

# Controlled Temperature Packaging Using On-Demand Cooling from Active Vacuum Insulation Panels

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## 1 Introduction

Vacuum insulation panels' (VIP's) three main commercial applications are currently domestic refrigeration, architectural, and controlled temperature packaging. For refrigeration, the temperature on each side of the VIP is essentially constant with time and hence, the important thermal property is the effective thermal conductivity. In contrast, insulation for architectural and controlled temperature packaging applications has very similar demands in at least one sense. It is desired to maintain the "inside" temperature of the box (container or building) at essentially constant temperature while the outside temperature is varying. Depending upon the geographic location and season, the purpose of the insulation may be to either prevent heat input to the box or restrict the loss of heat. For many instances, the net energy gain or loss over a 24 hour period is quite small but the maximum heat flux at a particular time can be significantly greater. Thus, for these applications, one is concerned with not just the thermal conductivity of the insulation but also the thermal diffusivity.

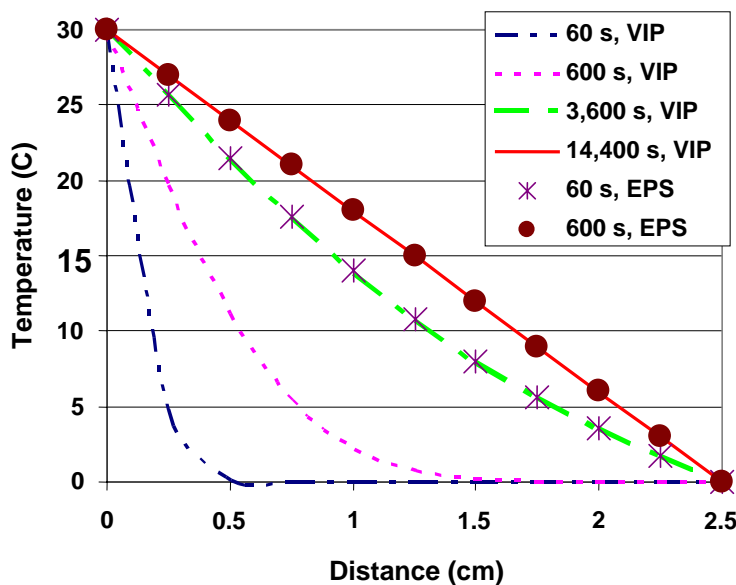
## 2 Thermal Diffusivity of VIP's

The key property for the time response of insulation is the thermal diffusivity ( $\alpha$ ) which is the thermal conductivity ( $\lambda$ ) divided by the product of heat capacity ( $C_p$ ) and density ( $\rho$ ). Thermal diffusivity has units of length squared divided by time and is analogous to mass diffusivity. Therefore, a characteristic time ( $\tau$ ) for a temperature change in insulation is given by the thickness ( $L$ ) and thermal diffusivity as  $\tau = L^2/\alpha$ . For a 2.5 cm thick slab of expanded polystyrene (EPS), the characteristic time to achieve steady state ( $\tau \sim 0.2$ ) is on the order of only 1 minute (i.e., much shorter than diurnal time scales). In contrast, for a typical inorganic VIP which is 2.5 cm thick, the characteristic time is on the order of one hour (i.e., still less than but approaching diurnal time scales). In Table 1, we have calculated typical thermal diffusivity values for a range of VIP types and compared them to expanded polystyrene. Please note that value of different manufacturer's VIP's can vary and these are representative values only. The key point is that because of the order of magnitude lower thermal conductivity and order of magnitude higher density, VIP thermal diffusivities are *almost two orders of magnitude lower* than conventional insulation.

**Table 1: Thermal diffusivity of typical VIP's compared to expanded polystyrene**

VIP Type	$\lambda$ (W/mK)	$\rho$ (kg/m <sup>3</sup> )	$C_p$ (J/Kg K)	$\alpha$ (m <sup>2</sup> /s)
Silica/carbon VIP	0.0036	165	835	$2.6 \times 10^{-8}$
Silica/titania VIP	0.0040	200	835	$2.4 \times 10^{-8}$
Fiberglass VIP	0.0036	220	830	$2.0 \times 10^{-8}$
Foam VIP	0.0060	120	1,210	$4.1 \times 10^{-8}$
EPS	0.040	20	1,210	$1.7 \times 10^{-6}$

For an insulation slab of a given thickness,  $L$ , the temporal and spatial temperature variation can be calculated by solving the governing partial differential equation. For insulation which is initially at 0 °C everywhere and for which the surface temperature at the outside ( $x=0$ ) is changed from 0 to 30 °C and the surface temperature at  $L$  is maintained at 0 °C, an infinite series eigenvalue solution is obtained. For a 2.5 cm thick slab, the temperature distribution within the slab at different times is shown in Figure 1 for both VIP and EPS insulation. For EPS, the effect of the change on the outside wall is “felt” on the inside wall within a minute and steady-state is reached in less than 10 minutes. In contrast, for VIP insulation, 4 hours are required for steady state to be achieved. We should note that more realistic boundary conditions of the third kind (i.e., flux through the insulation coupled to convection into the air on each side) as well as a continually-varying rather than a step-change in surface temperature could have been employed but the timescales of the changes would be similar.

**Figure 1: Spatial temperature variation in a 2.5 cm insulation as a function of time and type**

### 3 Thermal Mass and Phase Change Materials

Although the external temperature variation with time for both controlled temperature packaging and architectural applications are similar, there are two large and significant differences. The thermal mass of a building is many orders of magnitude greater than a controlled temperature shipping container. For a small syringe shipment, the product thermal mass may be only a few grams. To provide thermal mass and control, one normally adds a mixture of frozen (-20 °C) and conditioned (+5

°C) gelled water packs with the amount and ratio depending upon the expected ambient and shipment duration. Because of the high cost of air freight, there is a large premium on package weight and volume. In contrast, for architectural applications, thermal system weight and volume are not major issues. The second major difference is design life. The vast majority of controlled temperature shipping containers are used once (i.e., 2-7 days). In contrast, building life is measured in decades.

Despite the differences, phase change materials are employed in both applications to significantly increase the time scale of temperature variations as compared to simply adding thermal mass. Typical phase change materials (PCM's) used in both packaging and architectural use are described in Table 2. Key properties are obviously the transition temperature and the heat of fusion which quantifies the amount of heat released (absorbed) during the transition. Other important issues related to PCM selection include; 1) cost, 2) phase transition behaviour (supercooling, phase segregation, etc.) and 3) safety and environmental.

**Table 2: Properties of typical phase change materials<sup>1</sup>.**

PCM	Melting point (°C)	$\Delta H_f$ (J/g)	$\Delta H_f$ (J/cm <sup>3</sup> )	$\rho$ (g/cm <sup>3</sup> )
Ice	0	333	306	0.917
Tetradecane	5	165	126	0.764
Octadecane	28	244	189	0.814
CaCl <sub>2</sub> ·6H <sub>2</sub> O	30	171	256	1.71
Na <sub>2</sub> SO <sub>4</sub> ·10H <sub>2</sub> O	32	254	377	1.48

For controlled temperature packaging, where the product usually must be maintained at 2-8 °C, ice is the PCM of choice because of its' high energy density, low cost and excellent safety/environmental even though it does not melt within the control range. As a comparison to thermal mass only, the cooling of liquid water from 20 °C to 0 °C requires ~84 J but freezing that same mass of water would yield 333 J, a 4x increase per mass. Unfortunately, for building applications, there is not a convenient PCM choice from both transition temperature and energy density viewpoints.

In order to demonstrate the dramatic effect that adding phase change materials to VIP's can have, we have modified our transient thermal model to include a PCM of specified thickness on the inside wall of the VIP. This is accomplished by taking the space derivative of the infinite series and solving for the flux at  $x$  equal to  $L$ . For this example, we have assumed that the PCM is water and initially, it is completely frozen. In figure 2, we plot the flux at the inner wall as a function of time following a step change in the surface temperature to 30 °C for 2.5 and 5 cm thick VIP's. For the 2.5 cm VIP, the steady state flux of ~4.3 W/m<sup>2</sup> is reached after 4 hours. In comparison, for the same conditions using EPS, the steady state flux would be 48 W/m<sup>2</sup> and be reached in minutes. The effect of the PCM is to delay the heat flux at the inside wall. Because we have taken the inside surface temperature to be the same as the melting point, the flux at the inner wall is zero until the ice completely melts and then jumps to the no PCM value because the thermal resistance of the PCM is very small as compared to the VIP. For the 2.5 cm VIP, adding an equal thickness of water PCM delays the onset of heat flux into the box for six full hours. However, for a 5 cm VIP, much less water (1 cm thickness) is required to achieve an eight hour non-penetration time. This illustrates the trade-off between using VIP thickness and PCM thickness to solve the transient problem. The 2.5 cm VIP and 2.5 cm PCM weighs 29.1 kg/m<sup>2</sup> whereas the 5 cm VIP with 1 cm PCM combination is only 18.2 kg/m<sup>2</sup> and has better thermal performance but requires more volume and is presumably more expensive.

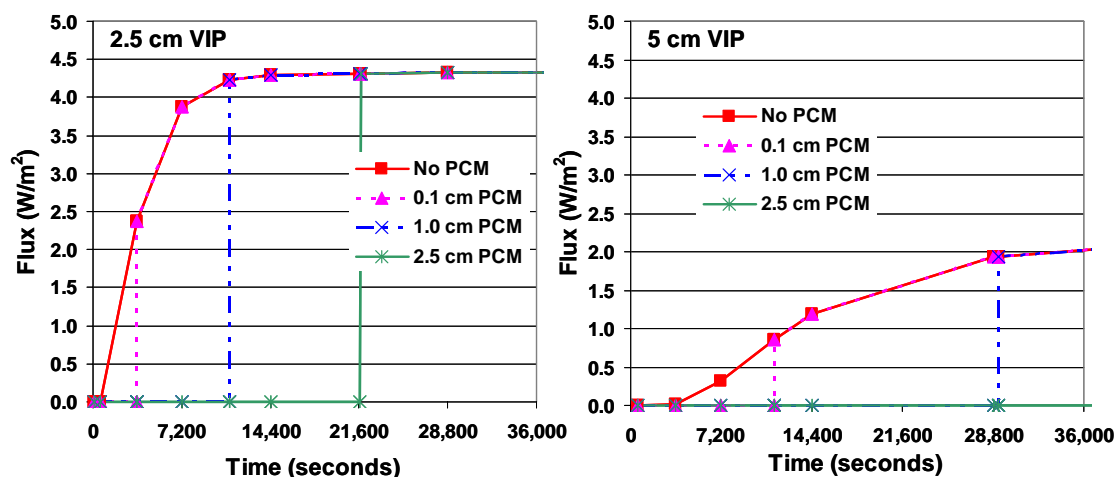


Figure 2: Temporal inner wall heat flux variation following a 30 °C step change in outer surface temperature as a function of VIP thickness and amount of PCM

## 4 Active Vacuum Insulation Panels

Although solid-liquid phase change materials are widely employed, they suffer from two main disadvantages, the inability to widely vary the transition temperature and relatively low energy density. As a result, we have been exploring the use of liquid-vapor phase change as an alternative. In particular, water has a factor of 7.5 higher heat of vaporization than heat of fusion (see Table 3). In addition, by varying the operating pressure, the temperature at which the phase change occurs can be varied over a wide range. The disadvantage of this approach is the large change in volume that occurs in a liquid-vapor phase transition as compared to a solid-liquid transition. Our solution to this problem is to employ very high capacity desiccants which can adsorb up to 300% of their mass in water vapor<sup>2</sup>. When this concept is employed in concert with vacuum insulation, we have an active vacuum insulation panel.

Table 3: Properties of water phase changes<sup>3</sup>.

PCM	Transition point (°C)	$\Delta H_f$ (J/g)	$\Delta H_f$ (J/cm <sup>3</sup> )	$\rho$ (g/cm <sup>3</sup> )
Ice melting	0	333	306	0.917
Water evaporation	Depends on pressure	2,502*	2,502*	1.00*

\* at 0 °C

Although there are a number of active vacuum insulation panel configurations<sup>4,5</sup>, we will illustrate with the two concepts shown in Figure 3. For both of these designs, water evaporates at the bottom producing cooling and is adsorbed on the top side producing heat. The design on the left uses a vacuum panel which is encapsulated in a second, outer barrier that contains water, vapor flow paths, and desiccant. This approach is employed when the VIP core either cannot be exposed to water vapor or when it must operate at pressures below the typical water vapor pressures of 5 to 50 mbar (depending upon the temperature on the cold side of the panel). The simpler and more inexpensive

approach is to simply allow the water vapor to diffuse through the VIP core material from the cooling side to the desiccant (right side of Figure 3). Because of the high heat of vaporization and the high adsorption capacity of the desiccant, energy densities much greater than traditional solid-liquid phase change materials are possible. Also, by controlling either liquid water feed rate or operating pressure, the transition temperature of the liquid water can be varied.

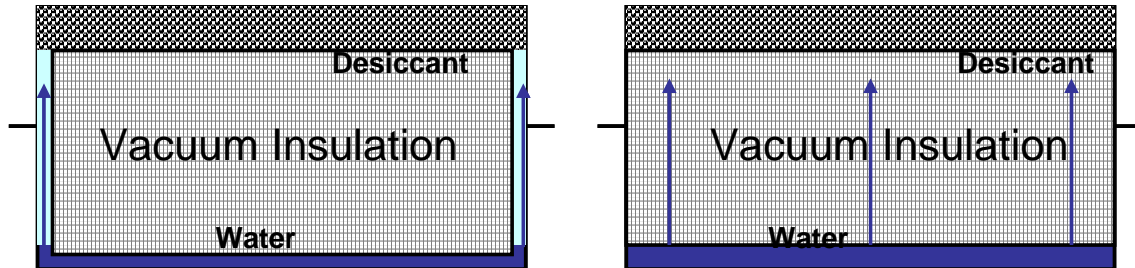


Figure 3: Active VIP schematic diagrams (arrows indicate water vapor flow)

We will illustrate the use of this approach for controlled temperature packaging. By using one active panel for cooling and five conventional silica/carbon VIP's, we are able to significantly reduce the outer volume of a shipping container as compared to a "conventional" box made of moulded EPS and containing a mixture of frozen and conditioned gelpacks. An example of this volume reduction is shown in Figure 4. In this case, 10 conventional EPS/gel pack systems designed for maintaining product at 2-8 °C for 48 hours in a 30 °C ambient are compared to 10 systems designed for the same specifications but using an active VIP as well as five conventional VIP's. Part of the reason that the volume reduction is so great is that the refrigerant (the water and desiccant) do not have to be insulated as compared to conventional systems for which the product and gelpacks must be insulated. This reduces the container's controlled temperature section surface area and further reduces the heat load on the cooling system.

By combining a box of 12 mm thick VIP's with an active VIP lid, temperature swings on diurnal timescales can be essentially damped out. Figure 5 shows the internal, product temperature of four different systems as they are subjected to thermal cycling between 31 and 16 °C. The product temperature stays within the desired 2-8 °C range for ~60 hours. This result is even more remarkable given the small outside volume (~8 liters) and low mass (~1.4 kg) of these systems.

Although we have used controlled temperature packaging as an example for the use of active VIP's, the same concepts can be successfully applied to architectural applications. In that case, instead of a one-time movement of water vapor from one side to the other of the active VIP, the water vapor is repeatedly cycled from side to side of the panel. This is accomplished by employing speciality desiccants with narrow pore size and controlled surface chemistry on one or both of the internal surfaces of the active VIP.



Figure 4: Comparison of EPS/gel and NanoCool active VIP's

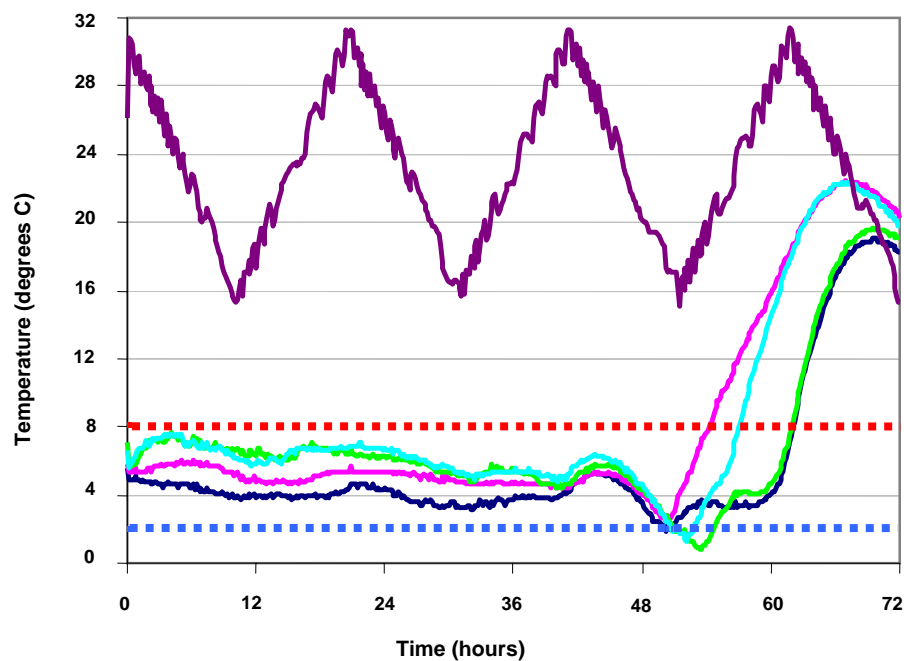


Figure 5: Thermal performance of four different NanoCool active VIP systems subjected to repeated 31-16-31 °C cycles simulating European summer shipments

## 5 References

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