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A new type of testbed platform for education and research: a "modular biosphere" has emerged from research beginning with Biosphere 2 and associated efforts to develop bioregenerative technologies for space life support. Two examples of this type of facility are the Biosphere 2 Test Module, a glass and spaceframe structure which used incident sunlight for plant growth; and the Laboratory Biosphere, a cylindrical opaque chamber which uses artificial lights for plant growth. Both types of system require a variable volume ("lung") chamber to relieve pressure differences between the modular biosphere and the outside environment. Modular biosphere facilities offer unique research and public real-time science education opportunities. Ecosystem behavior can be studied since many state conditions can be precisely specified and tracked over different ranges of time. With material closure (apart from a small air exchange rate which can be determined), biogeochemical cycles can be studied as elements transit between soil, water, plants and atmosphere. 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. Modular biospheres differ from ecological microcosms because of their material closure and their larger volume. Though large in comparison with phytotrons and microcosms, modular biospheres are small enough that they can be reconfigured - with elements changed - to reflect a changing research agenda. For example, the Biosphere 2 Test Module in Arizona had a footprint around 36m2 and a volume of around 480m3. The Laboratory Biosphere, in New Mexico, has planting areas of around 5.3 m2 of soil bed inside a cylindrical housing with a volume of 34-43m3 including variable volume chamber, depending on state of expansion.

"Modular Biospheres" – New Testbed Platforms for Public Environmental Education and Research

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Abstract
A new type of testbed platform for education and research: a "modular biosphere" has emerged from research beginning with Biosphere 2 and associated efforts to develop bioregenerative technologies for space life support. Two examples of this type of facility are the Biosphere 2 Test Module, a glass and spaceframe structure which used incident sunlight for plant growth; and the Laboratory Biosphere, a cylindrical opaque chamber which uses artificial lights for plant growth. Both types of system require a variable volume ("lung") chamber to relieve pressure differences between the modular biosphere and the outside environment. Modular biosphere facilities offer unique research and public real-time science education opportunities. Ecosystem behavior can be studied since many state conditions can be precisely specified and tracked over different ranges of time. With material closure (apart from a small air exchange rate which can be determined), biogeochemical cycles can be studied as elements transit between soil, water, plants and atmosphere. 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. Modular biospheres differ from ecological microcosms because of their material closure and their larger volume. Though large in comparison with phytotrons and microcosms, modular biospheres are small enough that they can be reconfigured – with elements changed – to reflect a changing research agenda. For example, the Biosphere 2 Test Module in Arizona had a footprint around $36m^2$ and a volume of around $480m^3$. The Laboratory Biosphere, in New Mexico, has planting areas of around 5.3 m^2 of soil bed inside a cylindrical housing with a volume of 34-$43m^3$ including variable volume chamber, depending on state of expansion.

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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 potentiality 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 opportunities.

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 also developed from very simple algal-based systems to ones including higher crop plants. Research efforts at a multiplicity of sites extend to ongoing research in those two countries as well as significant European and Japanese research in the field (Shepelev, 1992; Terskov et al, 1979; Wheeler et al, 1996; Nitta, 2001; CEEF, 1998; Nelson et al, in press(a); Lasseur et al, in press).

This paper focuses on the potentiality 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 demonstrated 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.

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), energetically and informationally-open (Morowitz et al, 2003; 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 include a variable volume chamber which permits a neutral pressure while the enclosed atmosphere expands or contracts. The life chamber can include soils, 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 be easily incorporated in the modular biosphere so that such monitoring is done automatically and without necessitating entry into the main living chamber.

Modular biospheres are designed with 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, allows the connection of modular biosphere units which are 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 etc. tracked. This can also be accomplished using one modular biosphere, by iterative sequential experiments. As an education resource for students or general public, these iterations have the elegance of computer simulations, but instead of merely seeing theoretical or predicted results, real-time changes can be tracked by altering starting conditions or one of the state variables.

Two 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. 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 artificial lighting. The scale of the system will also determine possibilities – whether the focus is on human life support including food production; or geared towards ecosystem studies, genetic or physiological studies; or growth of targeted crops and plants. The possibilities can be readily seen by reviewing the design and experimentation carried out in these two types of modular biospheres.

Biosphere 2 Test Module prototype

The Biosphere 2 Test Module is a sealed glass and spaceframe structure, with ambient light provided by incident sunlight (Figure 1). This testbed has a floor area approximately 6.1 x 6.1 meters, six metres tall, and with a variable volume of 360 - 480 cubic meters. The structure is open to sunlight and connected by air ducting to a variable volume chamber (lung). It was the largest closed ecological life-support systems facility before Biosphere 2 was constructed and the current Japanese CEEF (Closed Ecological Experimental Facility) (Nitta, 2001; CEEF, 1998). It 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.

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. The weight of the pan on the air inside the lung ensures a positive pressure from inside the closed system to the outside of about 3 pounds per square foot. It also enables leak rates to 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 patented glazing design provides a tight air-seal for the glass/steel spaceframe structure. Underneath, an air-tight welded steel liner provides the ground seal in both biochamber and lung. The Biosphere 2 Test Module achieved tight closure, with a leak rate of about 24 percent per year – or 2 percent 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 percent 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, 1991, Alling et al, 1989, Nelson et al, 1991a, Nelson et al, 1990). The system had an active research program for about three years from 1986-1989. 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.

The first closed system experiment involving a human in the Test Module took place in September 1988 (Figure 2). 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, the Biosphere Test Module had a number of components designed to close the loops in nutrient recycling and to provide a limited amount of food as well as air and water regeneration (Figure 3). 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 approximately one kilogram of carbon dioxide exhaled by a person each day, to provide water purification through evapotranspiration, and to provide a a variety of food crops to supply balanced nutrition for meeting human nutritional needs for closures of days to weeks. The balance between of soil and human respiration, plant photosynthesis (and nighttime phytorespiration) is a major element 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 CO2 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 CO2 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 which enables them to be studied as independent living systems. But this condition also makes air purification, especially of trace gases of prime importance. For this reason, our design makes both types of modular biospheres soil-based systems because of the tremendous concentration and diversity of microbial function which soil bacteria provide. Soils, as on the Earth, are a vital bioregenerative system both by 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 (Alling et al, 1990; Hodges and Frey, 1990). They showed that for some gases, some time was required before trace gas levels were brought under control. Presumable, microbial populations rose to adjust to the introduced contaminant. Trace organic gases and potential toxic gases were kept within acceptable concentrations during these human closure experiments (Hodges and Frey, 1990; Alling et al, 1990).

A major challenge in "bioregenerative" life support is designing systems which 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, 1991a; 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 litres 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 microbial control. 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).

Laboratory Biosphere: Opaque Modular Biosphere prototype

The Laboratory Biosphere (Figure 4) 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 than 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 space-frame type of modular biosphere if desired. Table 1 shows the volume of the various components of the Laboratory Biosphere and Figure 5 shows its internal layout (Dempster et al, 2004).

Research conducted to date in the Laboratory Biosphere

A series of experiments have been conducted in the Laboratory Biosphere facility since 2002 focused on response 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, in press(b); 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 (e.g. the Mars on Earth project) (Silverstone et al, 2003; Allen and Alling, 2002).

Carbon Dioxide and Atmospheric Dynamics

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 grams (37 g/hour) 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 (e.g. Figure 6). 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 et al, in press).

Real-time Display of Data for Researcher and Public Education/Participation

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. The Laboratory Biosphere system was designed by our team in collaboration with specialists from National Instruments, a leader in such research and display systems (such as LabView).

Because of its scale, a modular biosphere, while it is being used for cutting edge ecosystem/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 visitors access to exactly the same data as the operating scientists themselves will be 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, especially geologists, anthropologists, ecologists, artists, teachers, politicians, environmentalists, corporate executives, and the media.

Rapidity of Cycling: Research and Educational Opportunities

The really new education and research opportunity arises from the fact that each modular biosphere represents a separate metabolic and cycling system – another 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 and living biomass carbon to atmosphere. This results in a rapid passage of CO2 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, for example, 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.

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 far better opportunities for seeing unexpected interactions than laboratory or phytotron studies offer.

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 ~~ranges of~~ time periods. Specific cycles in ecosystem behavior can be broken out for special studies 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" (1-10 liter generally) had shown the power of such microbial/algal systems if sufficiently diverse to continue indefinite operation given a source of incident energy (Folsome and Hansen, 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).

On the other hand, the challenge of making modular biospheres healthy and sustainably functioning, leads to developing new approaches to ecosystem studies and eco-engineering. Even in the design phase, engineers and ecologists must dialogue since every material and machine used in the system must be measured for out gassing, and its 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.

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Figure

Figure 1. Biosphere 2 Test Module, Oracle, Arizona, a 480 cubic metre volume, glass and spaceframe structure functioned as an experimental facility from 1986-1993.

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

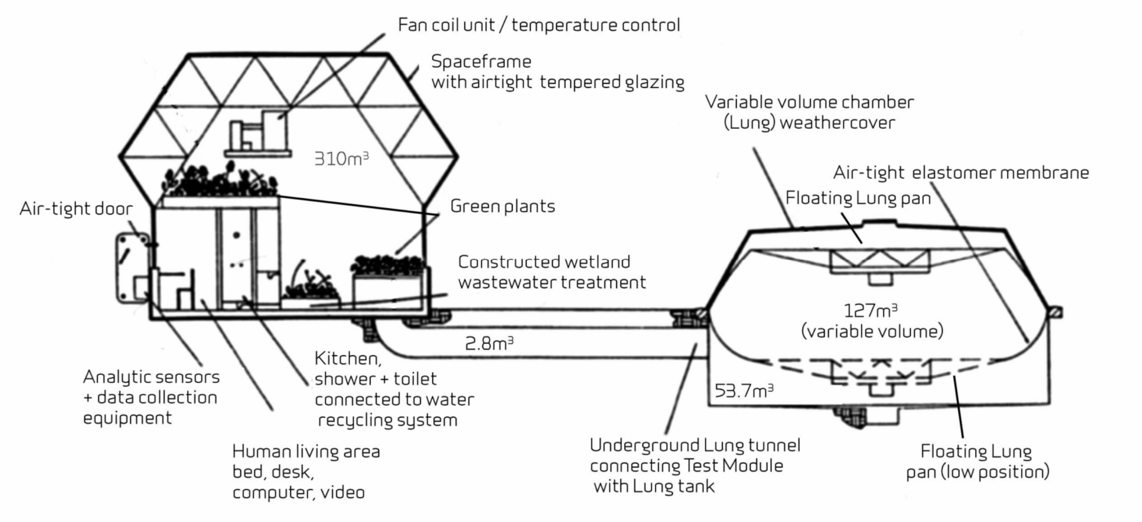

Figure 3. Schematic of the Biosphere 2 Test Module. The engineering and ecological research program included air-tight sealing techniques, the feasibility of a variable volume chamber to alleviate stress on the structure, the efficacy soil bed reactors, constructed wetlands for wastewater recycling and the response of a variety of plants and human beings in closed ecological system conditions.

Figure 4. 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.

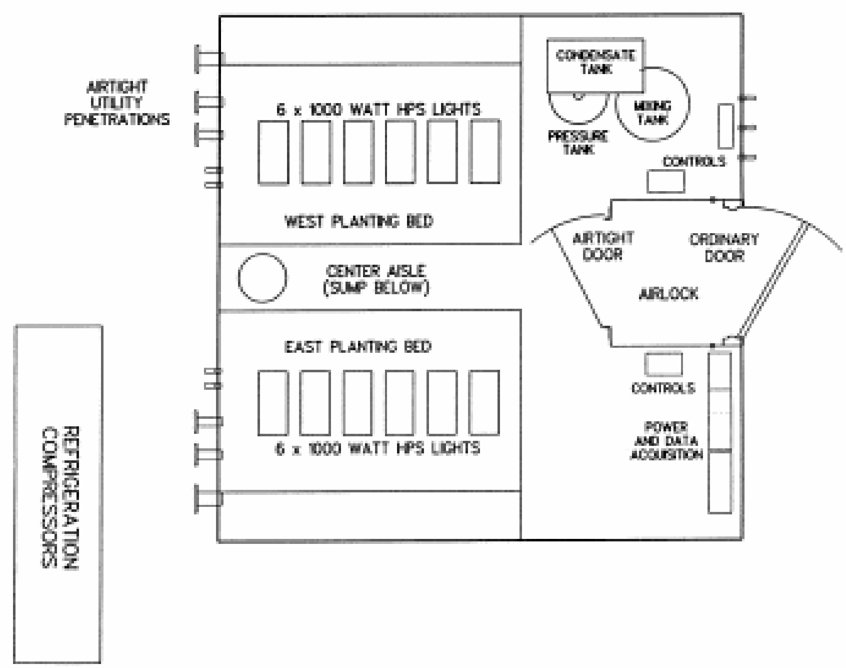

Figure 5. Plan View of the Laboratory Biosphere modular biosphere (Dempster et al, 2004)

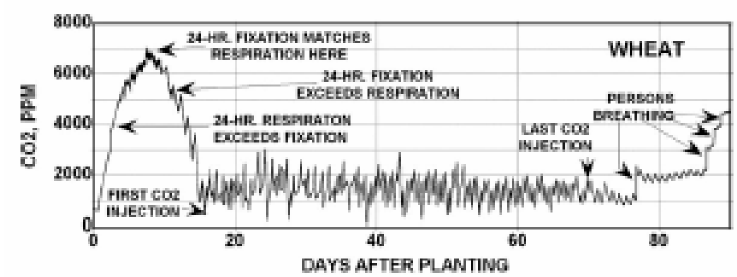

Figure 6. Atmospheric carbon dioxide dynamics in the Laboratory Biosphere during a 2003 experiment with wheat (Dempster et al, 2005). Early rise in CO2 was from soil respiration exceeding uptake by young plants; the rise at the end reflected human respiration during the process of wheat harvest operations. During the main growing period, CO2 was injected as needed and drawn down during hours of light by the crop.

Table

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)

Table 1. Component Volume and Mass of Laboratory Biosphere Closed Ecological Facility, Santa Fe, New Mexico

	Earth	Biosphere 2	Laboratory Biosphere
Ratio of biomass C: atmospheric C	1:1 (at 350 ppm CO2)	100:1 (at 1500 ppm CO2)	240-700:1 (mature crop to atmosphere at 1500 ppm CO2)
Ratio of soil C: atmospheric C	2:1	5000:1	1500:1 (atmosphere at 1500 ppm CO2)
Estimated carbon passage time (residence in atmosphere)	3 years	1-4 days	0.5-2 days

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. Data was taken from Schlesinger, 1991; Nelson et al, 1993; Bolin and Cook, 1983; Dempster et al, 2004 (Nelson et al, 2003a).