toxoids. While it would not be possible to assure the total lack of serious pathogenic microorganisms in the human inhabitants, all candidates should be checked microbiologically to assess their carrier state.

The very potent tool of genetic engineering no doubt will be useful in establishing strains of microorganisms or plants with special properties, making it possible to introduce (1) better food crops, (2) organisms with special metabolic functions, and (3) disease-resistant plants.

While this treatise is directed at a lunar ecological system, it is worth noting that a laboratory in low Earth orbit or one in a modified external tank placed in orbit by a Space Shuttle offers certain advantages over the lunar environment as a place to establish and study space ecosystems for application elsewhere, as on Mars, where water and carbon dioxide exist in relative abundance.

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