

Applications of Vacuum Insulation Panels in Extreme Environments

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1 Introduction

Vacuum insulation panels' three main commercial applications are currently domestic refrigeration, architectural, and controlled temperature packaging. However, a number of new and potentially large VIP applications are in development such as:

- Medium temperature (50-150 °C) for use in process, oil and condensate piping, PEM fuel cells, and hot water heaters,
- Cryogenic for LNG systems,
- Flexible VIP's for apparel,
- Active VIP's for controlled temperature packaging and architectural use¹.

VIP use in each of these applications has primarily been limited by lifetime issues associated with the more extreme environments rather than thermal performance or economic reasons. These lifetime issues can be either core material related (flexibility, outgassing, required pressure level) or barrier related (water vapor or oxygen permeation, outgassing/decomposition, seal failure, barrier fracture, etc.).

2 Water permeation / Adsorption

As VIP operating temperatures increase, water vapor becomes the dominant problem for VIP lifetime for two reasons. First, the equilibrium vapor pressure of water dramatically increases with moderate temperature increases as shown in Figure 1. This higher vapor pressure; 1) creates a larger driving force for permeation through the barrier and seals, 2) increases the maximum possible water vapor pressure possible in the VIP and 3) makes water adsorption (desiccant) much more difficult. The rate that water vapor permeates through the barrier and seal depends upon the concentration driving force across the barrier. As a first order approximation, increasing the operating temperature from 0 to 40 °C increase the driving force by an order of magnitude. However, the water vapor transmission rate will increase by an even larger factor since the diffusivity is also a function of temperature. Depending upon the barrier, the total water transport rate will increase a factor of 50 or more with the 40 °C temperature increase. At 40 °C and 100 %RH, the water partial pressure inside a 25 mm VIP will rise to 1 mbar in less than ½ year and to 10 mbar in five years (see Figure 2). This example assumes no water adsorption on core or desiccant, no permeation through the seals, and uses a multi-layer barrier with a WVTR of 0.05 g/m²d measured at 38 °C and 90% RH. Also included is the predicted O₂/N₂ pressure which is an order of magnitude lower than the water vapor pressure.

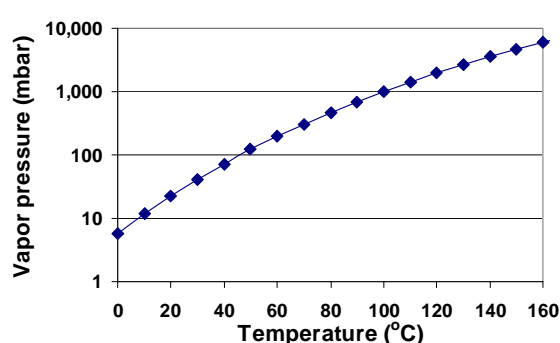


Fig. 1: Water vapour pressure as a function of temperature

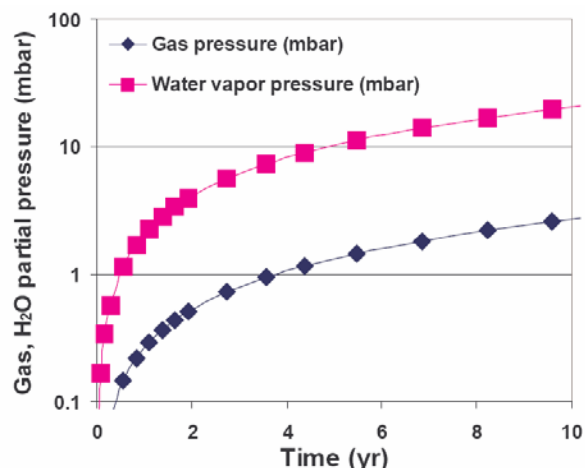


Fig. 2: Predicted temporal variation of gas and water partial pressure for a 25 mm thick silica VIP at 40 °C and 100 % RH

At 40 °C, the equilibrium water vapor pressure of ~72 mbar in a VIP will affect the thermal conductivity of a VIP to different degrees depending upon the core type. For open-cell foams and fiberglass cores, thermal performance will be completely compromised and conductivity will rise to over 0.020 W/mK. In contrast, the conductivity will only increase to 0.005 to 0.008 W/mK for nanoporous silica VIP cores at 40 °C. It is important to point out that for the issue of the equilibrium/steady-state VIP water vapor pressure, it is the coldest side of the VIP which sets the maximum water vapor pressure in the VIP. As an example, for a domestic refrigerator with the inside VIP wall at ~0 °C and the outside wall at 26 °C, the water vapor pressure will only ever rise to ~5 mbar over the refrigerator's life. For a nanoporous silica panel, this implies that water vapor permeation is not a significant factor in VIP lifetime.

There are two possible solutions to this water vapor problem. One can use standard multilayer metalized barriers and try to adsorb the water vapor within the VIP or one can employ ultra barriers with much lower water permeation rates than conventional metalized films. Before considering the addition of a desiccant/adsorbent, one must consider the water adsorption properties of the core material itself. Because of their large pore size/low surface area, fiberglass and open-cell foams have negligible water uptake. In contrast, nanoporous silica can adsorb significant quantities of water vapor depending upon their surface chemistry. Figure 3 shows water adsorption isotherms at 25 °C measured using a Hydrosorb 1 automated adsorption analyzer. Hydrophobic silica aerogels only adsorb 2-3% of their weight in water despite their high surface area. A conventional hydrophilic silica gel with 2 nm pore size can adsorb 10% of by weight at only 20% RH. However, the 2 nm pore size is too small for a VIP core material and a more conventional silica/carbon core material with ~50 nm pores will only pick up 10% of its' weight at 90% RH. For low temperature VIP applications, the adsorption capacity of silica cores will provide some value. However, for temperatures over ~40 °C, additional adsorption capacity which operates at lower humidity is required.

When considering the choice of an adsorbent/desiccant, one must consider the equilibrium water vapor pressure at the VIP operating temperature and the maximum acceptable pressure from a thermal viewpoint for the particular core material being used. As an example, if the operating temperature is near 50 °C, the equilibrium vapor pressure is ~100 mbar. If when one has a silica core, it is desirable to keep the water vapor pressure less than 10 mbar and therefore, the operating RH for the adsorbent is 10/100; 10% RH. Therefore, the key attribute of the adsorbent will be how much water it can adsorb at 10% RH. In contrast, for fiberglass or open-cell foam cores, the maximum desired water pressure would be ~0.1 mbar or an RH of 0.1%. It is clear from Figure 3 that physical adsorbents such as shown in Figure 3 will not perform at this low RH. Therefore, one must either use small-pore zeolites like 3A (0.3 nm pore size) or chemical desiccants such as calcium oxide or calcium

chloride. The disadvantages of those types of desiccants are their lower capacity (>0.15 g/g) which means that a higher mass loading must be employed and which can affect thermal performance. At an operating temperature of 100°C , the vapor pressure is 1,000 mbar and the required adsorbent operating RH becomes 1% for silica cores and 0.01% for fiberglass/open-cell foams. It is very difficult to maintain water pressures at a relative humidity of 0.01%.

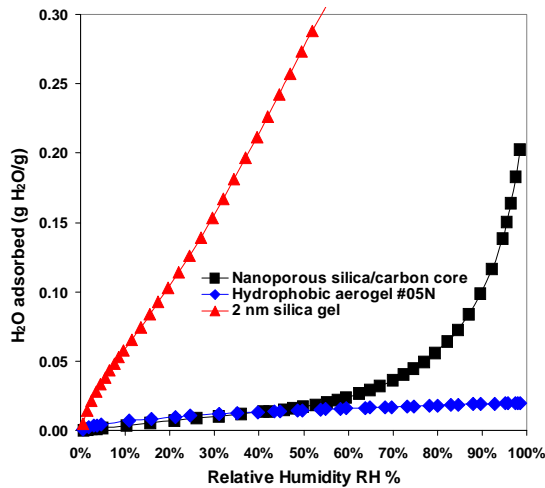


Fig. 3: Water adsorption isotherms at 25°C

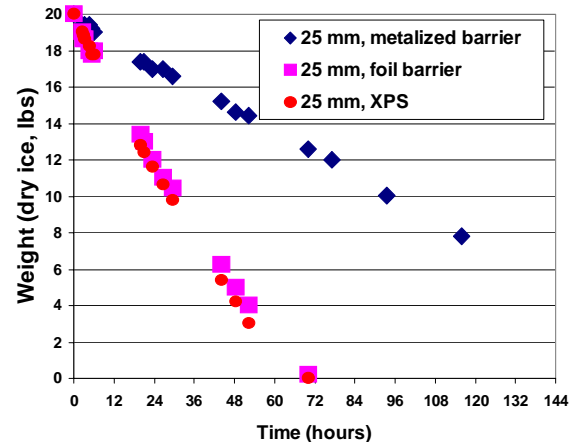


Fig. 4: Dry ice sublimation from 27 liter boxes produced using various insulation

3 Ultra-barriers

The other approach to solving this moisture and oxygen/nitrogen problem is to employ a barrier with much lower water vapor and oxygen/nitrogen permeation than conventional metalized films which are the barriers of choice for most applications. Aluminium foil film has been employed as ultra high barrier film. However because of the extremely high thermal conductivity of aluminium as compared to VIP's (>200 compared to ~ 0.004 W/mK), thermal edge effects are a major problem leading to a loss of VIP thermal performance. In a recent test (see Figure 4) using a commercial foil-based barrier, the effective thermal performance of $300\text{ mm} \times 300\text{ mm}$ VIP's produced with a fiberglass core material was an order of magnitude worse than a VIP with the same core material produced with a metalized barrier. In fact, thermal bridging was so severe that the performance was no better than an equivalent thickness of extruded polystyrene (~ 0.025 W/mK). Alternatively, one can employ metal foils such as stainless steel or nickel which have thermal conductivity over an order magnitude lower than aluminium (i.e., 10-20 W/mK) but cost, flexibility, and sealing are all issues. We have previously produced vacuum panels using electroplated nickel² but costs precluded use in most current applications.

A fertile area for improved ultra barriers using new technological approaches is the area of OLED packaging. OLEDs' have extremely low water and oxygen tolerances (orders of magnitude lower than VIP's) to maintain their operational life. A number of different approaches are possible to meet these demanding criteria depending upon the display type (i.e., forward or backward projecting). Metal foil approaches can work for OLED's but of more interest are new approaches which use multi-layers of very thin co-depositions of vapor-deposited polymer and ceramic. By using very thin layers in an ultra-clean environment, three key problems associated with conventional lamination of metalized barriers are avoided. By using submicron vapor deposition of polymers for the planarization layers, the polymer

thickness for diffusion between defects in adjacent barrier layers is greatly reduced as compared to the ~10 micron polymer thickness in laminated metalized barriers. By using a clean environment, the presence of particles and other contamination are minimized which reduces the defect density. Finally, by using thin layers, many parallel layers can be built up and still maintain low total thickness to reduce thermal bridging effects. Also, the thermal conductivity of alumina is low compared to aluminium so that the total parallel conductivity of these barriers is on the same order of as conventional metalized barriers and much lower than metal foil barriers. One issue with these ultra barriers is how to measure their barrier performance when permeation is orders of magnitude below the detection limits of "Mocon-type" permeation measurements. The method of choice is deposition of elemental calcium inside the package³. The reaction of calcium to either calcium oxide (O_2 permeation) or calcium hydroxide (H_2O permeation) can be determined gravimetrically or optically. Based on these measurements, water/oxygen permeation of $<5 \times 10^{-6} \text{ g/m}^2\text{day}$ at 21 °C and 50% RH. These films have several orders of magnitude better performance than conventional films without any detrimental thermal bridging effects.

4 Seal leakage

Even with extremely impermeable barriers, one weakness in VIP lifetime is permeation through the edge seals. For typical barrier films, the water vapor transmission rate is typically ~50 times greater through the seal layer than through the barrier. For oxygen, typical seal layer materials offer little oxygen diffusion resistance and the permeation rate can be up to 105 greater (i.e. $103 \text{ cm}^3/\text{m}^2\text{dbar}$). As with any permeation/lifetime question, operating temperature and panel thickness are two key parameters. However, for seal permeation, three additional variables are seal layer thickness, seal width, and type of seal structure (three versus four seals). A typical polyolefin seal layer is ~50 microns thick although some films have been produced with seal layers as thin as 5 microns (DuPont RSBL300). Our experience with very thin seal layers was that a much higher percentage of seal failures were observed in production arising from the tight tolerances on heat seal conditions and film cleanliness. In contrast, 50 micron seal layers are very robust.

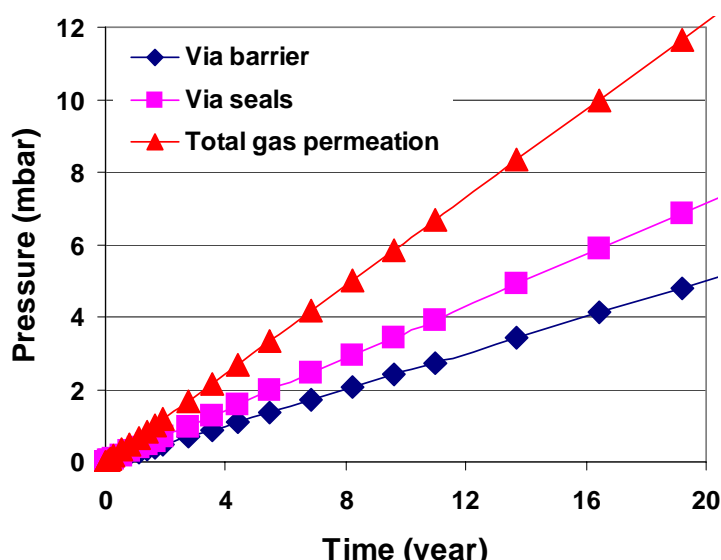


Fig. 5: Predicted gas pressures in a 25 mm thick, 300 x 300 mm VIP with 6 mm seals at 40 °C and 50 % RH

For a barrier with 50 micron seal layers, there is essentially a 100 micron thick pathway from the ambient to the inside of the VIP which has very high permeation relative to the barrier. Although 100 microns sounds small as compared to 100's of mm for the VIP sides, the high oxygen permeation rate

implies that oxygen/nitrogen permeation through the seals can be important. However, water vapor permeation will not. In Figure 5, we have calculated the internal gas pressure resulting from permeation through the seal layer and the barrier. For this example, we use 6 mm seal width and a 300 x 300 mm VIP which is 25 mm thick with seals on all four sides. The barrier is a typical multi-layer, metalized composite and the operating conditions are taken to be 40 °C and 50% RH. For this example, the gas pressures are acceptable for a silica VIP but are two orders of magnitude too high for a fiberglass or open-cell foam panel. The simplest solution would be to increase the seal width but 12 mm is about as wide as is commonly used in heat sealing. This would only reduce the total pressure rise from 12 to 8.6 mbar after 20 years. Another solution would be to use a “t-seal design” or fold the barrier to form a bag on one side such that one of the long seals is eliminated. This reduces the seal permeation by 25% for this square panel and will be even more effective for higher aspect ratio panels. Of course, as the panel thickness decreases, this problem will become even more significant. Another approach is to use an additional seal layer over the seal in an effort to increase the effective diffusion distance but this is time consuming and costly. Another approach would be to employ heat seal materials with improved permeation characteristics but these types of barriers are not currently available. Even if the seal thickness was reduced from 50 to 5 microns, seal permeation will be significant for fiberglass and open-cell foam panels since the pressure increase would still be ~0.04 mbar/year. For fiberglass and foam panels, one must always employ getters except for very short lifetime applications (1-2 months). When sizing the getter, one must consider the load through the seals in addition to the oxygen/nitrogen load from permeation through the barrier sides.

5 Barrier flex

Many current and future VIP applications require manipulation of the barrier material beyond simply making the panel. This can include bending along the axial length of the panel (process piping), folding and gluing flaps to allow making boxes without gaps (controlled temperature packaging) and even applications where thin (2-3 mm thick) VIPs are repeatedly flexed (apparel). Since we noted a statistically higher failure rate in panels that had the tapes folded back and glued or taped as compared to similar size panels which were not bent, we began a study with barrier suppliers to determine the effect of twisting on barrier materials.

Two different multilayer metalized barrier materials were subjected to a twisting experiment using a commercial twisting apparatus. Samples were 190 by 280 mm and were subjected to 4400 of rotation. At the same time, the sample ends move together approximately 40 mm. After two and ten twist cycles, samples were measured for water and oxygen permeation using conventional Mocon machines. Control samples of untwisted material were also tested. After ten cycles, the barrier material had 19 roughly parallel creases across the surface and had a great deal of texture as compared to normal films (see Figure 6).



Fig. 6: Barrier A after 10 twist cycles

The severe twisting had a relatively minor effect on water vapor permeation through the films considering the amount of creasing in the materials (see Table 1). However, the oxygen permeation increased by a factor of ~100 after only two twist cycles for both films. Although it is difficult to relate

these results back to the creasing that occurs on VIP corners and with folding of flaps, it does illustrate the potential magnitude of this problem.

Table 1: Water vapor and oxygen permeation through twisted VIP barrier films

Number of twists	WVTR		OTR	
	38 °C, 90%RH (g/m ² d)		23 °C, 75% RH, (cm ³ /m ² dbar)	
	Barrier A	Barrier B	Barrier A	Barrier B
0	0.02	0.04	<0.01	0.02
2	0.12	0.09	1.50	1.89
10	0.25	0.17	4.29	5.67

6 References

- 1 D. Smith, K. Roderick, R. Perkes, V. Sinclair, L. Warren US Patent 6,688,132, (2004)
- 2 E. Merrill, C. Call, K. Roderick, D. Smith and M. Powell US Patent 6,838,146, (2005)
- 3 G. Nisato, P.C.P. Bouten, P.J. Slikkerveer, W.P. Bennett, G.L. Graff, N. Rutherford, L. Wiese US Patent 6,838,146, (2005)