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Chapter 25

BIOREGENERATIVE LIFE SUPPORT FOR SPACE HABITATION AND EXTENDED PLANETARY MISSIONS

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22.1 Introduction

A fundamental component of the ability of man to explore and eventually to live for extended periods in space is the design and creation of closed ecological life-support systems and artificial biospheres which can regenerate, reuse, and recycle the air, water, and food normally provided by the Earth's biosphere.

K. S. Tsiolkovsky, the Russian space visionary who laid the basis for modern rocketry and astronautics around the beginning of this century, saw travel into space as the step where mankind leaves its "planetary cradle." He also foresaw the need for regenerative life-support systems in the spacecraft: "the supply of oxygen for breathing and food would soon run out, the byproducts of breathing and cooking contaminate the air. The specifics of living are necessary – safety, light, the desired temperature, renewable oxygen, a constant flow of food." [49]

The expansion of human presence into space, both in the microgravity conditions of orbital space and on lunar or planetary surfaces, will in one sense be but the latest in the series of expansionary advances of life. From its origins in aquatic environments of the Earth through its successful colonization of land surface habitat, its occupancy of the near airspace with the evolution of rigid-stemmed trees, of the lower atmosphere with winged-bird life, and its penetration miles deep by anaerobic bacteria, Earth's biospheric life has continually exerted a pressure to occupy new habitats and include additional resources in the biotic circulation. It has even participated in dramatic alterations of the basic conditions for life, first adding free oxygen in significant quantities to the atmosphere and then evolving life forms capable of using that oxygen for metabolic processes [20, 28], and in the process, creating the ozone layer that protects the Earth from deadly ultraviolet radiation which would have made life on land surfaces impossible for most life forms. With man's growing technical ability to create living spaces out of contact with the Earth's biotic regeneration (as in submarines, high altitude aircraft, and spacecraft), and to voyage to extraplanetary ones, a new chapter in this biospheric expansion stands ready to be opened. The creation, initially ground-based and later off the Earth, of simple closed ecological life-support systems, and eventually of stable and evolving biospheric systems, will mark the transition of life from a one-planet phenomena to one capable of permanent expansion into the Solar System and beyond.

22.2 Terminology of Bioregenerative Life Support Systems

The emerging science of biospherics deals with the functioning of a variety of ecological systems which vary in size, degree of material closure, and complexity as measured by its number of internal ecosystems. There is some confusion in the terminology that has been used to define types of systems. What follows is an attempt to introduce and explain a set of terminology that may hopefully lead to closer agreement among those working in this field. It is based on agreements on terminology used for man made (synthetic) ecosystems reached amongst many of the leading researchers in the field at the Second International Workshop on Closed Ecological Systems Research held at Krasnoyarsk, Siberia, in September 1989.

Materially-Closed Ecospheres

Folsome and colleagues who first initiated small laboratory-sized systems saw that a crucial way in which such systems differ from previously developed ecological microcosms and mesocosms is that they are essentially materially-closed (less the leak rate the facility suffers). By contrast, microcosms (the miniaturized ecosystems that ecologists use) were developed to permit study in the laboratory, e.g., a pond or coral reef system, housed in a manmade container and enhanced by appropriate supporting technology such as artificial lights or mechanical wave generators to replace functions performed naturally in the wild. These ecological micro- and mesocosms are open to interchange with the surrounding air, and generally require inputs of nutrients and water to replace that lost by evaporation. Folsome therefore saw his laboratory flasks as heralding a new type of object – the materially-closed ecosystem. To differentiate these laboratory-sized systems from systems large enough to provide human life support, we can call them "materially-closed ecospheres." They are open to energetic input (indirect sunlight or artificial lighting) and information exchange (monitoring, sensors, observation).

Bioregenerative Technology

Any type of technology capable of providing life-support materials that employs a biological mechanism, even if enhanced and supported by other technology, may be termed a "bioregenerative technology." Examples are plant growth chambers in which a particular crop is grown that regenerates part of its atmosphere, purifies some quantity of water through transpiration, and produces food; or a wastewater processing unit in which aquatic plants and microbes digest graywater and/or sewage, producing biomass as well as air and water regeneration. Bioregenerative technologies are potential elements in a completely sufficient or partially sufficient closed ecological life support system.

Controlled Ecological Life Support Systems (CELSS)

Any system that is developed for space life support will to some extent rely on machinery as well as biology – for controlling temperatures, pumping air and water, processing food, etc. Such life support systems are only partially bioregenerative, with some use of physiochemical means of handling wastes and producing required food, air, and water. Hence, in short-duration missions and in the early phases of developing space life-support systems when CELSS-type systems are used, some food, air, and water will be carried from Earth or stored as a backup for emergencies or failure of other regenerative systems. Controlled ecological life-support systems are systems in which at least a portion of the necessary life-support materials are produced using bioregenerative technologies. As the name implies, these systems employ a variety of technologies to enable and closely control biological elements, providing the chosen range of temperatures, atmospheric element concentrations, pH, nutrient delivery, light intensity, and duration. However, a portion of the necessary life-support materials are provided by stored supplies and/or physiochemical methods of recycling or cleanup (e.g., lithium hydroxide canisters for CO_2 removal, catalytic oxiders for trace gas metabolism, or vapor compression distillers and membrane technology for water revitalization, rather than using only biological methods for their uptake and regeneration).

Closed Ecological Life Support Systems

A life support system that would be completely sufficient materially and which is biologically-based would be a closed ecological system, meaning that it is essentially materially closed, energetically open, and recycling its material. Both the CELSS and Closed Ecological Life-Support Systems terms assume that there is integration with mechanical devices, and that environmental parameters are manipulated to ensure optimal production and operation. Both these types of systems have generally concentrated on a few species of plants and/or algae for food production as well as air and water purification, in addition to the crew compartments and associated mechanical/computer technologies. Energetically, such a system must be open or it would inevitably decline because of increasing entropy. Whether the light needed for photosynthesis is supplied by artificial lights or by sunlight, direct or delivered through light pipes, there is a need for such inputs and for a heat sink on the outside for unneeded heat. Since the technology required to make the closed ecological system airtight is expensive and rigorous, in most cases, whether in ground-based testbeds or in actual space applications, it will be more practical and safer to house the energy-generating unit outside the sealed life-support zone. This will also lessen the amount of air-scrubbing that is required if the energy production method produces pollutants. But while the definition of a closed ecological life-support system does not require energy production within its sealed boundary, it is certainly true that the lessening of energetic requirements and the accomplishment of energy generation (via solar arrays, nuclear energy, use of extra-terrestrial energy resources, etc.) in space are important considerations in accomplishing the reduction of logistical dependence on resupply from Earth. If the energy must be supplied from Earth, it diminishes the fundamental goal of bioregenerative life-support systems to make feasible longer and eventually indefinite habitation in space.

Biospheric Systems

Since both CELSS and closed ecological systems contain essentially only one type of ecosystem – a basically agricultural one – for human life support, we must distinguish them from "biospheric systems," such as the Biosphere 2 project in Arizona, which include a number of internal ecosystems. Biospheric systems are essentially materially closed, energetically and informationally open like a closed ecological life-support system, but their complexity provides complete life support for its human crew for an indefinite period of time and therefore may be far more relevant for long-term or permanent space habitation.

As with other scientific and engineering fields, these differing systems will be relevant for differing space missions and applications. Their research and development will likewise yield insights into a variety of scientific problems.

22.3 Tools for Understanding Our Global Biosphere and Creating Environmental Spin-Off Technologies

The construction of biospheric systems has important implications for advancing our knowledge of how our global biosphere functions. The recent appreciation by scientists and the public of threats to the Earth's biosphere due to the magnitude of human population increases and technological impacts makes the understanding of how our biosphere operates and what perturbations it can tolerate of enormous consequence. It is interesting that just as the advent of remote sensing as a tool for studying the biosphere's large-scale behavior is a product of the Space Age, so biospheric systems important for the permanent extension of life into space also makes available unique "laboratories" for the study of biospheric processes.

This dual significance was noted in 1971 by Cooke when he considered the ecology of space travel: "The fact that we are not now able to engineer a completely closed ecosystem that would be reliable for a long existence in space...is striking evidence of our ignorance of, contempt for, and lack of interest in the study of vital balances that keep our own biosphere operational. Therefore, future efforts to construct a life-support system by miniaturizing the biosphere and determining the minimum ecosystem for man is a goal that is as important for the quality of human life on Earth as it is for the successful exploration of the planets." [7]

The program of research proposed by the National Research Council for global ecological studies has great parallel with the practical questions faced by ecologists and engineers designing bioregenerative systems for space habitats. Their list of top questions include:

> What are the sizes of the major pools of carbon, nitrogen, sulfur, potassium and phosphorus, especially biological ones in active exchange with other components of the biosphere...What are the major transport rates of the four elements from one component of the biosphere to another...[especially] the flux to and from biotic components, i.e., between land biota and the atmosphere, between marine biota and the atmosphere, from land biota to oceans (via rivers); from land and marine biota to short-term sediment storage. What factors control these rates? How much and in what ways does the cycling of one of these chemical elements affect the others? What were the states of these cycles prior to anthropogenic perturbations? What will be their future states? What must be known to permit us to reverse or stabilize anthropogenically induced trends? [43]

Not surprisingly, these questions are ones which will be addressed in part by biospheres designed for space; their functioning depends, as does the global biosphere, on the creation and operation of adequate buffers and sufficient internal pathways for all trophic and energetic exchanges. The modeling and data acquisition possible in artificial biospheres with their vastly smaller dimensions and faster cycling times should yield considerable insight for our comprehension of global biospheric functioning. Eventually, this field of "comparative biospheres" should yield both descriptive and predictive knowledge, much as the science of comparative planetology is beginning to do.

Indeed, the entire field of closed ecological systems has much inherent interest for both global and specific questions of habitability and sustainable development. The necessity posed in such systems to integrate all life and technical processes and products for the assistance of life support makes an interesting paradigm for our activities in Earth's biosphere. The potential environmental benefits from the development of space life-support systems are enormous, given our pressing need to tackle analogous problems on Earth. For example, ways of purifying air can be used to prevent urban air pollution, as well as pollution inside buildings. The "sick building syndrome" caused by odors and trace gases in tightly sealed homes and offices may be analogous to the problems faced in spacecraft and lunar bases which are tightly insulated from inhospitable outside conditions. Methods of reutilizing wastes by biological processing are relevant to finding alternatives to the current dumping in 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 non-polluting laboratories. The volumes of air, water, and soil of space life-support 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 is also of relevance in developing more productive plant crops, and in understanding how to manage lighting, nutrients, and temperatures to maximize food production. As the Gitelson team notes: "Thanks to the evidence and common nature of the goals one can hope that many technologies of waste-free and economic satisfaction of the vital needs of people that have been found during the development of closed systems will replace the less profitable modern methods that contaminate the biosphere of the planet." [48]

Controlled and closed ecological life-support systems are an important enabling technology for extended periods in space – for initial research into manned space stations and extended planetary missions or industrial space outposts. Biospheric systems are necessary for permanent and evolving habitation in space. Learning to create biospheric systems for life in space may also provide valuable lessons and tools for better managing the long-term health of the global biosphere on the home planet.

22.4 Calculations of Life-Support Quantities

Calculations of the quantities of critical variables (air, water, food) needed for human life support are essential to understanding at which point bioregenerative systems for spacecraft and space stations will become competitive with the approach currently used on both short- and long-duration flights, namely physiochemical systems supported by resupply of water, air, and food from Earth.

Such calculations, while critical, are inherently difficult, and have yielded quite differing results. Furthermore, all such values to date are based on terrestrial situations which may differ radically from those encountered in space. Table 22.1-A shows the life support requirements data compiled by Modell and Spurlock [29]. Thus, from these projections, "in the course of a year, the average person is calculated to consume three times his body weight in food, four times his weight in oxygen, and eight times his weight in drinking water. Over the course of a lifetime, these materials would amount to over one thousand times an adult's weight." [20]

In separate studies, Rummel of NASA and Volk of New York University [44] using computer modeling and simulation of bioregenerative life support systems have utilized the following estimates, compiling several sources, and for purposes of the study, basing the diet on nutritional needs being met solely by wheat. Their calculations differ from the Table 22.1-A figures in estimating food inputs at 855 g/day, drinking/food preparation water at 4577 g/day, and wash/flush water at 18000 g/day. The development of more economical technologies for these needs in space may of course reduce these quantities considerably. They also provide a useful indication of the metabolic by-products of each human in space, which becomes potential inputs into their bioregenerative life-support system [44] (see Table 22.1-B).

Despite the widely differing estimated values, the implications of these calculations are clear: extended, and certainly, permanent human presence in space makes necessary "closing the loop" in the regeneration of air, food, and water involved in human life support.

22.5 Laboratory Ecosphere Research

In 1967, Folsome of the University of Hawaii at Manoa initiated experiments with sealed, small (100 ml – 5 l) aquatic solutions containing a range of microbial communities and air in a laboratory flask, and exposed them to artificial light or indirect sunlight. These flasks were materially closed, i.e., there was no exchange of air or nutrients with the outside, but they were energetically open to light energy. They were also informationally open as Folsome developed non-intrusive ways of conducting measurements. These closed ecological systems, or laboratory "ecospheres," exhibited surprising properties. As long as the initial sample contained a full functional representation of microbes, i.e., fulfilling the entire range of metabolic functions from biosynthesis to detritus feeding, they proved to be indefinitely persistent. Ecospheres initiated in 1967–8 are still alive, exhibiting periodic changes in microbial content. Subsequent ecosphere experiments with single-culture starts demonstrated a progressive failure to recycle elements and eventual death [14, 15]. Folsome was joined by other pioneers in this field of closed ecological systems, such as Maguire of the University of Texas, Taub of the University of Washington, and Hanson of the Jet Propulsion Laboratory, California Institute of Technology.

In order to measure the dynamic changes occurring in these first laboratory closed ecospheres, Folsome and colleagues developed simple indices to monitor their balances. Measured parameters included determination of the eucaryote/procaryote ratio as an index of the system's state [40], ATP (Adenosine triphosphate, the molecule in the cell which stores energy for metabolism), determinations of biomass [22, 23], monitoring of oxygen and carbon dioxide cycling in stable and unstable systems [38, 39], and determination of efficiency of energetic use in the system [22]. These laboratory ecospheres are quite different from the microcosms studied by ecologists in the past, because their sole input is radiant energy. Their gas exchange cycles, for example, operate without the large buffers and consequent long cycling durations available to open systems.

Kearns and Folsome [14, 15] demonstrated persistence of materially-closed microbial ecosystems for over twenty years. Measurements of oxygen, partial pressures, and of carbon cycling rates were conducted. These data indicate that biological activity is maintained consistently. These systems have primary productivity and quantum efficiencies similar to terrestrial climax ecology values. Folsome [13, 14] demonstrated that replicate closed microbial ecosystems can be constructed with ease, making such laboratory ecospheres a valuable experimental tool. Hanson [15] has kept large (14 mm) crustacea in synthetic brackish water with a variety of algae under closure for more than five years. These data show closure with sustained biological activity is not restricted to algae/microbial systems, but can be extended experimentally to include metazoans. Maguire [27] has shown persistence of fresh water systems of microcrustacea for over four years. Although the eucaryotic components decreased, both procaryotes and eucaryotes persisted. These experiments demonstrate: 1) some closed ecological systems persist, 2) they have measurable properties, 3) replicate systems can be created, and 4) the complex and difficult challenges inherent in even the simplest of closed ecosystems, laboratory ecospheres, and 5) the important role microbes play in elemental cycles.

In these closed ecospheres, the many complex factors of global geochemistry, with its massive reservoirs of inorganic bioelements and interacting webs of species interactions, are not present as on the Earth. Yet essential biology, that of the closure of bioelemental cycles, persists and becomes amenable to laboratory study. These laboratory studies of ecospheres are an important frame of reference in the creation of larger closed ecological life-support systems for space. As Folsome and Hanson noted in a review of the field: "Recent experience suggests that almost any reasonably diverse assemblage of biota and inorganic materials will sustain some level of balanced redox metabolism indefinitely when kept under adequate materials-closure, and within energy-fluxes that are normally tolerable by some life-forms...these systems offer a multitude of potential miniature worlds which might closely model or might depart from the one world that is our Biosphere...and because of their rigorous material boundaries and resultant constant elemental make-up, they offer research opportunities which are qualitatively different from those of non-materially-closed microcosms." [14]

22.6 Algae-Based Systems

Initial efforts, both in the U. S. and U. S. S. R. space programs, to create bioregenerative life-support systems concentrated on the development of single species systems, generally a *Chlorella* sp. algae link with man [7, 47]. *Chlorella* is an extremely productive green algae, capable of doubling its mass in nine hours under favorable conditions. It is an efficient producer of oxygen and its protein content is high. However, its utilization as a food source has proved an intractable problem except in very small quantities (about 25−50 g/day) because of unpalatability, and in larger quantities to gastrointestinal upset and illness [47]. In addition, its cell wall, made of crude fiber, requires pulverization, its small size (5 μm) makes separation for harvest difficult, and it is very vulnerable to contamination. Under some growing conditions, it also produces gas by-products toxic to higher plants [47, 48].

Nevertheless, some outstanding achievements were accomplished both by the U. S. and Soviet efforts with *Chlorella*-based systems. The first such experiments were conducted by U. S. researchers after the flights of the first space satellites. Experiments were conducted at the United States Air Force School of Aviation Medicine in 1961 in which monkeys were linked in gas exchange with algae tanks for up to 50 hours [7, 30]. During 1960−61, researchers at the Institute of Plant Physiology and Institute of Biomedical Problems in the Soviet Union conducted experiments along the same lines with rats and dogs for periods up to seven days. Shepelev of the Institute of BioMedical Problems, U. S. S. R. Ministry of Health, Moscow, was the first human to place himself as an experimental subject in a human/algae system in 1961. The basic oxygen / carbon dioxide gas exchange between Shepelev and his supporting *Chlorella* was successful, although a build-up of odors indicating trace gas contamination was noticed [47].

Later closures of 15 and 30 days were achieved. In the Soviet 30-day experiment, the human lived in a 4.5 m^3 sealed room, sustained by a 30-liter algae apparatus which absorbed his carbon dioxide and supplied his oxygen, going through 15 cycles of regeneration. Two potentially toxic components of the air system stabilized during the course of the experiment: carbon monoxide after 3 days, and methane (generated from the digestive tract of the person) after 12 days. Water was condensed from the air, filtered and re-used, as was the urine. There are problems even in the simple air linkup of man and C*hlorella*, because the coefficients of CO_2 and O_2 production and assimilation ratios differ. On average, every liter of carbon dioxide produced by human respiration, when absorbed by *Chlorella* growing tanks, results in the production of 1.2 liters of oxygen. So if carbon dioxide levels are maintained, the systems will have an oxygen increase. In the 30-day trial, the oxygen was held constant, resulting in an excess of carbon dioxide which was removed by chemical filters [47]. Myers and colleagues experimenting with chlorella/mouse systems reported fluctuations in respiratory rates associated with a build-up of algal by-product toxicants [11].

It was discovered that *Chlorella's* respiratory quotient and production of organic gases depend on many factors, including the density of algae, illumination intensity and cycle, conditions of the nutrient medium, etc. In one experiment reported by Shepelev, there was a sharp increase in carbon monoxide, evidently correlated with a sudden increase in the acidity of the medium to pH 4, after 14 days [47]. Methane in this experiment took 11 days to stabilize.

22.7 Higher Plants in Life-Support Systems

The investigation of higher plant-based life-support systems followed this earlier stage of algae-based systems. The motivations for this include:

1. As for algae, crop plants have the capability of fulfilling the basic autotrophic (primary producer of complex organic molecules) link in a closed system, and thereby closing the regenerative loops for CO_2, O_2, and water. (This basic equation:

$$(672\text{ Kcal})\ 6\ CO_2 + 12\ H_2O \xrightarrow[\text{chlorophyll}]{\text{light}} 6\ (CH_2O) + 6\ O_2 + 6\ H_2O$$

   is complemented by the action of heterotrophs such as man reversing the equation in his oxidation of complex hydrocarbons (food) and in respiration, producing carbon dioxide, water, and minerals).
2. Higher plants are easily digested and are customary sources of human food. Extensive literature on terrestrial (i.e., not in a closed environment or in microgravity) human nutritional needs and higher plant composition exists and forms a starting point for designing such systems.
3. Higher plants can purify water through the process of transpiration. Transpiration is the method whereby plants utilize the passage of water to achieve evaporative cooling. This has been estimated at about 300 grams of water evaporated for every

gram of CO_2 fixed in photosynthesis [12]. Such water can be condensed from the atmosphere of a closed system.

4. Higher plants also have the capability of processing waste materials from the crew members and other heterotrophs in the system.

"While the potential benefit of using higher plants in life support systems for space missions is apparent, the research necessary to develop and test this system may also produce spin-offs in technology applicable to partially closed, high intensity food production systems useful on Earth, and to basic discoveries in plant science that might allow advances in food production technology within ongoing, long-term crop improvement programs." [12]

Because of the unique properties of closed ecological system apparati, that of material closure and potential manipulation of all vectors affecting growth and production, many fundamental studies of plant growth behavior become available for study. These include: response to elevated or decreased carbon dioxide and oxygen, response to illumination and photoperiod, interactions with soil or medium, other plants and other systems interactions, influence of humidity, study of release of trace gases from plants and their ability to absorb and deal with such biogenic, anthropogenic, or technogenic gases and contaminants, effects of plant density, canopy configuration, and microbiological requirements. Nevertheless, the use of higher plants in such systems is still in an early stage of development. Numerous conceptual studies have been carried out defining the research program for such work, including the development of ground-based pilot projects. But the number of actual testbed systems is still few.

22.8 NASA CELSS Program

The NASA CELSS (Controlled Ecological Life Support Systems) program, which was begun in 1977, is being principally carried out at NASA Ames Research Center, Kennedy Space Center, and Johnson Space Center. In addition, a number of NASA-funded contractors and Principal Investigators have been carrying out intensive studies of individual potential food crops in a CELSS, including wheat, potatoes, soybeans, and sweet potatoes.

Work begun by Salisbury at Utah State University in Logan is illustrative of the advances in basic plant physiology which have resulted from research on higher plants for life-support systems. Salisbury, Bugbee, and associates have conducted studies of wheat production in intensive cultivation and under strict environmental control by conducting their studies in plant growth chambers, where temperature, humidity, PAR (Photosynthetic Active Radiation – the part of the light spectrum which can be utilized by plants for photosynthesis), photoperiod, and airflow can be manipulated, and their effects and interactions studied [45]. Some of the results of the wheat research has been:

- Plant densities over ten times denser than those used in normal open field crops yield significant increases in light interception, total biomass production, and increased grain yield. With developments in techniques of supporting wheat plantlets and using inert rockwool to anchor the seeds, they have tested cropping densities of up to 2000 plants/m^2.

- There is a linear relationship between light levels and plant biomass. The efficiency of utilization, however, decreases at levels above some 800 micromolar per meter per second.
- Control of hydroponic (i.e., soilless growing method, utilizing prepared nutrient irrigation water) nutrients for such intensively grown crops have shown promise of solutions for problems of lodging and of increasing the percentage of edible biomass produced.
- The development and study of phasic environmental control, where conditions are varied during different stages of the crop's development. Manipulations of photoperiod and temperatures during these stages can markedly increase crop yields.
- An extensive cultivar selection and breeding program has resulted in the development of lines of short (ultra dwarf) wheats with good head size and seed set. These 30–50 cm tall varieties avoid many of the problems of lodging of taller varieties, are amenable to high density planting, and may be advantageous for space life-support systems where volume may be a limiting factor.

Yields of 23–57 grams per meter per day of edible biomass have been reported by Salisbury and associates. The implications of these high yields have been outlined:

> One hundred grams of typical, whole grain, hard-red spring wheat contain about 13 g of water, 14 g of protein, 2.2 g of fat, and 69.1 g of total carbohydrate (including 2.3 g of fiber). Bomb calorimeter studies indicate that 100 g of wheat would provide 1647 kJ (394 Kcal) of food energy, and if we assume that 94% of this energy is digestible, this would provide 1500 kJ (370 Kcal). To provide the 11,700 kJ/day required by a human being, about 680 g/day of oven-dry wheat...or its equivalent in other food would be required. If this were to be produced in 12 m^2, yields would have to reach 57 g/m^2 per day. If the production area was 30 m^2, then average daily production would have to be 23 g/m^2 per day. Even if the 30 m^2 is doubled for safety, a moon farm about the size of an American football field (about 6000 m^2) would support 100 inhabitants of Lunar City. Our objective has been to see what yields...can be achieved in a totally controlled environment and thus test the reality of these figures...although our yields are well above those obtainable in the field, they are still well below what they could be based on photosynthetic and cropping efficiencies. Much progress remains to be made" [45]

In 1986, the Breadboard Project, NASA's higher plant-based CELSS program, was begun at Kennedy Space Center. The Breadboard Project has as its goal the demonstration of the scaling-up from previous laboratory-sized research study 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 renovated cylindrical steel hyperbaric facility approximately 3.5 meters diameter by 7.5 meters 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. Ventilation of the chamber is accomplished by ducts which lead into an external air-handling system including filters. Temperature and humidity are controlled by a chilled water system and through atomized water injection. A compressed gas delivery system is used in the manipulation of atmospheric carbon dioxide and oxygen.

The current leak rate in the Breadboard BPC is 5% of its volume per day. The configuration of growing areas inside yields a total plant area of 20 m^2. The initial crop that was tested was wheat, grown in nutrient film, with plant supports holding the plant canopy about 50 mm above the nutrient level. Air turnover in the BPC is about three times a minute, with ventilation air being ducted at the rate of 0.5 m^3/sec into the chamber between lights and growing trays. Other studies underway include nitrogen flow studies which track nutrient movement throughout the system feeding trials, and operation of an aquaculture (tilapia fish) and lettuce system, as well as waste management trials using water leachate of wheat straw as a component of the hydroponic medium.

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 continuous 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 to a crew of 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 [24].

22.9 NASA Waste Processing, Air and Water Recycling Research

An extremely 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 plant/microbial associations to perform the waste processing, metabolizing or concentrating potential pollutants, while at the same time producing valuable biomass growth.

One of the pioneers in the field is Wolverton, who conducted research while working at the NASA Stennis Center. He has studied 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, as well as in developing aquatic plant/microbial systems for wastewater treatment [51]. Wolverton notes that "the scientific basis for waste treatment in a vascular aquatic plant is the cooperative growth of both the plants and microorganisms associated with the plants...This relationship produces a synergistic effect resulting in increased degradation rates and removal of organic chemicals from the wastewater surrounding the plant root systems. During microbial degradation of the organics, metabolites are produced which the plants absorb and utilize along with nitrogen, phosphorus, and other minerals as a food source. Microorganisms also use some or all of metabolites released through plant roots as a food source. By using the other's waste products, this allows a reaction to be sustained in favor of rapid removal of organics from wastewater. Electric charges associated with aquatic plant root hairs also react with opposite charges on colloidal particles such as suspended solids causing them to adhere to the plant roots where they are removed from the wastewater stream and slowly digested and assimilated by the plants and microorganisms. Aquatic plants have the ability to translocate oxygen from the upper leaf areas into the roots producing an aerobic zone around the roots which is desirable in domestic sewage treatment. Aquatic plants are also capable of absorbing, concentrating and in some cases translocating toxic metals and certain radioactive elements, therefore removing them from the water system. In addition, aquatic plants have demonstrated the ability to absorb certain organic molecules intact where they are translocated and eventually metabolized by plant enzymes as demonstrated with systemic insecticides." [50]

Applied marsh waste processing systems have utilized floating, emergent aquatic plants such as water hyacinth (*Eichhornia crassipes*) and duckweed (*Lemna* spp.); rooted, emergent aquatic plants such as giant bulrush (*Scirpus californicus*), reed (*Phragmites communis)*, and cattail (*Typha latifolia*); vascular plant/microbial rock filters utilizing canna lily (*Canna flaccida*), pickerelweed (*Pontederia cordata*), and arrowhead (*Sagittaria latifolia*). These systems have produced considerable biomass while performing waste processing, with much of the plant material being converted into energy, feed, and fertilizer. "As more aquatic plant wastewater treatment systems become operational, additional research is expected to expand the uses of harvested plant material" [50] and the range of potential plants to be used. Other potential uses of marsh waste processors for a bioregenerative life-support system include biogas production from anaerobic fermentation of substrate such as water hyacinth, which produces 350–400 liters of 60% methane biogas per dry kilogram of water hyacinth [50]. The high rate of productivity of such systems also make them useful as sources of purified water in a bioregenerative system after condensing the moisture transpired through plant leaves.

The Stennis work also involves research with the BioHome, a 650 ft^2 facility which is testing the integration of a number of bioregenerative technologies, including plants as indoor air purifiers and aquatic plant waste processing (see Figure 22.2). Current work involves increasing the amount of plants in the BioHome to achieve adequate water recycling, and to compost biomass from the waste processing unit to support food crops [19]. Other NASA-sponsored work led by Crump and Janik at the University of Alabama in Huntsville has examined plant transpiration as the source of potable water for space life-support systems. Since water by weight constitutes over half of needed life-support materials, its bioregeneration is especially important, and the efficacy of plants as bio-filters to produce highly purified water has been examined and demonstrated in their work [18, 26]. Schwartzkopf at Lockheed has led a NASA-supported effort in plant production methods for spacecraft and conceptual studies for bioregenerative life support for the proposed lunar base [46]. MacElroy and Bubenheim at Ames have been involved in the design work for the "Salad Machine" for microgravity application and in the design of plant growth chambers for the U. S. Space Shuttle and Freedom Space Station utilization [6].

22.10 Japanese and European Research in Bioregenerative Systems

Japanese and European CELSS programs, although smaller, are also underway. The Japanese efforts, under the leadership of Nitta and 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, as well as animal and fish physiology and breeding [37]. European efforts have included much work on microgravity issues of biological development, essential to the successful translation of ground-based CELSS to space, and work on basic physiological responses of plants to environmental factors (such as that of André and associates at CNRS, Cadarache, France [4]). Binot and colleagues at the European Space Technology Center at Noordwijk, The Netherlands are studying various microbial systems as elements in spacecraft life-support systems.

22.11 U. S. S. R. Bios Series of Experiments

The oldest and most advanced work in the field of closed ecological life support was begun in the 1960s at the Institute of Biophysics, Krasnoyarsk, Siberian Branch of the U. S. S. R. Academy of Sciences. This work, begun under the direction of Kovrov and now directed by Gitelson, had strong early support from the "Chief Designer" of the Soviet space program, Korolev.

After extensive tests of algae-based systems in Bios–1 and –2, the Bios experiments began incorporating higher plants. From 1972–1984, experiments were conducted in the Bios–3 facility, including closures of up to six months with two and three person crews with near complete air and water regeneration, and with considerable food production. The current testbed, Bios-3, is a stainless steel welded structure with a volume of about 315 m^3. It is divided by airtight divisions into four internal compartments, each with a volume of about 79 m^3, which can be variously linked or decoupled from the system (see Figures 22.3 and 22.4) [48]:

a) Two phytotrons, for the growth of the higher plant crops, each with a hydroponic growing area of about 20.5 m^2.
b) An algae compartment with provisions for three algae culture tanks for the production of chlorella.
c) A living compartment for the crews of two to three people.

Illumination for the higher plants is provided by water-cooled xenon lamps with an irradiation level of 140−180 Watts/m^2. During various experiments, some eleven to fourteen plant species were grown as food crops, including wheat (harvested and processed into bread inside the complex), potato, chufa (for vegetable fat), radishes, lettuce, carrots, beets, kale, onions, and dill. In a four month experiment conducted in 1977, the phytotrons produced about 650 g/day of dry biomass for the crew's nutrition. The system included no animals, and lyophilized meat was added to the diet to supply needed protein. From 30%−70% of food needs were met by production during the closures.

The water cycle was almost completely closed within Bios-3. Sanitary and general purpose water was reused in both phytotrons and algae tanks. Water transpired by the algae and plants was condensed, run through a purifying filter, boiled, and used as drinking water. Water contained in feces was recovered externally and returned to the chamber. The solid wastes were not treated or recycled. Urine was added to algae tanks and, during the course of these experiments, caused no specific problems. The upper limit of nitrogen supplied by the urea was 70% and NaCl concentrations of 2 g/l of the algal growing medium. Cooling was by heat exchange with river water which passed through Bios–3 in a closed loop system. This cooling water, though not materially part of the inside structure, accounted for the greatest volume of water used, as it was not reclaimed.

The atmosphere of Bios–3 also approached closure, but problems with higher plants were reported in several trials which linked the algae tanks' air system directly with that of the phytotrons. Build-up of potentially toxic trace gases required a catalytic burner to oxidize these substances. The source of this toxin was not determined, although it is known that man himself produces many gases, including hydrogen sulfide, methane, mercaptans, aldehydes, nitrogen oxides, hydrogen, and carbon monoxide. Higher plants and their associated microbes, algae, and also technogenic out-gassing from the structure and equipment of the chambers may have also contributed. The phytotrons produced about 1800−2000 liters of oxygen daily, sufficient to supply the crew. About 600 grams of the inedible portion of the grown biomass was periodically burned, producing ash, water, and CO_2. Manipulations of this oxidation maintained CO_2 levels in the living compartment between 300 and 1400 ppm, with short-term levels of up to 2000 ppm (0.2%). The remaining inedible biomass (generally about 300 g/day) was dried and removed from the system. Table 22.3 gives the results of the gas exchange during the 1977 four month closure in Bios–3 [48].

Some of the unresolved problems which were identified in the Bios experiments are:

1. The loss or unavailability of essential trace elements from the system. In the Bios facility, such losses were traced to removal of a portion of the nonedible plant biomass, feces, solids precipitated from the sanitary / general purpose water, and ash from combustion of biomass.
2. The simplification and depletion of human intestinal microflora, possibly rendering inhabitants susceptible to bacterial and fungal infection. Many studies of closed

ecological systems with few inhabitants and a simplified range of organisms (spacecraft and submarine crews, and isolated stations in the Arctic and Antarctic) have revealed loss of diversity of normal intestinal microflora [25]. None of the Bios–3 human closures reported health problems. The issue, however, was enough of a concern such that they cautioned that the microflora issue demands further research, since "the accompanying microflora, as a biological component of the system ...contains many uncontrollable potentials and capacity for rapid evolution that could unbalance the system." [25]

3. Bioregeneration of solid human wastes and long-term usage of liquid wastes were not studied.
4. Biological methods for the recycling of biogenic, anthropogenic, and technogenic trace gases and elements need to be identified. In these experiments, utilization of the catalytic burner for removing these compounds has the effect of decreasing the closure of the system, taking both nitrogen and trace elements out of the system, necessitating their introduction to the system and decreasing the inherent stability biological processes demonstrate.

The Bios line of research has been a landmark in the field of closed ecological systems – they have moved a long way towards fulfilling the creation of the first systems where man is not simply a mass-exchange unit, but an active participant and manager of his life-support system. Productivity in their experiments was such that if a "conveyor-belt" system of continuous plantings and harvestings was used, they estimated that complete life-support requirements for one human could be accomplished with perhaps 23 m^2 of growing surface. As Gitelson's team notes, despite the apparent attractions of physiochemical techniques, "reproduction of the organic part of the medium, food products in the visible future is possible only by biological methods...thanks to the interweaving of metabolic paths of the main biogenic elements, oxygen, carbon and hydrogen, it is impossible to create closed cycles of regeneration for atmosphere, water and food that are isolated from each other. Physical-chemical regeneration of water and oxygen in principle, therefore, cannot be completely closed. For the same reason, biological regeneration of food automatically included regeneration of the atmosphere and water to the same percentage as food is reproduced from the human metabolite." [48]

22.12 Biosphere 2 Test Module Research

In preparation for the Biosphere 2 project near Oracle, Arizona, an attempt to create a large-scale biospheric system using bioregenerative technologies, Space Biospheres Ventures undertook a program of research and development to create requisite technologies and systems. This research included building the Biosphere 2 Test Module. This testbed is a steel space frame and glass structure with an area approximately seven meters by seven meters square and a volume of some 480 cubic meters. The structure is open to sunlight and connected by air ducting to a variable volume chamber (lung). It is the largest closed ecological life-support systems facility (see Figures 22.5 and 22.6). It has been used to test materials outgassing, operation of the variable volume chamber, sealing techniques, and for evaluation of various ecosystem configurations. The results from over four years of research in this facility have been an important input into technology and sensor selection for Biosphere 2, and facilitated experience in the real-time management of bioregenerative systems capable of full human life support.

Ecological systems experiments in the Biosphere 2 Test Module with plants, animals (including insect populations), and soils have examined the regeneration of atmospheric gases, plant growth and photosynthetic efficiencies in closed systems [2, 3 3 , 36]. In operation since December 1986, the first closed system experiment involving a human in the Test Module took place in September 1988. This experiment had two phases: a three day period in which the person occupied the Test Module along with representative plants from the Biosphere 2 biomes, followed by a 17-day period in which closure was maintained and systems studied to see how they continued to respond in the absence of the person. Further one-person closures of five days in March 1989 and 21 days in November 1989 were conducted.

22.12.1 Analytic and Sensor Systems of Biosphere 2 Test Module

Periodic testing of air samples from the Biosphere 2 Test Module for trace gases by gas chromatograph mass spectrometer (GC/MS) as well as by gas chromatographs with thermal conductivity and flame ionization detectors was carried out. In addition, continuous monitoring of up to eleven gases (NH_3, CO, CH_2O, H_2S, NO_2, O_3, SO_2, CO_2, non-methane hydrocarbons, SOx, NOx) was accomplished with sensors attached to the exterior of the Test Module. SBV has gone through three developmental generations to create complete and reliable systems to perform this monitoring. The SBV systems are composed of analyzers, special software for computer control, automatic data acquisition, analysis, trending and alarm systems, multi-point sampling, and automatic calibration systems for analysis of the major trace gases of concern. Specially designed automatic systems sample and analyze air and water quality continuously. In addition to continuous analysis, a detailed analysis of soil, plant tissue, water, and air samples is done in the laboratory. To enable the system developed for the Test Module to be used in Biosphere 2, SBV drastically reduced the quantity of toxic solvents and reagent chemicals used, and exercised methods to contain or neutralize those employed [2, 36].

22.12.2 Life-Support Systems of Biosphere 2 Test Module

A prime challenge of the life support systems in the Biosphere 2 Test Module is to achieve enough uptake of carbon dioxide to compensate for the approximately one kilogram of carbon dioxide exhaled by a person each day, to provide water purification through evapotranspiration, and to provide a complete range of foods for human nutritional needs. The life-support system design included the following elements: plant species were chosen with a high growth rate, high photosynthetic rates, and selected at a young growth phase and pruned to encourage regrowth to maximize the amount of carbon dioxide which could be utilized by each plant. Included were a savannah canopy with C4 grasses (a metabolic pathway that some primarily tropical plants utilize, which permits more efficient utilization of CO_2 and higher productivity in high temperature/light conditions), intensive agricultural plants such as sweet potatoes, sugarcane, and peanuts which have very high photosynthetic rates, a ginger belt of plants from the rainforest which includes bananas and the fast growing Zingerberacae order plants, and marsh recycling system with a high growth rate water hyacinth as the dominant species [2, 3].

22.12.3 Soil Bed Reactors as Air Purification Systems

Soils were introduced into the closed system ecology of the Biosphere 2 Test Module and designed by SBV to be a primary bioregenerative system using the soil bed reactor (SBR) method of air purification. This technique operates by pumping the chamber's air volume through the soil, facilitating microbial metabolism of potentially dangerous trace gases from technogenic, biogenic, and anthropogenic off-gassing. Table 22.4, based on data from the first human Test Module closure, shows the complexity of outgassing products that closed ecological systems must be prepared to handle [2]. The Environmental Research Laboratory of the University of Arizona, a consultant on the agricultural and engineering systems of Biosphere 2, worked with SBV on developing and testing soil bed reactors. A series of benchtop experiments studied the dynamics of introducing fixed quantities of trace gases to SBRs and control systems. Other research focussed on optimal soil media, air flow, and whether soil fertility would be maintained through the use of SBRs as cropping areas [2, 17]. A series of experiments in the Biosphere 2 Test Module were dedicated to examining the uptake of introduced gases like methane and ethylene by SBRs and the effects of air pumping on soil respiration levels [2, 33]. They showed that for some gases, a certain amount of time was required before trace gas levels were brought under control, during which time, presumably, microbial populations rose to adjust to the introduced contaminant. Trace organic gases and potential toxic gases were kept within acceptable concentrations (as defined by the U. S. Occupational Safety and Health Administration and the American Conference of Governmental Industrial Hygienists) for human and plant life during all these human closure experiments [2, 36].

22.12.4 Water Systems of Biosphere 2 Test Module

The water recycling system consists of three subsystems: potable water, wastewater recycling from the habitat, and plant irrigation water. The waste recycling system, designed by SBV in consultation with Wolverton, has permitted complete recycling of all human wastes for the first time in a closed ecological system. The sewage and graywater is purified first anaerobically and then by the action of aquatic plants and associated microbes. Next, the water passes into the irrigation supply. This waste processing system is designed to clean 5–15 gallons of effluent per day, and during all the Test Module human closures, the 2.6 m^2 system operated effectively and without malodor. The potable water system operates by distilling moisture from the atmosphere by two dehumidifiers. This water is highly purified because it is largely a product of plant evapotranspiration. An ultraviolet system is used for microbial control. Irrigation water includes all run-off water from life systems, the end-product of waste processing, and excess potable water. Water is held in a reservoir and pumped to the plants through computer controlled solenoid valves to various irrigation zones [2, 35, 36].

These human closures in the Biosphere 2 Test Module advanced the field of closed ecological system research by achieving:

- the first time a closed ecological system had total air and water recycling, human waste treatment, as well as complete food production using bioregenerative technologies,
- no buildup of potentially toxic trace gases [2, 36].

22.13 Biospheric Systems

While the principal assets of CELSS and closed ecological life-support systems approach lies in their potential for high productivity at minimal weight/volume cost, their major risk arises from the same factor. In ecological systems, stability increases with diversity [41], therefore such simplified CELSS systems would be predicted to have much less capacity to handle perturbations. CELSS systems and technologies will doubtless play a significant role in near-term, long-duration space activities. In the longer context, CELSS systems may well form a part of the intensive food production or recycling component within the larger space biospheric system, relying on them for buffering function, completion of biotic cycling, and overall balances in an analogous manner to how our present planetary biosphere functions for specialized commercial agricultural systems.

Gitelson's team underscored the difficulty that even relatively sophisticated closed life-support systems such as Bios–3 face in replicating the complexity of material cycling and energetic pathways that the Earth's biosphere accomplishes: "a weak spot in the biological regeneration is the complexity of the synthetic processes that form a broad spectrum of inevitable satellite [by-products] in addition to the target product. The separation of these satellites by a biological method causes difficulties that are possibly insurmountable. This is a consequence of the multiple-plan nature of metabolic paths in any living organism. After selecting the most efficient living destructor to break down any inedible product, as a result of side processes one can still attain a new spectrum of inedible substances that will need their own destructors, etc." [48] The solution proposed, that of physiochemical means, may indeed be a reasonable solution for near-term space station and extended planetary missions which will utilize single ecosystems similar to agricultural systems in their complexity, but is not a solution for the construction of permanent habitations, or of biospheric systems capable of full closure, a high degree of stability and persistence, and – as with our global biosphere – the creation of free energy and evolutionary potential.

H. T. Odum summarized some of the advantages of using complex multi-species life- support systems:

> In appraising the potential costs of closed system designs, one has the alternative of paying for a complex ecosystem with self-maintenance, respiration and controls in the form of multiple species as ecological engineering, or in restricting the production to some reduced system like an artificial algal turbidistat and supplying the structure, maintenance, controls and the rest of the functions as metallic-hardware engineering. Where the natural combinations of circuits and biohardware have already been selected for power and miniaturization for millions of years, probably at thermodynamic limits, it is exceedingly questionable that better utilization of energy can be arranged for maintenance and control purposes with bulky, nonreproducing, nonself-maintaining engineering. [42]

Biosphere 2 was designed to utilize as much ecological engineering as possible (being a time-tested technology), but it also incorporates the backup of sophisticated technology for monitoring and manipulating key variables (such as air circulation, temperature, and moisture), as is required for the health of the various enclosed ecosystems [33, 34]. An especially interesting area of research is the biological/physiochemical and technological interface, and use of physiochemical sensors and mechanical controllers within a biological system. In the Soviet terminology, this is referred to as the interrelation between the biosphere and the technosphere [20].

22.13.1 Biomic Design in Biosphere 2

Biosphere 2 is designed for a total lifetime of a hundred years. The first closure experiment for a two year period commenced in September 1991. The facility supports a crew of eight biospherians who operate the intensive agricultural system, manage and monitor the other biomes, and maintain the equipment and computers inside the facility.

Biosphere 2 is a man-made biospheric system. It is materially isolated from its surroundings by a skin of stainless steel spaceframe and double laminated glass panels for air-tightness above ground, and by a stainless steel liner which acts as a seal from interaction with the ground. Energetically, it is open to both sunlight (an average of 65% of photosynthetic active radiation passes through the glass structure and 40-50 % is received by its ecosystems after losses to structural shading) and energy produced for the operation of its heating, cooling, and other mechanical systems. It is also informationally open [5]. Biosphere 2 is designed to achieve a complex life-support system by the integration of seven areas or biomes: rainforest, savannah, desert, marsh, ocean, intensive agriculture, and human habitat. It covers 12,766 m^2 (137,000 ft^2) (see Table 22.5) in its airtight footprint, including its two lungs (variable volume chambers). The tallest structure, that of the rainforest, is 27.7 m high. The ocean contains a coral reef ecology and a shallow lagoon area, and has waves that are generated by a vacuum pump wave generator. An ecosystem modeled on the estuarine Everglades ecology adjoins it with a series of communitites that grade from freshwater marsh to oligohaline spartina grass marsh, through areas dominated by white mangrove (*Laguncolaria racemosa*) and black mangrove (*Avicenna germinans*) to the more highly saline saline waters that support oyster beds and red mangrove (*Rhizophera mangle*).

This recognition of the key role that biomes (also called biogeocoenoses) play in the structural organization of the biosphere was seen by the Soviet biologist Kamshilov, who recognized their "ability to withstand various external effects...[due to their] homeostasis or buffering power. There seems to be a direct relationship between the complexity of biocoenosis and its ability to withstand diverse external effects...greater resistance not only to intrusion of individual species from different ecosystems but also to abiotic factors...The stability of the biosphere as a whole, and its ability to evolve, depend, to a great extent, on the fact that it is a system of relatively independent biogeocoenoses...[which] compete for habitat, substance and energy provides optimal conditions for the evolution of the biosphere as a whole." [20]

The variety of habitats the Biosphere 2 system offers was included in an attempt to ensure the full complement of microbial function that is now understood to be crucial to the completion of gas and materials cycling in our Earth's biosphere [13,28]. Procaryotic microbes, those most ancient of life forms which lack a nucleus, were the sole constituents of the biosphere for nearly two billion years, and have been recognized as the agents which "produce and remove all of the major reactive gases in the Earth's atmosphere: nitrogen, nitrous oxide, oxygen, carbon dioxide, carbon monoxide, several sulfur-containing gases, hydrogen, methane, and ammonia among others." [28]

The biomes were the key design elements in planning Biosphere 2. In our planetary biosphere, they work as important functional units, and compete against each other for territory, providing an integrative matrix for maximizing numbers of eco-niches, stable and complex food chains, and biogeochemical cycling routes. The success of the operation of Biosphere 2, with its over 3000 species, will be measured not so much by the life and death of any individual species, but rather by the overall functioning of the system: how well the eight-person crew is sustained, to what extent the biomes retain integrity and overall health, and by the successful maintenance of all cycling processes. Therefore, the principle of redundancy was key in the ecological design of the biomes – introducing several potential pathways in each foodchain, so that if one link does not survive, vital linkages may be maintained. Ecologically, the people inside Biosphere 2 are treated as keystone predators – responsible for maintaining balances in all the biomes by assisting important species and reducing the numbers of species that threaten to go out of balance. The marine and wilderness terrestrial biomes also offer an important buffer and source of free energy to counter the entropy produced by human technology and intensive agricultural units [1, 3 3].

A point of major interest and concern in the operation of Biosphere 2 is the carbon cycle. The far greater ratio of living biomass (estimated at 70 tons when plant biomass reaches its maximum) and soil material (some 30,000 tons of soil were introduced, from 1 meter deep in the agriculture to depths of 4-5 meters to provide a deep medium for wilderness tree species) to atmosphere will result in a far shorter residence time for CO_2 in Biosphere 2's atmosphere than in the Earth's biosphere. During the first closure, this is estimated at four days as opposed to the global biosphere's three to ten years. Therefore, in the operation of small ecological systems, this implies that carbon dioxide sources (people, animals, compost) must match rates of uptake (plants) rather closely. A strategy of stocking Biosphere 2 with sources of carbon accessible for uptake as the system is maturing has also been developed. In addition, two of the biomes in normal operation tend to balance each other – the desert is normally winter-active and the savannah is summer-active, though its growing season can be extended or shortened as atmospheric conditions warrant. How long a rainy season is produced in both these biomic areas determines how much growth they produce. Consequently, they form one of several management tools for the crew to manipulate atmospheric cycles. In addition, for seasonal buffering of CO_2, (winter day length decreases to 9.5 hours and summer increases to 14.5 hours at the project location) and to assist in the early years when total system plant biomass is increasing and the young soils may be oxidizing organic materials at a higher rate, a CO_2 recycling system is utilized. The recycler precipitates atmospheric CO_2 as $CaCO_3$ which can be released during the longer daylengths when CO_2 levels may fall to growth-limiting levels. The CO_2 precipitator operates via a two step process: $CO_2 + NaOH \text{-->} CaHCO_3$ and $CO_2 + 2NaOH \text{-->} Na_2CO_3 + H_2O$; then $NaHCO_3 + CaO \text{-->} CaCO_3 + NaOH$ and $Na_2CO_3 + CaO + H_2O \text{-->} CaCO_3 + 2NaOH$. To return the CO_2 into the atmosphere, the limestone can be heated in an oven at 950 deg. C. until the $CaCO_3$ disassociates back to CaO and CO_2, completing the cycle. Thus, all the chemicals can be regenerated for reuse, and the CO_2 recycled into the atmosphere of Biosphere 2.

22.13.2 Technosphere/Biosphere Interplay in Biosphere 2

An important design element in Biosphere 2 is the integration of technosphere and biosphere to support an optimally functioning life-support system. For example, the architecture of the structure with its glass and space frame construction are designed to permit a maximum of sunlight, the photosynthetic driver, to enter. The solar energy entering the glass is estimated at its peak to equal 6,963,000 kJ (1,934 kW) in the intensive agriculture biome, and 16,247,000 kJ (4,513 kW) in the wilderness biomes. The positioning of the desert at the low end of one side of the natural biomes permits hot, moist air to rise towards the rainforest.

Despite the fact that Biosphere 2 is modeled on tropical biomes and requires some heating to ensure minimum winter temperatures are met, cooling in summer is a chief engineering concern and energy demand because the equilibrium temperature in summer for such a "greenhouse" in southern Arizona would be 156°F. This is accomplished for the wilderness biomes by heat exchange through a closed-loop piping system with water that is evaporatively cooled outside Biosphere 2. This does not violate material closure, as only the energy is transferred. The humidity in Biosphere 2 is generally high, sometimes approaching 100%. Both temperature and humidity are more closely controlled in the intensive agriculture biome to assure crop productivity. This has required refrigerated cooling, accomplished through a combination of ammonia chillers and absorption systems using waste heat from the electric generators running on natural gas, which are located in a building outside the Biosphere 2 structure. The refrigerated cooling capacity is approximately 4000 tons. Air circulation rates are on the order of 5700 m^3/min in each biome for summer cooling and about one-tenth as much for winter heating. Water recycling for potable water is accomplished by condensation, mainly at cooling coils. In the intensive agriculture, this totals about 4000 l/day. Artificial rain is provided in the wilderness areas and intensive agriculture as needed [9, 10]. Table 22.6 outlines the design parameters for permissible temperature variation in the biomic areas.

22.13.3 Atmospheric Cycling in Biosphere 2

Atmospheric recycling is one of most challenging aspects of Biosphere 2 because of the relatively small buffer sizes and high ratio of biomass to atmosphere. Because of the 1170 m elevation of the project, atmospheric pressure is only 663 mmHg. Hence Biosphere 2 has a normal atmospheric operating volume of 185,026 m^3 (depending on the degree of inflation of the variable volume chambers. However, if atmospheric concentrations of CO_2 were similar to the global environment, there would only be 67 kg in the entire atmosphere (see Table 22.6). During the first year of closure, CO_2 levels averaged about 2000 ppm.

22.13.4 Intensive Agricultural Biome

The intensive agricultural system features the soil bed reactor, whereby air flowing underneath the growing areas is recirculated through the soil beds when required for control of trace gases. The entire air volume of Biosphere 2 can be pumped through the agricultural soil bed reactor every 16 hours at full operation. Studies have been underway for several years to assess the impact on soil fertility by this type of intensive agriculture (eight people being fed a complete, balanced diet from 2232 m^2 of growing area). Prior to the construction of Biosphere 2, SBV conducted research on cultivars of crop species, comparison of cropping techniques, disease and insect control approaches without using pesticides or herbicides, and recycling methods. Insects such as ladybugs, praying mantis, and parasitic wasps; safe sprays; manipulation of environmental conditions; and manual interventions are used to control insect pests on agricultural plants as part of an Integrated Pest Management approach [16, 17].

The animal species which form part of the diet of the crew in Biosphere 2 included chickens, pigmy African goats, and feral pigs for the first closure experiment. The aquaculture system includes tilapia fish, azolla (a water fern which forms an important part of the fish diet), and rice, growing together in small tanks. Mechanical and bacterial clean up of fish water (naturally occurring bacteria in a bio-filter convert ammonia excreted by the fish to nitrates valuable for plant growth) permits it to be recycled through the rice paddies.

22.13.5 Computer Control and Management System for Biosphere 2

To manage the complex interface between mechanical and living systems, a five-level hierarchy of computer-based monitoring and control was developed for the Biosphere 2 project. This system operates by "mission rules" which specify tolerable environmental parameters and has default positions in case of failure. Human intervention is possible at any level of the system. The five functional levels which the system utilizes are: 1) point sensing and activation, 2) local data acquisition and control, 3) system supervisory monitoring and control, 4) global monitoring and historical archive, and 5) telecommunications between crew and monitor stations inside and those in the Mission Control building outside. The "nerve system" developed for Biosphere 2 can be used for simulations and then checked against the results in actual operating bioregenerative systems. This was first applied to Test Module experiments and was then further developed for Biosphere 2, which has more than 2000 internal data points [35].

The lessons from the operation of Biosphere 2 may stimulate other research and greater interest in bioregenerative systems:

> Never before have such complete cropping areas / buffering volumes of air, water, and soil been mated to technical/engineering systems of environmental control and support. In addition to insights Biosphere 2 may yield on the operation of natural ecosystems and global biospheric systems, it will function as a unique test bed for space, where crews will operate both bioregenerative and technical life support systems. Learning to integrate and harmonize both life support systems and observing their behavior during perturbations over time will be an important milestone in being able to predict the behavior of created habitats ("eco-syntheses") for space. It should also project a powerful vision for permanent space habitation, where the vital ecological life sustaining functions of our global biosphere will have to be recreated in miniature, and sustained robustly for our well-being. [35]

22.13.8 Initial Results from the Closure Experiment 1991-1993

Some of the most striking results from the first closure experiment are the strong diurnal and seasonal fluxes in atmospheric CO_2. Diurnal variations on a sunny day can range from 500-700 ppm of CO_2 and while it is too early to determine if recurrent annual cycles will emerge, data since closure indicate strong correlation of CO_2 with seasonal

PPF (Photosynthetic Photon Flux) levels [Figure 22.8] [31]. An interesting pattern which has been observed is that subsequent to a series of cloudy days there is a notable increase in photosynthesis and a sharper initial drawdown of CO_2 on the initial sunny day which lessens over succeeding days. The maximum CO_2 level during the first year of closure occurred around the winter solstice when the PPF reached its lowest annual value of 16.8 moles/m^2/day of average outside incident light during December 1991. December's average CO_2 level was 2466 ppm. June 1992 had both the lowest average CO_2, 1060 ppm, and the highest PPF, 53.7 moles/m^2/day, since closure. During the second winter, the highest CO_2 daily average was about 4240 ppm reached on January 19 and February 9, 1993 during periods of prolonged cloud cover produced by storm fronts. .

Atmospheric oxygen unexpectedly declined after closure, confirmation that the complexity of ecological and bioelemental interactions are sufficiently great that unanticipated chemical reactions and pathways will develop over time. Oxygen declined from a starting level of 20.9% to a low of around 14% in January 1993 [Figure 22.8]. At that time, to relieve medical symptoms in some of the crew attributable to hypoxia, pure oxygen was injected into Biosphere 2 to raise oxygen levels back to more than 19 percent. Studies are underway to determine the exact reactions which account for the decline of atmospheric oxygen, which has shown signs of significant slowing by the spring of 1993.

Leak rates are being monitored through depletion determinations of several trace gases (SF6, He and Kr) with which were spiked into Biosphere 2's atmosphere. These indicate an air exchange of below 10% per year, far less than in previous closed systems. After an initial period during which Biosphere 2's lungs were operated to give the facility a positive pressure in order to locate and seal leaks, the system has been operated at neutral pressure to minimize air exchange. The low rate of air exchange allowed tracking of the slow loss of atmospheric oxygen and allows close tracking of trace gas dynamics in the facility [8, 32]. To date, use of the soil bed reactor has not been necessary because trace gases have remained below levels of health concern.

The agricultural system produced about 90 % of crew food during the first year of closure. The remainder was supplied by food reserves previously grown inside. Crop production was diminished because the fall and winter seasons during the two year experiment were marked by exceptionally cloudy weather and because of depredations by a crop pest, broad mite, for which control strategies are being implemented. As anticipated, about 30% of the crew's work day goes into agriculture and food system labor. Crew diet during the first mission was nutrient-dense and calorie-restricted and offered the opportunity for the first study of humans under such a nutritional regime. Physiological changes showed similar reductions in cholesterol, blood pressure, and other indices as have been observed in previous laboratory animal studies of such regimes [52]

Overall system biomass continues to increase, with woodland canopies rapidly developing in rainforest, savannah, and marsh. The Biosphere 2 desert biome has shown a community dominance shift from cacti/succulents to subshrubs/annuals since closure.

Ocean water clarity has been improved with installation of protein-skimmers constructed from materials available inside Biosphere 2. This purification process removes organic molecules by aeration through long cylinders and is currently complementing the algae scrubber system initially installed for marine nutrient control. Overall, fewer species appear to have been lost than anticipated, though what level of biodiversity will be maintained in the various biomes is a question to be studied over the long-term operation of Biosphere 2.

A change of Mission Rules during the first closure has allowed export of scientific samples for analysis to outside laboratories on a regular monthly basis. To increase research potential, some of the analytic equipment originally operated within Biosphere 2 has been exported to the research laboratory on site at the project.

Transition periods between closure missions will be utilized for completion of research projects and initiation of new studies, and for engineering modifications and upgrades. During transition periods, airlocks will be used to allow personnel to enter and exit the structure without disrupting the integrity of the atmosphere.

22.14 Bioregenerative Life Support in the Changing Framework of Space Development

Permanent human presence in space and a number of ambitious long-duration missions are beginning to emerge as significant goals in the evolving international space agenda. This changing framework of space development has had a number of important inputs, including the U. S. National Commission on Space, headed by Thomas Paine, and the Sally Ride report for NASA which looked at the next fifty years in space and outlined a coherent set of objectives which could build an effective space infrastructure. These studies emphasized the importance of bioregenerative life support as a key enabling technology. In 1988, President Reagan included permanent human presence in space as one of the nation's goals. In the same year, the U. S. Congress amended NASA's charter to include permanent human presence as a legitimate part of its activity. President Bush, in his speech on the twentieth anniversary of the Apollo moon landing, announced a Space Exploration Initiative which includes Space Station Freedom, a permanent lunar base and then Mars exploration. This emerging American space agenda is similar to what many saw as the central focus of the U. S. S. R space program. They have already achieved the Mir space station, have considerable experience in year-long space stays, and have plans for lunar bases by early in the 21st century, to be followed by manned exploration, and finally, Mars bases. For many years, the motto of the Soviet space life scientists has been: "On Mars we must grow our own apples!" It is unclear whether the political changes that have recently occurred in Russia will change this space strategy, although economic pressures both in Russia and the United States make cooperative international ventures increasingly attractive. The strategy of "evolutionary expansion" into space as opposed to space spectaculars with no infrastructural increase (known as "footprints and flags") is beginning to dominate space exploration planning.

This far-reaching space agenda requires, and is producing, a shift in life support away from the type of technologies that were developed for the sprint missions to the

Moon or for short duration spaceflights. It is now becoming clear that bioregenerative life support is one of the chief technologies that can make possible our long-term future in space. There are a growing number of exciting, ongoing research and development programs to advance our understanding of this frontier. Clearly, parallel efforts are needed to translate ground-based test bed work into plausible space-based systems. Among them are a better understanding of radiation hazards and defenses, microgravity and reduced gravitational effects on living systems, and the ability to utilize extraterrestrial materials. But what is becoming clear to space planners and the public alike is that bioregenerative life-support systems are the key to being able to **live** in space.

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Tables for ISU textbook chapter:

Table 22.1-A

Inputs Required to Support a Person in Space (after Modell and Spurlock [29]).

Inputs	One Day (kg/person)	One Year (kg/person)	Lifetime (kg/person)
Food (dry)	0.6	219	15,300
Oxygen	0.9	329	23,000
Drinking Water	1.8	657	46,000
Sanitary Water	2.3	840	58,800
Subtotal	5.6	2045	143,100
Domestic Water	16.8		
Total	22.4		

Table 22.1-B

Human Daily "Waste" Products (after Rummel and Volk [44]).

By-Products	One Day (kg/person)	One Year (kg/person)	Lifetime (kg/person)
Water:			
water in urine, feces	3.0	1095	76,650
metabolic water (vapor)	0.4	146	10,220
perspiration (vapor)	1.7	621	43,470
wash/flush water	18.0	6570	459,900
Solids:			
feces, urine, sweat solids	0.2	73	5,110
Gas:			
CO_2 from metabolized wheat	1.1	402	28,140

Table 22.3

Calculation of Daily Gas Exchange of Crew in Bios–3 Experiment.

Indicator	I stage			II-III Stages		
	Proteins	Fats	Carbohydrates	Proteins	Fats	Carbohydrates
Composition of ration (g)	230	230	1150	165	165	825
Assimilability of foodstuffs (%)	86.9	96.9	99.4	86.0	86.9	99.4
Assimilated quantity of foodstuffs (g)	200	223	1143	143	160	820
Quantity of O_2 necessary to oxidize 1 gram of substance (l)	0.966	2.019	0.829	0.966	2.019	0.966
Quantity of CO_2 formed during oxidation of 1 gram of substance (l)	0.774	1.427	0.829	0.774	1.427	0.829
Quantity of O_2 necessary to oxidize assimilated substances (l)	193	450	948	138	323	680
Quantity of CO_2 formed during oxidation of assimilated substances (l)	155	318	948	111	228	680
Total quantity (l)						
of consumed O_2		1591			1141	
of released CO_2		1421			1019	
Respiratory coefficient		0.893			0.893	

Table 22.4

Trace Organic Gases Identified by Three Methods in the Biosphere 2 Human in Closed Ecological System Experiment, September 10 – 30, 1988.

A. Identified by Gas Chromatograph / Mass Spectrometer

Compound	No. Isomers Found	Probable Origin
Alkyl Substituted Cyclopentane	1	c
2-butanone	1	c
Carbon Disulfide	1	b
Cyclohexane	1	c
Decahydronaphthalene (decalin)	1	a
Decamethylcyclopentasiloxane	1	a
Decane	1	c
Dimethylbenzene	2	a
Dimethylcyclohexane	3	c
Dimethylcyclopentane	4	b
Dimethylhexane	2	c
Dimethyloctadienol Acetate	2	b
Dimethyloctane	2	c
Dimethyloctatrine	1	b
Dimethylpentane	1	b
Ethylmethylcyclopentane	1	c
Ethylbenzene	1	c
Ethylcyclohexane	1	c
Heptane	1	c
Hexamethylcyclotrisiloxane	1	a
Hexane	1	c
Isopropyl Substituted Cyclopentane	1	b
Methyl (methylethenyl) Cyclohexane	1	b
Methylbenzene	1	a
Methylbicyclohexene	1	b
Methylcyclohexane	1	c
Methylcyclohexene	1	c
Methylcyclopentane	1	c
Methylheptane	1	a
Methylhexane	2	c
Octamethylcyclotatrasiloxane	1	a
Substituted Cyclohexane	3	b
Substituted Cyclohexene	1	b
Tetrachloroethene	1	a
Tetrahydrofuran	1	a
1,1,1 Trichloroethane	1	a

Trichloromethane	1	a
Trimethylbicycloheptene	1	b
Trimethylcyclohexane	2	c
Trimethylcyclopentane	3	b
Trimethylpentane	1	c
Trimethylsilanol	1	a

Table 22.4 Trace Organic Gases . . . (cont.)

B. Identified by Gas Chromatograph / Flame Ionizer Detector

Compound	No. Isomers Found	Probable Origin
Ethane	1	c
Ethylene	1	c
Methane	1	c
Propane	1	a

C. Monitored with Continuous Sensors

Compound	No. Isomers Found	Probable Origin
Ammonia	n/a	b
Carbon Monoxide	n/a	b
Formaldehyde	n/a	a
Hydrogen Sulfide	n/a	b
Nitrogen Dioxide	n/a	b
Ozone	not detectable	
Sulfur Dioxide	n/a	b

_ *Probable Origin: a = Technogenic, b = Biogenic, c = a + b*

Table 22.5

Area and Volumes of Biosphere 2.

	AREA		VOLUME	
	m^2	(ft^2)	m^3	(ft^3)
Intensive Agriculture	2,232	(24,020)	37,832	(1,336,012)
Habitat	1,077	(11,592)	10,677	(377,055)
Rainforest	1,900	(20,449)	34,690	(1,225,053)
Savannah/Ocean	2,555	(27,500)	48,668	(1,718,672)
Desert	1,360	(14,641)	22,042	(778,399)
West Lung (airtight portion)	1,822	(19,607)		
South Lung (airtight portion)	1,822	(19,607)		
Lungs (at maximum)			50,137	(1,770,546)
Total Airtight Footprint:	12,766	(137,416)		
Total Volume:			204,045	(7,205,737)
Soil, Water, Structure, Biomass			19,019	(671,635)
Air			185,026	(6,534,102)
Ocean Water (a)			3786	(133,690)
Fresh Water (b)			757	(26,738)

(a) approximately 1,000,000 gallons

(b) approximately 200,000 gallons

Table 22.6

Temperature Parameters for Biosphere 2 Biomes.

	Minimum		Maximum	
	°C	(°F)	°C	(°F)
Rainforest	13	(55)	35	(95)
Savannah	13	(55)	38	(100)
Desert	4	(40)	43	(110)
Intensive Agriculture	13	(55)	30	(85)