Biosphere 2 Test Module Experimentation Program

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The scale of closed ecological system experiments to date has ranged from studies with 100 ml systems to the largest existing system — Space Biospheres Ventures' Biosphere 2 Test Module, a variable volume facility of some 480 cubic meters. The science of materially closed ecological systems started in 1968 with Prof. Clair Folsome's ecosphere work at the University of Hawaii. Folsome began by sealing aquatic microbial assemblages in 100 ml to 5 liter flasks and exposing them to indirect sunlight. These ecospheres have remained indefinitely viable; the oldest are now over 20 years old, demonstrating that closed ecological systems can persist over time with an input of energy. The CELSS research program pioneered by the National Aeronautics and Space Administration includes studies of biomass production with higher plants and other aspects of bioregenerative life support. The largest current testbed is the Breadboard project at Kennedy Space Center [see William Knott's presentation] where studies are conducted within a closed 3.5 meter by 7.5 meter cylindrical, steel biomass production chamber. The Institute of Biophysics at Krasnoyarsk, Siberia has also experimented with a 300 cubic meter steel structure (Bios-3) with closures of up to two to three people for six months. The aim of Bios-3 was to establish a near complete air and water regeneration with considerable food production.

It is in this context, that the Biosphere 2 Test Module research at Space Biospheres Ventures is significant. Over the past four years, progressive research has been conducted within the Biospheric Research and Development Center to design and test a total system approach to closed ecological systems research. In the Biosphere 2 Test Module the first experiments to utilize completely biological methods of air, water and waste regeneration and food production were conducted.

THE FACILITY

The Biosphere 2 Test Module is the largest closed ecological research facility ever built with a sealed variable volume of some 480 cubic meters and a unique steel and glass skin which allows an average of 65% of ambient Photosynthetic Active Radiation to penetrate into the system (Figure 1). It was designed to test both ecological and engineering systems developed for Biosphere 2. During the early phases of research, the physical structure itself was under investigation. The nature of closed system research necessitated that the Test Module be sealed and that SBV develop a method to determine leak rates.

The sealing techniques utilized by SBV underwent considerable development. The first system employed, which utilized butyl rubber sealants on

single-paned glass joints with the steel spaceframe members, provided as tightly sealed a structure as any which had previously been utilized in the field. It was judged inadequate to 'the task of providing the sealing for the 3.15 acre Biosphere 2 structure, with its over 20 miles of glass and steel seals. A second system, patented by SBV, was developed which increased the sealing efficiency considerably. When last measured in March/April 1989 the Test Module had a leak rate of about 24 percent per year (a turnover of air in a little over four years) which when translated to the larger volume per structure ratio of Biosphere 2 gives a projected leakrate of about three percent per year.

Similarly, SBV moved from a single-paned glass system used on the first Test Module roof to a double laminated glass system after two of the original single panes cracked about a year after installation, probably as a result of hairline factory fractures. Initially, it was also planned to install a louver system on Biosphere 2. This was tested on the first Test Module roof structure but was eliminated on the present structure because of the reduction in incident light it caused.

SBV also had to develop a method of managing the effects an internal temperature and external barometric pressure change could cause in a fixed, sealed, glass structure. This problem was solved with a design called a "lung", a variable volume system joined to the module by an air duct. With increased temperature or decreased barometric pressure in the Test Module compared to the outside environment, the variable chamber expands; with a decrease in temperature or a increase in pressure, the chamber contracts. The lung structure provides an effective means to prevent the possibility that the Test Module would implode or explode when subjected to these forces. Further, the reservoir of air provided an increased buffering; adding approximately 20-40% to the total atmospheric volume. Further, the weight of the pan on the lung structure insured a positive displacement from inside the closed system to the outside.

LIFE SYSTEM RESEARCH

Following the structural research during 1986, the next two years focused on studies of higher plants
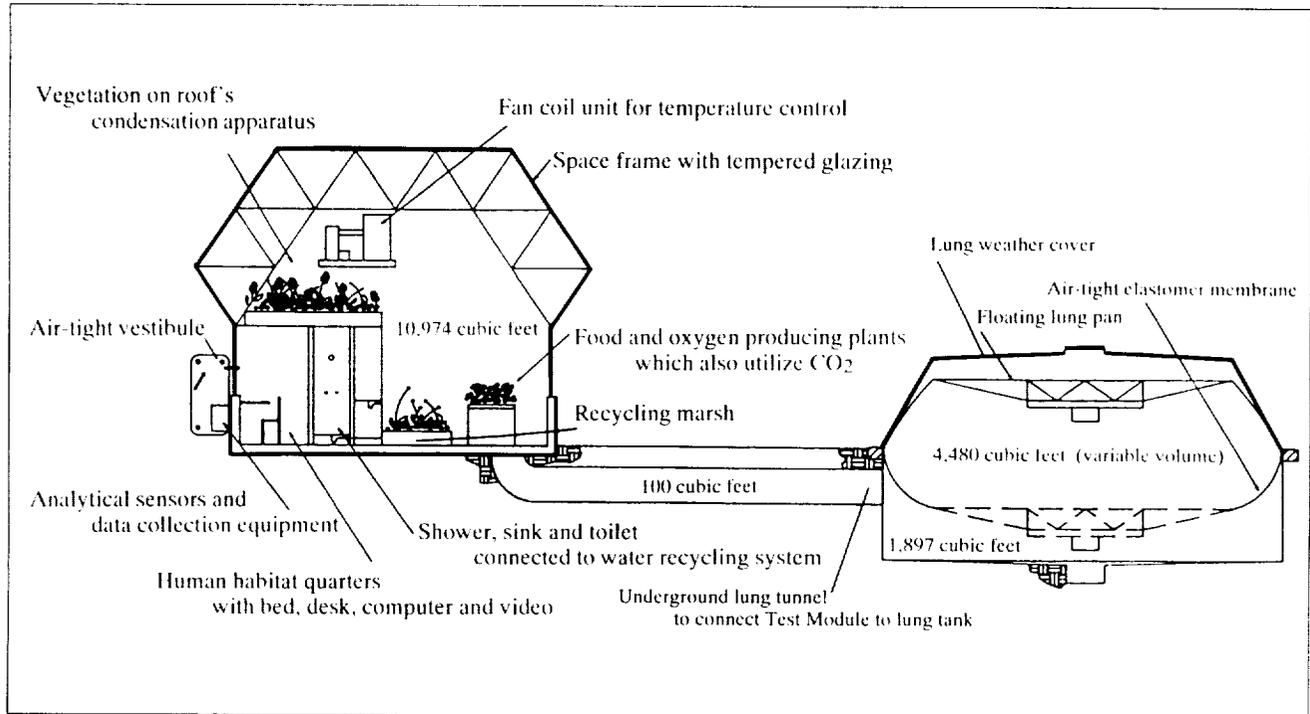

Figure 1. Biosphere 2 Test Module System Schematic. Surface area for plant growth area includes mezzanine platforms and areas within hollows of the space frame. (Copyright 1987. Space Biospheres Ventures.)

and soils and their interaction with the atmosphere, light, temperature and community structure. On December 31, 1986, the first of a series of ecological experiments commenced which lasted up to three months in duration. During these closures questions included:

1. Would plant species reproduce in a high humidity environment?

2. Would plants and soil microbial filters manage to remove trace gases from the atmosphere?

3. What effects would reduced ultraviolet light have on the behavior and navigation of foraging bees?

4. Would all the functions of microbes within the soil ecology be present?

This series of experiments provided information for doing detailed modeling of the basic parameters of closed ecological systems.

In September, 1988, Space Biospheres Ventures took a further step which was to include one human (John Allen) in the closed ecological system for 72 hours (Figure 2). The system was 100% closed with respect to water, food and air. All waste materials were recycled in the Test Module using a marsh recycling system developed in consultation with Bill Wolverton of NASA Stennis Space Center. When John Allen exited the Test Module after 72 hours, looking healthy and relaxed, and our sensors showed no buildup of potentially toxic trace gases, we knew we were on the way to establishing systems which not only support human life, but which create a habitat conducive to human life. We stress this point because an important key to living for extended periods off this planet will be the development of life systems which can provide humans with not only all of the physiological requirements of life support, but ones which are satisfying to live in as the terrestrial ecology that we are adapted to. The ecology within the Test Module system was such a design.

Drawing on the research of our Russian colleagues, we knew that algae and higher plants

Figure 2. Biosphere 2 Test Module.

were able to regenerate the oxygen required by human life while removing respired carbon dioxide. Never before, however, had waste materials been treated within the closed system and air completely recycled with biological methods. Following the design of Biosphere 2, we used higher plants and soils to recycle the atmosphere. For the first time, soils were introduced into closed system ecology and designed by SBV to be a primary bioregenerative system using soil bed reactor technology patented by SBV. Not only was carbon dioxide managed using this system, but trace organic gases and potential toxic gases were kept within acceptable concentrations for human and plant life.

Table 1 shows the type of range of trace gases found during our Test Module closures involving a human occupant. These gases were identified using a gas chromatograph mass spectrometer and a gas chromatograph flame ionization detector. In all of our closures none of these gases reached levels considered toxic to human life as defined by OSHA and the American Conference of Governmental Industrial Hygienists. However, monitoring gases with continuous sensors has been a significant challenge. In the first experiment sensor drift and noise made the continuous monitoring unreliable; we had to rely on recalibration of the entire system to locate the actual concentrations. These recalibrations were always far under concentration levels considered to be of concern. In the second "Human in Closed Ecological System Experiment", a five day closure with Gaie Alling, SBV changed the entire system using sensors internal to the Test Module, but these were evaluated as still not at the level required for this type of research and especially not for Biosphere 2. The third Human in Closed Ecological System Experiment began on October 26, 1989 for a one week material closure prior to the three week human closure (Linda Leigh) from November 2-23. A week closure followed her exit from the facility. For this experiment SBV developed an analytical system which is achieving to date a continuous and reliable record of 11 critical gases: CH_4, total non-methane hydrocarbons, NO_x, O_3, NO, CO_2, O_2, H_2S, SO_2, NO_2, and NH_3.

Data from this 21 day human closure experi-

Table 1: Trace organic gases identified by three methods in the SBV Human in Closed Ecological System Experiment, September 10 - 30, 1988.

Probable Origin: a = Technogenic • b = Biogenic • c = a + b

A. Identified by Gas Chromatograph/Mass Spectrometer

Compound	Number of Isomers Found	Probable Origin
Alkyl Substituted Cyclopentane	1	c
2-butanone	1	c
Carbon Disulfide	1	b
Cyclohexane	1	c
Decahydronaphthalene (decalin)	1	a
Decamethylcyclopentasiloxane	1	a
Decane	1	c
Dimethylbenzene	2	a
Dimethylcyclohexane	3	c
Dimethylcyclopentane	4	b
Dimethylhexane	2	c
Dimethyloctadienol Acetate	2	b
Dimethyloctane	2	c
Dimethyloctatrine	1	b
Dimethylpentane	1	b
Ethylmethylcyclopentane	1	c
Ethylbenzene	1	c
Ethylcyclohexane	1	c
Heptane	1	c
Hexamethylcyclotrisiloxane	1	a
Hexane	1	c
Isopropyl Substituted Cyclopentane	1	b
Methyl (methylethenyl) Cyclohexane	1	b
Methylbenzene	1	a
Methylbicyclohexene	1	b
Methylcyclohexane	1	c
Methylcyclohexene	1	c
Methylcyclopentane	1	c
Methylheptane	1	a
Methylhexane	2	c
Octamethylcyclotetrasiloxane	1	a
Substituted Cyclohexane	3	b
Substituted Cyclohexene	1	b
Tetrachloroethene	1	a
Tetrahydrofuran	1	a
1,1,1 Trichloroethane	1	a
Trichloromethane	1	a
Trimethylbicycloheptene	1	b
Trimethylcyclohexane	2	c
Trimethylcyclopentane	3	b
Trimethylpentane	1	c
Trimethylsilanol	1	a

B: Identified by Gas Chromatograph/Flame Ionizer Detector

Compound	Number of Isomers Found	Probable Origin
Ethane	1	c
Ethylene	1	c
Methane	1	c
Propane	1	a

C: Monitored with continuous sensors

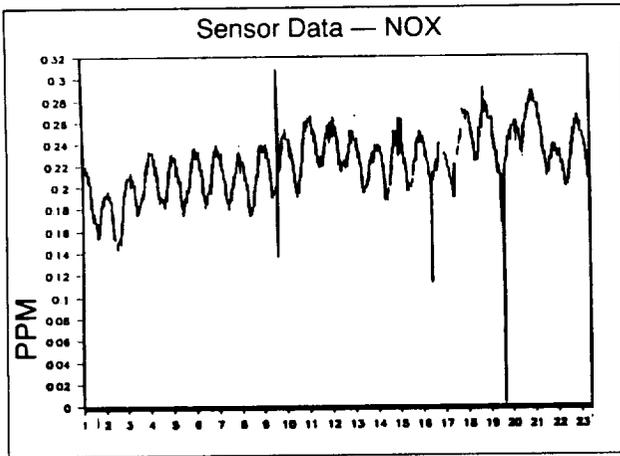| Compound	Number of Isomers Found	Probable Origin
Ammonia	n/a	b
Carbon Monoxide	n/a	b
Formaldehyde	n/a	a
Hydrogen Sulfide	n/a	b
Nitrogen Dioxide	n/a	b
Ozone	not detectable	
Sulfur Dioxide	n/a	b

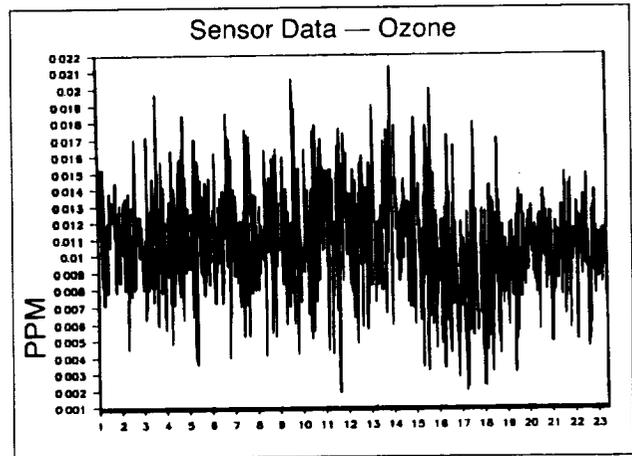Figure 3. NOx levels during Test Module human closure November 2-23, 1989.

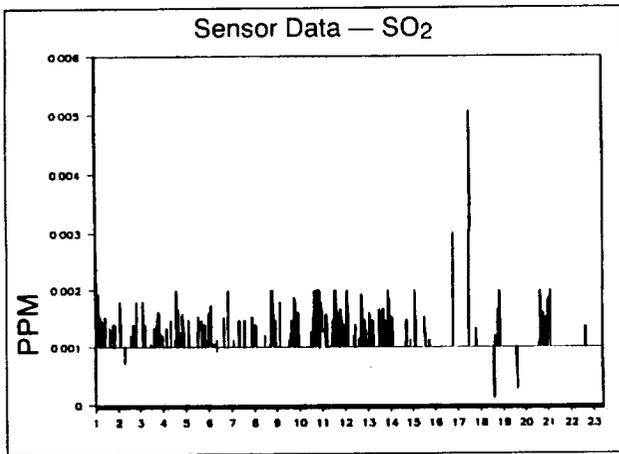Figure 4. Ozone levels during Test Module human closure November 2-23, 1989.

Figure 5. Sulfur dioxide levels during Test Module human closure November 2-23, 1989.
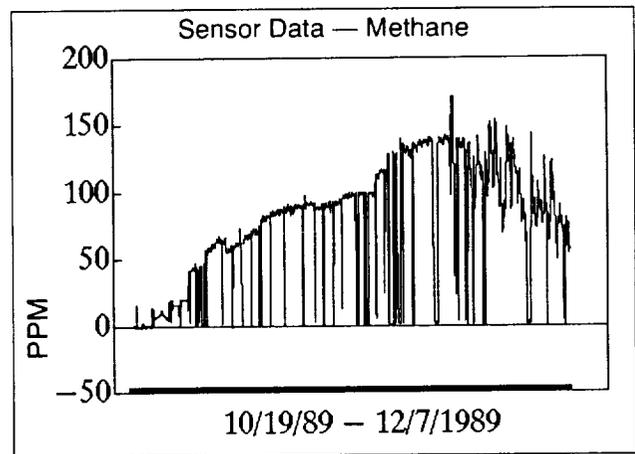

10/19/89 – 12/7/1989

Figure 6. Methane levels during Test Module human closure November 2-23, 1989 including unmanned closure phases pre- and post-human habitation.
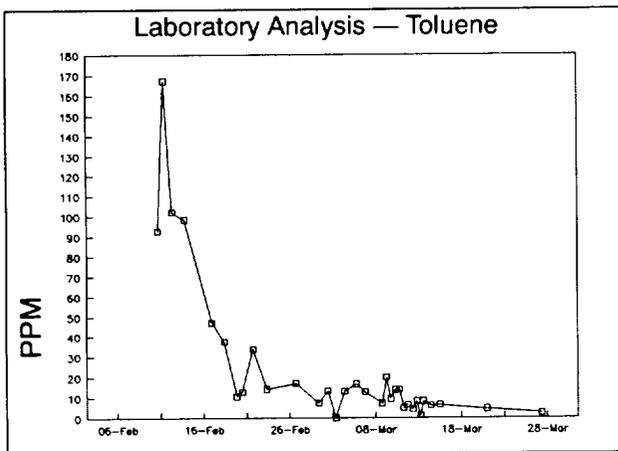

Figure 7. Toluene levels during Test Module human closure March 8-13, 1989 including unmanned closure phases pre- and post-human habitation.
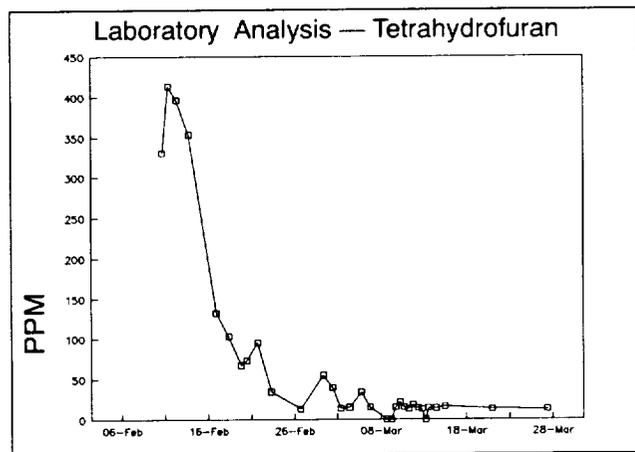

Figure 8. Tetrahydrofuran levels during Test Module human closure March 8-13, 1989 including unmanned closure phases pre- and post-human habitation.

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ment on trace gas levels is illustrative of the low levels maintained in all our experiments. Figure 3 shows nitrogen oxides (NOx) concentrations which ranged from 0.15 to about 3 ppm. Cautionary eight hour levels are considered to begin above 30 ppm.

Figure 4 shows ozone levels which show highs of 0.021 ppm. Cautionary levels begin at 0.1 and danger levels at 0.3 ppm.

Figure 5 is a graph of sulfur dioxide where levels stayed below. 0.005 ppm — well below the alert levels of 2-5 ppm.

Figure 6 is methane. The slight rise shown to about 150 ppm (still far below those of concern) during the human closure corresponds to other experiments conducted at SBV and at the Environmental Research Laboratory, University of Arizona. For methane, data suggests the hypothesis that it takes some time before the methane-metabolizing microbes build up their populations to bring down atmospheric concentrations. It then forms a classic negative feedback loop.

Figures 7, 8 and 9 are typical of the data we obtain for technogenic gases in the Test Module. Figure 7 shows toluene, which often is found in the outgassing from paints. Figure 8 is tetrahydrofuran, a solvent, often implicated in the "sick building syndrome", and which is released from glues used in such things as carpets and plywood. Figure 9 shows ethyl benzene, a solvent used in resins, probably an outgassing from particle board and
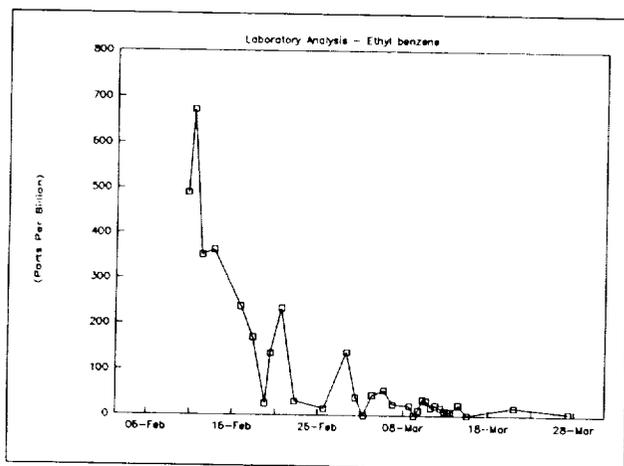

Figure 9. Ethyl benzene levels during the Test Module human closure March 8-13, 1989 including unmanned closure phases pre- and post-human habitation.

plywood. All three gases show, in these graphs from our March 1989 experiment, an initial rise after closure, following the flushing of the Test Module air. Then they are quickly brought down to extremely low levels by the action of soil bed reactors and other biological metabolizers.

The major subsystems of the Test Module designed for human closure experiments include the following:

Human Habitat Living Quarters

In addition to providing basic accommodations, the Test Module human habitat was designed to allow the human resident to observe and participate in manned closure experiments as a researcher (Figure 10). Human living quarters are comparable to a small efficiency apartment plus a compact workstation. Within an area of 100 square feet, the habitat includes:

1. a small kitchen (microwave oven, electric induction coil heat plate, electric water heating urn, small refrigerator, sink with hot and cold potable water, food weighing and preparation counters, and utensils);

2. a "Murphy" bed which folds up into a self contained wall cabinent when not in use;

3. a water-conserving toilet, and shower which uses only 0.9 liters/minute of water;

4. a workstation area with computer, desk, and bookshelves;

5. telecommunications systems — telephone, video link for audio/visual teleconferencing, computer links to internal SBV networks (to access the analytic monitoring system and databases) and to external telecommunications networks;

6. basic human physiological monitoring apparatus which vary according to the experiment.

Analytic System

The analytic requirements include a continuous monitor of the eleven trace gases with continuous atmospheric sensors. In addition other trace organics in the air were tested once a day using a gas

chromatograph and ion chromatograph system. Testing of the potable, recycle and irrigation water quality is done once a day as well.

Life Systems

The ratio of carbon dioxide consumed (photosynthesis) to carbon dioxide produced (respiration) must be greater than one before introduction of the human so that the system can compensate for the 850-1100 grams of carbon dioxide (depending on body weight, diet, level of activity) exhaled by a person each day; to provide high quality potable water through condensation of the evapotranspired water of the plants; and to provide all a person's nutritional needs. The Test Module life system designs for human closure have included the following (Figures 11 and 12):

1. Plants. Plant species were chosen with a high growth rate, high photosynthetic rates and selected at a young growth phase to maximize the amount of carbon dioxide which could be utilized by each plant.

a. Included in this design were the following sub-systems:

1) savannah mezzanine area with C_4 grasses, adapted to high temperatures and light levels

2) intensive agricultural plants such as sweet potatoes, sugar cane and peanuts which have very high growth rates, as well as a range of other vegetable, bean, salad and grain crops,

3) a "ginger belt" which includes the fast growing zingerberacae order plants, such as banana, ginger and canna, and

4) marsh recycling system with water hyacinth as the dominant species.

b. A focus of some of our experiments has been to examine the production and activity of methane within the Test Module. The November

Figure 10. Biosphere 2 Test Module Human Habitat during the first "Human in Ecosystem" experiment, September 1988. John Allen prepares a meal in the Test Module habitat kitchen.

1989 closure included a 2.6 square meter marsh system and a 0.65 square meter rice paddy with Tilapia fish. Methane dynamics are of great concern globally as methane is a component of the greenhouse effect and its quantitative outputs from known sources like marshes and rice paddies is poorly known.

c. A bioaccessions list, computer linked, inventoried all the plant species introduced. Biomass determinations of soil and foliage were made at closure and upon completion of the experiment.

2. Soils. To decrease the amount of soil respi-

ration, soils were composed with low organic carbon and a high nutrient mixture of pumice, natural soil, and bat guano.

Monitoring System

The computer monitoring system (termed the "nerve system") design has access to varied sensors which relay information in a five-level structure to a command center located in the SBV Mission Control building. The five functional levels are 1) point sensing and activation, 2) local data acquisition and control, 3) system supervisory monitoring

Figure 11. Biosphere 2 Test Module interior view, ground story. Marsh waste recycling system at lower left; part of "ginger belt" at lower right. SBV Researcher Linda Leigh stands next to intensive agriculture system planted in the soil bed reactor (white planting box). Savannah mezzanine section with C_4 grasses is located above.

and control 4) global monitoring and historical archive and 5) telecommunications.

The G2 software controls and monitors continuous gases and checks the analytic sensor calibrations. G2 is also the program with which we are modeling carbon dioxide cycling. This program is dynamic and allows for a real time interaction to occur between our predictive model and the data as observed in the Test Module experiment. RTAD is the software designed for data acquisition and control.

Water Systems

The water recycling system consists of three subsystems: potable water, wastewater from the habitat, and plant irrigation water.

1. The waste recycling system provides complete recycling of all human wastes. With this system, no wastes are removed from the Test Module; the sewage, kitchen and domestic water is purified by the action of microbes and plants and then used to irrigate the plants in the

Test Module. The system is designed to clean 5-15 gallons of effluent per day and during all three "Human in Closed Ecological System Experiments", the 2.6 square meter system effectively and without malodor cleaned the waste products using both anaerobic and aerobic processes.

Figures 13 and 14 present data from the operation of the waste recycling and irrigation water systems during the November 1989 experiment. They show levels of nitrates and phosphates in the aquatic waste processing system — after being held in the anaerobic holding tank where anaerobes start the process of regenerating the waste water, batch additions are made to the aerobic tank where the aquatic plants and their symbiotic microbes continue the process, bringing levels down so that the water can then be routed to the irrigation water system, while producing an abundant increase in plant biomass. Data from the irrigation water samples show concentrations of nutrients rise after entry of the human into the system and
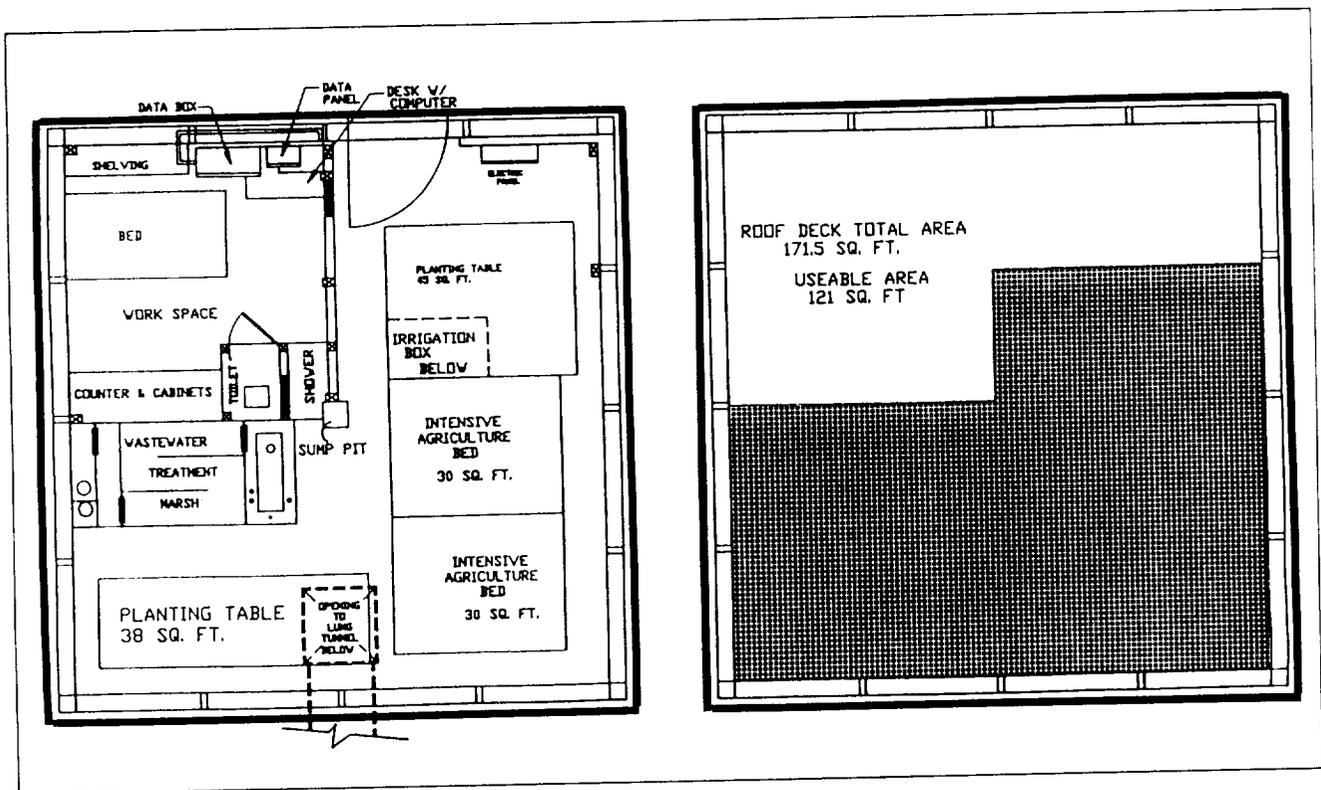

Figure 12. Biosphere 2 Test Module Floor Plan (excluding lung) during the "Human in Ecosystem" experiments conducted in September 1988, March 1989, and November 1989. (Copyright 1988, Space Biospheres Ventures.)

periodic rises with batch additions from the waste recycling system followed by uptake by plants.

2. Potable water is distilled from the atmosphere by two dehumidifiers and sterilized with ultraviolet sterilizer systems. Potable water supplies all kitchen water as well as a 0.9 liter/minute shower.

3. Irrigation water includes all run-off water from life systems and some potable water. Water is held in a reservoir and pumped to the plants through computer controlled solenoid valves to various irrigation zones.
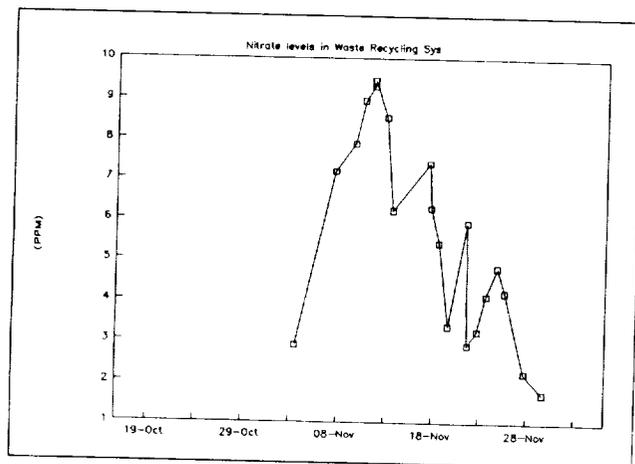

Figure 13. Nitrate levels in aquatic plant/microbial waste recycling system during Test Module human closure November 2-23, 1989 including unmanned closure phases post-human habitation.
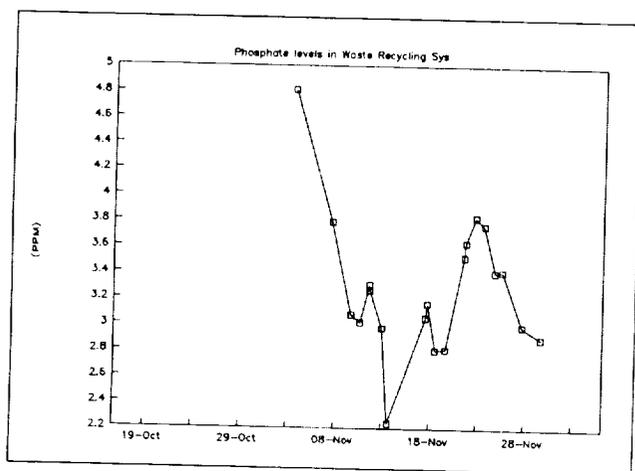

Figure 14. Phosphate levels in aquatic plant/microbial waste recycling system during Test Module human closure November 2-23, 1989 including unmanned closure phases post-human habitation.

In all these experiments, the inhabitants of the Test Module lived in material closure from the outside and depended on the ecology and technics within the Test Module to maintain the environment, recycle nutrients, the atmosphere, and water, and provide an esthetic and comfortable home. SBV has to date conducted over sixty days of human closure experiments in the Biosphere 2 Test Module.

SUMMARY

The Biosphere 2 Test Module is a facility which gives us the capability to do either short or long term closures; we have conducted five month closures with plants. We can also conduct detailed investigations of specific problems, such as trace gas purification by our bioregenerative systems by in-putting a fixed concentration of a gas and observing its uptake over time. In other Test Module experiments the concentration of one gas was changed to observe what effects this has on other gases present or the system. We are looking forward in the coming year after the completion of studies necessary for Biosphere 2 to use the Test Module for experiments related to near-term space applications, such as space station life support systems, technologies for extended planetary missions and initial lunar base requirements.

Until recently, humankind has not played a direct part in the management of the biosphere of the Earth, which we have termed Biosphere 1. Life itself has managed total system ecology in our global biosphere — particularly the microbes which play a great and frequently unappreciated role. Now humankind can and must participate in cooperating with the processes of the biosphere. The science of biospherics which encompasses the study of closed ecological systems provides an opening into the future in space as well as in our Earth's biosphere. Like the first steps that initiate all exploration, we have described these experiments in the Test Module — our first steps between Biosphere 1 and Biosphere 2.