Journal Title: The World & I.

Article Title: Leaving the Planetary Cradle

Article Author: Nelson, M

Volume: unknown

Issue: 2

Month: Feb

Year: 1991

Pages: 288-295

ISSN: 0887-9346

Cross Reference ID: 4988073

Notes 1:

Borrower: RAPID:LUU

Library Name:
NEW: Main Library

Lender: CVU :: Main Library

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Leaving the Planetary Cradle

Mark Nelson

In preparing to live in space, mankind has had to relearn the wisdom of the biosphere, progressing from simple systems to complex, closed ecosystems that can support human life.

SPACE BIOSPHERES VENTURES

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All life on earth, including man, has evolved in an environment that provides the essential needs of life, including atmospheric gases, nutrition, water, and an equable climatic regime. We live for the most part unappreciative of this life-support infrastructure and are just beginning to unravel the mechanisms and dynamics of its operation. The commencement of space exploration a few decades ago underlined the uniqueness of our planetary biosphere and accelerated the scientific study of closed ecological systems, which is needed if we are to learn to live in space independent of supplies sent from the earth.

The biosphere has been defined as the thin layer where life is found on the surface of the earth. More generally, a biosphere may be considered to be a stable, complex, adaptive, and evolving life system. Biospheres are closed in terms of matter, and open in terms of energy and information. The earth's biosphere is relatively closed materially, although relatively small gains and losses are recorded with both outer space and the crustal layers underlaying the biosphere. Energetically, the earth's biosphere is open, primarily powered by incoming solar radiation which heats the earth and is also captured by plants in energy-rich molecules that provide energy for most forms of life. Informationally, our biosphere is also open for exchange of communications with the rest of the cosmos—as was dramatized when we received radio signals from the *Voyager* space probes and were able to reprogram them over distances of millions of miles.

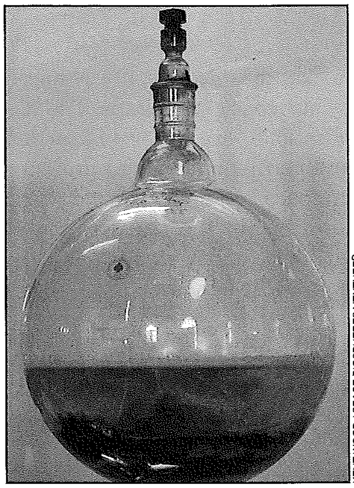
■ **Research on food production and life support in space must be initiated in testbeds on earth. Here, during a five-day enclosure test of the Biosphere 2 Test Module, created by Space Biospheres Ventures in Oracle, Arizona, a researcher harvests food grown inside the test module.**

Although a few intrepid underwater explorers, and later, submariners, experimented with carrying an essential component of the biosphere, oxygen, along with them, serious research into closed ecological systems capable of providing life support was sparked by the Space Age. A simple calculation reveals why space visionaries have long recognized that for man to truly emerge from his "planetary cradle," to live for extended periods and eventually expand off the planet, regeneration of life-support requirements would be indispensable. It takes, on average, about one and a quarter pounds of food, two pounds of oxygen, and four pounds of drinking water, a total of more than seven pounds, to support a person each day. If we add domestic water (for washing, cooking, laundry, etc.) it adds another 30 pounds to this requirement. In addition, a closed life-support system should be able to process each day over six pounds of solid and liquid wastes and two pounds of carbon dioxide that are respired by our space inhabitant. The implications are clear: Extended and permanent human presence in space requires that we "close the loop" in the regeneration of air, food, and water involved in human life support.

Controlled and closed ecological systems

Such closed-loop systems are called "bioregenerative" if they depend on biological processes for utilizing and transforming nutrients. At the same time, miniaturizing a biosphere to provide life support in space is likely to require the use of machinery as well as biology for such functions as controlling temperatures, pumping air and water, and processing food. These systems may be only partially bioregenerative, making some use of physicochemical means of handling wastes and producing required food, air, and water. In addition, for short-duration missions and in the early phases of space life-support system development, some food, air, and water may be carried from the earth or stored as a backup for emergencies, such as failure of other regenerative systems.

Any system that regenerates life supplies, at least partly through biological processes, could be called a "*controlled* ecological life-support system." A life-support system that would be completely sufficient would be a "*closed* ecological system,"



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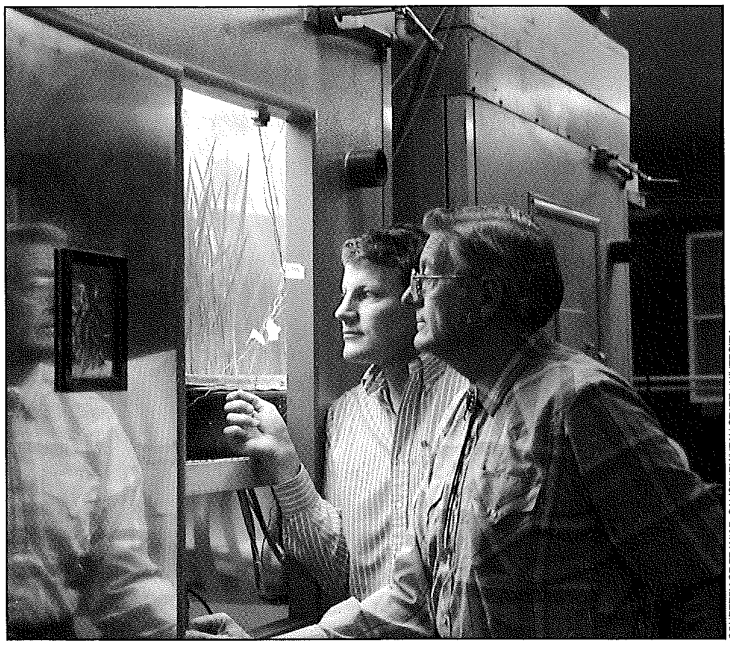


COURTESY OF FRANK B. SALISBURY/UTAH STATE UNIVERSITY

■ *Left:* **The oldest laboratory "ecosphere" has maintained healthy life cycles of marine algae and microbes in this sealed bottle for more than 20 years. The system is closed materially but open energetically, requiring only exposure to indirect sunlight.**

■ *Below:* **NASA-supported laboratory-scale research on the food production potential of target species has been apportioned to several universities. Here, Bruce Bugbee and Frank Salisbury at Utah State University observe hydroponically grown rice plants being tested for their response to different levels of carbon dioxide in the atmosphere.**

meaning that it was essentially materially closed and dependent on recycling. Both these terms imply that there is integration with mechanical devices and that environmental parameters are manipulated to ensure optimal production and operation. These systems have generally concentrated on a few species of plants and/or algae for food production, air and water purification in addition to the crew compartments, and engineering and computer technologies. Since they contain essentially only one type of ecosystem—an agricultural one—for human life support, we may distinguish them from "biospheric closed ecological systems," which include a number of internal ecosystems. (The Biosphere 2 project in Arizona, mentioned later in the article, is an example.)

Soviet Closed Ecological System Research

Researchers in the Soviet Union, like those in the United States, began developing life-support systems for space utilizing the high productivity of chlorella, a green algae. In 1961 at the Institute of Biomedical Problems in Moscow, Yevgeny Shepelev became the first man to live for 24 hours in a completely closed ecological system. Chlorella supplied his oxygen and utilized the carbon dioxide he breathed out. Later, Soviet researchers succeeded in such closures for periods of up to 30 days.

Because eating more than a little chlorella caused health problems, it was clear that to close the loops for food would require using higher plants like grains and vegetables. From 1972–1984 this step was accomplished by scientists at the Institute of Biophysics in Krasnoyarsk, Siberia. There, under the direction of Josef Gitelson, the Bios-3 facility with a volume of about 3,000 cubic feet was created. Bios-3 included two small artificially lit growing areas for eleven plant crops, a food processing area,

> *Virtually all the air and water was recycled in Bios-3 and about half the required food was grown inside.*

kitchen, and dining room, and living-quarter compartments for the two to three crew members included in the experiments. Virtually all the air and water was recycled in Bios-3 and about half the required food was grown inside. Meat for high protein was "imported" and most of the human wastes were "exported" from the facility. Successful experiments lasting up to six months were achieved in Bios-3. These experiments were landmark advances in the science and engineering of bioregenerative life support.

Current Soviet work in closed systems includes experiments conducted by the Institute of Biomedical Problems on very small aquatic closed systems in space to determine the effects of microgravity on their functioning. Space Biospheres Ventures has participated in this research on the first closed ecological system to fly in space, doing water and air analysis of a one-liter (about one quart) system which orbited in the Soviet Biosatellite flight of September 1989. At the Institute of Biophysics, further detailed work on plant selection and cropping techniques for closed systems is underway, as well as studies of how to miniaturize such systems for use in space stations and in extended spaceflights.

NASA's Controlled Ecological Life-Support System Program

In 1978, after a decade-long hiatus in such work, NASA re-instituted a program in the development of bioregenerative systems called CELSS (Controlled Ecological Life-Support Systems).

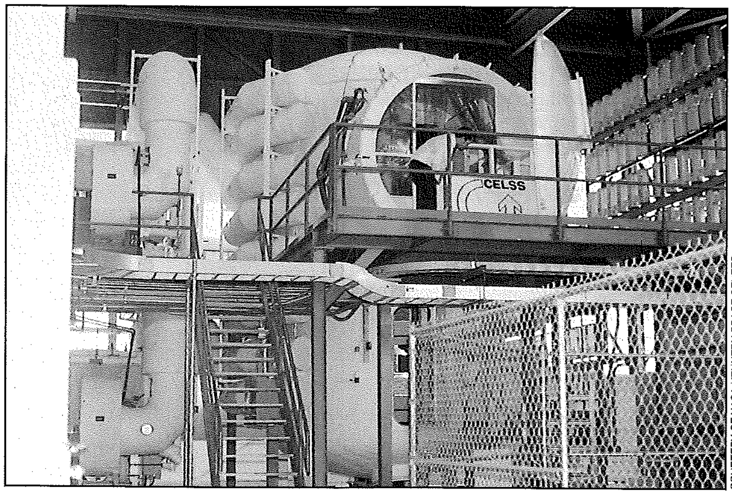
CELSS has funded research at NASA Ames Research Center, the Kennedy Space Center, and at several universities. Much of the work has focused on systems that produce high yields of biomass and food. CELSS investigations are conducted at a number of universities, with principal groups working on the production of wheat (led by Frank Salisbury and Bruce Bugbee at Utah State University), potatoes (headed by Ted Tibbits at Wisconsin University), sweet potatoes (headed by Walter Hill at Tuskegee Institute), and lettuce (headed by Cary Mitchell at Purdue University).

In 1986 the Breadboard Project, NASA's most ambitious higher plant-based CELSS program, was begun at Kennedy Space Center. The Breadboard Project under the leadership of Bill Knott has as its goal the demonstration of the scaling-up from previous laboratory-sized research into the production of food for human life support, water recycling, and atmospheric gas control in its biomass production chamber. Support laboratories are investigating associated questions of waste recycling, food preparation, and overall data management.

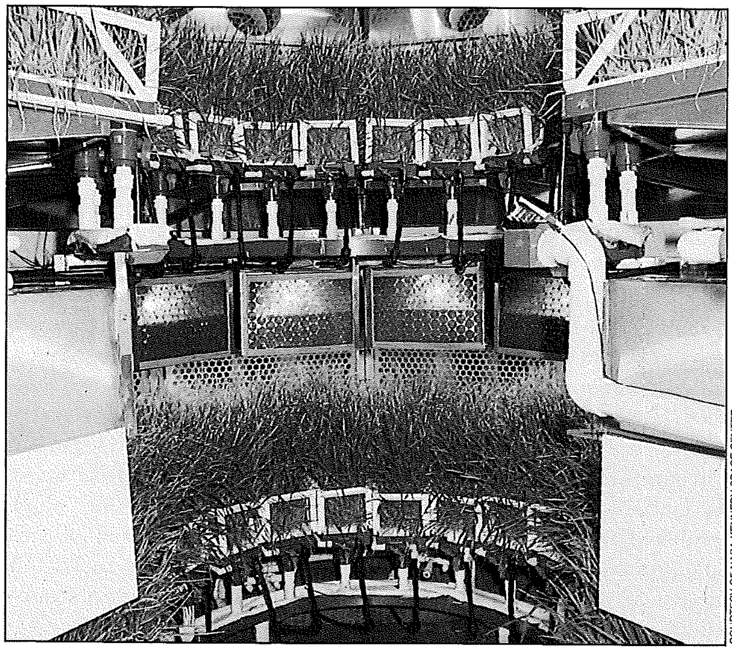
The Biomass Production Chamber (BPC) being used is a cylindrical steel hyperbaric facility approximately 10 feet in diameter by 24 feet high. Originally used in the Mercury program, it has been modified for plant growth by the creation of two floors with eight plant racks and the installation of high pressure sodium lamps.

This first phase of Breadboard, scheduled through 1993, calls for integrating and demonstrating three major components of a CELSS— biomass production, biomass processing, and waste conversion. Following planned studies of soybean, potato, and multiple crops in continu-

LEAVING THE PLANETARY CRADLE



COURTESY OF NASA-KENNEDY SPACE CENTER



COURTESY OF NASA-KENNEDY SPACE CENTER

■ *Left:* **NASA's Biomass Production Chamber (BPC) at Kennedy Space Center is a controlled environment configured for growing the maximum amount of plant biomass possible while carefully measuring mass flow through the total system. The unit is being developed to provide life support for one person continuously by revitalizing the air and regenerating potable water.**

■ *Below left:* **Viewed from inside, the BPC is a hanging garden laden with lush foliage, in this case, wheat. By 1993, tests of all the target species will be complete and integrated plantings of a variety of food plants will be tested.**

ous production, the goal of the Breadboard Project is to operate the BPC for extended periods of time—growing a crop community adequate to supply food, water, and oxygen for at least one person. From this first phase it is planned that data and conceptual designs for further ground-based and ultimately space systems will emerge.

Japanese and European research

Japanese and European programs in closed ecological systems for life support, although smaller, are also under way. The Japanese efforts, under the leadership of Keiji Nitta and Mitsuo Oguchi of the National Aerospace Laboratory in Tokyo, have concentrated on gas recycling systems involving oxygen and carbon dioxide separation and concentration, water recycling systems, plant and algae physiology and cultivation techniques, and animal and fish physiology and breeding. The European research has addressed one of the questions essential to the successful translation of ground-based CELSS to space: What are the effects of microgravity on biological development? Other work includes studies of the basic physiological responses of plants to environmental factors. One center of such research is at the European Space Technology Center at Noordwijk, Netherlands, under the director of Chris Savage of the United Kingdom and Roger Binot of Belgium.

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Biosphere 2 Test Module

Starting in late December 1984, Space Biospheres Ventures, an independent corporation started by Edward Bass of Texas, launched a privately financed project to advance the science and engineering of biospherics. The Biosphere 2 project is a three acre laboratory that will test a complete life-support module for living closed-off from material interchange with the planet and will provide better understanding of key Earth biosphere processes. [More detail about Biosphere 2 will be included in a forthcoming THE WORLD & I article on the development of the science of biospherics.] As a precursor to Biosphere 2, Space Biospheres Ventures (SBV) created a smaller testbed, the Biosphere 2 Test Module, to develop technologies needed in a closed ecological system. In so doing, they made important advances in the science and engineering of such systems.

The Biosphere 2 Test Module consists of a biological section and a variable-volume air chamber to which it is connected by air duct. The biological section is 22 feet square, and approximately 20 feet tall. The total volume of the biological section plus the air chamber is approximately 17,000 cubic feet. The module is sealed both underground and above ground.

Commencing in December 1986, SBV has conducted life-support systems research in the facility with a research team headed by Linda Leigh, John Allen, and Abigail Alling. In September 1988 the first manned closure experiments commenced. That 3-day closure, a 5-day one in March 1989, and 21-day one in November 1989 advanced the engineering and science of closed systems by being the first ones in which complete air and water regeneration, food production, and waste recycling was accomplished in a bioregenerative system.

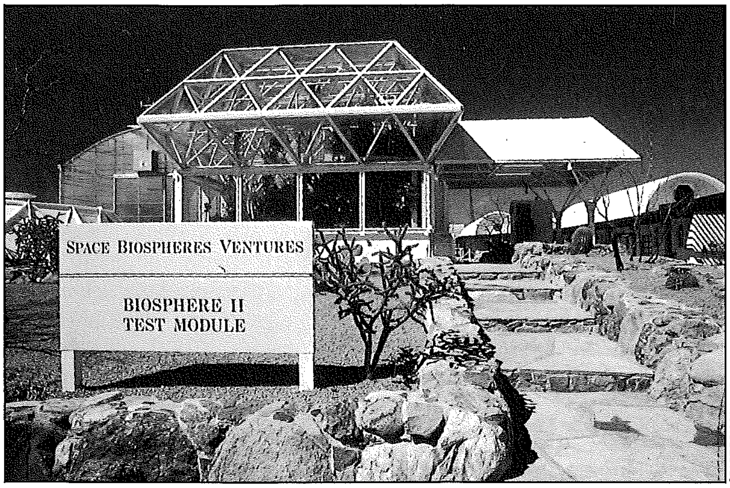
Spin-off benefits from bioregenerative system research

The potential environmental spin-off benefits from the development of space life-support systems are enormous, given our pressing need to tackle analogous problems on the earth. For example, the "sick building syndrome" caused by odors and trace gases in tightly sealed homes and offices is analogous to the problems faced in spacecraft and lunar bases, which are insulated from inhospitable outside conditions. Ways of purifying air developed through research in controlled or closed ecological systems can be used to reduce or prevent air pollution inside buildings. Methods of reutilizing wastes by biological processing are relevant to finding alternatives to the current practice of dumping wastes into rivers and marine environments.

The unique requirements of small closed ecological systems may also lead to important applications in the fields of sustainable agricultural systems and nonpolluting laboratories. The volumes of air, water, and soil of space life systems are simply too small to permit cleansing of toxic chemicals, such as pesticides, herbicides, conventional chemical reagents and medical residues. The necessity of such systems to maximize food production also is of relevance in developing more productive plant crops, and in understanding how to manage lighting, nutrients, and temperatures to maximize food production.

We need to learn to recycle "wastes" from one process into another; to develop clean technologies rather than try to clean up pollution after the fact; and to have methods to ensure clean air, good water, and safe and abundant food supplies. Thus, in developing bioregenerative life systems we accelerate the creation of technologies that will be critical if we are to live healthy lives in a healthy global biosphere.

—M.N.



SPACE BOIOSPHERES VENTURES

ROBERT HAHN / SPACE BIOSPHERES VENTURES

Left: **The Biosphere 2 Test Module has operated since 1986 to test individual components and integrated life-support systems. It is the largest such testbed in the world and the first open to sunlight.**

Below left: **The wastewater processing system inside the Biosphere 2 Test Module. It utilizes aquatic plants and microbes to extract the nutrients from domestic graywater and sewage from the crew compartment. This is the first time all wastes have been regenerated inside a closed ecological system.**

The Biosphere 2 Test Module is the first closed-ecological system that has included soil as a major component. To develop the necessary air purification, SBV researched and developed "soil bed reactors" (SBRs), which operate by pumping the chamber's air through the soil, facilitating microbial metabolism of potentially dangerous trace gases.

Benchtop research on soil bed reactors was conducted for SBV by the Environmental Research Laboratory of the University of Arizona. It was found that soils could do two functions simultaneously: support intensive plant growth while purifying the air of the closed system.

Biological waste recycling systems

A promising approach to bioregenerative waste processing has been pioneered within NASA and is finding increasing applications to environmental problems. This involves the creation of "artificial wetlands" or "marsh waste processing systems" to utilize the natural ability of communities of plants and microbes to metabolize or concentrate potential pollutants in waste streams, while at the same time producing valuable biomass growth.

One of the pioneers in the field, Bill Wolverton, has conducted years of research while working at the NASA Stennis Center in Mississippi. He has been a leader in studying the ability of higher plants to remove potential trace gas pollutants in tightly sealed environments, such as highly insulated energy efficient houses, or in spacecraft, and in developing aquatic plant and microbial systems for wastewater treatment.

Wolverton consulted with SBV on the development of a waste recycling system for the Biosphere 2 Test Module, which provides complete recycling of all human wastes. With this system, no wastes are removed from the test module; the sewage water is purified by the action of microbes and plants and then used to irrigate the plants in the test module.

The necessity to deal with the consequences of material closure forced extremely interesting adaptations on Space Biospheres Ventures. It meant that all technologies included inside would have to be made virtually pollution-free, and that whatever sources of potential contaminants existed, such as outgassing from equipment or building materials, would have to be utilized and transformed by other biological or mechanical systems to prevent their buildup to environmental or health hazard levels.

Rather than utilize conventional approaches to agriculture, the Biosphere 2 Test Module has advanced systems that, instead of using chemical fertilizers, recycle nutrients from human, animal, and plant residue and return them to the soil.

The changing framework of space development

In addition to a rapidly developing ecological concern around the world in the 1990s, the prospects are also for a reflowering of space exploration. In preparation for near-term space applications of bioregenerative life support, SBV and the External Tanks Corporation of Boulder, Colorado, are planning a ground-based demonstration using the nosecone (oxygen part) of the fuel tanks built for use in the launch of the space shuttles to orbit. The fuel tank's nosecone alone is about 10 percent larger than the Biosphere 2 Test Module, and should be able to accommodate a closed-ecological system that can provide continuous life support for two people, using some of the Biosphere 2 technology and other technologies derived from the CELSS program. This could be used to supply *Space Station Freedom* or other space infrastructure crew. This testbed would also be an opportunity to develop "hybrid" systems that are partly physical-chemical and partly bioregenerative to see how the two types of systems can be integrated. Such testbeds and others being prepared for meeting the needs of a permanent lunar base and eventual Mars exploration are needed if we are to be ready with bioregenerative options when critical space decisions are made.

The framework of the international space agenda has evolved significantly in the past five years to focus on programs involving long-duration and eventually permanent human presence in space. Furthermore, the strategy of "evolutionary expansion" into space as opposed to space spectaculars, such as the U.S. moon landing with no infrastructural increase, is beginning to dominate space exploration planning.

Such a space agenda requires some fundamental shifts of thinking about life support from the type of technologies that were developed for the sprint missions to the Moon or for short-duration spaceflight objectives.

NASA's recent *Report on the 90-Day Study on Human Exploration of the Moon and Mars* identified perhaps the biggest challenge in meeting human needs in space as being "the development of regenerative life support systems, which could eventually provide food as well as recycle wastes, with a subsequent reduction in the quantity of supplies that must be transported from Earth."

As this new framework for space exploration gains widespread acceptance, the critical importance of bioregenerative life-support systems will also gain recognition. As we have outlined in this survey of closed ecological systems, a number of programs are under way to provide the key to our future in space—the ability to live there.■

Mark Nelson is chairman of the Institute of Ecotechnics in the United Kingdom and director of space applications at Space Biospheres Ventures in Oracle, Arizona.