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Technical review of the Laboratory Biosphere closed ecological system facility

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Abstract

Laboratory Biosphere is a 40 m^3 closed life system that commenced operation in May 2002. Light is from 12,000 W of high pressure sodium lamps over planting beds with 5.37 m^2 of soil. Water is 100% recycled by collecting condensate from the temperature and humidity control system and mixing with leachate collected from under the planting beds. Atmospheric leakage was estimated during the first closure experiment to be 0.5–1% per day in general plus about 1% for each usage of the airlock door. The first trial run of 94 days was with a soybean crop grown from seeds (May 17, 2002) to harvest (August 14, 2002) plus 5 days of post-harvest closure. The focus of this initial trial was system testing to confirm functionality and identify any necessary modifications or improvements. This paper describes the organizational and physical features of the Laboratory Biosphere.

Keywords: Closed ecological system; Laboratory Biosphere

1. General description

1.1. The main chamber

Laboratory Biosphere is a cylindrical painted steel chamber with horizontal axis 3.68 m long and 3.65 m diameter. Two soil-based planting beds are provided, one on each side of a center aisle, which are each $1.26 \times 2.13 \times 0.30$ m deep. Together they provide 5.37 m^2 of planting area. Laboratory Biosphere is intended to experiment with closed system plant growth in soil as may be contrasted with hydroponics. The center aisle is 46 cm wide. The soil beds are supported about 35 cm above the curving bottom of the chamber which forms a sump and excess moisture in the soil drains down to the sump. At one end a man-sized airtight door is provided with a small airlock. Viewing windows are on both sides, at one end and in the airtight door. The outer surface is covered with sprayed-in-place urethane foam to a thickness of about 6 cm, effectively insulating the chamber from ambient temperature conditions (Figs. 1–4).

1.2. The lung

To enhance airtightness of the system, a large Saran™ plastic bag, called the "lung", is connected to the chamber with about 7 m of 3 in. PVC pipe and housed in a separate small building close to the chamber. When the contained air volume expands, for example due to a warming temperature change, the excess volume flows through the pipe and into the lung, which expands without causing a pressure increase in the chamber. Conversely, when the air volume contracts, the lung contracts and air flows from the lung into the chamber without causing a decrease in pressure. Prevention of

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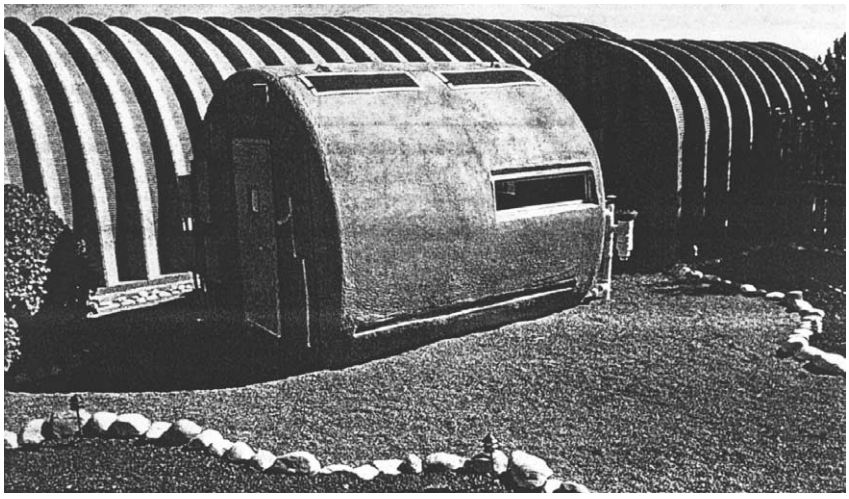

Fig. 1. The Laboratory Biosphere.

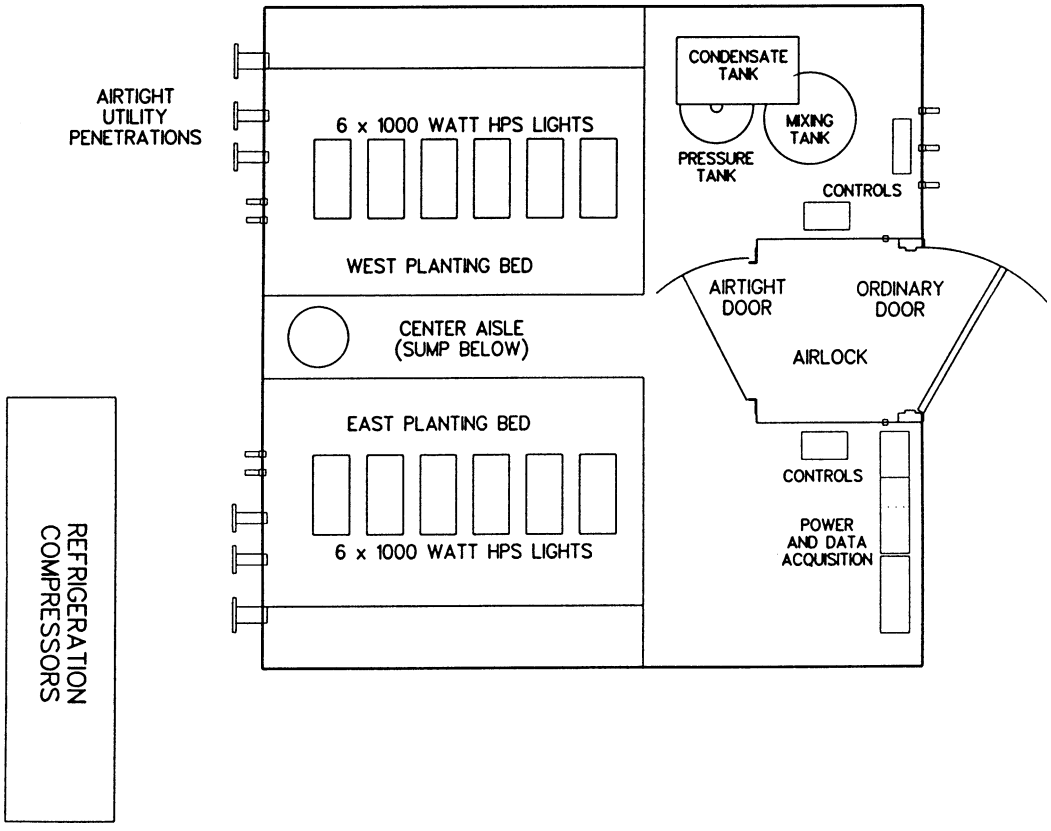

Fig. 2. Plan view of Laboratory Biosphere.

pressure differentials between the contained air and the outside ambient air greatly reduces the rate of exchange of air between inside and outside that would otherwise happen through any very small holes that may exist. It also avoids serious pressure differentials that could structurally threaten the enclosure. This method was also used to reduce the leak rate and protect against dangerous pressure differentials in the Biosphere 2 project. The effects are discussed in detail in (Dempster, 1994). The lung is fabricated of Saran^{TM} (0.15 mm thick) which has extremely low permeability to gases and water vapor (Dow Chemical Co, 2000). If fully inflated, the lung volume is about 9 m^3 or roughly 27% of the fixed volume of the main chamber. Ordinarily the lung does not approach maximum inflation, but stays in a varying state of partial inflation.

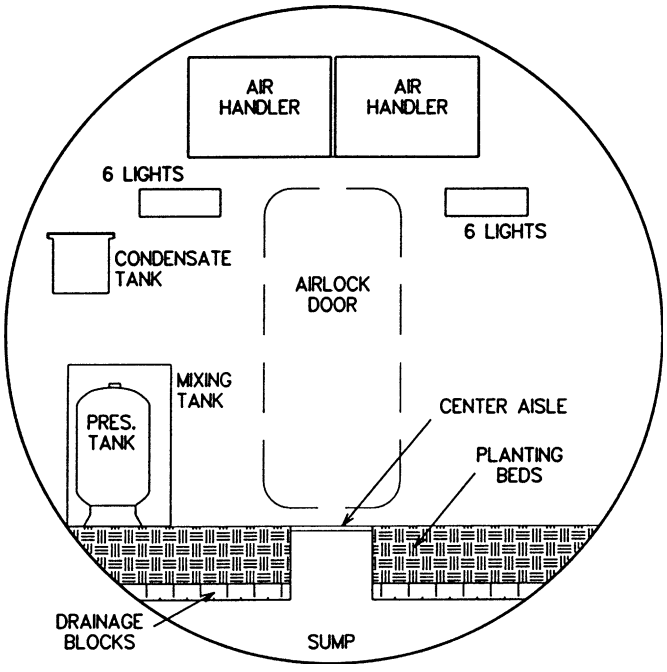

Fig. 3. Cross section of Laboratory Biosphere.

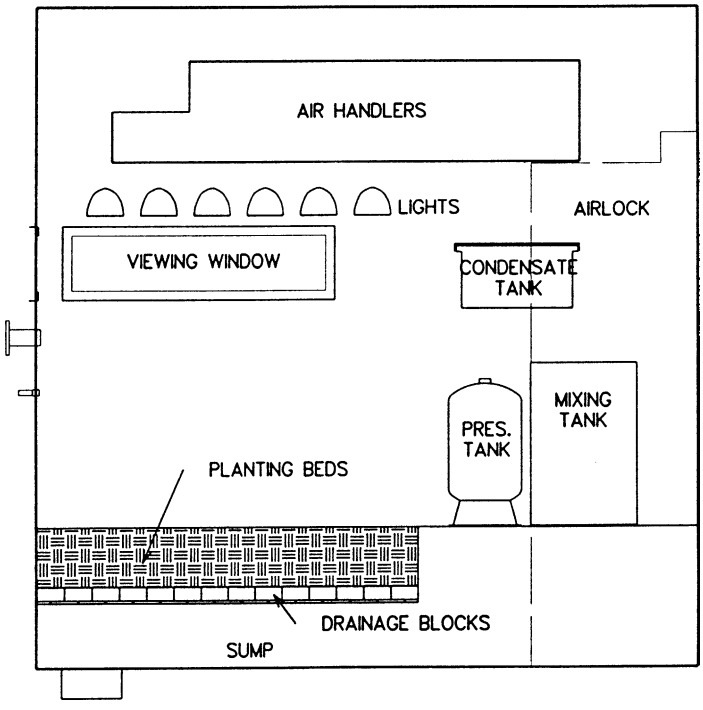

Fig. 4. Side section of Laboratory Biosphere.

1.3. Leakage

Helium was spiked into the atmosphere to provide the means to measure leakage by its progressive concentration decay. A simple conceptual model of leakage is that every day a certain percentage of the interior air exchanges with ambient air and for every use of the airlock door a different percentage of the interior air exchanges with ambient air. Helium concentration measurements were made by GCMS on samples sent to an independent laboratory on May 21 (948 ppm), June 3 (568 ppm), June 4 (545 ppm), July 1 (456 ppm) and

August 13 (258 ppm). In each interval there were 0, 2, 0 and 35 operations of the airlock door, respectively. This many data points overdetermines an exact solution in terms of the simple conceptual model, but an order of magnitude fit is taken to be about 0.5–1% daily leakage (although higher during the first interval) plus about 1% for each airlock usage.

2. Volume of components

The main categories of ecologically active components are air, water, soil and plants. Their quantities are listed in Table 1. The airlock is included within the cylinder and reduces the total sealed air volume by 2.7 m^3. The variable volume lung adds to the air volume. For air, since the volume varies (by expansion/contraction of the lung) with temperature, humidity and the external barometric pressure, it is more accurate to state the quantity in kg or moles of dry air and recognize that varying amounts of water vapor are present by exchange with liquid water within the system. At the elevation of the Laboratory Biosphere site, 1900 m, and assuming initial conditions of 20 °C, 30% relative humidity and the lung inflated to 4 m^3, there will be 1243 mol of dry air in the system.

3. Airlock

Personnel entry is through an airlock with an airtight inner door and an ordinary outer door. Entry through the airlock into the main chamber is done by opening the outer door, stepping into the airlock, closing the outer door, opening the inner (airtight) door, stepping into the main chamber and closing the inner door. It is estimated that this procedure results in exchanging about 10–15% of the volume of air in the airlock with the main chamber. Exit from the chamber is by reversal of the entry procedure and incurs a similar air exchange. The airlock volume is 2.7 m^3, so for each entry/exit combination (a round-trip) about 0.5–0.8 m^3 is exchanged with the 38 m^3 of air inside the closed system, or about 1.5–2%. Although there were several entry/exits during the first trial run of the system (May 17–August 19, 2002), it appears feasible that a whole crop growth cycle can be achieved with very few entry/exits and possibly even with none if weeds can be eliminated by attrition and if crop thinning is not necessary.

Table 1
Component quantities of Laboratory Biosphere

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 (estimate)

4. Plant growth lighting

Each of the two planting beds are lit by six 1000 W high pressure sodium lights mounted 1.75 m above the planting beds. To reduce spillage of light beyond the edges of the planting beds, mylar reflecting sheets surround three sides of each bed. The fourth side of each bed faces the center walkway so that, except for light which falls on the walkway itself, light which spills beyond the fourth side crosses over to the other bed. Measurement of photosynthetic photon flux (PPF) at twelve points using a Li-Cor model LI-250 light meter showed an average of 1343 μmol m^{-2} s^{-1} ranging from 990 to 1700 with a standard deviation of 282. Thus, there is considerable variation of intensity over the planting beds. As might be expected, the variations show symmetry; the light patterns in each bed are approximate mirror images of each other. At the average PPF, 12 h d^{-1} of light gives 58 mol m^{-2} d^{-1} and 18 h d^{-1} gives 87 mol m^{-2} d^{-1}. The ballasts associated with the light fixtures are located in a nearby building in order to keep the heat they generate (about 10% of the light energy) outside the chamber and for easy maintenance access. The power wires for the lights pass through the north chamber wall using airtight electrical penetrations, as do other power and data acquisition wires.

5. Environmental control

Overhead in the chamber are two air handlers that each move about 0.7 kg s^{-1} of air which at site barometric pressure of 812 mBar and assumed temperature of 20 °C and 30% relative humidity is also about 0.7 m^3 s^{-1}. In the first test run of Laboratory Biosphere while growing a soybean crop, the discharge air was arranged to sweep through the space from one end to the other. The average air recirculation time is about 25 s. It was found that as plant growth progressed and increasingly obstructed airflow among the plants that temperature sensors below the canopy showed temperature differences approaching 10 °C. Additional ductwork has since been designed to distribute the airflow directly into the sides of the crop and will be installed before the next crop experiment.

In simple terms, the air handlers can control both temperature and humidity by independently cooling the airstream to a selectable temperature and then reheating the airstream to another selectable temperature. When the airstream is cooled moisture condenses and is removed as liquid. The amount of moisture remaining in the airstream is a function of the cold temperature which

is selected to correspond to the desired humidity. Actual details of the operation are somewhat more complex due in part to an energy saving heat recovery design in which heat is initially extracted from the airstream prior to the final cooling stage and returned to the airstream prior to the reheat stage. This design reduces the load on the refrigeration compressors by about half. Further energy savings are realized by using captured waste heat from the compressors for the reheat step.

The Laboratory Biosphere uses a total of four refrigeration compressors, which are located immediately outside and deliver cold refrigerant to the air handlers through airtight tubing penetrations. The compressors discharge heat partly into an external circulated water storage tank and partly to the ambient air. Heat captured into the water storage tank is used for reheat of the airstream as described above and any excess is available to heat the nearby building that serves as the external control center for the project.

6. Water cycle and water delivery system

Evapotranspiration from the planting bed provides a continuous supply of moisture into the air within the chamber. Extraction of this moisture from the airstream passing through the air handlers is the means both to recapture the water for recycling and to control the humidity. As noted above, the air handlers cool the airstream to water vapor saturation at a selected temperature. The moisture condenses out of the airstream during this step and is collected in a tray in the bottom of each air handler. Drain tubes then take the condensed water through a tipping bucket rain gauge, which measures the amount collected, and then to a condensate collection tank which is equipped with a level sensor to report the quantity in this tank. The condensate water so collected is theoretically very pure which was also confirmed by measurement of total dissolved solids, giving a reading of 0 ppm on an instrument with minimum detection level of 1 ppm.

In general, there may also be water in the sump, either remaining from an original provision of water to the system or as may have drained down after irrigation of the soil beds, or both. This water is likely to have a substantial level of dissolved solids and also varying amounts of organic compounds such as from fallen leaves from planting beds above. The sump is also provided with a level sensor to report the amount of water plus a sump pump.

Another tank called the "mixing tank" stands at floor level below the condensate tank. By opening a drain valve, the condensate tank can be drained down by gravity into the mixing tank, and by operating the sump pump, the sump water can be delivered to the mixing tank, thereby creating a mixture in controllable proportions of water both from the condensate tank and from the sump. The mixing tank has a level sensor and a TDS sensor to report the water quantity and total dissolved solids, respectively.

A diaphragm pump draws water from the mixing tank to pressurize a bladder type pressure tank, which, in turn, is connected to the irrigation tubing for the planting beds. Each planting bed can be independently irrigated by opening a solenoid valve to its irrigation tubing.

Fundamental physical considerations define the way water recycling and distribution operates in this system. The soil moisture content may theoretically range from 0 to a maximum of about 45% by volume (at which point it would be draining rapidly to the sump). Given 1.46 m^3 of soil, this means a theoretical maximum of 650 l, but in practice, we will initially provide only about 300–500 l to the whole system. The soil only receives water from the watering system, i.e., by controlled actions, and there are soil moisture sensors in each bed to report the moisture status.

At a typical 20 °C and 40% relative humidity, the air only holds less than 1/2 l of water as humidity. Even at 40 °C and 100% relative humidity, water in the air is less than 2 l. The amount in the air is almost negligible by comparison to the amount in the remainder of the system. It is already observed in the first operational run with a soybean crop that condensate collection rates are on the order of 2.5–3 l/h while the lights are on. This demonstrates that humidity is a very small reservoir of water – the amount of water passing through the air in the course of a 12-h operational day is two orders of magnitude greater than the amount stored in the air. Thus, if enough water is initially provided to wet the soil beds, it is evident that enough will always be available to keep them wet – either in the soil beds themselves or combined among the three storages, condensate tank, sump, or mixing tank from which it can readily be provided to the soil bed again as needed.

7. Data acquisition and control

Thirty-eight sensors are dedicated to monitoring conditions inside the chamber and an additional 22 to the status of support systems outside the chamber. Of the 38 inside, 20 directly measure operational conditions of the air handlers. The remaining 18 report temperatures, humidity, water levels, water pressure, total dissolved solids, soil moisture and carbon dioxide and oxygen concentrations in the air. The data is collected by National Instruments Field Point modules and transmitted to a dedicated personal computer over an ethernet network where it is displayed continuously and recorded every 15 min using Labview software. The data archive is also scanned for out of range values and

converted to other formats using in-house software. Biosphere Foundation is also building an internet web site to provide project information and data display for public education and to share with other closed ecological system researchers.

Five air sampling tubes plus one air sample return tube run from the south end of the chamber to the external control room where gas analyzers for carbon dioxide (Vaisala model GMT222) and oxygen (Rosemount ROX-GP) are located. Currently only one sample airstream is drawn from the chamber, but it will be possible to draw samples from additional points within the chamber in the future if desired. The gas analyzers are fitted to be airtight so that the sample airstream is analyzed and returned to the chamber without causing leakage from the system.

Additional air analysis is performed by sample collection and GCMS analysis using outside laboratories. Of particular interest are methane, nitrous oxide, carbon monoxide, ethylene and hydrogen. Helium is also spiked into the system and its concentration decay is used to evaluate the chamber leak rate.

Control of equipment is selectable as manual or automated at a switch panel in the nearby control room. Software for fully automatic control is under development and will include monitoring of sensor data for out of range conditions and generation of alarm signals if they occur.

8. CO_2 Injection

In anticipation of the high demand for CO_2 of a crop grown from seeds to maturity, a CO_2 injection system is provided through a port in the south end of the chamber. Injections are delivered at a constant rate and measured with a Rotameter type flow meter for recorded durations. During the course of the first trial run there were 86 mol (3.8 kg) of CO_2 injected. Many aspects of the atmospheric dynamics, focusing especially on CO_2 and results of the first crop trial (soybeans) are discussed in Nelson et al. (2003). The crops will be mulched back into the soil and as the soil becomes richer in organic matter it is anticipated that more CO_2 will be produced from soil respiration. Soil building and the associated ecosystem dynamics are a central focus of the Laboratory Biosphere. Self-sustaining and fully recycling technologies will be critical for closed life support systems in space or planetary bodies. Soil is a vital resource for recovering plant waste material via decomposition and even human wastes, although Laboratory Biosphere is not intended to recycle human wastes.

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