Boxing Match

Vacuum insulated panels have made significant advances in recent years with the introduction of better core fillers and improved barrier films. This promising technology must be improved in order to increase its performance and reduce its cost

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Insulated containers are generally used in the pharmaceutical cold chain for the transport of heat-sensitive health products such as vaccines, medicines, blood and analysis samples. These containers are made with various insulation materials, and are refrigerated by eutectic gel packs or other phase change materials (PCMs). Conventional insulation materials used for this application are polyurethane, expanded polystyrene and extruded polystyrene, although closed cell polyurethane, in the form of rigid panels, is the most effective. Polystyrene is commonly used for short- and medium-duration shipping, as well as for moderate temperature profiles, whereas polyurethane is used for medium- and long-duration transportation and for extreme temperature profiles.

Insulation under vacuum is used in several sectors: aeronautics, marine, building, domestic and commercial refrigeration, and insulated packaging. It is a super-insulating material allowing thermal performances above that of polyurethane (up to 240 hours).

Vacuum Insulation Panels

To create thermal insulation, gas must be captured in very small, closed, or partially closed cavities, using a minimum amount of material (or a very high porosity of above 90 per cent). Consequently, in an insulated material the main contributor to heat transfer is captured gas – generally air which has a thermal conductivity of 0.025W/mK. The most efficient method of heat transfer reduction is to remove the gas through a vacuum or by applying low pressure – the method used in a Thermos flask.

A vacuum insulated panel (VIP) has a porous core material with open cavities (fibrous filler, foams, pellets and so on) wrapped in a watertight film. VIPs are produced by sealing the core material in a barrier film under vacuum. The main core materials used are open cell polymer foams, fibreglass

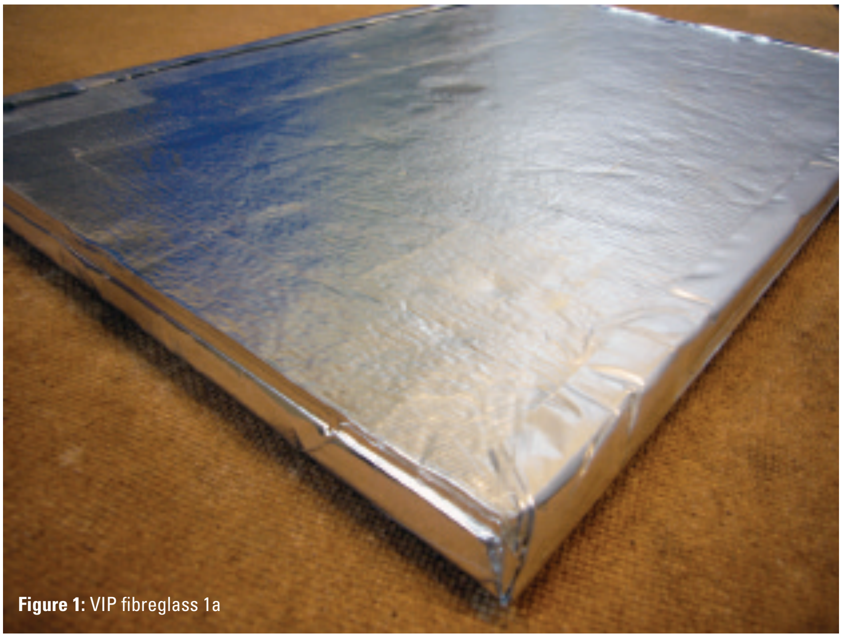


Figure 1: VIP fibreglass 1a

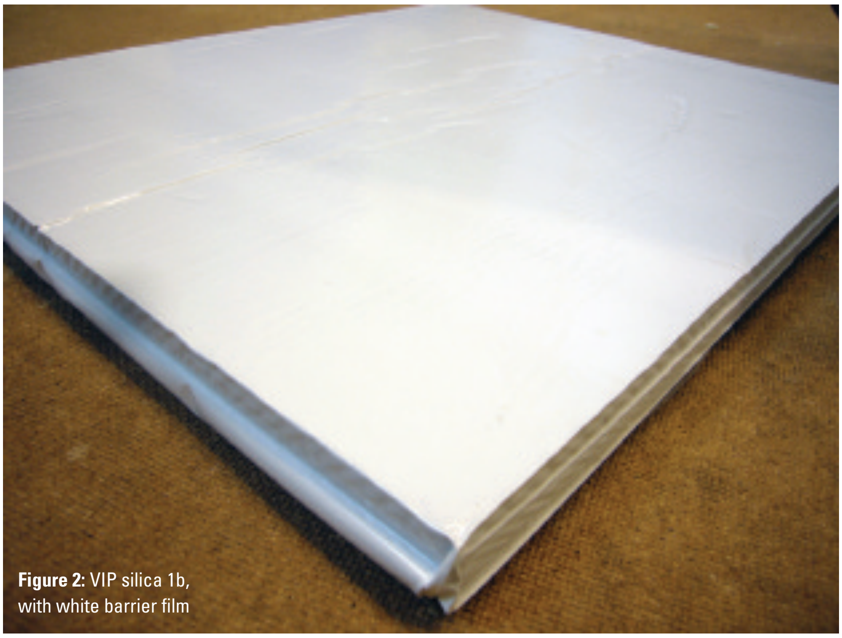


Figure 2: VIP silica 1b, with white barrier film

Figure 3: Dry ice sublimation

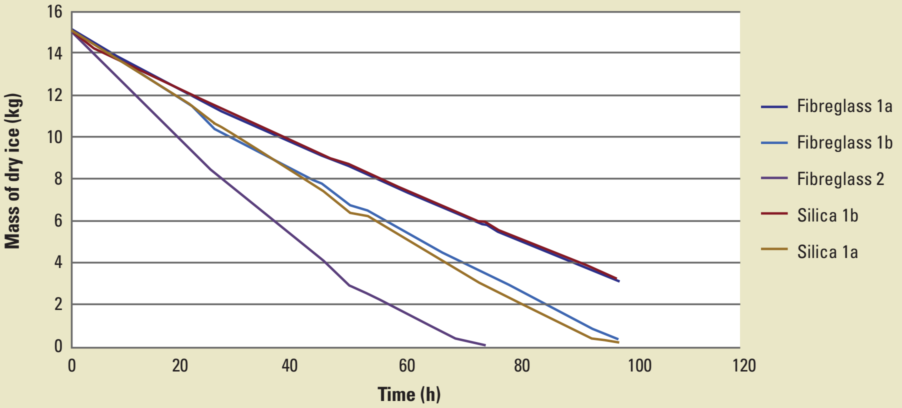


Table 1: Mass of sublimated dry ice, after 70 hours 10 minutes

VIP box	Sublimated dry ice (kg)
Fibreglass 1a	9.2
Fibreglass 1b	11.5
Fibreglass 2	14.9
Silica 1a	12.1
Silica 1b	9.1

and 'pyrogenated' silica, which has the advantage of containing several nanoscopic pores, increasing the VIP's vacuum durability.

The film is generally a polymer-metalised-polymer multi-layer material which guarantees the VIP's durability. It must prevent penetration of air components in the material – specifically nitrogen and oxygen – and, most importantly, water vapour. The sealed edges of the barrier film create a flap which extends out from the edges of the panel and can be folded and taped against the panel in use. The selection of the barrier film depends on the core material, cost, temperature and lifetime required by the application in question.

The selection of the core material for VIPs depends on the requirements of the application, technical and environmental constraints, the industrial process, and obviously the cost. Two core materials are currently used in the manufacturing of VIPs, silica or fibreglass, and both materials have advantages and disadvantages – see *Pros and cons of silica and fibreglass VIPs* (page 76).

Design of Insulated Boxes

Cooling boxes are designed on the basis of a heat balance, using a coefficient of heat transfer (*K*). Heat balance takes into consideration product requirements, as well as logistical constraints. The main parameters used to determine the size of the container (including its dimensions, insulating thickness and the necessary cold load) are:

- Product requirements, such as temperature range, thermal inertia, dimensions and quantity
- Logistical constraints, such as the required duration and an ambient temperature profile

For VIP boxes tested with dry ice, insulated boxes are made with vacuum insulation panels 20mm thick and with various barrier films. Vacuum insulation panels are only taped, without polyutherane (PU) or cardboard protection. These boxes have the same dimensions and are tested with the same mass of dry ice. For VIP boxes tested with gel packs, the boxes are made by combining VIPs and PU panels. The barrier film which maintains vacuum is fragile and must be protected by another material. PU panels are used to protect the external face of the VIP, and cardboard to protect the internal face. The set is placed in a simple outer wall of corrugated cardboard. In the following case study, various VIPs are compared in various test conditions.

Case Study: Interpreting Results

Comparison of VIPs by Monitoring of Dry Ice Sublimation

Imagine a scenario where three insulated boxes are made with VIPs using fibreglass and two with VIPs using silica. The boxes have the same dimensions. Fibreglass boxes 1a and 1b use different aluminium films. Metalised film is used in silica box 1 and white polymer multi-layer film in silica box 2 VIPs.

- The idea is to fill each box with 15kg of dry ice and monitor its weight resulting from the sublimation of dry ice at 45°C. The sublimated mass of dry ice for each box is shown in Figure 3
- The panels of the bottom of fibreglass box 1b and silica box 1a were damaged by the dry ice. It can be concluded that the quality of the barrier film is important for withstanding very low temperatures
- Fibreglass box 2 is not damaged, but it provides the worst result. The level of vacuum must be lower for fibreglass VIPs to achieve better performance
- This test gives information on the quality of VIPs. It allows the selection of the best combination of core material and barrier film, to manufacture a range of VIP insulated boxes

Comparison Test of VIPs and PU Boxes at 40°C

Another scenario sees insulated boxes made with 20mm thick VIPs and others with 10mm VIPs. Each VIP box is combined with PU panels 20mm thick. These VIP boxes, as well as a conventional PU box 40mm thick, are tested at 40°C, with the same quantity of gel packs. The results of this stress test are used to determine the performance ratio of VIP boxes and the PU box. Performance

Figure 4: VIP box 26L (VIP 20mm + PU 20mm), fibreglass 1a: 101 hours at 40°C

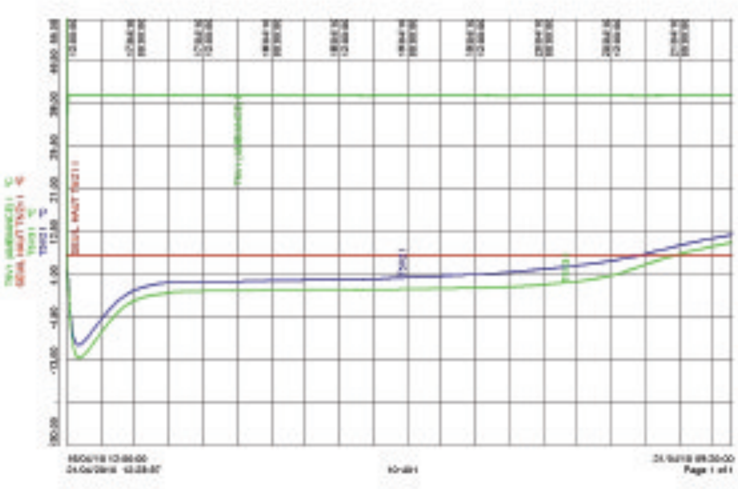
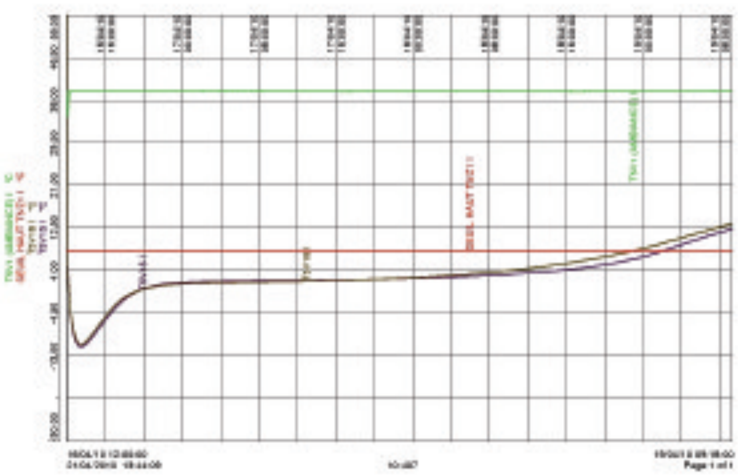


Figure 5: VIP box 26L (VIP 20mm + PU 20mm), fibreglass 2: 59 hours at 40°C



corresponds to the ability of the box to maintain products below 8°C. The ratio of thermal performances is equal to the ratio of thermal transfer coefficients because the other parameters are the same (exchange surface, ambient temperature and internal temperature).

Comparative tests at 40°C showed that the core material alone does not determine the performance of a VIP. Other conclusions include:

- Fibreglass 1 VIPs give a good result but fibreglass 2 VIPs return bad results. The required vacuum level was probably not reached in the second, or the quality of the barrier film was not sufficient (Figures 4 and 5)
- Silica VIPs give good and reproducible results
- In theory, the thermal conductivity of a VIP is below 0.003 W/mK, and the conductivity of PU panels is 0.023 W/mK. The ratio of thermal conductivities is above 7
- The theoretical coefficient of thermal transfer of the double wall box, made with 20mm VIP and 20mm PU, is 0.17W/m²K. The thermal transfer coefficient of the conventional 40mm thick PU box is 0.58W/m²K.

Pros and cons of silica and fibreglass VIPs

Availability
Silica is more readily available in Europe since the fibreglass used in the VIP is manufactured in China.

Performance
Silica and fibreglass VIPs have equivalent performance levels, but fibreglass requires getters (deposits of reactive material placed inside the vacuum), lower vacuum levels and an aluminium film, which results in a shorter lifetime.

Weight
Fibreglass is heavier than silica, with a density of between 180 and 220kg/m^3, versus 150 to 180kg/m^3 for silica. Weight leads to higher transport costs.

Vacuum Level
The vacuum level of VIPs is about 0.1 to 1mbar for silica core fillers, and 0.01 to 0.001mbar for fibreglass. Fibreglass requires getters and a certain particular quality level of aluminium barrier film to maintain a vacuum. Silica has the advantage of not requiring very low levels of vacuum and maintains VIP performance for longer.

Thermal Conductivity
Both materials can achieve a thermal conductivity of between 0.003 and 0.004W/m K, but fibreglass requires lower vacuum level. Thermal conductivity does not correspond to the thermal coefficient of heat transfer of the insulated container because of various thermal bridges and the 'edge effect' of the barrier film.

Price
It is difficult to compare the prices of both core materials because they do not have the same shape. However, as with any new product, the cost of VIPs depends on the quantity manufactured, and as the sales volumes increase, the cost will significantly decrease.

Manufacturing Process
Fibreglass VIPs require a vacuum packing system equipped with high vacuum pump, which also requires getters. The handling of fibreglass is undoubtedly simpler than silica.

Life Span
Silica allows for longer lifespan. A silica VIP with a metalised barrier film can offer a lifespan of up to 50 years, whereas a fibreglass VIP with an aluminium barrier film and extra getter materials provides a lifespan of up to 10 years. Performance stability depends on the vacuum level of the core material, the quality of the barrier film, and the panel environment (temperature, humidity and so on).

Environmental Impact
Fibreglass and silica are exempt from any carcinogenic classification, but the getters used within fibreglass VIPs have a negative impact on human health and the environment. For both materials, it is possible to reuse the core material to make a new panel. Recycling is also possible, but requires special processes.

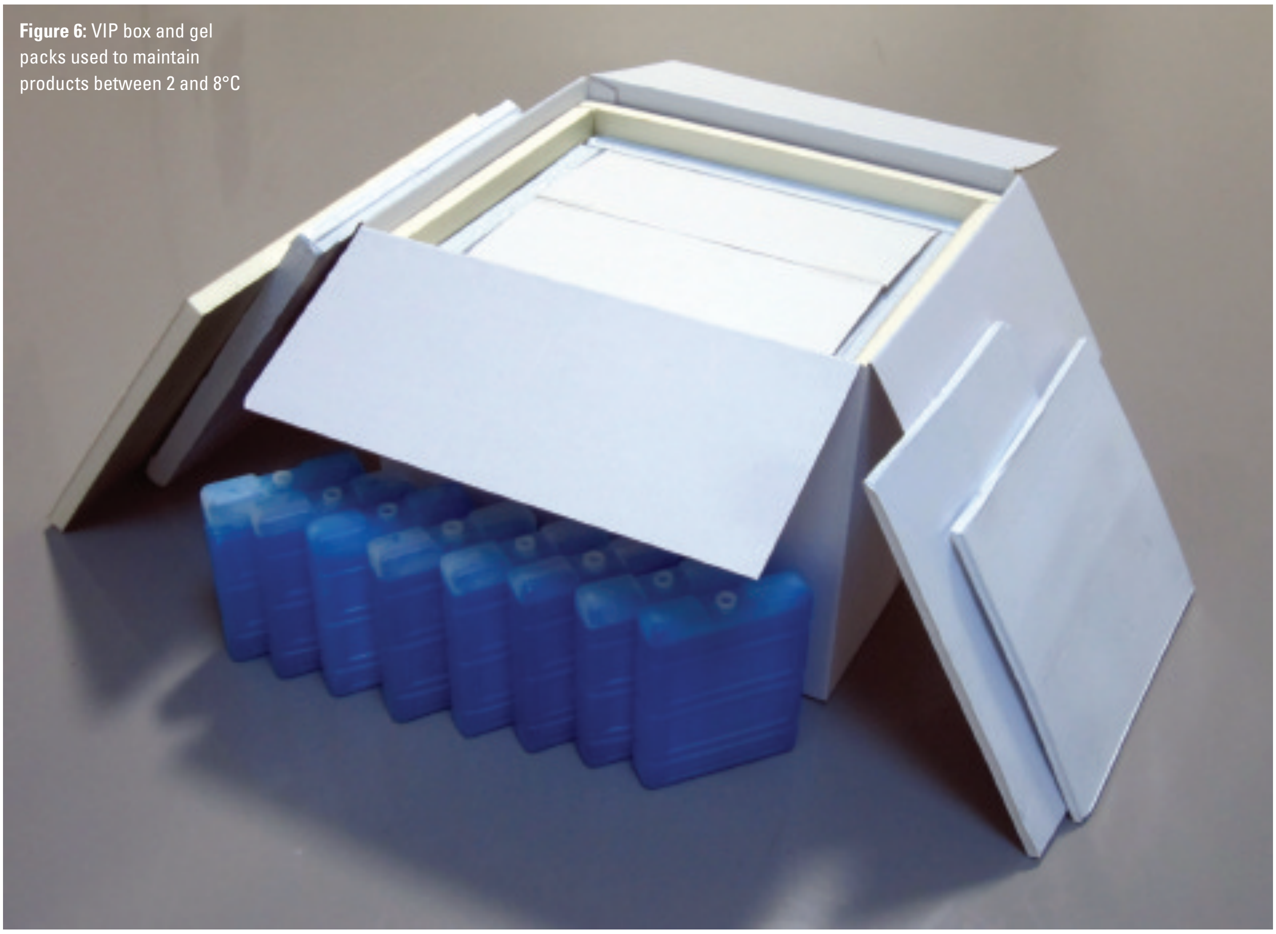


Figure 6: VIP box and gel packs used to maintain products between 2 and 8°C

The theoretical ratio of the thermal transfer coefficients is 3.4

- The ratio of the real thermal performances (based on the autonomy) of VIP and conventional PU boxes is 1.9 for the worst result and 3.3 for the best
- If the thickness of the VIP as reduced to 10mm, the real ratio of performances is 1.6 for the worst result, and 2.5 for the best result. The exchange surface of the VIP box is reduced in this case

Performance Tests for Varying Temperature Profile

Here, silica 1b VIPs are selected to develop a range of boxes capable maintaining products between 2 and 8°C for a duration of seven to 10 days. Insulated boxes made with VIPs combined with PU panels are tested with gel packs under the standard temperature profile ST-96-a of the French standard NF S99-700 (see Figure 6). The description of the tested boxes and the test results obtained (durations) are given in Table 2. These tests have shown that:

- Two 26-litre VIP boxes (the same internal dimensions) are tested with the same load of products and gel packs under the same temperature profile. The first, made with 20mm VIPs combined with 20mm PU, maintained products between 2 and 8°C for 168 hours (seven days). The second,

Table 2: Description of the tested containers and the performances obtained

VIP	26/20/20	26/20/25	62/20/25	265/20/25
Internal volume (litre)	26	26	62	265
Internal dimensions (mm)	365 x 295 x 240	365 x 295 x 240	450 x 380 x 365	840 x 540 x 585
VIP thickness (mm)	20	25	25	25
PU thickness (mm)	20	20	20	20
Temperature range	2 to 8 °C	2 to 8 °C	2 to 8 °C	2 to 8 °C
Ambient temperature profile	ST-96-a	ST-96-a	ST-96-a	ST-96-a
Minimum duration (hours)	168	240	225	198

Figure 7: VIP box 26L (VIP 25mm + PU 20mm): 240 hours between 2 and 8°C, under varying profile

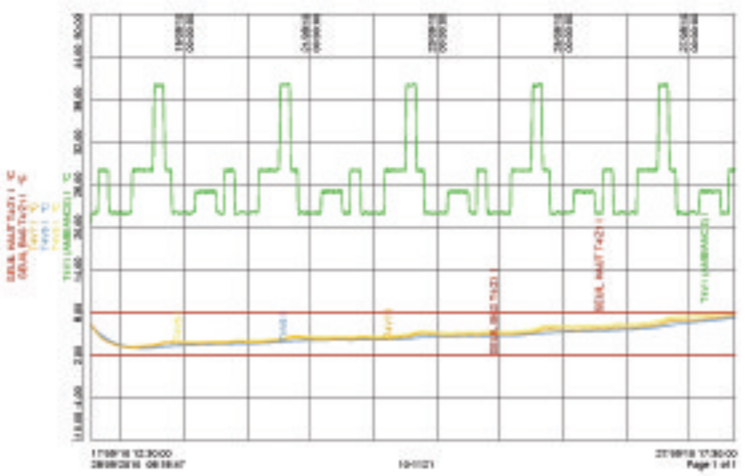
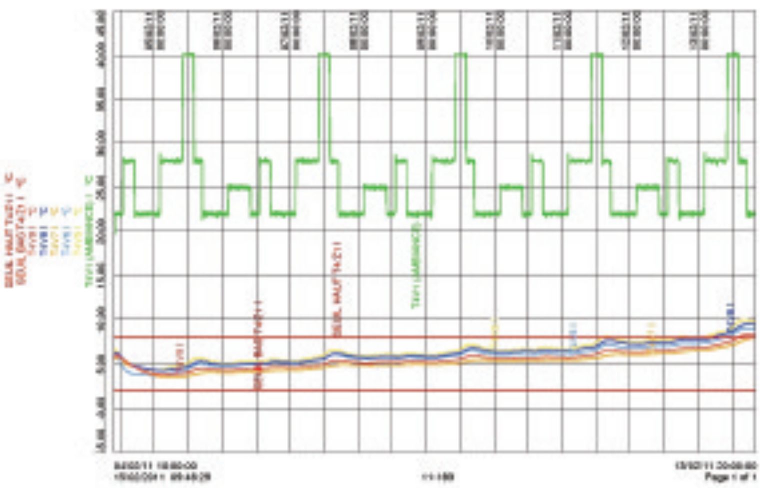


Figure 8: VIP box 265L (VIP 25mm + PU 20mm): 198 hours between 2 and 8°C, under varying profile



made with 25 mm VIPs combined with 20mm PU panels, maintained products between 2 and 8°C during 240 hours (10 days)

- The VIP allows good results for large containers refrigerated by gel packs; 62L and 265L containers, made with a combination of 25mm- and 20mm-thick VIPs, maintained products between 2 and 8°C for 225 hours and 198 hours respectively under the standard profile ST-96-a. The use of VIP increased performance by 100 per cent and reduced thickness by 35 per cent

Figures 7 and 8 show the test results of boxes made with 25mm-thick VIPs combined with 20mm PU panels.

The core material, the quality of the barrier film and the vacuum level are the main parameters to achieving and maintaining low thermal conductivity of the VIP, but they are not sufficient in themselves. For example, efficient VIP boxes can be obtained with fibreglass and silica. The barrier film must be selected and validated carefully, according to the core material and to the required vacuum level. Fibreglass requires getters, specific aluminium film and a lower vacuum level. The vacuum packing machine must achieve 10^{-6} bar and the barrier film must withstand this vacuum level for the required life span. The best values of thermal conductivity are not sufficient the best performance. Badly manufactured containers and thermal bridges caused by the edge effect strongly reduce their performance. VIPs can increase the thermal performance of insulated containers (up to 240 hours) and/or reduce the thickness. The ratio of VIP boxes to conventional PU boxes varies between two and three.

Conclusion

VIPs are a promising technology for insulated packaging. VIP boxes allow controlled temperature shipping to last seven to 10 days. Their performance is around three times better than polyurethane boxes and consequently 4.5 times better than polystyrene.

The success of VIPs requires improvements in the manufacturing process in order to increase efficiency and reduce cost. The integration of a resistant protective layer in the manufacturing of VIPs can be a way to improve quality and make their use easier. The re-use of the insulated boxes will also make VIPs profitable and justify their high price.

About the author

Abbes Kacimi is a certified engineer in refrigeration and air-conditioning and a teacher of mathematics and thermodynamics. Abbes graduated from Constantine University in 1988. In 2001/2002, he attended training at the French Institute of Industrial Refrigeration in Paris before joining Sofrigam. After a role as the head of Engineering, responsible for the development and qualification of cooling containers for pharmaceutical products, Abbes is now Cold Chain Expert and Project Manager. He is a member of several cold chain commissions (including the IIR Working Party of Commission D2), and co-author of 'Practical Guidelines, Cold Chain for Medicines'. He has contributed to several projects, and published a variety of articles on cold chain issues. He recently presented a thesis on project management at Ecole Centrale, Paris.

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