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LIVING IN SPACE: RESULTS FROM BIOSPHERE 2'S INITIAL CLOSURE, AN EARLY TESTBED FOR CLOSED ECOLOGICAL SYSTEMS ON MARS

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The following summary of results from the first 2-year closure experiment (September 26, 1991 to September 26, 1993) in Biosphere 2 is excerpted from a chapter written by William Dempster and myself for a book, Strategies for Mars, *edited by Carol Stoker and Carter Emmart of NASA Ames Research Center. The book will be published later this year by Krieger Publishers. It brings together a number of the most striking initial results, including food production and nutrition; ecosystem changes; oxygen and carbon dioxide dynamics; and the human role and response to living in a small, recycling life support system. The references cited are useful as a guide to currently available articles in journals. Hopefully, the next year will see a proliferation of papers presenting more data from the first 2 years of Biosphere 2's operation. There was a wealth of data collected during the closure and by teams of researchers who had access to the facility during the 5-month transition period following the departure of the first crew and the commencement of the second closure experiment in March, 1994.*

On September 26, 1991 a crew of eight people passed through the airlock beginning an experimental habitation of Biosphere 2, a closed ecological system built in the Arizona desert north of Tucson. Two years later they emerged—somewhat thinner but against considerable odds in overall good health and with a viable life support system. The project marked the first long-duration habitation by humans in a closed environmental system, and, not surprisingly, the first 2 years of its operation included a multitude of problems, including several that were unanticipated. The initial 2-year closure in Biosphere 2 revealed the sharp fluctuations in atmospheric cycling that will be expected in small closed systems because of its concentration of living biomass and small air volumes. CO_2 during the 2 years ranged from under 1000 ppm to over 4000 ppm. Oxygen was depleted from the atmosphere by reactions with organic C in the system's soils, dropping from an initial 20.9% (ambient) to around 14% after 16 months of closure, when additional oxygen was injected to sustain the crew. Food production supplied over 80% of the eight person crew's nutritional needs and was strongly influenced by seasonally fluctuating light levels and unexpected insect problems. Lowered caloric intake and a nutritionally dense diet produced sharp drops in blood cholesterol and other health improvements previously seen in laboratory trials of similar diets. The created ecosystems grew rapidly, with large increases in biomass evidenced in tree canopy development. Some ecosystem changes, particularly in the desert, were observed as the biomes developed. Wastewater

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treatment and water recycling was accomplished during the 2-year closure. The lessons from the Biosphere 2 experiments may prove valuable in preparation for the challenges of utilizing Martian resources and creating at first limited weight and volume life support systems and eventually permanent habitation modules on Mars.

INTRODUCTION

Biosphere 2 is the first testbed created for complex ecosystem bioregenerative life support on a long-term basis (50–100 years) to determine its viability and dynamics over time. The Biosphere 2 facility is essentially materially closed (with an annual air leakage rate under 10%), energetically open to electricity and sunlight, and covers some 3.15 acres in its airtight footprint, including over 7 million cubic feet of volume. The name Biosphere 2 was chosen to emphasize that the Earth's biosphere (Biosphere 1) is the only biosphere known to science. Biosphere 2's structure includes a human living and work area, agricultural zone including waste recycling and potable water system, five areas modeled on natural ecosystems: rainforest, savannah, desert, marsh, and ocean, and via air ducts is connected to two variable volume chambers ("lungs") permitting expansion/contraction of the internal atmosphere without incurring leakage.

Research and development for Biosphere 2 has included work on a number of technologies for potential space application as components of smaller systems including soil beds for air purification, aquatic plant waste water recyclers, nonpolluting analytic and monitoring labs, multilevel cybernetic systems for system operation and analysis, and sustainable soil-based agricultural systems. These were tested in the Biosphere 2 Test Module, a 17,000 cubic foot facility, which has advanced the field by closing the loop for the first time in air and water purification and in recycling of human metabolic waste products.

Although the concept of the biosphere is scarcely 100 years old, understanding the workings of our global biosphere is a much more recent scientific endeavor. We are just on the threshold of coming to a proper appreciation for the complex, adaptive, and evolutionary life system that has enabled life on Earth to flourish for at least 3.8 billion years. Recent scientific findings have changed our notion of this biosphere from being simply the fortunate beneficiary of favorable planetary and geological conditions to being a more active shaper of Earth's environment. The Biosphere 2 project is the first attempt to create a man-made biosphere where similar processes as occur in our global environment may be studied but on a scale that permits experimentation and detailed analysis. Started at the end of 1984, research and development for the project preliminary to the first 2-year closure experiment spanned some 7 years during which time component technologies and ecological research was conducted in the Biospheric Research and Development Center at the project site in Oracle, Arizona. The construction of the Biosphere 2 facility itself was a 4-year endeavor from its groundbreaking in 1987 until its initial closure experiment was begun in September, 1991. The motivations behind its creation were many, including creating a new type of laboratory for studying biospheric processes such as biogeochemical cycles, the viability and interaction of small analog ecosystems to those found on the Earth, and as a testbed for developing new environmentally beneficial systems (e.g., biological means of wastewater regeneration and air purification, sustainable nonpolluting agricultural systems, and laboratory techniques that minimize the use of toxic chemicals).

In this chapter we will focus on its potential value as a baseline for studying the dynamics of life support systems that may be used for long-term habitation in space. Although much simpler life support systems, evolving from purely physicochemical ones, will be required in the early phases of space habitation, it seems inevitable that to provide an evolutionary basis for such expansion into space, we will require the added ecological stability and potential that more complex life systems, biospheres, will offer.

LIFE SUPPORT REQUIREMENTS – THE DRIVER

Calculations of the quantities of critical variables (air, water, food) needed for human life support are essential for understanding at which point bioregenerative systems for spacecraft and space stations will become competitive with the approach currently used, physicochemical systems supported by resupply of water and food from Earth. These quantities of water, air, and food also underline the importance of developing bioregenerative life support systems. The quantities are simply too large to consider for long-term resupply from Earth, and such a long supply line poses significant safety hazards. Finally, developing the ability to recycle and utilize local resources in creating bioregenerative systems is essential to achieving long-duration habitation and eventual expansion of human population on Mars.

Rummel and Volk developed computer modeling and simulation of bioregenerative life support systems using estimates of daily human requirements (37). These estimates for metabolic needs may in fact be low, because their study based the diet on nutritional needs being met solely by wheat, ignoring nutritional complexities and the need for variety. These calculations (given in grams/person/day) estimate food inputs at 855 g, drinking/food preparation water at 4577 g, water in food, 128.3 g, wash/flush water at 18,000 g, and oxygen (for food metabolism) at 804.6 g. The development of more efficient technologies for water utilization and reclamation in space may of course reduce the quantities required for uses other than metabolism.

Metabolic by-products of each human in space are at present a problem, but can become significant resources for bioregenerative life support systems. For example, waste products may provide valuable organic material to help amend Mars soils to support crops. These outputs they estimated as: Water: water in urine, feces 3025.5 g/person/day, metabolic water (vapor) 406.0, perspiration water (vapor) 1680.0, wash/flush water 18000.0; Solids: feces, urine, sweat solids 161.4; CO_2: from metabolized wheat 1092.3.

From projections similar to these, Modell and Spurlock have estimated that "in the course of a year, the average person consumes 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 amount to over one thousand times an adult's weight" (25).

The implications of these calculations are clear: extended, not to speak of permanent, human presence in space makes necessary "closing the loop" in the regeneration of air, food, and water involved in human life support. Little wonder the Soviet space program took as its goal: "We must grow our own apples on Mars!"

ECOLOGICALLY BASED SYSTEMS: THE HUMAN FACTORS

In addition to the above necessity for developing bioregenerative systems for space, the design team at Biosphere 2 sought to create systems that would meet additional requirements of making an enjoyable, safe, reliable, and satisfying environment for its inhabitants. Although crews have survived in submarines, cramped space stations, and underground isolation chambers for periods of months to years, these type of sterile and mechanical environments are hardly conceivable as permanent habitations for people. There are also significant concerns about the long-term reliability and stability of such systems if they are to be used in space, outside the safety net of the Earth's biosphere.

We are just beginning to unravel the functions that our biosphere performs in biogeochemical cycles, air and water purification, creating free energy and increasing ecosystem organization, maintaining vital life parameters, etc. The Biosphere 2 project attempted to change our paradigm about what life and permanent habitation in space will be like. All life that we know exists in a biosphere, which is essentially its life support system. To expand life, including humans, in space on a permanent basis, we must begin to consider that we will be ultimately building biospheric units there. The problem (and research opportunity!) is that there are many unknowns about how to miniaturize and operate a biospheric system. This was the fundamental challenge of the Biosphere 2 experiment.

THE HISTORICAL SETTING

The Biosphere 2 project built on the experience gained from experiments conducted over the past three decades in bioregenerative life support. Especially in the U.S. and Russia such research dates back to the beginning of the space age. Initial work concentrated on two species systems, predominantly using *Chlorella vulgaris*, a fast-growing green algae, as a "partner" for humans. Both Russian and American researchers were able to engineer systems that provided air and water recycling using small algae tanks. The Russians at the Institute of Biomedical Problems, Moscow, conducted 15- and 30-day experiments with people in small chambers (40). However, the goal of making the *Chlorella* also suffice for food supply was never realized, as ingestion of more than 30–50 g per day caused a variety of gastrointestinal health problems in man.

The next major step was the inclusion of higher plants as food sources. This step was first taken at the Institute of Biophysics in Krasnoyarsk, Siberia. After previous work with algae systems in Bios 1 and 2, their 315 cubic meter apparatus powered by artificial lights, Bios-3, was the locale for a series of experiments from 1972 to 1984. In it, crews of two and three people lived for periods as long as 6 months. Inside the air was nearly completely regenerated, although catalytic burners were needed to handle trace gas buildups, the water was purified by plant evapotranspiration, and the hydroponic cropping area of about 400 square feet grew up to 11 grain, vegetable, oilseed, and root crops. These crops met about half of their nutritional requirements. Human wastes, except for some of the urine, were not processed inside the facility, but were "exported," and some food, including dried meat for additional protein, was "imported" (42).

The volunteer crews included doctors, engineers, and agronomists. They had access to phones, TV, and newspapers that were delivered through their airlock. They harvested their wheat and other crops, processed them, and baked bread and cooked meals in their kitchen. When carbon dioxide levels dropped to about 300 ppm (a bit lower than normal atmospheric concentrations of 350 ppm), they oxidized some of the straw from the wheat crops, pushing CO_2 levels up to about 1400 ppm to maximize plant photosynthesis. CO_2 poses no particular human health problem at levels below 10,000 ppm, although optimal levels for plants are not yet well characterized. Crew members' health was intensively monitored, and although some simplification of their intestinal microbiota occurred due to the limited diversity of their life environment (22), they maintained good health during their stay inside Bios-3 (42).

The Bios line of research is a landmark in the field of closed ecological systems. It moved the field a long way towards fulfilling the goal of space rocketry pioneer Tsiolkovsky's "closed ecocycles" in space greenhouses by creating the first systems where man is not simply a mass-exchange unit, but an active participant and manager of his life support system (17,42).

The NASA efforts, directed through the CELSS (Controlled Ecological Life Support Systems) program since 1978, have supported research in a variety of universities and at the NASA Ames Research Center, NASA Johnson Space Center, and NASA Kennedy Space Center to conduct basic research and engineering applications of the various components necessary for life support. Much of this work has focused on high-yield systems of biomass and food production. Here as well as with other closed ecological system research, there is potential for important spin-off benefits "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" as an early NASA study noted (25).

In 1986 the Breadboard Project, NASA's most ambitious higher plant-based CELSS program, was begun at Kennedy Space Center. The goal of their Biomass Production Chamber is to demonstrate the production of food for human life support, water recycling, and atmospheric gas control. Although experiments of this type had been previously performed, the Breadboard project is considerably scaled up from previous laboratory-sized research. Support laboratories are investigating associated questions of waste recycling, food preparation, and overall data management. Human closure experiments are presently scheduled for later in the 1990s (7,21).

RESEARCH AND DEVELOPMENT IN PREPARING FOR BIOSPHERE 2

The program of research and development that was required to prepare for Biosphere 2 included 4 years of operation in the Biosphere 2 Test Module with closed systems demonstrating that bioregenerative life support systems can close the loop in water, air, and food as well as recycling waste products. Development and testing of automated real-time analytic systems for monitoring air and water quality in closed ecological systems was conducted. This was part of a multilevel cybernetic system developed for managing systems and processing data from some 2000 data points and 800 sensors in Biosphere 2. Laboratory and Test Module research has demonstrated the air regeneration capabilities of "soil bed reactors" which force air through the agricultural soil, thus exposing the airstream to the soil microbes that can metabolize potentially toxic trace gases. Biosphere 2 research has broken new ground in the development of this technology by the integration of this air regeneration by the soil bed reactors with crop production in agricultural soils. Preceding the 2-year closure experiment were 4 years of operation in Biosphere 2 Test Module with closed systems, from 1987 to 1990, including experiments with humans lasting up to 21 days (4,5,31).

This research phase also included the design and engineering of variable volume chambers ("lungs") as a solution to pressure differential problems (12), developing a training program for crew members to handle complex biological and technical systems, selection and development of nonpolluting technologies compatible with operation inside a closed ecological system for analytical and biomedical laboratories, and food production/processing. A marsh aquatic plant system for recycling of human wastes and household water was developed. Breakthroughs in air-tight sealing technologies were also needed to approach the degree of closure aimed for in Biosphere 2 (12, 31,33).

Biosphere 2 Test Module: A Total Systems Laboratory

One of the lessons from the Biosphere 2 endeavor is that complete bioregenerative systems are feasible, however much they may be improved and made more volume/mass efficient in future developments. Just as the Apollo program in the 1960s accelerated development timelines by instituting "all-up systems testing" rather than exhaustive component by component analysis, SBV moved to develop needed innovative technologies and include them in complete bioregenerative systems testing. To accomplish this acceleration of development, the Biosphere 2 Test Module was designed and constructed in 1985 as a precursor to Biosphere 2 and as a testbed for individual and integrated systems components.

The Biosphere 2 Test Module is a 17,000 cubic foot materially closed ecological facility, the largest such facility in the world prior to the completion of Biosphere 2. It was designed to test both the engineering and structure planned for the much larger Biosphere 2, and life system interactions in conditions of a closed ecological system. In operating the testbed, there have been progressive approximations towards a successful integrated system. For example, experiments have tested two sealing methods, several generations of analytic/sensor systems, and the first application of the variable volume chamber concept.

The Biosphere 2 Test Module is sealed underground with a stainless steel liner and is connected via an air duct with a variable volume chamber ("lung"). This lung allows the atmosphere to expand and contract as do the lungs of Biosphere 2, which are described in below. The Test Module achieved a leak rate of 24% per year (31).

The Biosphere 2 Test Module was the first bioregenerative facility to achieve air purification through biological means (vs. catalytic burners), water cycling, and human waste and domestic graywater waste recycling. Food was grown to supply nutrition during the short-term human closures, but the limited growing area was not adequate to support long periods of human habitation. Over 60 person-days were logged in experiments, including a 3-week closure in November 1989 (4,5,31).

INNOVATIVE BIOREGENERATIVE TECHNOLOGIES

Some of the innovative technologies that SBV developed, tested in the Test Module, and are utilized in Biosphere 2, address crucial issues for bioregenerative systems.

Food Production—Intensive, Nonpolluting, and Sustainable

SBV and its prime consultant for the agricultural section, Environmental Research Laboratory of the University of Arizona, began with trials of hydroponic and aeroponic cropping techniques. A variety of reasons underlay the subsequent switch to soil-based agriculture. One, of course, is that hydroponics depends on a supply of chemical nutrients that cannot be produced from within the system. In addition, soils in a closed system can play a significant role in air purification, either through the soil bed reactor technology (discussed below) or simply through passive diffusion through the soil facilitating the diverse metabolic capabilities of soil microbial populations. Another advantage of using soil is that it simplifies creation of waste recycling systems for animal and human wastes and inedible portions of crops. Traditional and energetically low-intensity technologies like compost or utilizing plant/microbe systems for wastewater regeneration become available options (27,29).

Composting and marsh wastewater systems (see below) are far less energy-consumptive than alternatives like wet oxidation or incineration. Marsh wastewater and compost systems operate by time-tested biological mechanisms. The biomass produced in the marsh wastewater system in turn can be composted to produce high-quality topsoil for replenishing the nutrients that crops removed from the soil. An important requirement for the agriculture of the bioregenerative system is that it must be sustainable as well as highly productive. There are numerous historical examples of sustainable soil agriculture but none thus far of a hydroponic system that can persist without "complex outside additions in the form of fertilizers and pesticides" (18).

Another requirement of an agricultural system in a materially closed system is that it must be virtually pollution free. Even in the nearly 7 million cubic foot volume of a facility like Biosphere 2, water, soil, and air buffers are so small, and cycling times so rapid, that there is no way of introducing pesticides and herbicides without serious health hazards. The water cycle is a few weeks and CO_2 in air has a residence time of about 4 days in Biosphere 2 (28). Therefore, a variety of biological and cultural methods of pest and disease control (known as Integrated Pest Management) must be utilized for the agricultural crops.

These disease and pest control techniques include: selection of resistant crops, using many small plots and rotating crops, switching between several cultivars (varieties) of the major crops, maintenance of "beneficial insect" populations (ladybugs, praying mantis, parasitic wasps, etc.) to control pest insects, intercropping, and manual control. In addition, "safe sprays" such as soap, light oil, or *Bacillus thuringensis* may be employed (19,23,29).

For the first time in a closed ecological life support system, a complete nutritional diet was the goal and domestic animals were included. The diet for the eight crew members of Biosphere 2 included milk (from African pygmy goats), eggs (from the system's domestic chickens), meat (from the goats, chickens, and Ossabaw feral pygmy pigs), and fish (from Tilapia grown in the rice/azolla water fern paddies). In addition, a wide range of vegetables, grains, starches, and fruit are grown (Fig. 1). Biosphere 2 maintains semitropical temperatures in the agriculture area (60–85°F) permitting both temperate and tropical varieties to be grown.

In all, a total of over 86 crops (including herbs) were utilized during the first closure experiment. Though the diet includes some animal products, fat is in short supply and peanuts as a source of vegetable fat is an important crop. A computer program keeps track of nutrient intake and helps plan forward planting of crops to ensure a balanced diet (1).

The entire agricultural area must produce the fodder crops necessary for the animal food as well as direct human food crops. The reliance on ambient sunlight reduced by 50–55% in passing through the glazed envelope also limits area productivity and might differ in a space application where advantage may be taken of enhanced artificial light techniques to boost yields. Biosphere 2 marked the first time domestic animals have been utilized and that such a variety of crops will be harvested and processed in a closed system. This has required the use of a variety of processing equipment to lower labor requirements (41).

Air Purification—Soil Bed Reactors

The addition of soil also opens the way to potential solution to one of the most vexing of problems—the maintenance of air quality. The great diversity of outgassing products from anthropogenic, biogenic, and technogenic sources combined with the small volumes and rapid cycling times of atmospheric components in closed systems create a significant hazard for toxic gas buildups. In Apollo, Skylab, and Space Shuttle cabins, for example, there were 300–400 gases identified, and significant concerns about unanticipated reactions between such outgassing products (34,36). These air contamination concerns occurred in spite of the significant flushing of the air volume through the carbon dioxide removal system, and other measures such as "exclusion of material, equipment isolation, absorption using charcoal, or absorption of soluble substances on the condensate in humidity-control devices. The results of numerous studies performed in anticipation of a Space Station indicate that these methods would be inadequate for longer missions, larger crews and the anticipated greater variety of equipment" (20). The conventional solutions to this problem include filtering methods using charcoal or catalytic oxidation, which will require substantial energy costs and/or expendable parts, such as filters.

In addition to natural soil and vegetative interactions with the air, Biosphere 2 was designed so that the soil of the agricultural area can also function as a "soil bed reactor" when blowers are turned on to force air upwards through its soils. This technology, originally developed in Europe for control of industrial odors, passes the air volume through an active soil to expose it to the metabolic action of the microbial populations there. The diversity and high numbers of microbes are capable of metabolizing an extraordinary range of trace gases that could pose a toxicity problem (10). In preparation for Biosphere 2, research was conducted at Environmental Research Laboratory and in the Biosphere 2 Test Module to determine the efficacy of soil bed reactors in removing specific contaminants and those generated in a complex bioregenerative facility. This research demonstrated the ability of SBRs to scrub trace gases and maintain air quality while simultaneously ensuring good aeration and cropping productivity in a working soil (16,31). The entire air volume of Biosphere 2 can be pumped in less than a day through its soil bed reactor. In addition, the significant volumes of soil and diversity of soil types incorporated within Biosphere 2—along with its abundant vegetation—means that even without use of the soil bed reactor, there will be large biological interactions with the atmosphere.

Waste Recycling Systems

SBV worked with the consultation of B. C. Wolverton, now retired from NASA Stennis

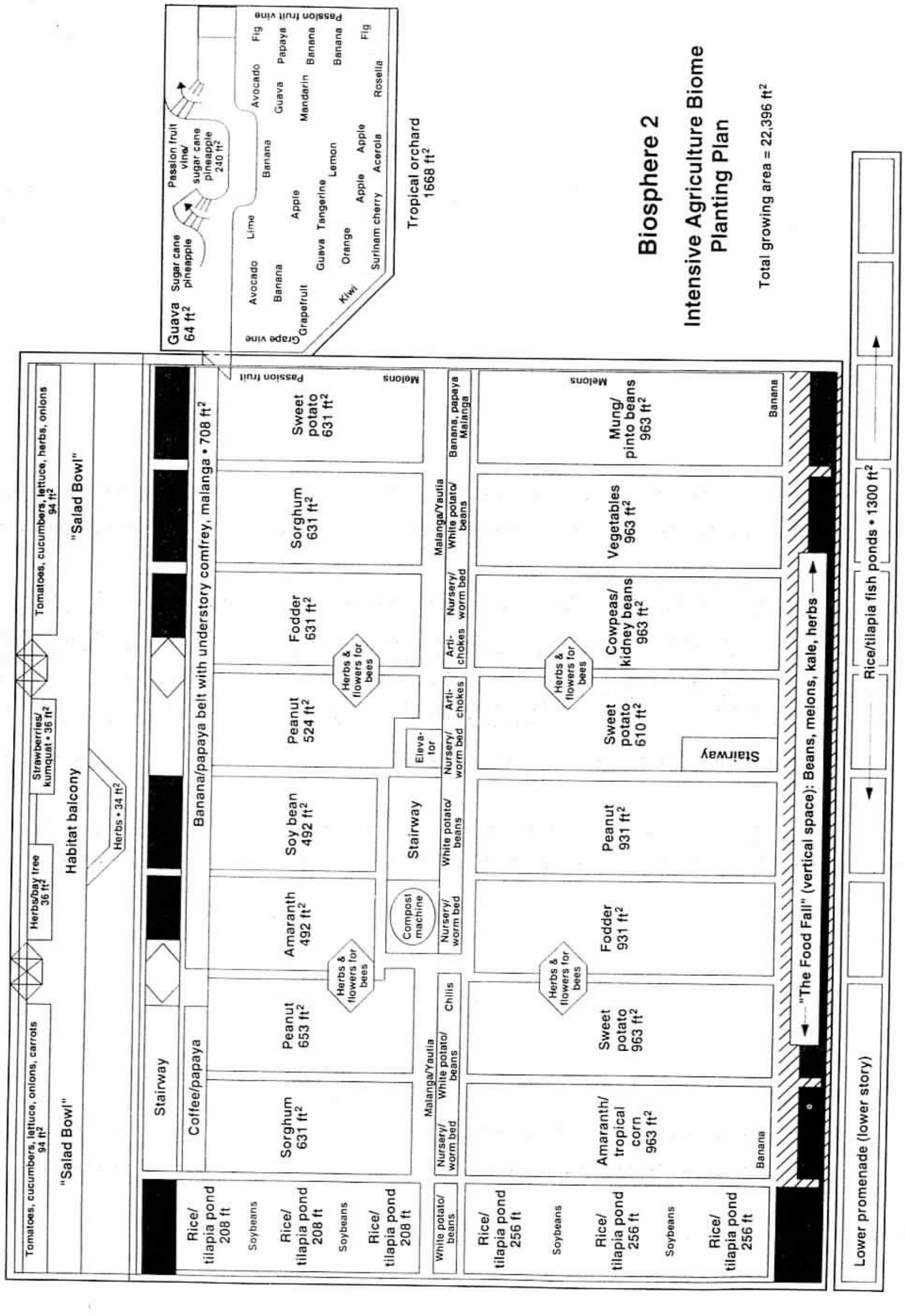

Figure 1. Schematic illustrating the polycultural planting plan in the Biosphere 2 agriculture areas. Apart from perennial trees and rice paddies, most planting beds were rotated in crop two to three times per year. Staggered planting/harvesting assisted in labor scheduling and in assuring a steady supply of food [from Nelson, Silverstone, and Poynter (29)].

Space Center, on the development of waste recycling systems that utilize aquatic plants and their associated microbes to purify water streams containing human and animal wastes and domestic graywater from the human residences and kitchen/laundry. These "constructed marsh" systems utilize the wastes to produce an abundance of plant growth valuable for animal fodder and compost material. The advantage of marsh systems is that they have low maintenance and energy requirements and produce valuable byproducts. As Schwartzkopf and Cullingford note: "Many previous CELSS concepts have incorporated high energy methods of waste degradation such as wet oxidation or super critical wet oxidation. In the process, all of the energy stored in the chemical bonds of the waste materials is lost. By using either bioregenerative technologies or appropriate physicochemical technologies . . . some of the chemical bond energy can be provided to the system by converting wastes into low complexity materials which can be used as foodstocks for bacteria, algae or higher plants" (38).

Some plants grown in the marsh waste treatment system can be used for animal fodder and grow rapidly in the nutrient-rich waters. After leaving the marsh waste treatment system, the water is added to the irrigation supply of the agricultural crops, which thus benefit from any remaining nutrients. A similar marsh wastewater system is employed for any chemical effluent that may occur from internal workshops and laboratories, taking advantage of the fact that aquatic plants will concentrate heavy metals, thus isolating them from soil and water contamination. A final advantage of this wastewater system is that the high rate of growth and transpiration of aquatic plants make them valuable sources of potable water through condensation of water vapor (45,46).

Analytic and Monitoring Systems

To operate Biosphere 2 it was necessary to develop unique capabilities for the analytic and monitoring systems. They had to be highly automated so they are operable with a minimum of human time, produce data about environmental parameters in real time so that corrective steps might be taken, sufficiently flexible to be able to deal with the wide variety of potential analyses of concern, minimize reliance on consumable supplies, and produce little or no pollution because they will operate in a closed ecological system. These requirements, of course, are directly analogous to the needs an operating Mars base will have of its monitoring systems.

To achieve these objectives, SBV developed a series of automated sensing systems that monitor continuously 11 key trace gases from each of the biomes of Biosphere 2 and key water variables of nitrite and nitrate concentrations. A computerized information processing system records data from over 800 sensors distributed throughout Biosphere 2 as well as providing remote control of equipment and data base inquiry and analysis (24).

All the consumables required by the analytical lab, with the exception of several high-quality chemicals needed in small quantities, are produced inside Biosphere 2. These include pure air, pure water, liquid nitrogen, gaseous nitrogen, hydrogen, and oxygen. Glove boxes and scrubber systems contain and neutralize solvent or acid fumes (24,43).

Cybernetic Systems

To assist the crew in operating Biosphere, many of the control and management functions are automated using an artificial intelligence system termed the "Biosphere 2 Nerve System." It is this system (developed by SBV and a team from Hewlett-Packard) that is programmed to carry out the complex and routine control of the infrastructure of electromechanical devices, airhandlers, pumps, and valves, which maintain overall environmental parameters (43). It includes environmental sensing and response (sensors and actuators); local data acquisition and control; system supervisory (by biome) monitoring and control; overall Biosphere 2 monitoring, optimization, information analysis, reporting and historical archiving; and telecommunications networks.

Software for these systems include programs specifically designed for life support system use.

These are carbon dioxide modeling and real-time monitoring, thermodynamic modeling, simulation and real-time control, global monitoring of overall system status, nutrition/diet planning, and crop production scheduling.

BIOSPHERE 2—THE FIRST MAN-MADE BIOSPHERIC LIFE SUPPORT SYSTEM

Unlike previous closed ecological systems of the CELSS and Bios-3 types, which included essentially only one type of ecosystem—an agricultural one—in addition to its human habitat, Biosphere 2 is designed to be a "biospheric" system. That is, it includes several distinct ecosystems (analogous to Earth's biomes that contain characteristic climate, soil, and flora/fauna) with the aim of determining whether such a system might enable long-term life support. Biosphere 2 was designed to support (and be operated by) a human crew of eight. It is also virtually materially closed to exchanges with the outside atmosphere and underlying geology. Biosphere 2 is energetically open; that is, it receives energy inputs both from incident solar radiation plus electrical power, heating and cooling from an energy plant outside its airtight structure. Biosphere 2 is also informationally open; it receives information from outside scientists, technicians, and engineers, as well as being connected via computer telecommunications, telephone, video, radio, and TV. It also sends out a wide variety of communications and data.

Biosphere 2's 3.15 acre footprint and 7 million cubic foot volume (Table 1) is sealed above ground with a laminated glass mounted on spaceframe and below ground by a stainless steel liner (2,6). Its atmospheric leak rate is documented at less than 10% per year (12). Two variable volume chambers ("lungs") connected to the main struc-

Table 1. Areas and Volumes of Biosphere 2

Areas	Square Feet	Square Meters	Acres	Heclare
Glass surface	170,000	15,794	3.90	1.58
Footprints				
Intensive agriculture	24,020	2,232	0.55	0.22
Habitat	11,592	1,077	0.27	0.11
Rainforest	20,449	1,900	0.47	0.19
Savannah/ocean	27,500	2,555	0.63	0.26
Desert	14,641	1,360	0.34	0.14
West lung (airtight portion)	19,607	1,822	0.45	0.18
South lung (airtight portion)	19,607	1,822	0.45	0.18
Total airtight footprint	137,416	12,766	3.15	1.28
Energy center	30,000	2,787	0.69	0.28
West lung (weathercover dome)	25,447	2,364	0.58	0.24
South lung (weathercover dome)	25,447	2,364	0.58	0.24
Ocean water surface area	7,345	682	0.17	0.07
Marsh surface area	4,303	400	0.10	0.04
Volumes	**Cubic Feet**	**Cubic Meters**		
Intensive agriculture	1,336,012	37,832		
Habitat	377,055	10,677		
Rainforest	1,225,053	34,690		
Savannah/ocean	1,718,672	48,668		
Desert	778,399	22,042		
Lungs (at maximum)	1,770,546	50,137		
Total	7,205,737	204,045		
Soil, water, structure, biomass	671,635	19,019		
Air	6,534,102	105,026		
Ocean water (1,000,000 gallons, approx.)	133,690	3,786		
Fresh water (200,000 gallons, approx.)	26,738	757		

tures by underground air ducts allow for expansion and contraction without leakage and without dangerous pressure differences between inside and outside that could break the envelope of Biosphere 2. Each lung consists of a large cylindrical air tank (vertical axis) sealed on top by a flexible impermeable membrane which rises and falls as Biosphere 2's atmosphere expands and contracts. The variable volume of the two lungs combined is about 1,500,000 cubic feet. Each lung is further enclosed by a dome within which the air pressure can be controlled within a critical range by use of fans. This patented arrangement permits the air pressure within Biosphere 2 to be maintained anywhere from modestly positive to very slightly negative relative to external barometric pressure. This gives the powerful capability to limit as well as to determine the leak rate (12) (see further discussion of leak rate in below).

The life systems of Biosphere 2 are housed in two wings, which are connected in water/air circulation but that have insect screens to prevent flying insects from moving from one to the other. Like the global biosphere, Biosphere 2 is composed of various "biomes," with differing soils, climate regime, and vegetation. Five areas patterned on tropical wilderness areas are housed in the eastern wing, which is some 540 feet long and from 100 to 140 feet wide. Biosphere 2 had some 3000 species of plant and animal at initial closure. This "species-packing" strategy was designed so that should losses occur, there is a good chance that other species might fill required food-web econiches.

The biomes of Biosphere 2 are: a tropical rainforest with Neotropical, predominantly Amazonian species; savannah with species from Australia, South America, and Africa; a coastal fog desert area patterned on Baja, California; an estuarine marsh ecosystem collected in the Everglades of Florida; and a tropical oceanic system with coral reef collected off Yucatan and in the Caribbean, shallow lagoon and beach.

The western wing includes two man-made biomes: an agricultural area (including rice/fish paddies, fodder plants, tropical orchard, chickens/goats/pigs, and vegetable/grain systems) for growing a complete diet for the eight-person crew plus recycling wastewater and inedible biomass; the human habitat, with living and working areas for the crew.

Table 2. Energy of Biosphere 2

Electrical Peak Demands	Kilowatts		
Biosphere 2 airtight enclosure	1500		
Energy center	1500		
Total	3000		
Generating capacity (Fossil fueled generators)	3750		
Cooling Peak Demands	Refrigeration (tons)	Kilojoule/Hour	
Intensive agriculture	900	11,395,000	
Wilderness	1900	24,056,000	
Total	2800	35,451,000	
Heating Peak Demands	BTU/Hour	Kilojoule/Hour	
Intensive agriculture	3,400,000	3,587,000	
Wilderness	7,000,000	7,385,000	
Total	10,400,000	10,972,000	
Solar Energy Entering Glass (Peak)	BTU/Hour	Kilojoule/Hour	Kilowatts
Intensive agriculture	8,200,000	8,651,000	2,403
Wilderness	17,500,000	18,462,000	5,129
Total	25,700,000	27,113,000	7,532

Table 3. Food Production in Biosphere 2 During the 2-Year Closure Experiment, 1991–1993

Crop	Yields kg/sq. meter Year 1	Yields kg/sq. meter Year 2	Total 2-Year Yield (kg)	Grams per Person per Day	Protein (g) Person/Day	Fat (g) Person/Day	kcal/ Person/ Day
Grains							
Rice	0.29	0.20	276.47	46.76	3.52	0.85	167.82
Sorghum	0.24	0.17	189.83	32.10	4.24	0.64	106.63
Wheat	0.22	0.14	191.87	32.45	4.29	0.65	107.78
Starchy veg.							
White potato	0.63	1.42	240.41	40.66	0.86	0.48	31.22
Sweet potato	2.25	1.95	2765.13	467.64	6.68	1.34	494.36
Malanga	n/a	n/a	101.61	17.18	0.41	0.03	18.04
Yam	n/a	n/a	19.50	3.30	0.07	0.00	4.36
High-fat legumes							
Peanut	0.10	0.15	147.42	24.93	6.59	12.20	146.03
Soybean	0.15	0.34	21.41	3.62	1.32	0.66	14.56
Low-fat legumes							
Lab lab bean	n/a	n/a	143.79	24.32	3.88	0.33	84.33
Pea	0.05		14.52	2.45	0.61	0.02	8.42
Pinto bean		0.20	27.49	4.65	1.15	0.04	15.94
Subtotal			4111.95	695.41	32.47	17.20	1183.55
Vegetables							
Beans green	1.22	1.03	24.95	4.22	0.08	0.00	1.36
Beet greens	2.64	0.63	432.28	73.11	1.33	0.37	15.38
Beet roots	2.83	2.20	760.23	128.57	1.88	0.18	56.94
Bell pepper			65.73	11.12	0.10	0.05	2.67
Carrots	2.25	4.39	224.76	38.01	0.34	0.07	16.70
Chili			125.19	21.17	0.42	0.04	8.47
Cabbage	3.42	2.78	152.82	25.84	0.30	0.04	5.91
Cucumber			48.13	8.14	0.04	0.01	0.04
Eggplant			244.94	41.42	0.44	0.03	11.10
Kale	8.30		11.29	1.91	0.06	0.01	0.93
Lettuce	5.37	2.44	150.59	25.47	0.24	0.04	3.37
Onion			139.24	23.55	0.28	0.06	7.99
Pak choi	3.91	3.47	45.29	7.66	0.11	0.01	0.98
Snow pea	0.29		0.91	0.15	0.01	0.00	0.12
Squash seed			10.43	1.76	0.51	0.82	9.70
Summer squash	4.88	4.39	512.56	86.68	0.93	0.19	16.72
Swiss chard	12.69	14.65	141.52	23.93	0.43	0.05	3.93
S. Pot Greens			64.41	10.89	0.31	0.03	2.72
Tomato			352.90	59.68	0.53	0.11	11.72
Winter squash	4.15	4.05	342.47	57.96	1.05	0.10	36.82
Subtotal			3850.63	651.22	9.40	2.20	213.57
Fruit							
Apple			0.57	0.10	0.00	0.00	0.06
Banana			2170.92	367.15	2.36	10.49	220.29
Fig			54.34	9.19	0.07	0.03	6.70
Guava			53.50	9.05	0.06	0.04	3.64
Kumquats			4.17	0.71	0.00	0.00	0.42
Lemon			10.12	1.71	0.01	0.00	0.34
Lime			3.63	0.61	0.00	0.00	0.16
Orange			5.65	0.96	0.01	0.00	0.33
Papaya			1215.64	205.59	0.81	0.15	52.87
Subtotal			3518.53		3.31	10.71	284.79

Table 3. Continued

Crop	Yields kg/sq. meter Year 1	Yields kg/sq. meter Year 2	Total 2-Year Yield (kg)	Grams per Person per Day	Protein (g) Person/Day	Fat (g) Person/Day	kcal/ Person/ Day
Animal products							
Goat milk			841.84	142.37	4.58	5.59	99.05
Goat meat			16.96	2.87	1.02	0.48	7.54
Pork			58.74	9.93	1.70	2.06	26.11
Fish			10.21	1.73	0.32	0.07	2.03
Eggs 257			14.29	2.42	0.29	0.27	3.86
Chicken meat			8.07	1.37	0.25	0.20	2.92
Subtotal					8.17	8.68	141.50
Total produced					53.35	38.80	1823.41

From Silverstone and Nelson (41).

Energetically, the life systems are powered by ambient sunlight, and technical systems including those required for thermal control are powered by external cogenerating natural gas electrical generators (Table 2). Heated, chilled, or evaporatively cooled water as needed for thermal control passes through Biosphere 2 in closed loop piping into air-handler units where heat exchange occurs. Evaporative cooling water towers outside Biosphere 2 dissipate rejected heat. The air handlers provide airflow of such heated/cooled air over the system's ecosystems, providing thermal regulation. Temperature parameters have been set in accordance with the normal tolerances of the various biomes, and range from winter lows of about 15°C to summer highs in the desert and savannah of around 38°C. The agriculture and human habitat areas have the tightest temperature controls to provide better growing conditions for crops and comfort for the crew (29,33,41).

BIOSPHERE 2 PERFORMANCE DURING THE 2-YEAR CLOSURE

Food Production and Agriculture

The agricultural cropping area of 2000 sq m produced about 80% of the nutritional requirements of the eight biospherians during the 2-year closure. This was lower than expected, and utilizing 3 month's food supply that had been grown in Biosphere 2 before closure and some seedstocks resulted in average daily caloric intake over the 2 years of about 2200 calories, 73 g of protein, and 32 g of fat per person (Table 3). Caloric intake was somewhat lower during the first year, and that factor along with adaptation to the diet resulted in most of the 10–20% weight loss experienced by crew members (Tables 4 and 5). The combination of restricted caloric intake with high nutritional density produced a large decline in blood cholesterol levels and other healthy physiological adaptations as had been observed in previous laboratory studies of such a dietary regime (44). Modest gains or a virtually leveling off of weight marked the final year of the closure experiment (41).

Light was one of the obvious limiting factors for the Biosphere 2 agriculture. Comparison of crops grown in differing seasons and light conditions during the 2-year closure reveals that yield was strongly correlated with incident light (41). This was anticipated – the site in Arizona has a daylength that varies from 9.5 h of daylight at the winter solstice to 14.5 h at the summer solstice (correlating with some 25–65 Einsteins/sq m of incident light on the outside on cloudless days) and light attenuation by glass and structural shading lowers incident light by 50–60%. However, what was unanticipated was that the 2 years of closure would be ones with strong El Nino Southern Oscillation conditions producing an unusual number of stormfronts, especially during the winter months. This proved to be important not only in lowering crop yields, but on the effort to limit seasonal increase of carbon dioxide. One of the major agricultural improvements effected in the transition period after Mission One was the installation of artificial lights to supplement solar input, especially during the winter months. In addition, selection and experimentation with crops more adapted to lower light and other Biosphere 2 environmental factors should improve agricultural production in future closure experiments.

Insect and disease problems were caused by two types of mite, mealy bug, aphid, powdery mildew, root knot nematode, and cockroaches. The most serious of these proved to be the broad mite, which proved resistant to a number of control techniques. Its damage caused a shift from white potatoes to sweet potatoes among starch crops, and to increased reliance on lablab bean because both these crops proved highly resistant to attack. Crops of importance included grains: rice, wheat, sorghum; starches: sweet potato, taro; bean: lablab; oil seed: peanuts; vegetables: beet, chili, tomatoes, squash, greens, and lettuce; fruit: banana, papaya. The goats were the outstanding producers of the domestic animals (41).

Crew ingenuity resulted in the utilization of virtually every conceivable spot within the agricultural area and in tight intercropping where light permitted. Biospherians became highly attuned to helping Biosphere 2's plants capture all available "sunfall" entering the facility, both in the agriculture and wilderness areas. Some 200 sq m of additional food-producing planters in the agriculture area were created in this fashion, contributing hundreds of kilograms of "extra" food during the second year of closure (3).

"The diet and cooking became an extremely important part of everyday life in the Biosphere. The standard of the cooking on a particular day would have an effect on the general spirits of the crew . . . variety was extremely important. A new taste or a new dish became a real treat and every effort was made to enhance cuisine so as to avoid the monotony of the same foods. Much of the variety was provided by the various fruits, vegetables, herbs and spices and the different milk products such as cheese and yoghurt . . . much of the crew's social life became centered around food. Holidays were celebrated with huge feasts" (41).

Table 4. Average Protein, Calories, and Fats Consumed per Person per Day Over the 24 Months of Closure

Month	Protein (g)	kcal	Fats (g)
Oct 91	67	1789	28
Nov 91	62	1925	21
Dec 91	74	2183	27
Jan 92	62	1948	23
Feb 92	74	2247	37
Mar 92	74	2206	32
Apr 92	72	2092	29
May 92	71	2043	28
Jun 92	72	2038	30
Jul 92	62	2227	32
Aug 92	66	2307	28
Sep 92	72	2491	34
Oct 92	68	2307	37
Nov 92	70	2304	34
Dec 92	88	2345	30
Jan 93	82	2225	30
Feb 93	74	2247	37
Mar 93	99	2282	34
Apr 93	79	2204	29
May 93	69	2190	30
Jun 93	72	2337	40
Jul 93	67	2252	32
Aug 93	75	2397	39
Sep 93	72	2609	38
Overall average	73	2216	32

From Silverstone and Nelson (41).

Ecosystem Development and Changes

Even before closure, because Biosphere 2's biomes were installed about a year earlier, there had been rapid growth in the various ecosystems. Biomass increased some 50% in the rainforest between initial measurement in the fall of 1990 and July of 1991 when many of the trees were resurveyed (35). This rapid development of tree canopies continued throughout the 2-year closure in rainforest, savannah, and marsh biomes. Many *Leuceana glauca* trees, for example, designed to be "early successional" trees in the rainforest to prevent sun damage to more light-sensitive species, grew to be 12–16 m tall, and were cut down during the first transition to facilitate growth of later successional trees. The "gingerbelt," which forms the outer perimeter of the rainforest, and

Table 5. Weights of the Eight Biospherians Over the 2-Year Closure Period

Crew Member	Body Weight in kg				
	Sep 91	Mar 92	Sep 92	Mar 93	Sep 93
Male 1	67.2	60.5	56.8	61	59.2
Male 2	68.2	59.1	54.5	58	57
Male 3	67.3	55.5	54	58	56
Male 4	94.5	73.6	67.5	71	72.5
Female 1	75	64.5	66	69	70.5
Female 2	55.9	50.9	49.5	52	52.2
Female 3	59.1	52.3	51	53.5	53.9
Female 4	52.7	42.8	44	48	46.8

From Silverstone and Nelson (41).

the "bamboo belt," which shields the rainforest from potential salt drift from the ocean, also showed prolific growth (28).

A detailed resurvey of plants was conducted in all the biomes during the transition period following Mission One and before a second crew began a closure experiment (Mission Two) in March, 1994. Those data are still being analyzed for publication. But it was apparent during the course of the 2-year closure that one of the most striking ecosystem developments was a shift in the desert biome from the cactus/succulent vegetation dominance originally envisioned to a system more dominated by shrubs, annuals, and, in areas, grasses—thus more resembling a coastal succulent scrub ecosystem. This shift may have been occasioned by the strategy of keeping the desert watered longer and thus active to assist in carbon dioxide management during the low-light months it is normally active. Other factors may have been responsible as well, such as water condensate from the glazing, especially in winter and by relative humidity remaining higher in the system than would normally be the case in coastal, fog deserts (28).

Species losses in the coral reef were fewer than anticipated and evidence of coral reproduction was discovered during the transition surveys. Whiteband disease affected some brain corals during the 2-year closure. Manipulation of the ocean's pH was done with addition of buffering chemicals in response to the high levels of atmospheric carbon dioxide in the facility (28). Nutrient removal to maintain the low levels of nitrates and nitrites found in coral reefs was accomplished by banks of algae scrubbers under artificial lights, which treated waters from both ocean and marsh. To further lower nutrient levels, skimmers operated by air bubblers were constructed by the crew during the 2 years (4).

There was a noticeable decline in flying insects during the 2-year closure and loss of two bird species. Galago ("bushbaby," a prosimian) conception and birth occurred within Biosphere 2 during the closure (28). Explosion of some populations, including a species of ant and cockroach, has stimulated further research and potential control methods (41).

Management required in the ecosystems has varied. The explosive growth of a few plants, notably several vines—morning glory and passionfruit in rainforest and savannah, C4 grasses in savannah and desert, and macro-algae in the ocean, necessitated human intervention to prevent loss of other species through shading. In other cases (e.g., the thornscrub ecotone between savannah and desert) canopy development has tended to reduce understory invaders. Biosphere 2 was originally species packed, so some loss of species and emergence of hierarchies of dominance was expected to naturally develop. In some cases, biospherians intervened, acting as deliberate "keystone predators" in the small synthetic ecosystems. In the ocean, lobsters and trigger fish were culled by biospherians to prevent excessive predation. Several ecosystems were managed to assist in the control of carbon dioxide. For example, savannah grasses and rainforest gingerbelt were pruned and the cut biomass dry-stored to slow decomposition, whereas the rapid regrowth of the vegetation assisted in sequestering carbon dioxide during low-light seasons. The regulation of active/dormant seasons in savannah, thornscrub, and desert could be manipulated in the interests of atmospheric management as well (3,30).

Carbon Dioxide Dynamics

Fluxes of biogeochemical elements can be rapid in small, closed ecological systems because of the high concentrations of biotic elements and small buffer capacities. It is useful in discussing carbon dioxide dynamics in Biosphere 2 to understand that even in a facility with an atmospheric volume of some 6 million cubic feet (170,000 cu m), that a concentration of 1500 ppm in its atmosphere is only equal to about 100 kg of carbon (28). In addition, the ratios of distribution of organic carbon are quite different in Biosphere 2. Unlike the Earth with a 1:1 ratio of carbon in plant biomass to atmospheric carbon, Biosphere 2's ratio is on the order of 100:1. When we compare soil organic carbon to carbon contained in the atmosphere, the Earth's ratio is 2:1 whereas Biosphere 2 has a ratio three orders of magnitude greater [(27); Earth estimates from Bolin and Cook (11)].

Another factor accounting for Biosphere 2's carbon dioxide fluctuations is that the entire vegetated area is photosynthetically active during the daytime, whereas at night plant and soil respiration is dominant. This results in day/night fluctuations of up to 500–600 ppm for sunny days. In addition, Biosphere 2's carbon dioxide record during closure shows the strong effect of seasonal light variations. For example, June 1992 had an average carbon dioxide concentration of around 1050 ppm, whereas December 1991 had an average

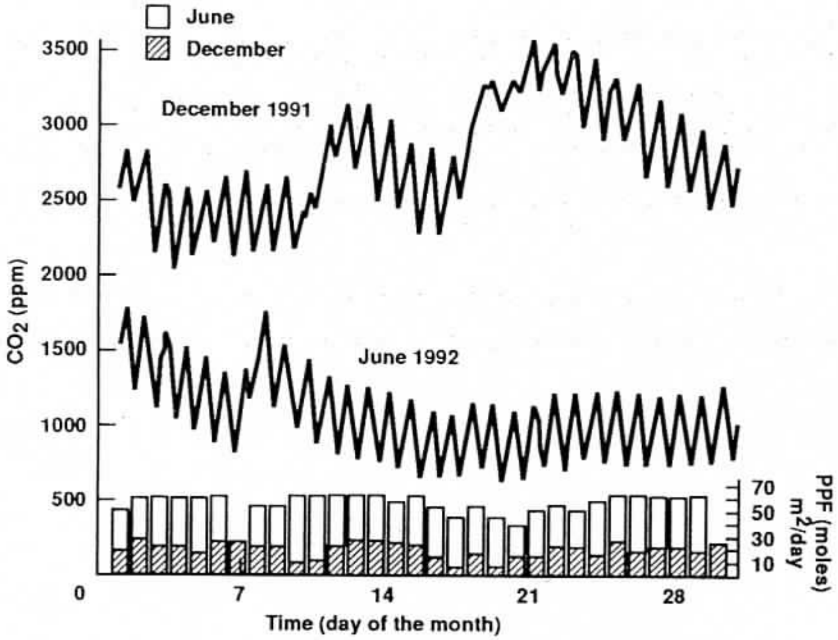

Figure 2. Atmospheric CO$_2$ dynamics within Biosphere 2 during December 1991 and June 1992. The overlapped bar values given for photosynthetic photon flux (PPF) are for total daily incident sunlight at the project site; internal light levels vary depending on location in the facility but average 40–50% of ambient sunlight. Cloudy days have a large impact on CO$_2$ dynamics and normal day/night variations are large, because photosynthesis dominates during the daylight hours, drawing CO$_2$ levels sharply down, and soil and plant respiration at night leads to large rises [from Nelson et al. (28)].

atmospheric concentration of about 2450 (Figs. 2 and 3) (13,27).

To assist in the management of CO_2 a physicochemical precipitator with capacity to lower CO_2 levels by 100 ppm/day was used. The chemical sequence of reactions is reversible, as the $CaCO_3$ formed could be heated to release CO_2. Other measures taken by the crew to increase photosynthesis and decrease respiration included pruning to stimulate regrowth and dry storage of cut biomass, lowering nighttime temperatures, cessation of composting, and minimizing soil disturbances during the winter (27).

Labor Requirements

Analysis of the crew time spent in various tasks reveals that agriculture and food-related jobs was the largest component, requiring about 45% of total work hours (Fig. 4). This included food processing, care and feeding of domestic animals, and cooking. There was a slight reduction during the second year as the agricultural soil became easier to till, and more efficient means of accomplishing tasks were developed (41).

On average, two-thirds of crew time was spent on operations and one-third on research and communications as opposed to the 50/50 split originally envisioned. A decision was made halfway through the 2-year closure to export some of the laboratory equipment originally inside the system, and to permit scheduled exports/imports of scientific samples and instrumentation. This was done with the goals of reducing crew time required and to increase the amount of research that could be accomplished. Each crew member worked an average of 66 h per week. The cooking duties were taken in turn, with each member doing three meals (1 day) every 8 days. This required on average 8 h of time. Sundays were days off for the crew, as were holidays observed on the outside, but every day food preparation, domestic animal tending, and system checks were required (3,43).

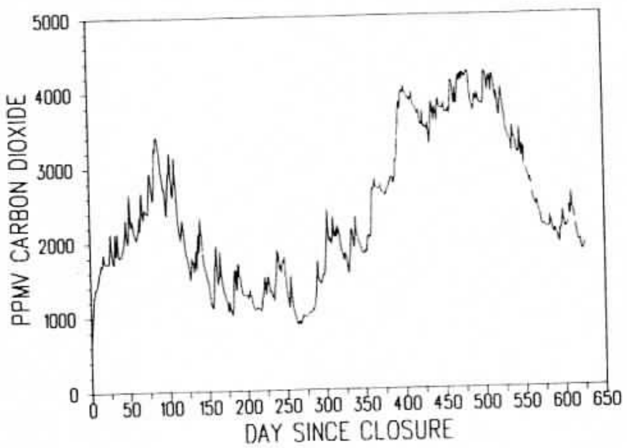

Figure 3. Graph of Biosphere 2 carbon dioxide levels, September 26, 1991 to June 13, 1993 [from Dempster (13), reprinted with permission].

Material Closure and Determination of Leak Rate

It is crucial to recognize when a closed ecological system is sufficiently closed to demonstrate its capabilities for fully recycling all materials or, conversely, the progressive increase or decrease of some. Biosphere 2 achieved a major step towards complete closure because its atmospheric leak rate is so small that material balances can be confirmed within narrow limits. The atmospheric leak rate has been measured by two independent methods at approximately 10% per year or less (12) (Fig. 5). It should be explicitly noted in this context that an "atmospheric leak rate of X% per time period" means that over the given time period, X% of the atmosphere is replaced by foreign matter (ambient air) outside the enclosure, whereas (100 − X%) of the atmosphere is matter originally contained in the system regardless of whether or not it has undergone transformations by chemical reactions. Thus, when we speak of leakage we do not mean simply inward or outward leakage, but net exchange.

One of the methods employed to determine leakage of Biosphere 2 was to spike the atmosphere with sulfur hexafluoride and with helium as trace gases and to measure their progressive dilution over time. A year's observation of these trace gases confirmed the 10% per year estimate (13). These two gases were selected, in part, as representatives of extreme ends of the spectrum of molecular weights; sulfur hexafluoride (mol.wt. 146) being heavy and helium (mol.wt. 4) being

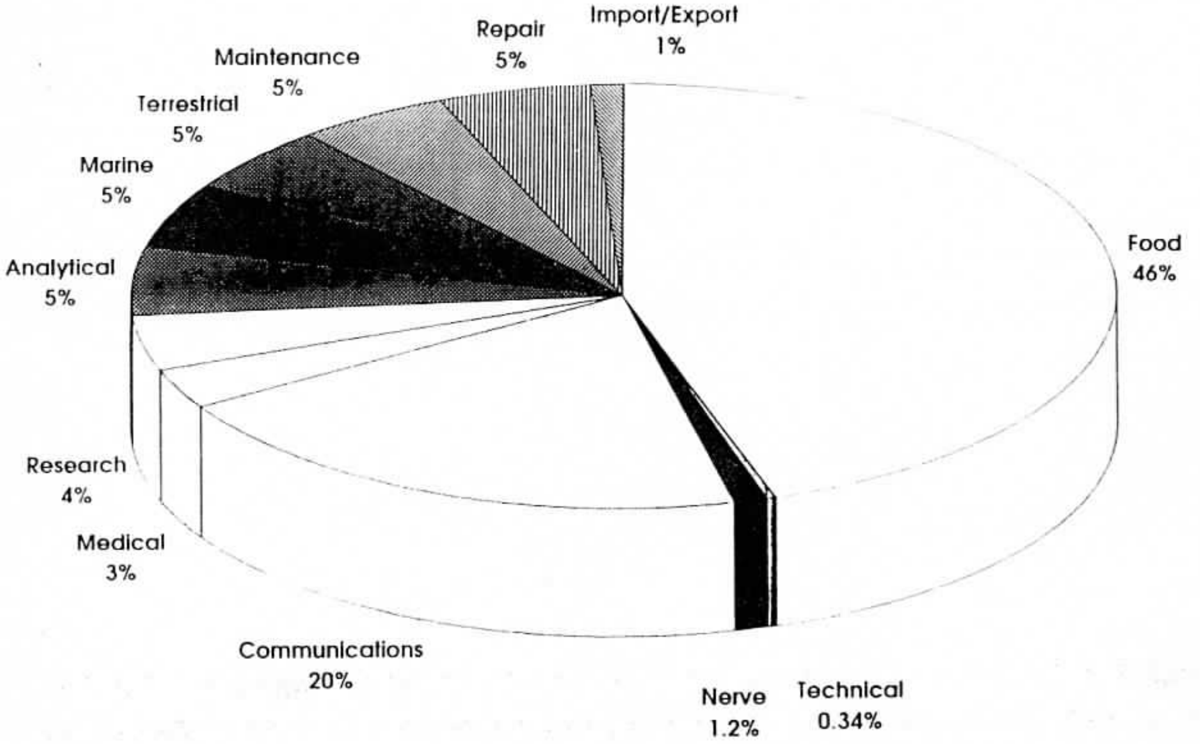

Figure 4. Biosphere 2 crew time spent on various tasks from March 1992 to February 1993 [from Van Thillo et al. (43)].

light. This selection is diagnostic of leak rate differences due to bulk leakage through flaws in the envelope vs. permeation through material or molecular diffusion through microscopic pathways. Because the progressive dilution of both gases was similar, it rules out the possibility that permeation or molecular diffusion are major contributors to the observed leak rate (12).

The second method involved a test period of constant measured overpressure of about 150 Pa relative to the outside ambient air pressure. This caused outward leakage as observed by the rate of volume decrease of the two lungs, which in turn led to an estimate of the total cross-section of open leak pathways in the entire facility. Subsequently, the inside-outside pressure differential was controlled to vary within approximate limits of ±8 Pa, which results in a calculable average rate of inward and outward exchange with a net volume change of zero. [A full discussion of this technique as well as the trace gas method is found in Dempster (13).] Both methods yielded initial estimates of about 5% per year exchange rate for Biosphere 2 with the higher estimate of 10% per year being attributable to excursions of the pressure control beyond the ±8 Pa range.

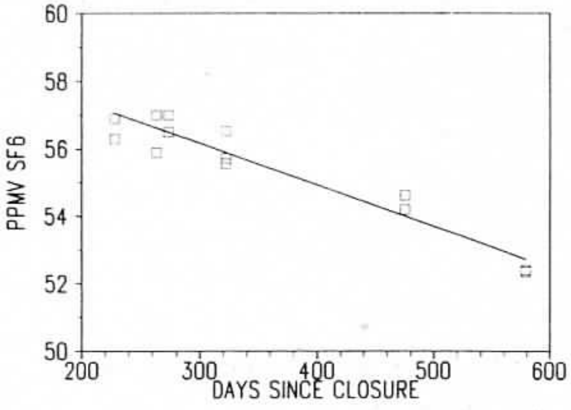

Figure 5. Sulfur hexafluoride progressive dilution May 11, 1992 to April 27, 1993. Determinations like this one with sulfur hexafluoride and helium establish that Biosphere 2's leak rate was less than 10% during the 2-year closure 1991–1993 [from Dempster (13), reprinted with permission].

Oxygen Loss and Carbon Dioxide

After the initial closure in September 1991, there has been an imbalance between respiration and photosynthesis resulting in a decline in oxygen in Biosphere 2 (Fig. 6). At first this appeared to be a mystery because atmospheric oxygen was observed to decline but the corresponding amount of CO_2 that would be expected from the respiration reaction did not appear in the atmosphere. The chemical equation of the reaction is

$$O_2 + CH_2O \rightarrow CO_2 + H_2O,$$

which shows that for each mole of oxygen lost there should be a mole of carbon dioxide produced and vice versa for the reverse reaction, photosynthesis. Thus, the sum of O_2 and CO_2 in the atmosphere should be constant. If the sum declines, then either O_2 or CO_2 can be regarded as "missing."

As previously described, the internal equipment of Biosphere 2 included a chemical scrubber to capture CO_2, but its operation only accounted for sequestering of about 1.6% of atmospheric carbon dioxide between September 1991 and June 1993, whereas about 12% of atmospheric oxygen disappeared during the same period. This left unaccounted more than a 10% loss of atmospheric oxygen.

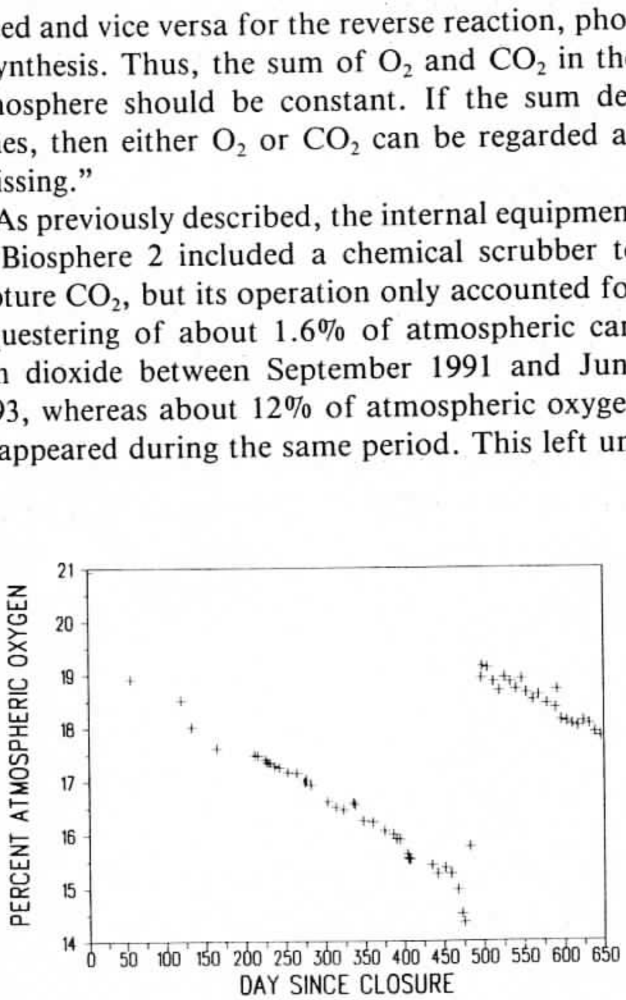

Figure 6. Oxygen concentrations in the Biosphere 2 atmosphere during the 2-year closure. The jump from approximately 14% to 19% shows the insertion of oxygen in January 1993, 16 months after the commencement of the 2-year closure [from Dempster (13), reprinted with permission].

A detailed investigation (39) employing isotopic analysis for carbon-12:carbon-13 ratios in soils, biomass, atmosphere, CO_2 scrubber product, and the structural concrete of Biosphere 2 revealed that the interior structural concrete of Biosphere 2 had sequestered substantial quantities of CO_2 that roughly accounted for the "missing" amount by the reaction:

$$CO_2 + Ca(OH)_2 \rightarrow CaCO_3 + H_2O.$$

Other possible sinks for the missing oxygen or carbon dioxide include formation of caliche ($CaCO_3$ precipitate) in the soils, oxidation of reduced forms of nitrogen, sulfur, iron, or hydrogen. However, if such processes are occurring they appear to have played a secondary role to the amounts that are confirmed to have been taken up by the concrete.

The Biosphere 2 agricultural soil and top soil in the wilderness areas are highly enriched with organic matter, which promotes rapid microbial respiration and evolution of CO_2, whereas the glazed structural envelope reduces the light available for plant growth, decreasing photosynthesis and slowing oxygen production. Future closed system experiments may strike a closer balance by using less rich soils and by using supplementary artificial lights.

Humans as Participants in Closed Ecological Systems

A somewhat subtle but important result of the 2-year closure experiment relates to the human dimension of living in a small biospheric system. As mentioned, the design of Biosphere 2 was motivated in part by the recognition that creating a place of beauty and high diversity of niche was important as the system is not only functional life support but effectively "the world" for the crew for the time that it is inhabited. Each of the eight biospherians of Mission One reported a heightening of awareness of their connection to this world.

It is so small that every action is seen to have an impact—for better or worse—on its functioning. There are no "anonymous" actions—the feedback loops are virtually instantaneous. Nor can one mistake that an action in one part of the system will not have consequences elsewhere (3).

In a paper written while still experiencing the reality of life inside Biosphere 2, two of its crew expressed it thus: "Our personal experience during the past nineteen months within this closed system has been extremely satisfying. Living as an integral component in our small world, both responsible for maintaining it and benefiting from its support, has been as rewarding as it has been challenging. It has changed our perspectives on the role of humans in all closed systems, whether they be artificial systems like Biosphere 2 or natural closed systems like Biosphere 1, our Earth's biosphere. We participate in a partnership with our biosphere to enhance its well-being by using our own resources, as well as by calling on an extensive network of scientists and engineers on the outside and employing technologies designed to assist in creating desired environmental conditions. There is a new harmony in this effort because our daily experience confirms the fact that we rely on the life systems for survival, and at the same time, the ecological systems depend on our efforts to maximize production and sustain overall health. In a small closed ecological system the equation 'our biosphere's health equals our health' becomes dramatically evident" (30).

STEPS TO MARS

The National Commission on Space, chaired by Thomas Paine, in its far-reaching vision of the next 50 years in space noted: "A biosphere is an enclosed ecological system. It is a complex, evolving system within which flora and fauna support and maintain themselves and renew their species, consuming energy in the process. A biosphere is not necessarily stable; it may require intelligent tending to maintain species at the desired levels. Earth supports a biosphere; up to now we know of no other examples. To explore and settle the inner Solar System, we must develop biospheres of smaller size, and learn how to build and maintain them" (26).

Some of the design of Biosphere 2 has been geared to optimize its value as a research tool for the study of ecosystem and biospheric functioning of Earth's planetary biosphere. Certainly, accommodating factors, including the radiation environment, ambient atmospheric pressure, and suitability of in situ materials for structure, make it unlikely that a biospheric system on Mars will look like Biosphere 2. However, the experience that has and will come from the operations of this first ground-based prototype of a permanent complex life and technical infrastructure yields valuable insights and data about the performance and stability of such systems.

Many of the innovative bioregenerative technologies that the Biosphere 2 project has developed may find application in the initial and near-term life support systems for early Mars exploration and settlement. Totally closed and recycling systems using bioregenerative technologies will probably evolve from and replace physicochemical life support systems and partially bioregenerative ones, whereas the drawback of bioregenerative systems lies in their mass requirements; the bulk of these are elements like water, soil, air that can be obtained from Martian resources. This will require the development of extraction techniques and bringing initial equipment to Mars.

Biosphere 2 used a soil-based system for the ecological functions that soil microbes play, and the ready completion of recycling steps. However, there will certainly be a place for hydroponic or aeroponic systems for food production in Mars habitations, especially in early stages of development. Banin has indicated that "on the basis of existing knowledge it is cautiously suggested that from the physical and chemical viewpoints, the Martian soil may constitute an appropriate medium for plant growth" (8,9). To supplement the plant nutrients already present in the Mars soil will require amendments with organic material and microbial inoculations. To a large extent this may be accomplished by the composting of flight and base crews' waste products. Then the types of systems pioneered by Biosphere 2, soil bed reactors, marsh wastewater systems, and sustainable intensive agriculture, may be constructed virtually entirely from local Martian resources.

The training of successive crews of "biospherians" in Biosphere 2 and in future testbeds in the operation of tightly integrated ecological and technical systems may also be very relevant to the adaptability that will be required of the Martian pioneers. They will make the transition to living—not simply exploring—in space.

During the design, construction, and 2-year closure of Biosphere 2, Mark Nelson was Director of Environmental and Space Applications and William Dempster was Director of Systems Engineering for Space Biospheres Ventures. Mark Nelson was a member of the eight-person biospherian crew, 1991–1993.

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