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AIRTIGHT SEALING A MARS BASE

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ABSTRACT

Atmospheric leakage from a Mars base would create a demand for continuous or periodic replenishment. This would in turn require extraction or mining for oxygen and other gases from local resources and attendant energy requirements for such operations. It therefore becomes a high priority to minimize leakage. This paper quantifies leak rates as determined by pressure and the size of holes and discusses the implications of pressure for structural configuration. The author engineered the sealing of Biosphere 2 from which comparisons are drawn.

KEYWORDS: Airtight, Sealing, Mars Base, Leakage, Pressure

INTRODUCTION

Man has imagined travel to the moon and planets and in particular to Mars, for decades. Long term habitation of Mars will require a substantial infrastructure for shelter and production of food. Enclosures for these purposes must retain breathable atmosphere and limit leakage to rates that can be practically replenished from local resources or resupply from earth, i.e. to very low leakage rates. Leakage is largely driven by a pressure differential between the inside and outside of an enclosure. It would be desirable to reduce the pressure to minimize leakage and reduce forces on the structure, but pressure is needed to support both humans and plants.

QUANTIFICATION OF LEAK RATES

Hypothetically considering air leakage through a hole in the case where the outside pressure is less than half the inside pressure, the mass flow rate is given by (Mark's, 1987):

$$dm/dt = -0.53CPA/\sqrt{T} \qquad (1)$$

where

m is the mass of gas in the enclosure, kg
C is the coefficient of discharge, about 0.6
P is the inside pressure, kg/m^2
A is the cross-sectional area of the hole, m^2
T is the temperature, degrees K

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The ideal gas law is

$$PV = nRT \qquad (2)$$

where

V is the volume of the enclosure, m^3
n is the number of kilogram-moles of gas in the enclosure
R is the ideal gas constant for SI units, 847.8 kg-m/(kgmole-°K)

and

$$n = m/M \qquad (3)$$

where

M is the molecular weight of the gas.

Combining (1) through (3) we obtain a differential equation for P as a function of time, t (seconds)

$$dP/dt = -0.53CPART/(MV\sqrt{T}) \qquad (4)$$

from which

$$dP/P = -0.53CAR\sqrt{T}/(MV)\ dt$$
$$= -269.6A\sqrt{T}/(MV)\ dt \qquad (5)$$

Integrating, we obtain a decaying pressure in the enclosure

$$P = P_0 e^{-kt} \qquad (6)$$

where

P_0 is the initial pressure at t = 0 and

and

$$k = 269.6A\sqrt{T}/(MV) \qquad (7)$$

depends on the area of the hole, the temperature, the molecular weight and the volume of the enclosure.

To get order of magnitude estimates of the leakage impact of small holes on a prospective Mars base we take some assumptions:

A) The average molecular weight of air within the enclosure is approximately 29.
(For instance, pure oxygen is 32, pure nitrogen is 28; Earth's atmosphere is 28.96.)
B) The temperature of the air is 18C (64.4F) or 291K.

We are only investigating the order of magnitude of leakage. In this context, the results are not significantly sensitive to the accuracy of the above assumptions.

We next construct Table 1 showing the percentage of the initial pressure that is lost over a year (t = 31,536,000 seconds) for postulated Mars bases of given atmospheric volume and a single circular hole whose cross sectional area represents the aggregate area of all holes in the system. One needs to consider what loss rate is acceptable in light of methods of replenishing

the atmosphere. If one sets an upper limit, for example, of ten- percent loss per year, then we see that the tolerable hole size for, say a 1000 cubic meter Mars base, is less than 1/5 of a millimeter that would be nearly invisible. For a Mars base the size of Biosphere 2 (180,000 cubic meters), less than ten percent per year loss would mandate aggregate equivalent hole size no larger than 2 mm diameter.

TABLE 1

PERCENTAGE OF INITIAL PRESSURE LOST IN ONE YEAR

HOLE	MARS BASE VOLUME - CUBIC METERS				
DIAM	100	1,000	10,000	100,000	1,000,000
(mm)					
0.01	0.392	0.039	0.004	0.000	0.000
0.02	1.56	0.157	0.016	0.002	0.000
0.05	9.36	0.977	0.098	0.010	0.001
0.1	32.49	3.85	0.392	0.039	0.004
0.2	79.23	14.54	1.56	0.157	0.016
0.5	99.99	62.55	9.36	0.977	0.098
1	100	98.03	32.49	3.85	0.392
2	100	100	79.23	14.54	1.56
5	100	100	99.99	62.55	9.36
10	100	100	100	98.03	32.49
20	100	100	100	100	79.23
50	100	100	100	100	99.99
100	100	100	100	100	100

COMPARISONS TO BIOSPHERE 2

The serious implications of even very small holes was recognized in the design and construction of Biosphere 2 which operated at an extremely low-pressure differential between inside and outside. The lung system of Biosphere 2 was built to absorb the expansion/contraction of the atmosphere while keeping the differential pressure less than 8 Pascal (0.08 mb or about 1/1000 psi). Testing by manipulating the pressure differential and measuring lung movements determined that the aggregate of all holes in Biosphere 2 was equivalent to a single hole about in the range of 13 to 19 mm diameter. The consequent exchange between inside and outside air amounted to between 5% and 10% of the total volume per year even with the very high degree of pressure neutralization (Dempster, 1994). The equation of fluid flow at low differential pressures is different than (1) above (Mark's, 1987; Dempster, 1994).

The primary concept of Biosphere 2's lung system was to protect the entire structure from explosion or implosion due to the inevitable pressure differences that develop between the inside and outside of an airtight vessel on earth as the inside temperature, inside humidity and outside barometric pressure fluctuate. These pressure variations would have far exceeded the Biosphere 2's strength, and yet they are almost trivial compared to the huge forces tending to explode a container in near vacuum which is pressurized to any significant fraction of a standard

atmosphere. Because the pressure variations in a Mars base will be very small compared to the absolute pressure, an expansion/contraction system analogous to that of Biosphere 2 would be irrelevant on Mars.

Biosphere 2 could not have been sealed without a bottom liner, which was fabricated from 1/8-inch thick stainless steel. A virtually infinite number of leak paths exist through the ground and the requirement for a bottom seal will be even more critical for pressurized containment on Mars. A Mars base liner must be robust and, if in direct contact with regolith, tough against abrasion and puncture. The chance of repairing a liner leak of uncertain location perhaps under equipment or infrastructure or tons of plant growth soil with very little time to stem the loss of atmosphere is very slim. Soil provides no significant barrier to airflow on a scale relevant to these concerns.

The possible range of atmospheric pressures and compositions is beyond the scope of this paper, but some general considerations and anecdotal information are offered. As we will see below, the absolute atmospheric pressure has profound structural implications and so it becomes desirable to minimize the required pressure. One can consider how much margin of extra pressure above an absolute minimum is affordable in terms of mission cost and weight associated with the enclosure's ability to contain the pressure.

It has also been considered that space missions could use an enriched or even pure oxygen atmosphere for human life support at reduced pressures. Provision of an oxygen partial pressure of about 200 mb offers equal oxygen availability to what humans experience in earth's atmosphere. If the composition were pure oxygen, it would be only about 1/5 of earth's atmospheric pressure. However, the fire hazard associated with enriched or pure oxygen atmospheres is extreme. The fire that claimed the lives of three astronauts in the Apollo 1 accident occurred in a pure oxygen atmosphere. The possibility of spontaneous combustion in enriched oxygen atmospheres is increased. The productivity of plants in various atmospheric compositions and pressures needs to be researched in detail before an acceptable artificial atmosphere for a Mars base can be designed.

Lowered oxygen availability has definite limits for human life support. The well-known slow oxygen decline in Biosphere 2 from 21% to 14.4% over a 16-month period approached the limit before oxygen was injected into the system to restore the vitality of the eight biospherians (Severinghaus et al, 1994). At 14.4% oxygen and total atmospheric pressure of 880 mb at the Biosphere 2 site (1160 meters or 3800 feet elevation) the oxygen partial pressure was equivalent to earth's atmosphere at 4160 meters or 13650 feet elevation. This approaches to the highest human settlements.

Replenishment of a mixed gas atmosphere may imply different methods and systems to restore each component. If, for example, in order to avoid the fire hazard of a pure or highly enriched oxygen atmosphere, nitrogen is designed to be the most plentiful gas as it is on earth, sources of both nitrogen and oxygen are required. Nitrogen is over 2% of Mars atmosphere (Meyer and McKay, 1996) and could possibly be obtained by separation, while oxygen might be obtained chemically from CO2.

STRUCTURAL IMPLICATIONS OF PRESSURE

Typical habitation structures on earth need not withstand strong differential pressures on opposite sides of their surfaces. A worst case is probably a building struck by a severe tornado with winds of, say, 300 miles per hour (134 m/s). Such a storm will destroy most earth buildings, yet the wind pressure is only about 1120 kg/m^2 (230 lbs/ft^2). The pressure of a standard atmosphere for comparison is 10330 kg/m^2 (2116 lbs/ft^2). The ambient atmospheric pressure of Mars is only about 70 kg/m^2 and is negligibly small as a counterbalancing force on the outside walls of a Mars base with pressure adequate to support human life.

Artist's renderings showing a Mars habitat built as a lightweight, transparent shell greenhouse sitting on the Martian surface are plentiful but contradict basic pressure considerations. Even assuming an atmosphere reduced to 1/5 standard pressure (which would need to be nearly 100 percent oxygen for human life support and carry attendant fire hazards as noted above), the force tending to tear it off the Martian surface is extreme. For example, a structure with a 10-meter diameter circular footprint and 1/5 standard atmosphere would have a total lift of 162,300 kg or 5166 kg per running meter of the perimeter, or 5.17 kg per running millimeter of the perimeter. See Fig. 1.

A construction engineer seeking to anchor a perimeter wall against such uplift might drill anchoring bolts into bedrock and set them with epoxy. If bedrock were not available and a perimeter concrete foundation ring were to be used to hold the edge down by weight, the foundation ring would need be 2.7 meters wide x 2.7 meters deep allowing for Mars gravity. The uplift per running meter of perimeter increases linearly with the overall diameter. This example assumes 1/5 standard atmosphere; higher pressures mean proportionally greater uplift.

To try to hold down the structure by loading a flat membrane floor with regolith fill faces the difficulties that the edges would pull up unless the floor were stiffened. Conventional construction techniques to stiffen a 10 meter wide floor against the bending forces generated from a 1/5 atmosphere pressure would call for 14-inch deep steel I-beams on 1 foot centers weighing over 300 kg each. Also the fill would need to be 4 meters deep to counteract 1/5 atmosphere. See Figures 2 and 3.

Other structural forms that present difficulties are sharp corners and flat surfaces. A structure with a rectangular footprint, even with a domed roof, will be subject to extreme stresses at the corners because the internal pressure will tend to flex out the right angle at the corners. A flat surface 1 meter x 1 meter resisting 1/5 atmosphere pressure would have to be 6 mm thick steel or 21 mm thick glass. If resisting 1 atmosphere, the thicknesses are 13 mm steel or 46 mm glass.

Inflatables with no corners seem much more feasible for their lightweight, compact storage, and easy deployment. However, the stresses must be carefully considered even with inflatables. The least possible tension is when the geometry is a sphere. See Fig. 4. In our example of a 10-meter diameter sphere and 1/5 atmosphere, the tension at any equatorial ring is 5.17 kg per running millimeter. If the thickness is, say, 2mm, the stress is 2.6kg/mm^2 or 3670 lbs/in^2. A spherical

fabric inflatable 10 meters diameter and 2mm thick would weigh approximately 625 kg (taking the density of the fabric to be comparable to water). Thicker is stronger, but also heavier.

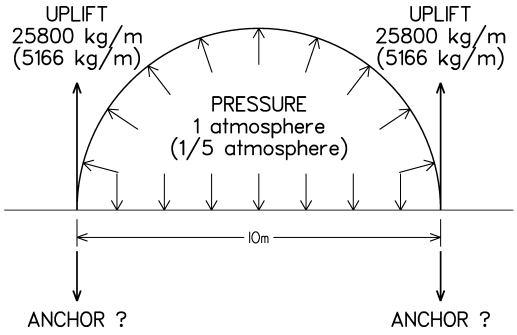


Figure 1

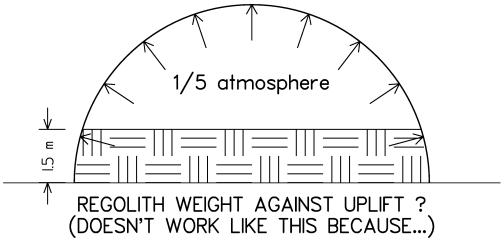


Figure 2

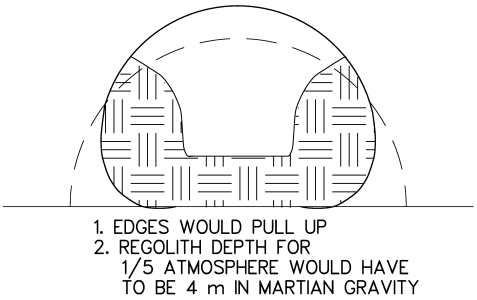


Figure 3

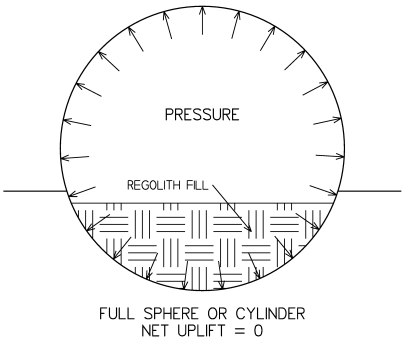


Figure 4

Key questions are: can a flexible, lightweight material be developed with the required strength (also transparent or translucent?) that resists ultraviolet degradation, and is tough against abrasion or puncture? Although the example of 1/5 atmosphere is used here, it is by no means assured that such a low pressure is viable considering the implication of high oxygen concentration and associated fire hazard. The forces should all be multiplied by 5 for a standard atmosphere.

ON-EARTH TESTING

Fortunately there are simple first approximation tests that can be performed on earth for the concerns raised above. Fabricate a candidate inflatable structure (or rigid structure, for that matter) and pressurize it to one atmosphere gauge pressure or two atmospheres absolute pressure. On earth this structure is experiencing the same pressure stresses as if it were at one atmosphere absolute pressure on Mars. If it has significant leaks they will be diagnosed by the loss of

pressure over time. Any gauge pressure, P, on earth will nearly simulate the absolute pressure P on Mars.

BROADER CONSIDERATIONS

The concept of building a greenhouse on Mars suggests that natural light could be sufficient for plant growth. This is a doubtful proposition. In Biosphere 2 the glass superstructure intercepted about 50% of the outside light in one manner or another, whether by absorption or reflection of the glass, by shading of the struts or from shading by sidewalls or parts of the structure. The net result was that between 45% and 50% of the exterior light was available inside for plant growth. This was a serious problem for plant growth at the low light period of winter months and didn't leave much extra margin even in summer, which led to the installation of supplementary artificial lights in the agriculture biome of Biosphere 2 after the initial 2-year closure trial. Mars is 1.52 times further from the sun, and so by the inverse square law, sunlight at the outer edge of its atmosphere is 43% that of Earth. Atmospheric absorption and the absorption spectrum determine how sunlight intensity at the surface of Mars compares to the surface of earth. One reference notes Mars surface sunlight to be about 60% of Earth's (Boston, 1988). Further loss will occur getting through the transparent or translucent greenhouse shell.

Maximization of entering sunlight argues for a thin shell. But this also means poor thermal insulation. Multi-layer transparent shells with trapped air between layers are a common approach to insulation but the penalty is additional loss of light at each layer. Typical temperature ranges on Mars may be roughly from -80C to 0C night to day (-112F to 32F). A greenhouse warmed only by direct solar radiation might only rise above freezing for a few hours on a relatively warm clear day. A 10m x 20m x 5m high greenhouse with 2 to 4 layers in the shell, artificially heated to internally stay above freezing in a nighttime ambient -50C, would require from 25 to 75 kilowatts continuous heating energy. A massive warm soil bed can help only partially because the heat will only weakly rise up among the plants without some artificial means of transfer and is also predicated on the soil bed having been thoroughly warmed in advance which will not happen from sunshine alone. A 10m x 20m vigorously growing planting bed could be enough to support about one person based on Biosphere 2 experience.

Exposed surfaces are also exposed to ultraviolet degradation and the effects of windblown sand. Sand abrasion might lessen sunlight transmission and, if extreme, threaten to wear a hole through the material. All of these considerations tend to support the concept of a deeply buried greenhouse for thermal insulation, protection from sand abrasion and from ultraviolet light as well as radiation hazards for humans. Drawbacks to deep burial are the requirement to dig deep and the energy demand of artificial lights to grow plants.

RESEARCH GOALS

New concepts have been advanced making travel to Mars seem increasingly possible (Zubrin, 1996). This paper may seem to have presented difficulties that oppose that concept, but, to the contrary, it is intended to focus attention on the challenges we must overcome to make

Mars habitation a reality. A vigorous program to develop the technics of habitation on Mars must be created. To this end the following research goals are suggested.

Materials

Create a flexible lightweight completely airtight fabric suitable for inflation to a full atmosphere pressure in large assemblies. It should be highly resistant to abrasion, puncture and ultraviolet degradation and capable of mounting fittings for airtight electric and fluid penetrations, for viewing windows and airlock doors. It should be able to be repaired simply and quickly in the field while under pressure.

Atmospheric

Develop a broad understanding of what atmospheric pressures and compositions are compatible with vigorous plant growth, including genetic variants to further this goal. Develop understanding of the health effects for both humans and animals of atmospheric pressures and compositions different from those of planet earth. Investigate fire hazards associated with enriched oxygen atmospheres. Develop high efficiency systems to separate Martian atmospheric components and to produce oxygen from atmosphere or other materials found on Mars.

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William F. Dempster graduated in mathematics and physics from the University of California, Berkeley in 1963 and subsequently worked in computer programming and systems analysis at Lawrence Berkeley Laboratory. He then participated in the founding of the Institute of Ecotechnics, which helped to establish several projects worldwide integrating ecology and technics in complementary balance. He participated in design and construction of an ocean-going expedition research vessel which circumnavigates the globe and on which he led a two-year expedition up the Amazon River. He directed the engineering of Biosphere 2 from 1985 to 1994, invented and designed the expansion chambers called "lungs", invented one type of airtight glazing system and controlled the development of another glazing system actually used on Biosphere 2. He devised and implemented the means of detecting leaks and measuring the leak rate of Biosphere 2. He also determined energy demands of Biosphere 2, selected equipment and configured systems to meet those demands and demonstrated the certainty of water recycling and the methods by which the recycled water is collected. He is Director of Systems Engineering for Biospheric Design, Inc. and is involved in planning further closed biospheric systems.