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“Modular Biospheres” – New testbed platforms for public environmental education and research

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Abstract

This paper will review the potential of a relatively new type of testbed platform for environmental education and research because of the unique advantages resulting from their material closure and separation from the outside environment. These facilities which we term “modular biospheres”, have emerged from research centered on space life support research but offer a wider range of application. Examples of this type of facility include the Bios-3 facility in Russia, the Japanese CEEF (Closed Ecological Experiment Facility), the NASA Kennedy Space Center Breadboard facility, the Biosphere 2 Test Module and the Laboratory Biosphere. Modular biosphere facilities offer unique research and public real-time science education opportunities. Ecosystem behavior can be studied since initial state conditions can be precisely specified and tracked over different ranges of time. With material closure (apart from very small air exchange rate which can be determined), biogeochemical cycles between soil and soil microorganisms, water, plants, and atmosphere can be studied in detail. Such studies offer a major advance from studies conducted with phytotrons which because of their small size, limit the number of organisms to a very small number, and which crucially do not have a high degree of atmospheric, water and overall material closure. Modular biospheres take advantage of the unique properties of closure, as representing a distinct system “metabolism” and therefore are essentially a “mini-world”. Though relatively large in comparison with most phytotrons and ecological microcosms, which are now standard research and educational tools, modular biospheres are small enough that they can be economically reconfigured to reflect a changing research agenda. Some design elements include lighting via electric lights and/or sunlight, hydroponic or soil substrate for plants, opaque or glazed structures, and variable volume chambers or other methods to handle atmospheric pressure differences between the facility and the outside environment.

Keywords: Material closure; Closed ecological system; Modular biosphere; Education; Research; Testbed; Biogeochemical cycles

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1. Introduction

A new type of education and research testbed has been developed in the fields of bioregenerative life support and biospherics. While previous research in the field has been mainly focused on the challenge of providing space life support, these closed ecological system chambers have the potential of also providing a new type of environmental education facility, geared either for general public or in an academic setting for increasing students’ “eco-literacy”. At the same time, modular biospheres offer researchers unique research capabilities.

The development of materially closed ecological systems is closely connected to the beginnings of the Space Age both in Russia and the United States. Research on the development of such systems to provide renewable sources of air, water and food began in the late 1950s and early 1960s. The field developed from very simple algal-based systems to ones including higher crop plants. Research efforts at several sites extend to ongoing research in those two countries as well as significant European and Japanese

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research in the field (Shepelev, ~~1992~~; Terskov et al., 1979; Wheeler et al., 1996; Nitta, 2001; CEEF, 1998; Nelson et al., in press; Lasseur et al., in press).

This paper focuses on the potential of such materially closed systems as educational and research facilities in addition to their necessity in space-related activities. Indeed, the widespread publicity which the Biosphere 2 project elicited demonstrates the high levels of interest which "real-time" science done in such chambers attracts from the general public around the world. We also illustrate some uses such systems have for advancing a diversity of scientific disciplines, by taking advantage of the benefits which material closure afford.

2. Definition of a modular biosphere

A modular biosphere is a reproducible apparatus which is materially closed (apart from a small and measurable exchange of atmosphere), but energetically and informationally open (Morowitz et al., 2005; Allen, 1991). It is large enough that a diversity of species can be supported in planting areas/soil beds. To avoid having to make the structure itself strong enough to withstand atmospheric pressure differences with the outside environment, modular biospheres may include a variable volume chamber which permits a neutral pressure while the enclosed atmosphere expands or contracts. The "life chamber" can include soils (or hydroponic media), plants, small animals, internal atmosphere, water delivery and recirculation – and potentially could support humans at least for limited periods of time. Internal sensors and a computerized data collection system can be located within the facility and in an external "mission control" room where experiments and functioning of the modular biosphere can be monitored and managed. The modular biosphere is outfitted with air-lock doors so that air exchange can be minimized (and measured) when researchers/managers enter and exit the facility. Systems for collecting air and water samples can also be incorporated in the modular biosphere so that such monitoring is done automatically and without necessitating entry into the main chamber.

Future designs of modular biospheres might include a standardized external interface so that they can be "plugged in" to a multi-unit configuration without each unit requiring a separate interface design. This expansion capability, for example, would allow the connection of modular biosphere units if they were components of a space life support system – with each modular biosphere having somewhat differing light and environmental parameters chosen to optimize crop growth of the plants it supports; another modular biosphere could be configured as the human habitat. These units can be engineered to share atmosphere and water resources continuously or by activating a program; and such exchanges can be tracked and analyzed. For research purposes, a configuration of modular biospheres permits running experiments where desired vector/state elements can be varied, all others kept uniform and thus the impact on ecosystem development, atmospheric dynamics and other vectors of interest tracked. This can also be accomplished using one modular biosphere, in sequential experiments. As an education resource for students or general public, these iterative/sequential experiments, e.g., by deliberately changing initial conditions or one of the state variables, would have some of the elegance but not the speed, of computer simulations, but instead of merely seeing theoretical or predicted results, real-time changes could be tracked.

3. Origins of modular biospheres

3.1. Laboratory ecospheres

The emergence of research using ecological systems with material closure can be traced to studies using small laboratory-sized flasks, which we might term "ecospheres" because of the relative simplicity of the ecosystems able to be studied. These studies begin in 1967 when Folsome 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 1967–1968 are still alive, exhibiting periodic changes in microbial content (Folsome, 1985). Subsequent ecosphere experiments with single-culture starts demonstrated a progressive failure to recycle elements and eventual death; underlining the importance of natural microbial diversity. Folsome was joined by other pioneers in this field of laboratory closed ecological systems, such as Maguire, Taub, and Hanson (Folsome and Hanson, 1986).

These laboratory ecosphere experiments demonstrated: (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. This research, which initiated the study of materially closed ecosystems 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 poten-

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tial 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" (Folsome and Hanson, 1986).

3.2. Russian Research – Bios-3 facility

Earliest research with bioregenerative life support and closed ecological system research targeted for space applications concentrated on very simple algae-based systems, both in the United States and Russia (Shepelev, 1972). At the Institute of Biophysics at Krasnoyarsk, a test chamber incorporating higher plants as well was developed – Bios-3. From 1972 to 1984, experiments were conducted 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. Bios-3, is a stainless steel welded structure with dimensions 14.9 m × 9 m × 2.5 m tall, a volume of 335 m^3. It is divided by airtight divisions into four internal compartments which can be variously linked or decoupled from the system (Fig. 1) The facility contains two phytotrons, for the growth of the higher plant crops, each with a hydroponic growing area of about 20.5 m^2, an algae compartment with provisions for three algae culture tanks for the production of chlorella and a living compartment for the crews of two to three people (Gitelson et al., 2003).

Illumination for the higher plants is provided by water-cooled xenon lamps with an irradiation level of 140–180 W/m^2. During various experiments, some 11 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. The system included no animals, and meat was imported to supply needed protein. Generally 30–50% of food needs were met by production during the closures (Terskov et al., 1979).

The water cycle was almost completely closed within Bios-3. Sanitary/general purpose water was re-used 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 apparent problems. 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 l of oxygen daily, sufficient for supplying the crew. About 600 g 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 (Gitelson et al., 2003).

The Bios-3 facility, a landmark in the development of closed ecological systems, was the first to include human inhabitants as active managers of its internal living and mechanical systems.

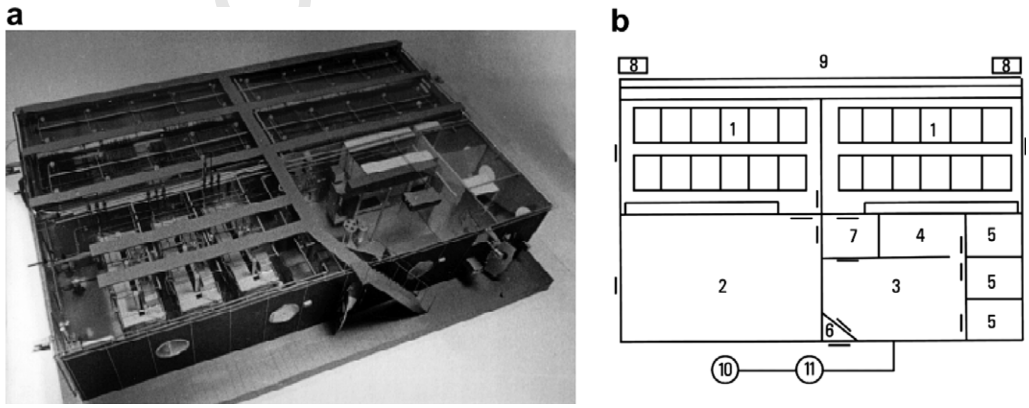

Fig. 1. (a) General view of Bios-3 (model with transparent roof). Front left, algal compartment; right, crew compartment; back, two higher-plant compartments. Light sources are mounted on the roof and ladders and gangways on the roof are for servicing light sources. On the front wall, to the right – entrance of one of crew's cabins. To the right and left of it – airlock doors for import/export. (b) Bios-3 schematic: 1, phytotrons; 2, algal cultivator compartment; 3, living quarters; 4, kitchen–dining-room; 5, cabins; 6, toilet; 7, vestibule; 8, pumps for the cooling system for light sources; 9, watering collector of the heat exchange wall of phytotrons; 10, pressurization compressor; 11, bacterial filter (Gitelson et al., 2003).

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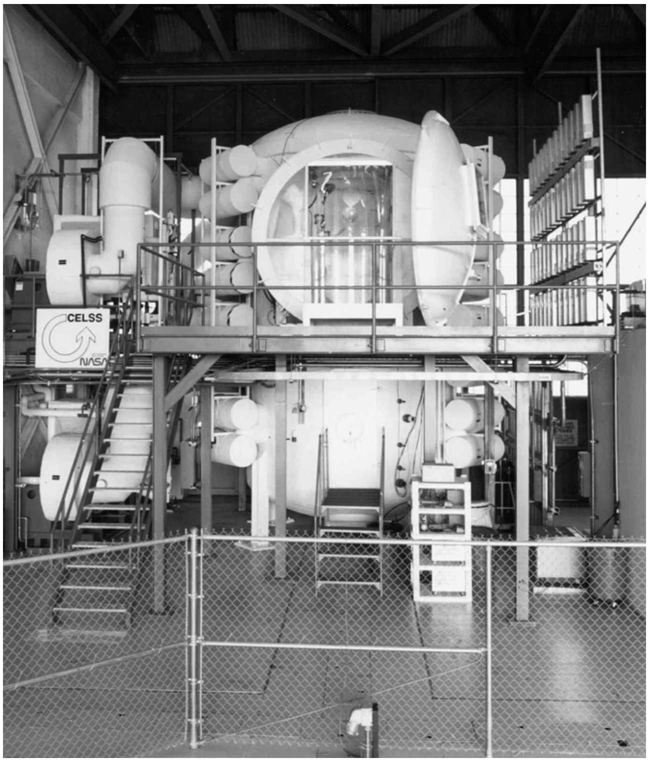

Fig. 2. Breadboard Plant Chamber at Hangar L at KSC, FL (front view, 1986). The chamber provided a closed atmospheric volume of about 113 m^3 (including air ducting) with 20 m^2 of crop growing area. External nutrient solution tanks were not in place at the time of this photo (Wheeler et al., 2003).

3.3. NASA CELSS (Controlled Environmental Life Support System) Research

In 1986, the Breadboard Project (Fig. 2) was begun at Kennedy Space Center with the goal of demonstrating 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. The Biomass Production Chamber (BPC) is a renovated cylindrical steel hyperbaric facility approximately 3.5 m diameter by 7.5 m high 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 best leak rate achieved in the Breadboard BPC was 5% of its volume per day. The configuration of growing areas inside yields a total plant area of 20 m^2. Many years of experimentation involved many of the prime candidate food crops for space life support, along with analysis of atmospheric dynamics inside the closed system (Wheeler et al., 2003, 1996).

In addition, a number of NASA-funded contractors and scientists have been carrying out intensive studies of individual potential food crops for space life support systems, including wheat, potatoes, soybeans, lettuce, and sweet potatoes. Advances have been made in understanding the physiology of food crops and developing methods of optimizing production with intensive planting, intracanopy lighting, and phasic environmental controls during the stages of plant development (e.g. Bubgee and Salisbury, 1988). Studies of community gas exchange were able to show distinctive features of uptake of CO_2 in the light and production of CO_2 in the dark (Barta and Henderson, 1998; Wheeler, 1992; Wheeler et al., 1993; Monje and Bugbee, 1997; Wheeler, 1996).

More recently a series of experiments were conducted with the Advanced Life Support System Test Bed (ALS-STB) at the Johnson Space Center. The system is the largest of the NASA life support test systems, and the first in the US to involve humans in a system based on technology using both bioregenerative and physicochemical methods. This facility consists of two large scale plant growth chambers, each with approximately 11 m^2 growing area. The root zone in each chamber is configurable for hydroponic or solid media plant culture systems. One of the two chambers, the Variable Pressure Growth Chamber (VPGC), is capable of operating at lower atmospheric pressures to evaluate a range of environments that may be used in a planetary surface habitat; the other chamber, the Ambient Pressure Growth Chamber (APGC) operates at ambient atmospheric pressure (Barta and Henninger, 1996).

3.4. Japanese CEEF (Closed Ecological Experimental Facility)

CEEF consists of a connected series of different subsystems: (1) for the cultivation of plants: Closed Plantation Experiment Facility, (2) for domestic animals, the Closed Animal Breeding (3) for the crew of two, the Habitat Experiment Facility, and (4) a Closed Geo-Hydrosphere Experiment Facility (Fig. 3). The material circulated in CEEF is strictly controlled in the materially sealed closed system by air-conditioners and material processing subsystems. Only energy and information are exchanged with the outside. Each facility can be independently operated or

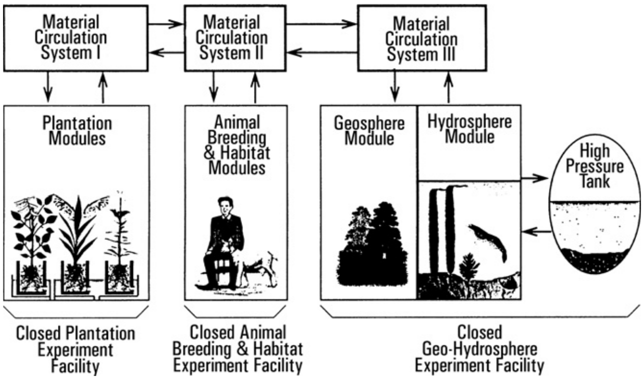

Fig. 3. Closed ecology experimental facility (CEEF) (Nitta, 2001).

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linked with another facility. The subsystems of CEEF are a unique tool for the environmental sciences and other fields of research such as test beds for life support systems for human and Mars base application, the global climate change problem and furthering the solutions for a pollution-free or "zero-emission society" (CEEF, 1998; Nitta, 2001).

A physicochemical subsystem was designed to form a closed loop of the material circulation of biological processes via the mineralization of wastes and end-products to return the elements for biological recycling. These technologies are termed the Artificial Material Processing Equipment of CEEF.

There are two basic objectives for the CEEF facility. One is the topical problem of thorough investigation of the migration of radioactive elements by the metabolic pathways in ecosystems. Another objective is to model global change, specifically the ecological consequences of global warming. Thus, closed ecological systems, modular biospheres, are beginning to be increasingly perceived not only as a means to support human life in a hostile environment – in space – but primarily as a tool for the experimental investigation of mechanisms of the Earth's biosphere (CEEF, 1998; Nitta, 2001).

3.5. Biosphere 2 Test Module

Two other examples of modular biospheres are the Biosphere 2 Test Module, constructed in 1985–1986 at Oracle, Arizona and the "Laboratory Biosphere" facility, constructed in 2001 near Santa Fe, New Mexico (Nelson et al., 1991; Dempster et al., 2004). Their differences illustrate some of the major design choices which can guide their application for education and research – for example, whether they are predominantly glass with sunlight the major driver of photosynthesis; or an opaque chamber with electric lighting. The scale of the system will also determine possibilities – whether the focus is on human life support including food production, ecosystem studies, genetic or physiological studies, or growth of targeted crops and plants.

The Biosphere 2 Test Module is a sealed glass and spaceframe structure, with ambient light provided by incident sunlight (Fig. 4). This testbed has a floor area approxi-

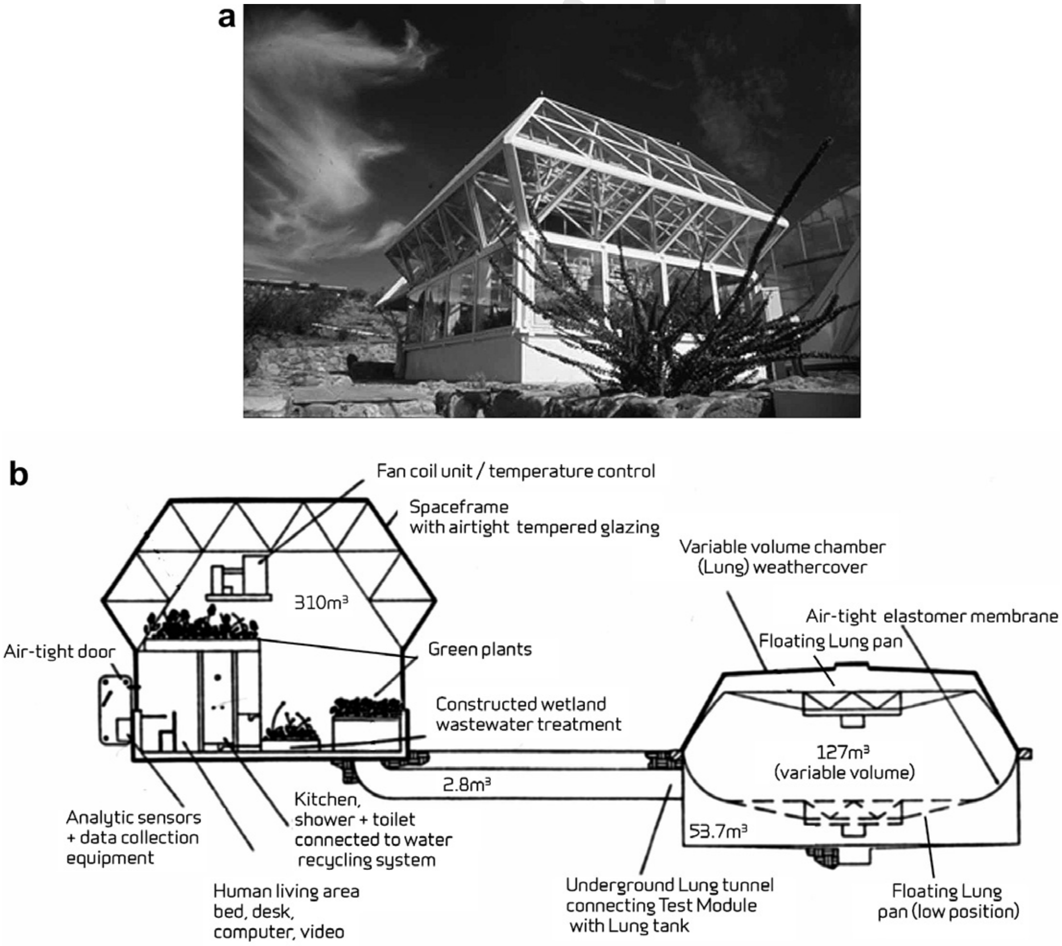

Fig. 4. (a) Biosphere 2 Test Module, Oracle, Arizona, a 480 cubic metre volume, glass and spaceframe structure functioned as an experimental facility from 1986 to 1993. (b) Configuration of the subsystems within the facility during human closure experiments 1988–1989. The engineering and ecological research program included air-tight sealing techniques, the feasibility of a variable volume chamber to alleviate stress on the structure, the efficacy soil bed reactors, constructed wetlands for wastewater recycling and the response of a variety of plants and human beings in closed ecological system conditions.

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mately 6.1 m × 6.1 m, 6 m tall, and with a total variable volume of 360–480 cubic meters depending on degree of inflation of the "lung". The structure is open to sunlight and connected by air ducting to a variable volume chamber (lung). The Biosphere 2 Test Module was used to test materials out-gassing, 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 were 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 (Nelson et al., 1991).

The Biosphere 2 Test Module was the first closed ecological system that employed a variable volume chamber ("lung"). With increased temperature in the Test Module or decreased barometric pressure in the outside environment, the variable chamber expands; with a decrease in temperature or an increase in pressure, the chamber contracts. The lung provides an effective means to prevent the possibility that the Test Module will implode or explode when subjected to these forces thus permitting a less reinforced and more sunlight-admitting structure to be utilized. While it is possible that this problem can be designed around with strength of physical structure housing the closed ecological system, the "lung" offers other advantages. By equilibrating the internal and external pressure through volume variation, leakage can be minimized; or by maintaining a small positive pressure, air leakage will only flow out of the facility. Leak rates can also be determined by measuring the difference in level between where the variable volume should be as a result of temperature and pressure and where it actually is. A glazing design provided a tight air-seal for the glass/steel spaceframe structure and underneath, an air-tight welded steel liner provided the ground seal in both biochamber and lung. The Biosphere 2 Test Module achieved tight closure, with a leak rate of about 24% per year – or 2% per month; a previously unprecedented degree of atmospheric closure. These same methods led to the Biosphere 2 achievement of air-exchange of less than 10% per year (Dempster, 1997; Dempster, 1994).

Ecological systems experiments in the Biosphere 2 Test Module with plants, animals (including insect populations), and soils examined the regeneration of atmospheric gases, plant growth and photosynthetic efficiencies in closed systems (Alling et al., 199~~1~~; Alling et al., ~~1989~~; Nelson et al., 1991). The system had an active research program for about three years from 1986 to 1989. Following the structural research, at the end of 1986, the first of a series of three ecological experiments commenced which lasted up to three months in duration. The next two years of research focused on studies of higher plants and soils and their interaction with the atmosphere, light levels, temperatures and community structure. In addition the overall dynamics of plant/soil systems in a closed ecological environment was studied to assist simulation models and resolve questions for the design of Biosphere 2.

Fig. 5. John Allen during the first three-day human closure experiment in the Biosphere 2 Test Module, 1988.

The first closed system experiment involving a human in the Test Module took place in September 1988 (Fig. 5). 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 (Allen, 1991).

To facilitate human closure experiments, and to develop and test prospective systems for Biosphere 2, the Biosphere 2 Test Module had a number of components designed to close the loops in nutrient recycling and to provide food as well as air and water regeneration. A prime challenge of the life support systems in the Biosphere 2 Test Module was to achieve enough uptake of carbon dioxide to compensate for the carbon dioxide exhaled by a person each day, to provide water purification through evapotranspiration, and to provide a variety of food crops to supply balanced nutrition for meeting human nutritional needs for closures of days to weeks. The balance between soil and human respiration, plant photosynthesis (and nighttime phytorespiration) is a major challenge of modular biospheres – and can provide dramatic educational displays because the daily fluctuations of carbon dioxide are so much greater than in our Earth's biosphere. Typical diurnal variation in CO_2 usually exceeds 1000 ppm. Even what are normally considered "minor" effects, such as the passage of clouds between the modular biosphere and the Sun are reflected immediately in a change of rate of photosynthesis; or the disturbance of the soil by cultivation or even harvesting a root crop will produce a spike of CO_2 release, which can be seen in the sensors and daily atmospheric graphs (Alling et al., 1993, 1990; Nelson et al., 1994, 1991).

Tight air-sealing is an engineering challenge for modular biospheres, because unless tightly sealed, they are little more than ecological mesocosms. It is the material closure that enables them to be studied as independent living systems. But this condition also makes air purification, especially of trace gases of prime importance since they may accumulate and increase in the relatively small atmosphere. The tremendous concentration and diversity of microbial function that soil bacteria provide was one of the considerations which led the designers of both the Biosphere 2 Test Module and Laboratory Biosphere decided to make both these modular biospheres soil-based systems. Soils, as on the Earth, are a vital bioregenerative system both through natural diffusion of the internal atmosphere through the soil, and by accelerating that function through the use of the soil bed reactor (SBR) method of air purification (Carlson and Leiser, 1966; Bohn, 1972; Bohn and Bohn, 1986). A soil bed reactor 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. 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. Trace organic gases and potential toxic gases were kept within acceptable concentrations during these human closure experiments (Alling et al., 1990; ~~Hodges and Frye, 1990).~~

A major challenge in "bioregenerative" life support is designing systems that close all vital cycles and thus can function long-term. This, of course, provides excellent analogies with the challenges we face on an Earth facing global warming and unprecedented impact by human technologies (Nelson et al., 2003a). One of the prime challenges is recycling "waste" products (e.g., Wignarajah and Bubenheim, 1997) – a necessity obvious for a small system where all resources must be maintained and recycled. For complete nutrient recovery from human sewage, a small constructed wetland was included in the Biosphere 2 Test Module where anaerobic/aerobic bacteria and wetland plants purified the wastewater and produced lush stands of vegetation. Nutrients from this system were fed into the irrigation supply for other plant stands in the facility (Wolverton, 1990; Nelson et al., 1991; Nelson et al., 1999; Nelson et al., 2002). The water recycling system in the Biosphere 2 Test Module consisted of three subsystems: potable water, wastewater recycling from the habitat, and plant irrigation water. This waste processing system was designed to clean 20–60 l 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 operated by condensing moisture from the atmosphere by two dehumidifiers. This water is highly purified because it is largely a product of plant evapotranspiration. An ultraviolet system was available if needed for complete disinfection. Irrigation water included all run-off water from life systems, the end-product of waste processing, and excess potable water (Alling et al., 1990; Nelson et al., 1991).

3.6. *Laboratory Biosphere: Opaque modular biosphere prototype*

The Laboratory Biosphere (Fig. 6a) is an example of a smaller dimension and volume, opaque modular biosphere system where lighting is provided artificially for plant growth. This allows closer control and management of light cycles and intensity; since day/night ratios can be manipulated and light levels can exceed that supplied in a glass-spaceframe structure where internal shading and light loss reduces incident light to about 50% of ambient levels. Supplemental lighting can be installed in a glass spaceframe type of modular biosphere if desired. Table 1 shows the volume of the various components of the Laboratory Biosphere and Fig. 6b shows its internal layout (Dempster et al., 2004).

A series of experiments have been conducted in the Laboratory Biosphere facility since 2002 focused on response

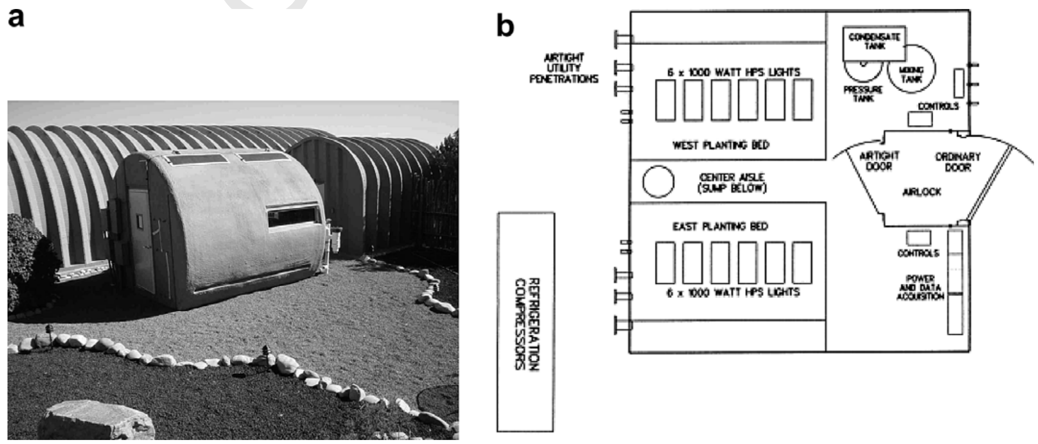

Fig. 6. (a) The Laboratory Biosphere, an opaque modular biosphere with side viewing windows, Santa, Fe, New Mexico. The steel cylindrical chamber in front houses the living systems, while the one in the rear contains the variable volume chamber. In the rear, a support workshop and laboratory/computer control rooms. (b) Plan view schematic of the facility (Dempster et al., 2004).

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Table 1
Component volume and mass of Laboratory Biosphere closed ecological facility, Santa Fe, New Mexico (Dempster et al., 2004)

Component	Volume (m^3)	Mass (kg)
Fixed air	33.6	32
Variable air (lung)	0–9	0–8
Soil (dry)	1.46	1650
Water	0.3–0.5	300–500
Plants (variable)	0–0.02	0–20 (depending on stage of growth)

of candidate life support crops (soybean, wheat, sweet potato, cowpea, pinto bean, and peanut) to manipulation of lighting, temperature and other environmental parameters (Nelson et al., 2003b; Nelson et al., 2005; Silverstone et al., 2005). Because of the tight air-sealing of the facility, research has also been done on accumulation and control of trace gases. Currently planned future research will investigate alternative lighting sources (e.g., LED lights), amending of Mars simulant soils to create viable growing media, development of improved composting and other methods of return of inedible biomass to the soil, and other studies useful for modeling and planning for full-size Mars/space life support systems (Silverstone et al., 2003; Allen and Alling, 2002).

In the Biosphere 2 Test Module, a prime challenge was balancing carbon dioxide uptake and release. The inclusion of a human in a small closed system means in addition to soil and phytorespiration, there is approximately 900 g (37 g/h) carbon dioxide exhaled by a person each day. In a modular biosphere the size of the Laboratory Biosphere, while people can enter for research or maintenance requirements, there is not the capacity to balance carbon dioxide on a continuing basis. Indeed, the opposite issue – the strong drawdown of carbon dioxide by the plants in the chamber necessitate a system for input of carbon dioxide. This allows the chamber to serve as a laboratory each day for the measurement of photosynthetic action of the plant community – and to make observations on rates of fixation at differing carbon dioxide levels. This makes the chamber an excellent teaching as well as research device because the changes in the stages of crops, from germination and early growth when soil respiration dominates, through the major growth period when photosynthetic rate maximizes, then a decline as the crops mature and senesce can be closely studied (Fig. 7). Conversely, there is a potential for increase of oxygen during the crop cycle, and a device for removing excess oxygen was incorporated into the design of this unmanned modular biosphere (Dempster et al., 2005; Dempster, in press).

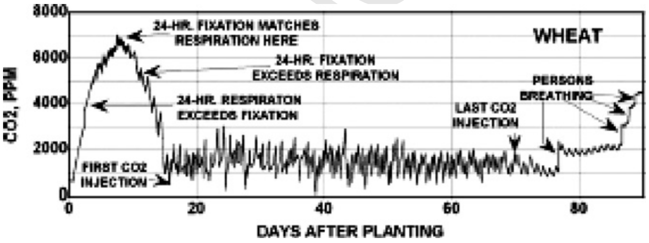

Fig. 7. Atmospheric carbon dioxide dynamics in the Laboratory Biosphere during a 2003 experiment with wheat (Dempster et al., 2005). Early rise in CO_2 was from soil respiration exceeding uptake by young plants; the rise at the end reflected human respiration during the process of wheat harvest operations. During the main growing period, CO_2 was injected as needed and drawn down by the wheat crop during hours of light by the crop.

4. Modular biospheres for environmental education and research

4.1. Real-time display of data

Depending on educational and research needs, a wide variety of sensors, software for computer control and display, automatic data acquisition, analysis, trending and alarm systems, multi-point sampling, and automatic calibration systems can be designed for the modular biosphere. For example, for the Biosphere 2 Test Module and Biosphere 2, automatic systems were developed to sample and analyze air and water quality on a periodic basis as a safety measure as well as for research data. In addition to automated periodic sampling and sensor operation, samples of soil, plant tissue, water, and air can be exported through the airlock to be analyzed in the laboratory. Modern computer software and integrated data acquisition and display capabilities mean that real-time data can be accessed and displayed for both research and education/public participation.

Because of its scale, a modular biosphere, while it is being used for cutting edge eco-system/and or extreme conditions and related research on habitation, makes an ideal real-time educational tool. Real time because a proper viewing station as well as computer readouts give students or public visitors (if used in a edutourism fashion) access to exactly the same data as the operating scientists themselves are using. It has been found that modular biospheres produce very interesting and instructive experiences for all age groups from nine on up; and for all classes of professionals interested in the interactions of ecology and humanity, including geologists, anthropologists, ecologists, artists, teachers, politicians, environmentalists, corporate executives, and the media.

4.2. Rapidity of cycling: research and educational opportunities

New environmental education and research opportunities arises from the fact that each modular biosphere represents a separate metabolic and cycling system. Each modular biosphere creates a mini-world which can be intensively studied, modified and analyzed to give insight into the basic processes and cycles which operate at far slower speed and with so much more complexity in natural ecosystems and our global biosphere. Inevitably, modular biospheres have different and much higher ratios of soil

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Table 2
Estimates of carbon ratios in biomass, soil and atmosphere in the Earth's biosphere, Biosphere 2, and the Laboratory Biosphere facility and an estimate of carbon atmospheric residence time as a consequence

	Earth	Biosphere 2	Laboratory Biosphere
Ratio of biomass C:atmospheric C	1:1 (at 350 ppm CO_2)	100:1 (at 1500 ppm CO_2)	240–700:1 (mature crop to atmosphere at 1500 ppm CO_2)
Ratio of soil C:atmospheric C	2:1	5000:1	1500:1 (atmosphere at 1500 ppm CO_2)
Estimated carbon passage time (residence in atmosphere)	3 years	1–4 days	0.5–2 days

Data was taken from Schlesinger (1991), Nelson et al. (1993), Bolin and Cook (1983), Dempster et al. (2004), and Nelson et al. (2003a). Values will vary somewhat depending on type of crop in the facility and stage of growth. Such a system with hydroponic plant growth media will have different carbon ratios and residence/cycling times.

and living biomass carbon to atmosphere. This results in a rapid passage of CO_2 through the atmospheric compartment, and a vastly accelerated cycling time. Table 2 shows comparative ratios and carbon cycle times for the Earth's biosphere, Biosphere 2, and the Laboratory Biosphere, as an example of a modular biosphere. This acceleration of cycling justifies the analogy made that modular biospheres and other closed ecological systems are essentially "cyclotrons for the life sciences" (Allen, 1991). This means that a year of experimentation offers the possibility for hundreds of cycles of carbon residence in the atmosphere and for changes in state variables to manifest results and impacts in a much faster and more pronounced way than in our natural ecosystems and biosphere. This rapid set of changes makes for research challenge and opportunities at the same time that it makes modular biospheres excellent teaching and public education tools.

4.3. Other examples of research opportunities

Because modular biospheres are materially isolated mini-worlds, they offer opportunities for the testing of genetically engineered organisms with far less risk to the environment than experiments conducted in materially open systems or in natural open air settings. Putting these experimental life forms into modular biospheres where a diversity of plants, soils and where environmental conditions can be readily manipulated offers better opportunities for seeing unexpected interactions than laboratory or phytotron studies offer. Such tests, in tightly sealed and controlled modular biospheres, should precede field studies where escape and unintended consequences of the propagation of genetically modified organisms might result.

Modular biospheres make an ideal research module for study of ecosystem behavior since basic state conditions can be exactly specified and precisely followed over different time periods. Specific cycles in ecosystem behavior can be studied by adjusting their variables while holding the others constant: atmospheric cycles and composition (of the utmost importance and interest today); water cycle and composition; changes in total biomass as well as changes in individual organisms and species; changes in soils with cyclic or discontinuous changes in life forms; total system effects of changing variables such as temperature, humidity, radiation, light, introduction of a new species, introduction of a specific pollutant.

The early development of laboratory sized "ecospheres" had shown the power of such microbial/algal systems if sufficiently diverse to continue indefinite operation given a source of incident energy (Folsome and Hanson, 1986). The scale of modular biospheres offers a supra-microbial testbed and laboratory for ecosystem studies and for study of the integration of bioremediation and environmental technologies to complete cycles and mitigate negative impacts of human technology.

For example, to demonstrate air and water purification, a modular biosphere experiment could be started with polluted water or specific air pollutants, and methods of cleanup by and/or impact on plant and soil communities studied. As Biosphere 2 demonstrated, small "biospheric systems" will have surprises (e.g., the decline in atmospheric oxygen or the self-organization of the desert biome into a community with different dominants than originally anticipated, see Nelson and Dempster, 1996; Allen and Nelson, 1999; Severinghaus et al., 1994) but offer a sufficiently small laboratory that sinks, sources and causative agents can be identified and altered for better long-term functioning. The oxygen decline at a constant atmospheric pressure in Biosphere 2 also demonstrates that some variables usually conjoined in natural Earth conditions can be separated for study. To give examples of some of unique research opportunities which Biosphere 2 afforded: the response of a rainforest or coral reef grown in seasonal light conditions and at elevations or latitudes not encountered in their usual geographical locations; the response of a coral reef to very high CO_2 atmosphere and lowering of ocean pH, or the metabolic response of humans to lowered oxygen without a corresponding decline in atmospheric pressure, two factors normally conjoined at high altitude and which results in physiological adjustments in such mountain conditions (Paglia and Walford, 2005).

5. Conclusion: the impact of closure and the opportunities for new educational and research applications

The challenge of making modular biospheres healthy and sustainably functioning, leads to developing new approaches to ecosystem studies and ecological engineering.

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Even in the design phase, engineers and ecologists must dialogue since every material and machine used in the system is measured for out gassing, and their byproducts evaluated for their integration with a living system with rapid cycling and small buffer sizes. Agricultural systems must be developed which do not need toxic chemicals and which sustain soil fertility. In short, these challenges to researchers and public education platforms offer ways for dealing with many of the challenges which we confront in our global biosphere – how to make the transition to renewable use of natural resources, integration of human technology and economy, and the sustainability of our civilization.

Modular biosphere experiments can yield valuable insights on the interactions between natural ecosystems and global technical systems. Their primary purpose and previous application has been to test systems for long-term space stations, travel, and space settlements where inhabitants must operate bioregenerative and technical systems as a synergy. But, modular biospheres offer great potential for advancing both student and public understanding of fundamental environmental realities and problems. Learning to integrate advanced technical systems with complex life systems can be of immense educational value, both in hands-on training of a managerial corps for complex projects, a corps able to handle the difficulties of contemporary life and in providing general principles for the general public by outreach education. Another use is to take advantage of the isolation of biospheric systems for conducting potentially dangerous experiments on new chemicals, pollutants or genetically modified life forms to see their impact on complex ecosystems. This potentially integrated world – the synergy of the human technosphere with the biosphere – has been called by Vernadsky and others a noosphere, or a world of intelligence (Vernadsky, 1985). Modular biospheres, a child of space life support research, may have a significant role to play in this historic endeavor both through new kinds of research and by inspiring and educating the public.

6. Uncited references

Allen et al. (2003), Salisbury et al. (2002), and Silverstone et al. (2005).

References

Allen, J. Biosphere 2: The Human Experiment. Penguin Books, NY, 1991.

Allen, J., Alling A. The design approach for Mars On Earth®, a biospheric closed system testing facility for long-term space habitation. A.I.A.A., IAC-02-IAA.8.2.02, 2002.

Allen, J., Nelson, M. Biospherics and Biosphere 2, mission one (1991–1993). Ecol. Eng. 13, 15–29, 1999.

Allen, J.P., Nelson, M., Alling, A.K. The legacy of Biosphere 2 for the study of biospherics and closed ecological systems. Adv. Space Res. 31 (7), 1629–1640, 2003.

Alling, A., Leigh, L., MacCallum, T., Alvarez-Romo N. Biosphere 2 Test Module experimentation program, in: Nelson M., Soffen, G.A. (Eds.), Biological Life Support Systems. Synergetic Press, Oracle, AZ. (Also in: National Technical Information Service Publication No. NASACP–3094.), pp. 23–32, 1990.

Alling, A., Nelson, M., Leigh, L., MacCallum, T., Alvarez-Romo, N., Allen, J., Frye, R., in: Beyers, R.J., Odum, H.T. (Eds.), Experiments on the Closed Ecological System in the Biosphere 2 Test Module. Appendix chapter, Ecological Microcosms. Springer-Verlag, New York, pp. 463–469, 1993.

Barta, D.J., Henderson, K. Performance of wheat for air revitalization and food production during the Lunar-Mars life support test project phase III test. Soc. Automotive Eng. Tech. Paper Series 981704, 1998.

Barta, D.J., Henninger, D.L., Johnson Space Center's Regenerative Life Support Systems Test Bed. Adv. Space Res. 18(1–2) 211–221, 1996.

Bohn, H.L. Soil adsorption of air pollutants. J. Environ. Qual. 1, 372–377, 1972.

Bohn, H.L., Bohn, R.K. Soil bed scrubbing of fugitive gas releases. J. Environ. Sci. Health A21, 561–569, 1986.

Bolin, B., Cook, R.B. (Eds.). The Major Biogeochemical Cycles and their Interactions. John Wiley & Sons, NY, 1983.

Bubgee, B.G., Salisbury, F.B. Exploring the limits of crop productivity. Photosynthetic efficiency of wheat in high irradiance environments. Plant Physiol. 88, 869–878, 1988.

Carlson, D.A., Leiser, C.P. Soil beds for the control of sewage odors. J. WPCF 38, 829–840, 1966.

CEEF Closed Ecology Experimental Facility, Institute for Environmental Science, Booklet, Tokyo, Japan, 1998.

Dempster, W. Methods for measurement and control of leakage in CELSS and their application and performance in the Biosphere 2 facility. COSPAR Adv. Space Res. 14 (11), 331–335, 1994.

Dempster, W. Biosphere 2 engineering and design: closure & energy. Life Support Biosphere Sci. 4 (3/4), 109–116, 1997.

Dempster, W.F., Alling, A., van Thillo, M., Allen, J.P., Silverstone, S., Nelson, M. Technical review of the Laboratory Biosphere closed ecological system facility. Adv. Space Res. 34, 1477–1482, 2004.

Dempster, W.F., Allen, J., Alling, A., Nelson, M., Silverstone, S., Van Thillo, M. Atmospheric dynamics in the "Laboratory Biosphere" with wheat and sweet potato crops. Adv. Space Res. 35, 1552–1556, 2005.

Dempster, W., Nelson, M., Silverstone, S., Allen, J., Alling, A., Van Thillo, M. Atmospheric dynamics of combined crops of wheat, cowpea, and pinto beans in the Laboratory Biosphere closed ecological system, COSPAR 2006 paper, Adv. Space Res., in press.

Folsome, C.E. Microbes, in: Snyder, T.P. (Ed.), The Biosphere Catalogue. Synergetic Press, Tucson, AZ, 1985.

Folsome, C.E., Hanson, J.A. The emergence of materially closed system ecology, in: Polunin, N. (Ed.), Ecosystem Theory and Application. John Wiley & Sons, NY, pp. 269–299, 1986.

Gitelson, J., Lisovsky, G., MacElroy, R. Manmade Closed Ecological Systems. Taylor and Francis, London and New York, 2003.

~~Hodges, C., Frye, R.,~~ Soil bed reactor work of the Environmental Research Laboratory of the University of Arizona in support of the Biosphere 2 project, in: Nelson M., Soffen, G.A. (Eds.), Biological Life Support Systems. Synergetic Press, Oracle, AZ. (also in: National Technical Information Service Publication No. NASACP–3094.), pp. 33–40, 1990.

Lasseur, Ch., Paillé, C., Lamaze, B., Rebeyre, P., Rodriguez, A., Ordonez, L., Marty, F. Melissa: The European project of closed life support system, paper at COSPAR 2006, Adv. Space Res., in press.

Monje, O., Bugbee, B. Characterizing photosynthesis and transpiration of plant communities in controlled environments. Acta Hort. 440, 123–128, 1997.

Morowitz, H., Allen, J.P., Nelson, M., Alling, A. Closure as a scientific concept and its application to ecosystem ecology and the science of the biosphere. Adv. Space Res. 36 (7), 1305–1311, 2005.

Nelson, M., Dempster, W.F. Living in Space: results from Biosphere 2's initial closure, an early testbed for closed ecological systems on Mars, in: Stoker, C.R., Emment, C. (Eds.), Strategies for Mars: A Guide to Human Exploration, vol. 86. AAS Publication, San Diego CA, pp. 363–390, 1996.

Nelson, M., Leigh, L., Alling, A., MacCallum, T., Allen, J., Alvarez-Romo, N. Biosphere 2 test module: a ground-based sunlight-driven

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prototype of a closed ecological system. Adv. Space Res. 12 (5), 151–158, 1991.

Nelson, M., Burgess, T., Alling, A., Alvarez-Romo, N., Dempster, W., Walford, R., Allen, J. Using closed ecological system to study Earth's biosphere: initial results from Biosphere 2. BioScience 43 (4), 225–236, 1993.

Nelson, M., Dempster, W.F., Alvarez-Romo, N., MacCallum, T. Atmospheric Dynamics and bioregenerative technologies in a soil-based ecological life support system: initial results from Biosphere 2. Adv. Space Res. 14 (11), 417–426, 1994.

Nelson, M., Finn, M., Wilson, C., Zabel, B., van Thillo, M., Hawes, P., Fernandez, R. Bioregenerative recycle of wastewater in Biosphere 2 using a created wetland: two year results. J. Ecol. Eng. 13, 189–197, 1999.

Nelson, M., Alling, A., Dempster, W.F., van Thillo, M., Allen, J. Integration of wetland wastewater treatment with space life support systems. Life Support Biosphere Sci. 8 (3/4), 149–154, 2002.

Nelson, M., Allen, J., Alling, A., Dempster, W.F., Silverstone, S. Earth applications of closed ecological systems: relevance to the development of sustainability in our global biosphere. Adv. Space Res. 31(7), 1649–1656, 2003a.

Nelson, M., Dempster, W.F., Alling, A., Allen, J.P., Rasmussen, R., Silverstone, S., Van Thillo, M. Initial experimental results from the Laboratory Biosphere closed ecological system facility. Adv. Space Res. 31 (7), 1721–1730, 2003b.

Nelson, M., Dempster, W.F., Silverstone, S., Alling, A., Allen, J.P., van Thillo, M. Crop Yield and Light/Energy Efficiency in a Closed Ecological System: Laboratory Biosphere experiments with wheat and sweet potato. Adv. Space Res. 35 (9), 1539–1543, 2005.

Nelson, M., Pechurkin, N.S., Allen, J.P., Alling, A.K., Somova L.A., Gitelson, J.I. Bioengineering of closed ecological systems for ecological research, space life support and the science of biospherics, chapter in vol. 1, in: Principles of Environmental Biotechnology and Bioengineering in the Handbook of Environmental Engineering series, The Humana Press, Inc., Totowa, NJ, in press.

Nitta, K. The CEEF, closed ecosystem as a laboratory for determining the dynamics of radioactive isotopes. Adv. Space Res. 27 (9), 1505–1512, 2001.

Paglia, D.E., Walford, R.L. Atypical hematological response to combined calorie restriction and chronic hypoxia in Biosphere 2 crew: a possible link to latent features of hibernation capacity. Habitation (Elmsford) 10 (2), 79–85, 2005.

~~Salisbury, F.B., Dempster, W.F., Allen, J.P., Alling, A., Bubenheim, D., Nelson, M., Silverstone, S. Light, Plants, and Power for Life Support on Mars, paper presented at NASA Mars Ecosynthesis workshop, Santa Fe, NM Sept 2000. Life Support Biosphere Sci. 8 (3/4), 161–172, 2002,~~.

Schlesinger, W.H. Biogeochemistry: An Analysis of Global Change. Academic Press, NY, 1991.

Severinghaus, J.P., Broecker, W.S., Dempster, W.F., MacCallum, T., Wahlen, M. Oxygen Loss in Biosphere 2, EOS. Trans. Am. Geophys. Union 75 (3), 33–37, 1994.

Shepelev, Y.Y. Biological life support, in: The Foundations of Space Medicine, Joint publication of the USSR Academy of Sciences/NASA, Washington and Moscow, 1972.

Silverstone, S., Nelson, M., Alling, A., Allen, J. Development and research program for a soil-based bioregenerative agriculture system to feed a four person crew at a Mars base. Adv. Space Res. 31 (1), 69–75, 2003.

~~Silverstone, S., Nelson, M., Alling, A., Allen, J.P. Soil and crop management experiments in the Laboratory Biosphere: an analogue system for the Mars on Earth® facility. Adv. Space Res. 35 (9), 1544–1551, 2005~~.

Silverstone, S., Nelson, M., Alling, A., Allen, J.P. Soil and crop management experiments in the Laboratory Biosphere: an analogue system for the Mars on Earth facility. Adv. Space Res. 35 (9), 1544–1551, 2005.

Terskov, I.A., Gitelson, J.I., Kovrov, B.G. Closed System: Man-Higher Plants (Four Month Experiment), Translation of Nauka Press, Siberian Branch, NASA-TM76452, Washington, DC, 1979.

Vernadsky, V.I. The Biosphere, an abridged version based on the French edition of 1929. Synergetic Press, Oracle, AZ, 1985.

Wheeler, R.M. Gas-exchange measurements using a large, closed plant growth chamber. HortScience 27, 777–780, 1992.

Wheeler, R.M. Gas balance in a plant-based CELSS, in: H. Suge (Ed.), Plants in Space Biology, Inst. Genetic Ecology, Tohoku Univ., pp. 207–216, 1996.

Wheeler, R.M., Corey, K.A., Sager, J.C., Knott, W.M. Gas exchange rates of wheat stands grown in a sealed chamber. Crop Sci. 33, 161–168, 1993.

Wheeler, R.M., Mackowiak, C., Stutte, G., Sager, J., Yorio, N., Ruffe, L., Fortson, R., Dreschel, T., Knott, W., Corey, K.A. NASA's Biomass Production Chamber: a testbed for bioregenerative life support studies. Adv. Space Res. 18 (45), 215–224, 1996.

Wheeler, R.M., Sager, J., Prince, R., Knott, W.M., Mackowiak, C., Stutte, G., Yorio, N., Ruffe, L., Peterson, B., Goins, C., Hinkle, C., Berry, W.L., Crop Production for Advanced Life Support System – observations from the Kennedy Space Center Breadboard Project, NASA/TM–2003-211184, 2003.

Wignarajah, K., Bubenheim, D.L. Integration of crop production with CELSS waste management. Adv. Space Res. 20 (10), 1833–1844, 1997.

Wolverton, B. Plants and their microbial assistants: Nature's answer to Earth's environmental pollution problems, in: Nelson, M., Soffen, G. (Eds.), Biological Life Support Systems, Proceedings of the Workshop on Biological Life Support Technologies: Commercial Opportunities. Synergetic Press, Oracle, Arizona, pp. 60–65, 1990.

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