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# Development of Transparent and Opaque Vacuum Insulation Panels for Energy Efficient Buildings

Esra Kucukpinar[a,]*, Oliver Miesbauer[a], Yoash Carmi[b], Marc Fricke[c], Leif Gullberg[d], Can Erkey[e], Roland Caps[f], Malcolm Rochefort[g], Araceli Galvez Moreno[h], Clara Delgado[i], Michael Koehl[j], Paul Holdsworth[k],Klaus Noller[a]

[a]*Fraunhofer Institute for Process Engineering and Packaging, Freising, 85354, Germany*
[b]*Hanita Coatings, Kibbutz Hanita, Israel*
[c]*BASF Polyurethanes GmbH, Lemfoerde, 49448, Germany*
[d]*Airglass AB, Staffanstorp, SE-24522, Sweden*
[e]*Koç University, Chemical and Biological Engineering Department, Istanbul, 34450, Turkey*
[f]*va-Q-tec AG, Würzburg, 97080, Germany*
[g]*Kingspan Insulation Limited, Herefordshire, HR6 9LA, UK*
[h]*Acciona Infraestructuras S.A., Madrid, 28108, Spain*
[i]*Gaiker Centro Tecnológico, Bizkaia, 48170, Spain*
[j]*Fraunhofer Institute for Solar Energy Systems, Freiburg, 79110, Germany*
[k]*Pera Innovation Limited, Leicestershire LE13 0PB, United Kingdom*

**Abstract**

One reason for heat losses in buildings is inadequate insulation. Vacuum Insulation Panels (VIPs) is emerging as a promising solution, being more energy efficient than conventional insulation materials, thinner and lighter. A VIP is made by placing a core insulation material inside a gas-barrier envelope and evacuating the air from inside the panel. The limitations to wide-scale VIP commercialization lie in lack of low-cost and high-volume processes to turn them into products suitable for use in buildings, and their short in-service lifetimes. These drawbacks were researched in a European funded project "NanoInsulate", and this paper gives an overview of results.


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*Keywords:* Transparent Vacuum Insulation Panels, Opaque VIPs, energy consumption reduction, aerogel, nanofoam, high barrier envelopes

* Corresponding author. Tel.: +49 8161 491 507; fax: +49 8161 491 555.
*E-mail address:* esra.kucukpinar@ivv.fraunhofer.de


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## 1. Introduction

Nearly 40% of total EU energy consumption is due to heat losses through buildings and windows, which is a significant contributor to greenhouse gas emissions. The successful entry of new nanotechnology-based insulation products to the transportation and refrigeration fields indicates that innovative insulation products should be explored in the building and construction sector, which accounts for over 40% of all energy usage. Among these innovative products, the development and use of VIPs is particularly advantageous as they are not only more energy efficient than conventional commercial counterparts but are also thinner and lighter and, thus, more resource-efficient than standard insulation systems. Furthermore, they are suitable not only for use in new buildings, but also for retrofitting older buildings, where installation space and simple component design are a premium. Robustness (both physical and in long term performance) and lower cost are key to success in the construction field. The NanoInsulate - Development of Nanotechnology-based High-performance Opaque & Transparent Insulation Systems for Energy-efficient Buildings" project has developed durable, robust, cost-effective opaque and transparent VIPs incorporating new nanotechnology-based core materials (such as nanofoams and aerogel composites) and high-barrier films, resulting in panels that are more energy efficient than current solutions.

## 2. Materials

A VIP is manufactured by packing core insulation materials such as fiber glass, silica, perlite, aerogel, open-celled extruded polystyrene, or open celled polyurethane in a high gas/water vapor barrier envelope. These core materials, upon evacuation in a vacuum-tight envelope (e.g. barrier films) lead to very low thermal conductivity values. The optimization of material performance (e.g. inhibition of thermal aging, inner pressure tolerance etc.) is critical in maintaining the thermal and mechanical performance in service. Issues with handling the products and increase of inner pressures with time and cost are also factors that need to be considered and evaluated. The novel VIP core materials developed within NanoInsulate project are organic nano-porous foam and nano-monolithic composites of inorganic silica aerogels. The properties of these new VIP core materials and the high barrier envelopes developed are summarized in this section.

### *2.1. Novel VIP core materials: Organic nano-porous foam*

The organic nano-porous material development was performed by the project partner BASF SE, Germany. The developed materials have low thermal conductivities below 5 mW/(m·K) under vacuum at a density of below 180 g/l. Producing this type of material in a cost-efficient manufacturing process could be a real breakthrough for commercialization and would allow wide-scale commercialization of VIPs feasible for the building and construction sector. It has been shown by BASF that careful selection of a number of synthetic pathways leads to ideal material performance with the opportunity of mass production. Based on that, the development of an industrial-scale product and process seems feasible.

Sol-gel chemistry has been shown to potentially give access to nano-porous materials with sufficient mechanical properties and a sufficiently low thermal conductivity. Suitable catalyst combinations were identified that achieved gelation speeds according to the technical requirements, without impact on the material property profile [1]. Screenings for suitable chemical building blocks, resin concentrations and monomer ratios were carried out to identify a parameter range leading to mechanically stable nano-porous materials after solvent removal and drying. These recipes led to materials which were successfully converted to laboratory-scale VIPs. Furthermore these materials passed the B2 fire-rating test. The lowest thermal conductivity values reached with large-scale VIPs are shown in Table 1. These VIPs were produced at the project partners Kingspan Insulation Limited, UK and va-Q-tec A.G., Germany with BASF nano-porous foam and the thermal conductivities were measured.

Due to the shrinkage and deformation problems after the evacuation, further optimization of the material mechanical properties was required. This resulted in flake-like material morphology with a similar density and a higher compressive strength (Figure 1, Table 2). The thermal conductivity has increased slightly after the material optimization. This material has been selected as one of the VIP core materials for the production of VIPs to be installed at the mock-ups in Spain and Poland at the project partner ACCIONA Infraestructuras SA facilities.

Table 1. Thermal conductivity of the most promising larger scale VIPs

| Sample size (cm) | Thermal conductivity [mW/(m·K)] | | Density (g/l) |
|---|---|---|---|
| | va-Q-Tec | Kingspan | |
| 40 x 45 x 1.5 | 3.9 | 3.6 | ~ 130 |

Table 2. Thermal conductivity of nano-porous foam based VIPs after the optimization of core mechanical properties

| Sample size (cm) | Thermal conductivity [mW/(m·K)] | | Density (g/l) | Compression strength ($N/mm^2$) |
|---|---|---|---|---|
| | va-Q-Tec | BASF | | |
| 40 x 45 x 3.0 | 5.0 | 4.8 | ~ 130 | 0.15 |

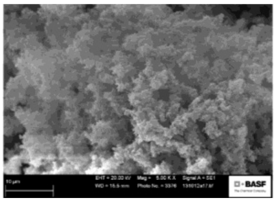

Fig.1. SEM micrograph of the optimized material showing flake-like morphology with higher compressive strength

### *2.2. Novel VIP core materials: Nano-monolithic composites of inorganic silica aerogels*

Silica aerogels are sol-gel-derived nanostructured materials that have high surface areas, high pore volumes and low densities. They are produced by the hydrolysis and condensation reactions of a silicon alkoxide precursor, such as tetraethyl orthosilicate in a solvent such as ethanol. Following gelation, alcogels are aged to strengthen the silica network. Solvent exchange is carried out to remove the water inside the pores. Supercritical drying of the alcogels leads to aerogels. The properties of silica aerogels can be tailored by manipulation of the reaction conditions and reactant concentrations during the synthesis, and they can be produced as monoliths in any shape [2]. Table 3 shows the properties of the monolithic silica aerogel panels developed by the project partner Airglass AB, Sweden in the project. Monolithic silica aerogel is the only transparent insulation material with such a low thermal conductivity, which makes it particularly attractive in development of transparent insulation systems.

Table 3. Properties of native aerogel panels produced by the project partner Airglass AB, Sweden

| Sample size (cm) | Thermal conductivity [mW/(m·K)] | Density (g/l) | Transparency |
|---|---|---|---|
| 55 x 55 (thickness: 1.0 to 3.0) | 15 (at atmospheric pressure) | 200 | High |

Fig.2. 3-glass aerogel transparent window (890 x 580 x 110 mm): Frame-Thermo pane

Airglass together with the project partner Koç University, Turkey collaborated to make the processed wet-gel a mechanically stronger aerogel by incorporating a polymer. The polymer molecules act as “cross-linker” between the silica dioxide grains, giving an increase to material flexibility. The most promising composites are found to be PDMS(OH)-silica aerogel composites that were produced by reactive supercritical deposition technique. The transparency of PDMS (OH)-silica aerogel composites can be retained up to 30 % in weight of the polymer amount in the composites. Although the transparency of the composite was a bit less than that of the native aerogel, its compressive strength is measured as 3 times higher than that of the native aerogel [2]. The project partner va-Q-tec produced a transparent VIP using the transparent high barrier encapsulation material developed and the aerogel composite (Figure 2). With a vacuum down to <1 mbar, the thermal conductivity is measured as 9 mW/(m· K). The U-value for a transparent VIP, at a thickness of 20 mm, is measured as 0.45 W/($m^2$· K).The encapsulation of these aerogel composites without any cracks is still a challenge and needs further optimizations [3].

*2.3. Novel VIP Envelopes*

VIP envelopes are produced using high barrier multi-layered films. Since the thermal conductivity of a VIP increases with increasing panel gas pressure for all core materials suitable for vacuum insulation, the low gas pressure inside the VIP envelope has to be maintained for a very long period of time for the system to function as an efficient thermal insulator. Therefore, the barrier materials that are used in VIP envelopes need to have very low vapor and gas permeation rates to prevent the pressure from rising inside the envelope.

Novel cost efficient high barrier opaque and transparent VIP envelopes were developed by the project partners Fraunhofer Institute for Process Engineering and Packaging (Fraunhofer IVV), Germany and Hanita Coatings RCA Ltd., Israel. This has been accomplished through the combination of inorganic barrier layers with hybrid polymeric (organically modified ceramics, ORMOCER®) barrier lacquers, which is an innovative approach in the field of VIP encapsulation material development. The VIP envelopes developed consist of alternating inorganic barrier layers (thickness of 60-80 nm) and ORMOCER® barrier lacquers (thickness of 3 µm).

ORMOCER®s are synthesized by a sol-gel process [4] at the Fraunhofer Institute for Silicate Research (Fraunhofer ISC), Germany. The application of the ORMOCER® barrier lacquer was performed from the liquid phase using reverse gravure coating unit at Fraunhofer IVV. The ORMOCER® barrier lacquer as an intermediate layer in between two inorganic barrier layers creates a so-called "tortuous-path effect", forcing the gas molecules to use longer permeation paths. In addition to that, the ORMOCER® material closes the defects or pinholes existing on the first inorganic barrier layer and planarizes the layer surface for the application of the second inorganic barrier layer. This concept has been successfully implemented for the first time for the production of VIP envelopes in the project.

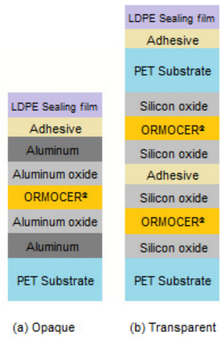


Fig.3. Structures of novel VIP envelopes

The difference in the production process of opaque and transparent VIP envelopes was that the opaque inorganic barrier layers were produced by deposition of Aluminum using thermal evaporation process at the project partner Hanita and the transparent inorganic barrier layers were produced by deposition of Silicon oxide ($SiO_x$) using electron beam evaporation at Amcor, Switzerland. The opaque and transparent VIP envelope structures with the most promising barrier performances are shown in Figure 3. The inorganic and ORMOCER® layers are deposited on top of a polymeric substrate, which is polyethylene terephthalate (PET). The final step is the lamination with a sealing film. In this project, low density poly ethylene was used as a sealing film. During the opaque VIP envelope production, an intermediate $AlO_x$ layer deposition was required as an adhesion promoter for the enhancement of the adhesion between the metallized Aluminum barrier layer and the ORMOCER®. The lowest measured oxygen permeability and water vapor transmission rate values of these materials are less than $5 \times 10^{-3}$ $cm^3/(m^2 \cdot d \cdot bar)$ (at 23ºC and 50% relative humidity) and less than $1 \times 10^{-3}$ $g/(m^2 \cdot d)$ (at 23ºC and 85% $\rightarrow$ 0% RH), respectively. The opaque barrier structure shown in Figure 3 has equal or better barrier to air permeation than the standard laminates existing in the market. This is an important achievement of NanoInsulate Project, considering the less number of metallized Aluminum layers (2 metallized Al layers) used [5].

*2.4. VIPs with NanoInsulate cores and envelopes for real-scale demonstration*

The applicability of well-defined VIP core materials such as fumed silica and also the novel developed organic nano-porous foam has been investigated at the Spanish and Poland mock-ups. The project partner Acciona has built two rooms (so-called "mock-ups) at both of these locations in order to test the developed materials in the real-scale in two-well differentiated climatic zones. One of these mock-ups was refurbished with conventional insulation material of polyurethane foam panels at a thickness of 4 cm with a thermal conductivity, $\lambda$ of 30 mW/(m·K) and the other one with NanoInsulate VIPs to compare mainly thermal and mechanical behavior.

More than 100 VIPs in total based on 100% recycled silica board core and organic nano-porous foam core were produced for the mock-ups by the project partner Va-Q-Tec using the various types of novel VIP-envelopes developed in the project. The size of the silica and nano-porous foam based VIPs was 600 mm x 400 mm x 20 mm and 600 mm x 400 mm x 25 mm, respectively. The mean thermal conductivity of the silica board VIPs was 3.8 ± 0.2 mW/(m·K) and that of nano-porous foam VIPs was between 4.5 and 5.0 mW/(m·K) at a mean temperature of 43 °C. There was no deformation of the VIPs after production. Maximum allowed gas pressure in silica and nano-porous foam VIPs of the project partner Va-Q-Tec is 5 mbar and 0.1 mbar, respectively. The VIP gas pressure control was performed by the Va-Q-Check system, and the measured values were all well below those limits before installation.

## 3. Results and Discussion

*3.1. Performance of NanoInsulate VIPs in comparison to conventional insulation*

The temperatures reached both inside the mock-ups and in the walls and also the heat-flow through the panels were monitored for more than one year. Figure 4(a) and (b) shows the reference mock-up with conventional insulation and NanoInsulate mock-up with NanoInsulate VIPs, repectively. Heat flow can be measured, and subsequently expressed, as U-value (or thermal transmittance co-efficient) being the heat flow through one square meter of a structure when the temperature on either side of the structure differs by one degree Celsius. Therefore, U-value depends on the thermal conductivities of the building materials and their respective thicknesses.

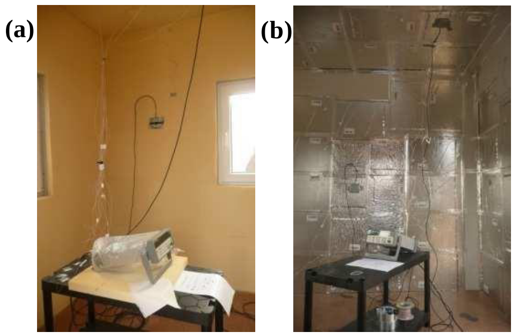

Fig.4. Madrid mock-ups inside: (a) Reference mock-up, (b) NanoInsulate mock-up

To establish the U-values of the NanoInsulate and reference mock-ups, a proper monitoring plan was implemented. Both mock-ups have more than 15 sensors recording data every 5-10 min and data evaluation was made to check failures in the panels. The internal temperature profiles, wall temperature profiles and the heat flow through the insulation were extracted from the recorded data. The U-values were calculated following the standard ASTM C1155 [6] using long periods of time to extract different U-values over the monitoring period. These calculations were made for two walls of the mock-ups: South side and West side. The U-value analysis through the months was used to evaluate the performance of the VIPs in different climatic conditions and also to monitor whether there is a loss in insulation capacity with time. The calculated "apparent" average thermal conductivity of the panels based on the measurements at the end of the monitoring period is shown in Table 4. NanoInsulate panels have up to 7 times higher insulation capacity than the reference case. These results are similar to those obtained at the laboratory before the installation of the panels in the mock-ups.

Active tests were carried out using climatic machines with the objective to assess the energy consumption in every mock up through keeping an indoor set temperature. The energy saving due to the use of NanoInsulate panels was calculated and found to be around 25% KWh/year and this reduction means 20% of decrease in $CO_2$ emission (SAP modelling). During the installation process some knowledge was gained about the handling of the panels. The installation of the nano-porous foam based VIPs seemed to be easier due to the improvements in the mechanical properties. Further work is still necessary for the enhancement of VIP fragility and mechanical stability.

Table 4. Comparison of "apparent" average thermal conductivity of panels in reference and NanoInsulate mock-ups

| Thermal Conductivity (mW/m· K) | Spain | | Poland | |
|---|---|---|---|---|
| | Reference mock-up | NanoInsulate mock-up | Reference mock-up | NanoInsulate mock-up |
| South side | 29 | 5.3 | 26 | 3.4 |
| West side | 23 | 5.0 | 33 | 4.9 |

### *3.2. Lifecycle assessment, safety of the novel insulation systems and service-life costing analysis*

The environmental evaluation of the advanced VIPs developed in the project has been carried out using Life Cycle Assessment (LCA) methodology [7]. The LCA includes comparisons of their environmental performance, through production, construction, use and end-of-life phases, with those of currently-available insulation alternatives, such as polyurethane rigid foam. The LCA results conclude that NanoInsulate VIPs surpass the overall performance of polyurethane foam boards, at an insulation thickness of 25 mm.

## 4. Conclusions

- Polymeric nano-porous foam has been developed as an alternative core material. It has been shown that it is feasible to design a production line for cost effective production of VIPs using new nanofoam cores.
- Envelopes with improved gas and water vapor barrier properties have been developed. This can enable longer in use lifetimes in construction, in excess of 50 years.
- NanoInsulate has succeeded in demonstrating that VIPs are more effective than conventional polyurethane insulation by the experiments conducted in Spanish and Polish demo-buildings.
- Transparent VIPs were investigated for use where high thermal insulation efficiency combined with high light transmission is required, using a modified aerogel core. Although the polymer modification of aerogels proved possible, and transparent gas-barrier envelopes were developed for the first time for transparent VIPs, cost effectiveness and fragility of these systems still requires improvement.
- Life Cycle Assessment (LCA) results show that NanoInsulate VIPs at an insulation thickness of 25 mm perform better than polyurethane foam boards.

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## References

[1] Fricke M, Elbing M. WO2012059388, PROCESS FOR PRODUCING AEROGELS OR XEROGELS, BASF SE [DE/DE]; 67056 Ludwigshafen (DE)
[2] Z. Ülker, D. Sanli, C. Erkey. Applications of Aerogels and Their Composites in Energy-Related Technologies. In Anikeev V, Fan M, editors. Supercritical fluid technology for energy and environmental applications. Publisher: Elsevier; 2014. p. 157-180
[3] R. Caps. New Core Materials for Vacuum Insulation Panels, High Performance Thermal Insulation Workshop, ZAE Bayern, Germany, 2013
[4] S. Amberg-Schwab, M. Hoffmann, H. Bader, M. Gessler. Inorganic-organic polymers with barrier properties for water vapor, oxygen and flavors, Journal of Sol-Gel Science and Technology 1/2 (8) (1998) 141–146.
[5] O. Miesbauer, E. Kucukpinar, S. Kiese, Y. Carmi, K. Noller, H-C. Langowski, Energy and Buildings 85 (2014) 597–603
[6] ASTM C1155 - 95(2013) Standard Practice for Determining Thermal Resistance of Building Envelope Components from the In-Situ Data
[7] C. Delgado, NANOINSULATE, El Programa Marco HORIZON 2020 desde la perspectiva del sector de la construcción, Spain, 2014