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Tightly closed ecological systems reveal atmospheric subtleties – experience from Biosphere 2

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Abstract

Processes which produce slow changes in air composition in a closed ecological system (CES) may not be noticed if the leak rate of the CES is significant. Dilution of the system's air with outside air can mask these processes. A tightly closed CES provides the opportunity for slow changes to accumulate over time and be observed and measured. Biosphere 2 (volume 200,000 m^3) had a low leak rate of less than 10 percent per year. Oxygen declined slowly at varying rates reflecting seasonal influences, which averaged to about 140 ppm per day during the first 16 months of the two-year closure. Computer simulations of the observed rate of oxygen loss combined with other hypothetical leak rates suggest that the decline would have been hidden by a leak rate as low as one percent per day. Sealing Biosphere 2 involved rigorous design specifications and inclusion of two expansion chambers (called "lungs") to accommodate expansion/contraction of the atmosphere, which enabled limiting the pressure difference between inside and outside atmospheres to the range of ±8 Pa (0.08 mBar). Measurement of leak rate was by two methods: the first, measuring the rate of deflation of the lungs while holding a constant elevated pressure differential enabled calculation of an estimated leak rate within the usual operating pressure differential range; the second was to measure the progressive dilution of trace gases spiked into the atmosphere. Both methods confirmed leakage to be less than 10 percent per year. Operational data from the 40 m^3 Laboratory Biosphere is used to illustrate how normal variations of temperature, humidity and barometric pressure would combine to force leakage and rapidly dilute the internal atmosphere if it were not equipped with a lung. It is demonstrated that very high degrees of closure for a CES enable experimental observation of small imbalances in atmospheric cycles or slow accumulation of trace gases that could otherwise be masked by dilution with atmosphere external to the CES.

Keywords: Closed ecological system; Closure; Leakage; Leak rate; Biosphere 2; Oxygen

1. Introduction

Biosphere 2 was conceived and built to begin large scale investigation of integrated life systems. During its initial two-year mission from September 26, 1991 to September 26, 1993 it was operated as a tightly closed recycling system providing regenerative life support for a crew of eight humans. Then, while substantially maintaining closure in respect to its essential ecosystem materials of atmosphere, water, soils and life forms, its technical systems were partially modified during 5–1/2 months and a second mission with a new crew of seven commenced in March 1994 and continued to September 1994. Since then, due to a change of management, Biosphere 2 has been physically modified, its rigorously designed seal is no longer intact, and it has not operated as a fully closed system nor as a regenerative human life support system (Zabel et al., 1999).

Biosphere 2 is a very large facility with a 1.27 hectare airtight footprint and a volume of 200,000 m^3. Energy for plant photosynthesis is supplied by direct sunlight through the glazed upper enclosure. Electrical energy for operating equipment is delivered through sealed wire penetrations and thermal energy for heating and cooling is supplied by hot and cold water in sealed piping systems from a separate

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energy center outside the airtight enclosure. Data and communications links are via networked computers, telephone, video and radio both inside and outside as well as direct observation through the glass. Biosphere 2 is sealed above ground by laminated glass panes mounted on steel space frame. Specially designed joints are caulked with silicone seal. Below ground it is lined with 3mm thick stainless steel (alloy 6XN) welded into a continuous sheet. There are five airtight doors, two of which are within vestibule chambers to serve as simple airlocks.

The initial configuration of biomes included rainforest, ocean, marsh, savannah and desert with thousands of plant and animal species, some 30,000,000 kg of soil, over 4,000,000 l (over 1,000,000 gal) of water plus anthropogenic biomes of agriculture and human habitat. The great complexity so assembled was intentionally created to begin a long term endeavor to broadly investigate biospheres as integrated systems for which the initial configuration of Biosphere 2 represents one of many possibilities of how man-made biospheres may be designed (Allen and Nelson, 1986). Further detailed descriptions are to be found in extensive literature (Allen, 1991, 1992; Dempster, 1993; Marino and Odum, 1999; Nelson et al., 1993; Nelson and Dempster, 1996). The salient physical feature of Biosphere 2 relevant to this paper is its high degree of closure, documented to be approximately 10% per year of atmospheric exchange between the inside and outside (Dempster, 1994).

2. Closure

2.1 Design

Closure of Biosphere 2 was achieved by pursuing two principal strategies:

1) There would be no aspect of the enclosure design that would permit flow of air between inside and outside, no matter how small. For example, a stranded electrical wire to penetrate the enclosure could not be sealed only at its insulation jacket because air could flow between the strands inside the insulation.
2) Neutralization of any pressure differential between inside and outside atmospheres. This was achieved by construction of two expandable chambers, called “lungs”, to absorb the expansion or contraction of the internal atmosphere as temperature and humidity varied without creating a pressure differential.[1] The lungs also absorbed pressure differences due to regional barometric pressure changes by allowing the internal atmosphere to expand or contract to match the barometric pressure.[1] In practice, pressure differentials of less than 8 Pa (0.08 mBar or about 1/1000 psi) were maintained and randomly distributed in the positive to negative range. This greatly reduced leakage that could occur due to any flaws in construction.

2.2 Measurement

Determination of atmospheric leak rate was by two independent methods. The first was to manipulate the lungs to create a modest and constant internal positive test pressure of about 125 Pa (1.25 mBar) throughout the whole of Biosphere 2 and measure deflation of the lungs over an extended time period (e.g. several weeks). This determines the leak rate at the test pressure. Air flow through an orifice at small differential pressures is proportional to the square root of the differential pressure, which enables calculation of the reduced leak rate at the much smaller differential pressures under which Biosphere 2 normally operated during the two-year closure experiment.

The second method is to spike the atmosphere with a known quantity of non-reactive trace gases and measure the decay of their concentrations over time, which is caused by dilution of outside air mixing with inside air. It should be understood that leak rate is considered as rate of exchange with outside air, not just outward leakage nor inward leakage alone. The trace gases used were sulfur hexafluoride, helium and krypton and their progressive dilutions were measured over time spans of a few months to nearly a year.

A detailed description of the lung system and these methods is given in Dempster (1994). The results showed the leak rate of Biosphere 2 to be less than 10 percent per year of its atmosphere exchanged with outside air. The testing indicated that in approximately 80 km of caulked glazing joints and 16 km of welded seams, the aggregate cross section of pinholes and construction flaws is approximately equivalent to a single hole about 19 mm diameter which would produce the measured leakrate.

3. A case in point

After closure of the facility on September 26, 1991 atmospheric analysis identified a decline in atmospheric oxygen concentration. Starting at normal ambient of 20.9%, oxygen declined to about 14.4% some 475 days later by mid-January 1993 and was attributed to transitory imbalance between all forms of respiration (mainly soil microbial respiration) and photosynthesis, combined with fixation of carbon dioxide as calcium carbonate in internally exposed concrete, thus trapping the “missing oxygen” into the concrete (Severinghaus et al., 1994). See Fig. 1. Let us develop an estimate of how this oxygen loss might have appeared under various hypothetical leak rates during the same period. Consider the equations that influence an atmospheric concentration as it depends on the leak rate.

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[1] Pressure and volume of the atmosphere, to sufficient accuracy for this paper, follows the ideal gas law, $pV = nRT$, known since the 19th century, or earlier.

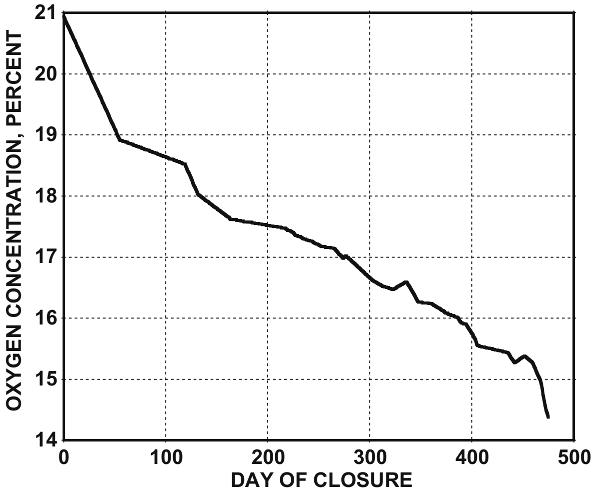

Fig. 1. Oxygen concentration in Biosphere 2, Sept. 26, 1991–Jan. 13, 1993.

3.1. Theory

Let C, concentration (mole fraction) of a given gas inside an enclosure.

C_a, ambient concentration of the same gas outside the enclosure.

r, exchange rate between inside and outside expressed as instantaneous fraction of the enclosure volume per unit time.

If only the leak rate and no other influences are affecting the internal concentration, C, then the concentration will behave according to

$$\mathrm{d}C/\mathrm{d}t = (C_a - C)r \tag{1}$$

which can be integrated to obtain C as a function of time

$$C = C_a - (C_a - C_0)\mathrm{e}^{-\mathrm{rt}} \tag{2}$$

where C_0 is the value of C at time $t = 0$. Eq. (2) simply shows that the internal concentration starts at its initial value, C_0, and asymptotically approaches the external ambient concentration, C_a, as ambient air exchanges indefinitely with and replaces the internal atmosphere.

Now also consider that an internal process is independently and simultaneously changing the concentration according to

$$\mathrm{d}C/\mathrm{d}t = f(t) \tag{3}$$

then the combined effects of leakage and the internal process will be

$$\mathrm{d}C/\mathrm{d}t = (C_a - C)\mathrm{r} + f(t) \tag{4}$$

It is not the purpose of this discussion to consider influences that the processes represented by Eqs. (1) and (3) might have on each other, we ignore any such effects to arrive at Eq. (4). (The reader should keep in mind that we are only developing an estimate of the effect of leak rate on our ability to see atmospheric composition changes.)

3.2. Observations

In the case of oxygen concentration in Biosphere 2, C followed the curve of Fig. 1 over 475 days, which gives us a numerical approximation to $\mathrm{d}C/\mathrm{d}t$ of Eq. (4). Assuming the leak rate to be 10% per year from independent data (Dempster, 1994), or $r = .000274$ per day, we can use Eq. (4) to calculate a numerical approximation to $f(t)$.

3.3. Simulations and implications

Taking this approximate $f(t)$ and combining it with various trial values of r (representing other leak rates) we obtain different curves of how the oxygen decline might have appeared for each leak rate as shown in Fig. 2. It is clear that as the leak rate increases by orders of magnitude, the "wash-out" effect compromises the ability to accurately determine $f(t)$ which is a subject of intense interest in closed ecological system and biospheric research. Even if sophisticated instrumentation can distinguish very fine gas concentration differences, determining $f(t)$ is also dependent on continuous and accurate knowledge of a possibly varying leak rate, r, not to mention the complications stemming from possible and unknown proximity of the sample site(s) to an unrepresentative large leak coupled with incomplete mixing. (For example, if the gas concentration detector was located in the plume of an inward leak, its readings would be distorted from a representative reading.) If all the leaks and their aggregate are extremely small these uncertainties become very limited in their possible effects. Fig. 2 shows the oxygen concentration curves that would have resulted for six other hypothetical leak rates as determined by computer simulation assuming that $f(t)$ is the same in each case. The upper two curves (1.9%/day and 10%/day) represent the lower and upper bounds of leak rate for NASA's Biomass Production Chamber at Kennedy Space Center (Wheeler et al., 1991; Corey and

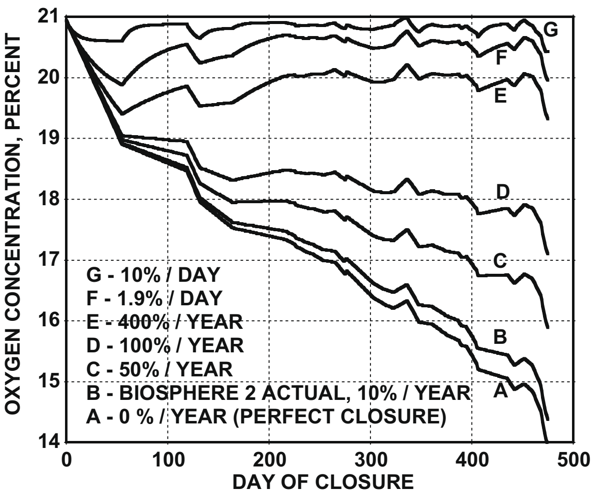

Fig. 2. Oxygen concentration in Biosphere 2, actual and simulated for six other leak rates.

Wheeler, 1992; Sager et al., 1988). As the leak rate becomes larger, it becomes progressively more difficult to estimate $f(t)$ because the difference between the inside and outside concentrations tend toward zero.

4. The inherent drivers of leaks

To realize the importance of the above analysis, the underlying basis of leakage in non-pressure-containing closed systems should be clearly understood. Simple containers ranging from small aquaria to large buildings cannot be made airtight no matter how much attention is paid to sealing joints and seams unless they are also strong enough to withstand substantial pressures. Variations in internal temperature and humidity and external barometric pressure must alter the volume of the contained atmosphere or create pressure differentials between the inside and outside of the container, which drive leaks through small holes (Dempster, 1994, 1997). Success in sealing all leaks will only result in bursting the container if it cannot withstand pressures on the order of 5000 Pa (about 100 pounds per square foot) or unless it is equipped with an expansion/contraction system to allow volume changes such as the “lungs” of Biosphere 2.

4.1. Contributing components

Water in the system can evaporate or condense. Evaporation expands the air volume by addition of water vapor as a component of the air, and conversely condensation contracts the air volume. Computation of the volume of humid air follows the formulas in Avallone and Baumeister (1987) using a computer program written in FORTRAN by the author which was spot checked against commercially available psychrometric charts. The influence of temperature and barometric pressure is included according to the Ideal Gas Law. We consider leakage, expressed as a percentage, to mean the percentage of the dry components of air exchanged between the system and the outside, excluding water vapor, because changes in water vapor can occur within the system by evaporation or condensation. For this purpose, we also make no distinction between carbon dioxide and oxygen since they exchange with each other internally by photosynthesis and respiration as approximately equal volumes, mole for mole, according to $CO_2 + H_2O \leftrightarrow CH_2O + O_2$. The differences of assimilation quotient and respiration quotient do not significantly impact the matter under consideration here.

4.2. An example with real data

To demonstrate the leakage of a non-pressure vessel that would be forced by the variations of internal temperature and humidity and external barometric pressure, we can draw on recent operational data of a 40 m^3 closed ecological system known as “Laboratory Biosphere” (Dempster et al., 2004) as an example to construct Fig. 3. This author is one of the investigators operating Laboratory Biosphere. Data from numerous sensors at this facility are automatically recorded every 15 min. These data enable computation of the expansion/contraction state of the system’s air at each recorded time. To each 15-minute interval, we apply the simple algorithm that any air forced out by expansion is lost and any air drawn in by contraction is mixed with the inside air. The daily ranges of temperature, humidity and barometric pressure are shown in Figs. 4 and 5 and illustrate the nature and scale of the variations that drive leakage by expansion/contraction for closed systems.

In actual fact, Laboratory Biosphere is equipped with a lung so that expanded air is held in the lung and the same air is returned without leakage upon subsequent contrac-

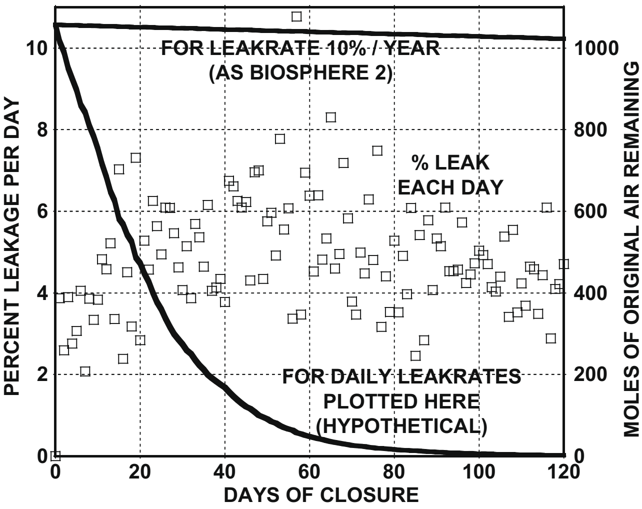

Fig. 3. Comparison of loss of air at a leakrate of 10% per year vs. air loss for leakrates representative of an enclosure without pressure/volume compensation and subject to the combined variations of temperature, barometric pressure and humidity. Percent daily leakage plotted as squares. See text for complete explanation.

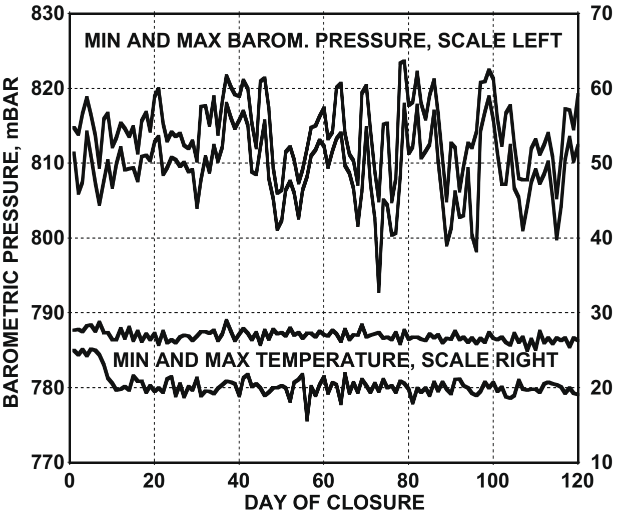

Fig. 4. Daily minimums and maximums of barometric pressure and temperature for Laboratory Biosphere, Sept. 10, 2003–Jan. 10, 2004.

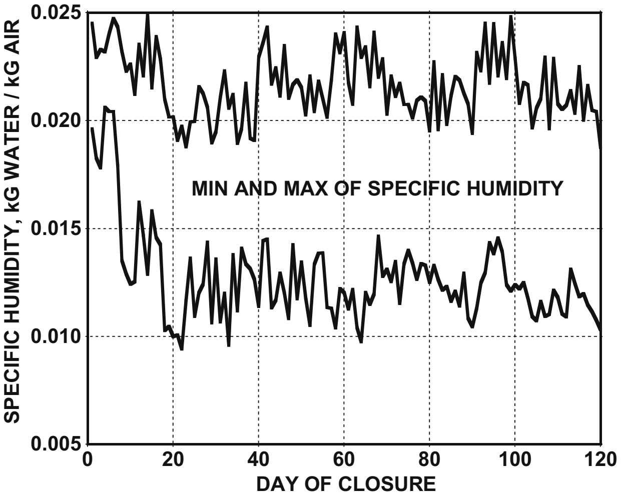

Fig. 5. Daily minimums and maximums of specific humidity for Laboratory Biosphere, Sept. 10, 2003–Jan. 10, 2004.

tion, but, for the purpose of this discussion to make use of the temperature, humidity and barometric pressure data from operating this system, we make the hypothetical assumption that there is no lung and leakage occurs according to the simple algorithm. We examine a period of four months during which a sweet potato crop was grown in Laboratory Biosphere under artificial light with a photoperiod of 18 h each day (for details of this experiment see Nelson et al., 2005). The results of this leakage simulation are presented in Fig. 3, which also compares the resulting loss of original air to the much slower loss of original air as for the low leakage system of Biosphere 2.

5. Significance of tightly closed experimental systems

On planet Earth investigation of ecosystem function is hampered by the inability to fully account for material exchanges. Perhaps the most prominent example is the great uncertainty as to where much of the carbon dioxide from burning fossil fuels has been sequestered and the present inability to balance the compartments of the Earth's carbon cycle (Houghton, 2003). Dispersal over great areas and to inaccessible locations prevents reliable determination of this important information. A tightly closed ecological system of workable size offers material traceability. The investigation of oxygen decline in Biosphere 2 (Severinghaus et al., 1994) is a classic example. Systematic pursuit of material balance accounting in tightly closed ecological systems may help elucidate other mysteries of biogeochemical processes and cycles.

The concept of a self-sustaining life system as a remote space colony has been discussed for decades. Much of the work toward that possibility has focused on quantitative questions of food and oxygen production, water purification and re-use of wastes. However, before a team of explorers of the solar system or beyond will trust their lives to the sustainability of a closed ecological system they will have to be convinced that a myriad of factors have been tested and are reliable. These include no slow build-up of dangerous gases or contaminants, long term stability of ecosystem functions, stability of vital co-species, ability to limit outbreaks of pests or disease organisms (or ability to exclude them entirely) and even the production of building materials and medicines. Small systems that exhibit leakage on the order of several percent per day are unable to work experimentally with many of these issues. The time scale of these experiments must be commensurate with their probable application, i.e. years, even decades or more. Biosphere 2 did not have the answers to these issues (Allen, 1991) but does demonstrate that the technology is available to begin such research programs.

6. Conclusion

Tightly closed life systems maintained for long durations offer powerful research advantages over systems with unacceptably high leak rates. Due to the inherent natural "pumping" caused by variations in internal temperature and humidity and external barometric pressure, special design and construction is required to bring leak rates below a few percent per day for closed systems which operate approximately at ambient pressure.

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