



METHODS FOR MEASUREMENT AND CONTROL OF LEAKAGE IN CELSS AND THEIR APPLICATION AND PERFORMANCE IN THE BIOSPHERE 2 FACILITY

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ABSTRACT

Atmospheric leakage between a CELSS and its surround is driven by the differential pressure between the two. In an earth-based CELSS, both negative and positive differential pressures of atmosphere are created as the resultant of three influences: thermal expansion/contraction, transition of water between liquid and vapor phases, and external barometric pressure variations. The resultant may typically be on the order of 5000 pascals. By providing a flexible expansion chamber, the differential pressure range can be reduced two, or even three, orders of magnitude, which correspondingly reduces the leakage. The expansion chamber itself can also be used to measure the leak rate. Independent confirmation is possible by measurement of the progressive dilution of a trace gas. These methods as employed at the Biosphere 2 facility have resulted in an estimated atmospheric leak rate of less than 10 percent per year.

INTRODUCTION

In any closed chamber, and specifically in a CELSS, it may not be obvious whether the atmosphere is leaking or not. Nevertheless, substantial atmospheric leakage can have a dramatic effect on CELSS experimental systems. If atmospheric contamination or composition changes are occurring slowly, leakage may conceal this crucial fact.

In Biosphere 2*, there have been important atmospheric changes which would have been difficult or impossible to observe had it not been effectively sealed./1/ The system is equipped with two expansion chambers called "lungs." The lungs protect the structure from dangerous pressures and provide both a dramatic reduction in the leak rate and a direct means to measure the leak rate.

LUNGS

In an airtight earth-based CELSS, differential pressures between the inside and outside may be caused by three factors. 1) Temperature changes will expand or contract the air. For example, a range of ± 10 C from 20 C will, by the ideal gas law, produce ± 3500 Pa pressure differential. 2) Humidity variations are variations in the partial pressure of water vapor, which in the system under discussion, are typically on the order of ± 500 Pa. 3) External barometric pressure variations on the order of ± 500 Pa occur every few days.**

Unless the CELSS is built to withstand pressures on the order of ± 5000 Pa (about 500 Kg f m^{-2}), it may explode or implode. More importantly from the standpoint of this article, leakage through even very small holes is driven by the differential pressure between inside and outside. These differential pressures are cyclical in nature, typically following diurnal photoperiod cycles or weather patterns. The result is that a fixed volume earth-based CELSS is alternately subjected to forced air injection and discharge if it has any leak path.

To accommodate the expansion and contraction, two chambers, called "lungs", are built into the system. Each lung is a cylindrical tank, sealed on top by a flexible, impermeable, weighted membrane which rises and falls in response to the changes of air volume. The membrane does not stretch, but only changes shape. The pressure created by the membrane weight is essentially constant throughout the normal range of movement (confirmed by pressure measurement). One lung could serve the function; two lungs allow for maintenance on one while temporarily using the other.

Because the lungs expand and contract, the system atmospheric "volume" should be calculated in moles rather than volumetric units. The volume continually changes, while, the moles of dry air are invariant, except for

*Biosphere 2 is a $180,000 \text{ m}^3$ closed ecological system with several ecosystems and 8 humans. It has been sealed for 15 months as of Dec. 1992. The envelope is glazed to admit sunlight and sealed below with a stainless steel liner./2,3/

**Typical of barometric pressures recorded at 1160 m elevation at this site near Tucson, Arizona

leakage or possibly for some chemical reactions. Note, however, that the simple photosynthetic reaction and its reverse (respiration) $n\text{CO}_2 + n\text{H}_2\text{O} \leftrightarrow n\text{CH}_2\text{O} + n\text{O}_2$ can shift the O_2/CO_2 composition, but do not change the total moles of dry air.

First Mode of Operation

In the first mode of operation, the weighted lung membranes simply rest on the air contained in the system. The weight creates a positive internal air pressure of the system relative to the outside ambient pressure. In this system, the differential pressure is about 150 Pa and drives leakage outward from the system through whatever holes may exist in the enclosure.*** To whatever degree leakage exists, the outward-leaking air results in deflation of the lungs and the leak rate is determined from displacement divided by time. The computation must allow for the expected displacements that accompany temperature, humidity, and barometric pressure variations. Computation is to determine the moles of dry air (not volume) in the system, which derives from all the factors, temperature, barometric pressure, humidity, and lung membrane positions. Given enough time, any leakage, no matter how small, will become evident by deflation of the lungs according to the following computational method.

Computation of Leak Rate

Starting with the ideal gas law, $PV = nRT$, where P = pressure, V = volume, n = number of moles, R = ideal gas constant, T = absolute temperature, we compute the number of moles by

$$n = PV/RT \quad (1)$$

where we intend the number of moles of dry air only, not including water vapor. Equation (1) is only rigorously applicable throughout a volume of uniform temperature and pressure. In practice we estimate the boundaries of many subvolumes of approximate uniform temperature, each with a separate temperature sensor, and apply equation (1). By summation of the moles in each subvolume we arrive at the total moles for the entire system. The subvolumes must include the lung, which volume is determined at any moment by its geometry and membrane position. If the CELSS structure could significantly dilate with pressure, the subvolumes must be properly estimated at each pressure condition. This consideration is negligible in the described system, the estimated volume dilation being less than 1 part in 10000 for all pressures under consideration. 150 Pa is a very low pressure in terms of common experience, equivalent to 1.1 mm Hg or 0.02 psi. The reader should note that in the remainder of the paper, the differential pressures contemplated are \ll the absolute pressure. The pressure, P , must be the partial pressure of the dry air component only, determined from

$$P = P_a + P_l - P_w \quad (2)$$

where P_a = ambient barometric pressure, P_l = pressure added by weight of lung membranes, P_w = partial pressure of water vapor as determined from measurement of the relative humidity in each subvolume:

$$P_w = rP_v(T) \quad (3)$$

where r = relative humidity (a fraction between 0 and 1 as measured by a sensor), and $P_v(T)$ = the water vapor pressure as a function of temperature, T . The vapor pressure is obtainable from tables of water vapor pressure.^{4/} The total moles of dry air, calculated by summing the moles of all subvolumes calculated from

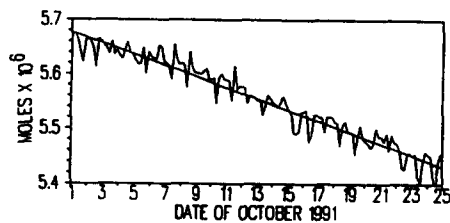


Fig. 1. Moles of dry air.

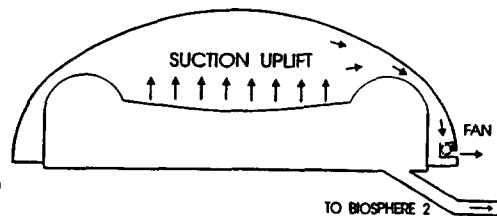


Fig. 2. Lung with membrane weight neutralized.

*It is possible that countering wind pressure could cause inward leakage if a hole were facing the wind and the wind exceeded about 12 m s^{-1} . At this site, such winds are infrequent.

equation (1), is plotted vs. time. The leak rate (a positive result implies outward) is then determined as

$$L = (n_0 - n_1)/(t_1 - t_0) \quad (4)$$

where n_0 = number of moles at time t_0 , n_1 = number of moles at time t_1 . It should be understood that we exclude water vapor from the calculation only because water vapor readily enters and leaves the atmosphere by evaporation and condensation within the system and is not indicative of leakage.

Errors

The estimation of subvolume boundaries plus inaccuracy of sensors plus deviation from the assumption of uniform temperature throughout each subvolume together contribute errors to this method. However, it is impossible for these errors to accumulate without limit in one direction for very long periods of time. By allowing enough time, the leak rate can be determined as accurately as desired in spite of these errors.

Computation of system moles and leak rate, while in the first mode of operation, using the above methodology for 1-24 Oct 1991 is graphically presented in Figure 1. In the first mode, the weighted lung membrane creates a constant positive internal pressure of about 150 Pa. Observation of certain small holes and test ports under this pressure prior to final system sealing showed unmistakable outward flow. There was clearly no possibility of reversal (inward flow) in the presence of 150 Pa differential pressure from inside to outside. The conclusion to be drawn from this observation is that individual fluctuations in the graph of Figure 1 are the momentary aggregate of the various errors for this system. Many of these fluctuations are on the order of 30000 moles. Although with positive internal pressure, a massive leak could cause sudden loss of some 30000 moles in a few hours, it is not possible for the reverse to occur under the same condition, hence the conclusion.

In this system, the atmospheric content is nominally 5.7×10^6 moles of dry air. A one-meter movement of either membrane displaces 1115 cubic meters of the system atmospheric volume. The system uses 2 lung position sensors, 1 barometric pressure sensor, 36 temperature sensors, and 27 relative humidity sensors. Sensitivity of the computed moles to sensor error is shown in Table 1.

Table 1. Resultant Error In Computed Moles From Given Sensor Error

Sensor Type	Hypothetical Error	Moles Error ^a	Percent Moles Error
Mean of all Temperature	2 C	38000	0.67 ^{b,c}
Lung Position	2 cm	800	0.014 ^a
Mean of all Humidity at			
15C	10% rel.H.	11000	0.19 ^b
25C	10% rel.H.	20000	0.35 ^b
35C	10% rel.H.	35000	0.61 ^b
Barometric Pressure	500 Pa	32000	0.56 ^b

^a Specific to this system. ^b Common to CELSS in general. ^c At 25 C.

In Figure 1, linear regression analysis of the 141 data points gives a loss rate of $10236 \text{ moles day}^{-1}$ with a 95% confidence interval of $\pm 441 \text{ moles day}^{-1}$ ($R^2=0.938$). This establishes an estimated leak rate of 65.5 ± 2.8 percent per year at the particular pressure condition of 150 Pa. ($365 \text{ days} \times 10236 \text{ moles day}^{-1} / 5.7 \times 10^6$ moles). Coincident drift of all of the 36 temperature sensors, 27 humidity sensors, and the barometric pressure sensor, all in the most unfavorable direction by the hypothetical error amounts in Table 1 would have falsely concealed a leak rate of 89.5 percent per year as opposed to the estimated 65.5 percent per year. This hypothetical comparison illustrates the power of an extended time span (eg. 24 days) to overcome errors inherent in the method. The maximum error is reduced in inverse proportion to the time span. The limited temperature/humidity/barometric patterns typical of CELSS systems, as well as errors in their measurement, are unavoidably "averaged out" as the time is extended. Note that errors in estimating subvolume boundaries are equivalent to having an incorrect temperature and/or humidity for part of a subvolume. Extension of the time will be limited by the point when the lung is fully deflated.* We next investigate the effect of pressure reduction.

*Expenditure of air for initial leak testing of this system required an approximate 10% recharge on 9 Dec 1991.

Second Mode of Operation

Having established the leak rate at a given pressure (eg. 150 Pa), we then move to the second mode of operation which is at reduced pressure. Pressure is reduced by creating suction within weathercover domes above the lung membranes. The suction applies uplift to the membranes and can be controlled to closely approximate cancellation of the membrane weight. This is accomplished by fans that slightly evacuate the space inside the weathercover domes. (Figure 2)

In the second mode of operation, the pressure differential of the system is reduced to zero plus or minus the accuracy of the suction control system. Practically, in Biosphere 2, the variation is \pm about 8 Pa (0.06 mm Hg or 0.0012 psi). The effect on leak rate depends on the shape of whatever holes may exist. Consider two types of holes. 1) For a hole that is like an orifice in a thin wall the leak rate is proportional to the square root of the pressure differential./5/ (Derived from the Bernoulli equation.) 2) For a hole that resembles a long tube, leakage is proportional to the pressure differential./6/ (From Poiseuille's law). When pressure is reduced to a fraction of the first mode of operation the worst case is 1), since the square root of a fraction is greater than the fraction.

Since the pressure differential varies in a small region around zero, the average leak rate will be found by integrating the instantaneous rate over the distribution of pressure differentials. To develop an estimate, we arbitrarily assume uniform distribution of pressure over time from -8 Pa to +8 Pa which is equivalent to

$$P(t) = 16t \text{ (pascals)} \quad (5)$$

while letting t range from $-1/2$ to $+1/2$ day. Then the representative outward and inward leakages during a 1 day interval are, as applied to the worst case :

$$L \text{ avg outward} = 10236 \int_0^{1/2} (P(t)/150)^{1/2} dt = 10236 (16/150)^{1/2} (2/3) (1/2)^{3/2} = 788 \text{ moles day}^{-1} \quad (6)$$

$$L \text{ avg inward} = 10236 \int_{-1/2}^0 (-P(t)/150)^{1/2} dt = 788 \text{ moles day}^{-1} \quad (7)$$

where the rate 10236 moles day⁻¹, and pressure 150 pascals, are taken from the observed first mode of operation. In one year, this is a total of 288,000 moles leaked outward from the system and an equal amount inward, or 5.04% per year for a system with 5.7×10^6 moles nominal atmosphere. It is noted that this is based on the assumption of uniform distribution of the pressure differentials in time, but also on the worst case of the physical shape of the leaks as orifices. If, instead, the leaks resemble long tubes with leak rate linearly dependent on pressure, the outward rate will be only

$$L \text{ avg outward} = 10236 \int_0^{1/2} (P(t)/150) dt = 10236 (16/150) (1/8) = 136 \text{ moles day}^{-1} \quad (8)$$

or 0.87 percent per year, and the same for the inward rate.

INDEPENDENT CONFIRMATION

Another method to determine leak rate of a vessel is to spike the air in the system with a trace gas. As leakage progresses, the tracer becomes diluted. Sulfur hexafluoride (SF₆) and helium are tracers in Biosphere 2. Concentration measurements began on 11 May 1992 and are repeated at later dates (Table 2). Regression analysis of the SF₆ data set gives a leak rate of 5.0% per year with an 80% confidence interval of \pm 4.3% per year. ($R^2=0.25$). The helium data set gives 4.4% per year, but $R^2=0.007$. These data can only be considered order-of-magnitude indicators until a longer time passes with further sampling. This method also becomes more accurate with time extension. A possible flaw in the method would occur if the trace gas were to bind to some of the internal materials in a manner that was dependent on the concentration. If the tendency to bind decreased with decreasing concentration, more would be released to the atmosphere making the leak rate appear less than actual and vice versa.

Table 2. Trace Gas Concentration on Given Dates

Date	Day	PPM SF ₆	PPM Helium
11 May 1992	228	56.90, 56.30	361, 359
15 Jun 1992	263	57.00, 55.90	336, 340
25 Jun 1992	273	57.00, 57.00, 56.50	378, 388, 374
13 Aug 1992	322	56.53, 55.73, 55.57	349, 354

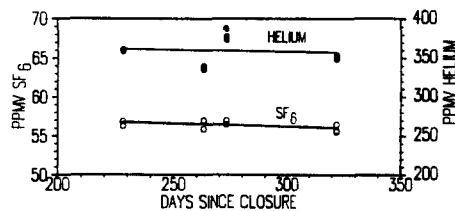


Fig. 3. Progressive dilution of SF₆ and helium.

ROLES OF PERMEATION AND DIFFUSION

Permeation may occur through the lung membranes or elastomeric seals. Permeation rate is generally dependent on the gas species and differential partial pressure, and will tend to shift the atmospheric composition. The trace gases will have different permeabilities than other components and to that extent will incorrectly represent the permeation leak rate. Permeation rates have been estimated for the system discussed as they depend on both the materials and geometry of the seals, and on the inside to outside concentration difference.^{7/} For carbon dioxide at 2500 ppm concentration, 2% of the atmospheric content permeates outward per year; oxygen at 15% concentration, 0.2% permeates inward per year. Nitrogen is an order of magnitude less than oxygen, the concentration difference being small. Water is estimated to permeate out at about 600 liters per year which is about 0.01% of the total water in the system.

Molecular diffusion through a leak must compete for significance with bulk flow through the leak. This is considered as two cases. In case 1), an orifice leak, the bulk flow velocity is $v = C(2P/\rho)^{1/2}$, where C = the orifice coefficient of discharge = about 0.6, P = differential pressure (pascals), ρ = air density = 1.03 kg/m^3 for air at 1160 m elevation (89000 Pa). By taking $P = 0.1 \text{ Pa}$ (a tenfold lower driving pressure than would be sustained), $v = 0.26 \text{ m sec}^{-1}$, or $9.5 \text{ mol m}^{-2} \text{ sec}^{-1}$. Taking the diffusion coefficient for CO_2 , $13.9 \times 10^{-6} \text{ m}^2 \text{ sec}^{-1}$, the diffusion rate at a concentration gradient of 12000 mol m^{-4} would be $0.17 \text{ mol m}^{-2} \text{ sec}^{-1}$, corresponding to a velocity of $.0046 \text{ m sec}^{-1}$, or 56 times smaller than the bulk flow rate. The concentration gradient, 12000 mol m^{-4} , corresponds to an atmosphere of pure CO_2 on one side and no CO_2 on the other side of a 3 mm wall with the hypothetical orifice. The diffusion through a leaking orifice is evidently overwhelmed by the bulk flow at the pressures considered.

In case 2), small tubular leaks, the viscous flow rate is proportional to the fourth power of hole diameter, while diffusion is proportional to the square. This admits the possibility that large numbers of very small holes would permit diffusion while blocking viscous flow. In that case, the diffusion leakage would not have been revealed during the first mode of operation, promoting a false sense of security. Space does not permit the full derivation here, but investigation of this case indicates that some 10^7 to 10^8 holes of diameter less than 0.05 mm could create this situation.^{8/} The helium tracer will diffuse some 2 to 4 times faster than any of CO_2 , O_2 , N_2 , or H_2O , and is a tool to diagnose this situation.

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