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18th - 19th September 2007

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BAVARIAN CENTER FOR APPLIED ENERGY RESEARCH

8th International Vacuum Insulation Symposium

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A CD of the proceedings (with the authors' contributions either in paper or presentation form, as delivered by the author) is attached at the back of the book.

Oral Presentations

Vacuum Insulation - Challenges and Opportunities for Becoming a Standard Insulation Technology

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It took about 100 years of vacuum insulation technology to develop marketable vacuum insulation panels (VIPs) for the building industry. Prof. J. Fricke presented the technological history from the first vacuum flask invented by the British scientist Dewar to the present VIP technology at the 7th International Vacuum Insulation Symposium [Fricke 2005].

The reason for the slow development was mostly the missing drive for better building insulation and less a lack of technological advances. Only since the availability of low-e windows with a thermal conductivity as low as 18 mW/(m·K) (4/10/4, krypton filled, U=1 W/(m^2·K)) it became obvious that traditional insulation materials such as polystyrene or mineral wool with a thermal conductivity >30 mW/(m·K) are no longer efficient enough for many applications.

Energy efficient buildings require a thermal insulation of 20 – 30 cm thickness, thus consuming valuable space. Vacuum insulation constitutes the ideal alternative when space is limited. However, traditional insulation is normally easy to apply and can have a very long service life. The performance of vacuum insulation is often much better, but the risks related to damage are considerably higher. Strong efforts have been made during the past years to limit and to control these risks.

Vacuum insulation panels using inorganic, nano-porous core materials such as fumed silica and a gastight metallised PE/PET film for maintaining the vacuum are presently state-of-the-art. This combination has proven to be best suitable for vacuum insulation technology used in the building industry.

This article tries to identify risks and opportunities of this insulation technology related to building applications and to give recommendations for additional efforts needed to turn vacuum insulation into a standard technology for the building construction market.

System evaluation

Thermal insulation

The conductivity of vacuum insulation panels (VIPs) can be as low as 3.5 mW/(m·K), i.e. about 10 times lower than the conductivity of tradition, air based insulation materials. However, due to unavoidable thermal bridges and slow gas permeation trough the envelope the real insulation is reduced to about 8 mW/(m·K) over its service life. In case of a loss of the vacuum due to damage, the thermal conductivity of the core material will be about 19 mW/(m·K), i.e. about 40 % lower than traditional insulation materials.

For achieving a U-value of 0.15 – 0.2 W/(m^2·K) a vacuum insulation panel of 36 - 48 mm thickness is required in combination with a 15 cm brick wall. 10 - 40 mm thick VIP's – covering most applications - are presently available on the market.

VIP's have to be pre-confectioned. This makes planning, handling and installation of this type of insulation much more demanding.

Recommendations for a better promotion and implementation of VIPs as an optional insulation technology are:

- Standard sized insulation panels should be easily available on stock at building materials supplier for an efficient construction process.
- An adequate, non-evacuated insulation material should be available to complement unavoidable remaining small insulation areas (e.g. fibre reinforced aerogels or fumed silica panels) to avoid thermal bridges.
- An easily applicable in-situ measurement should allow to check the quality of the vacuum inside the panel on site. This would improve quality control and with it the confidence in this technology.

Service life

Service life is probably the most critical issue for many applications. There is a relatively high risk for mechanical damage to VIPs during production and the construction process. A complete loss of vacuum can normally be easily detected, but replacement can cause complications (availability of replacement, secondary damages caused by repair work, disruption of construction process, responsibility for damage). Minor damages may only have consequences later on. The damage will normally be relatively small compared to the cost for repair. As a result, single damaged VIPs will hardly be replaced. However, the impact of single damaged VIPs is limited as long as the core material stays dry. A damaged 40 mm VIP will result in a U-value of 0.38 W/(m^2·K) (instead of 0.18), causing an additional heat loss of 18 kWh/a or up to 6 W/m^2.

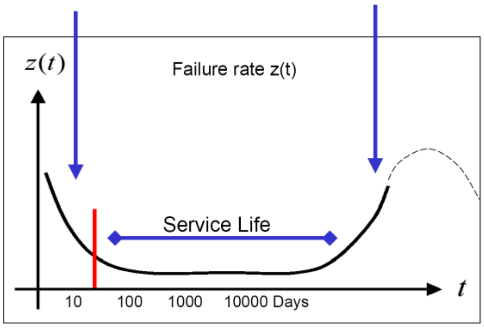

Figure 1: Failure rate of VIP's shown as a bathtub curve (Brunner 2005). Early life: failure due to imperfect production and handling; end of life: failure due to diffusion and physical/chemical aging (loss of vacuum)

The long term degradation of the vacuum due to gas permeation is probably the more critical problem because it may affect large areas of the building envelope. This problem can be handled if the VIPs are easily replaceable. It's more critical, if a replacement is not possible with reasonable measures. Based on laboratory tests we can expect that under good conditions the vacuum can be maintained over a period of 50 years. However no one knows whether the good conditions can be assumed over 50 years and whether no other unexpected degradation will occur. VIPs are sensitive to high temperatures and humidity. Precautions have to be taken that temperatures of 50 °C are not exceeded and high humidity exposure is prevented.

Also damages caused by incautious occupants or craftsmen may occur. Precautions to reduce this risk are possible but this type of risk is difficult to estimate.

Last but not least, there is a certain risk that in 20 – 30 years VIPs are no longer going to be produced. The replacement of VIP's – single panels or large areas – by traditional insulation materials could be difficult if the space necessary is not available.

Such risks also exist for traditional insulation materials but they are by far less critical. The only way to handle this problem is be aware of these risks and to take appropriate precautions. The recommendations are:

- Effective VIP protection measures and in-situ vacuum tests that allow a clearly defined manufacturer's quality guarantee from fabrication to installation on-site.
- Logistics that allow an easy and quick replacement of defective VIPs during construction.
- Semi-manufactured products such as sandwich panels that that reduce the risks for mechanical damages, temperature and humidity damages
- Recommendations for and accrediting of typical VIP applications (allowing a certain percentage of VIP's to fail during service life)

Economy

The relatively high material costs for VIPs are often considered as a major barrier for this technology. However this is only an issue if space is available and cheap. The cost for 20 cm mineral wool insulation (material and energy) will be - as shown in figure 2 - about 1.1 Euro/m^2 and annum whereas the costs for vacuum insulation with the same U-value (0.2 W/(m^2·K)) will cost 3.80 Euro/m^2 and annum.

However, in most situations space is very limited and expensive. Both types of insulation will cost about the same (4.7 €/(m^2·a)) if the land costs (see figure for cost assumptions) are also considered. If the loss of office or living space has to be considered, vacuum insulation costs even about 60 % less than mineral wool with the same insulation value (6.5 versus 15.4 €/(m^2·a) for mineral wool).

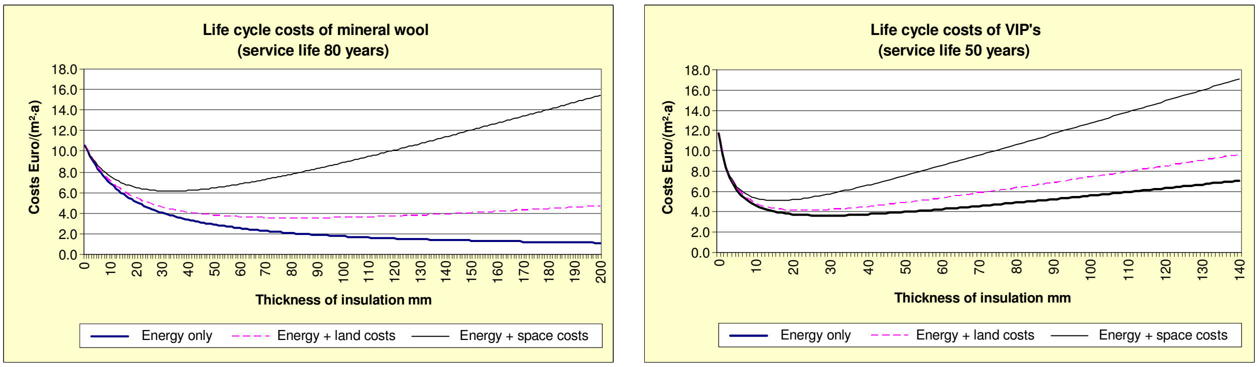

Figure 2: Life cycle cost comparison for mineral wool and vacuum insulation, for material and energy loss only, with land costs added and with office/living space costs added.
Assumptions: Insulation on 15 cm brick wall, $\lambda_{mineral\ wool}$ = 0.036, λ_{VIP} = 0.008, service life 80 / 50 years, degree days 3735, cost of mineral wool 100 €/m^3, cost of VIP 2000 €/m^3 + 60 €/m^2, energy costs 0.06 €/kWh, land cost 400 €/m^2 (maximum utilisation 0.4 m^2/m^{2}land), space renting costs 200 €/(m^2·a), floor height 2.8 m, capital costs 5 % p.a.

Recommendation:

- Advantages of VIPs as space saving solution have to be highlighted and documented.
- The market of VIPs should become more transparent. Standardized price indicators should be available.

Ecology

The environmental impact of VIPs has been analysed by [Schonhardt 2004]. The study shows that the energy demand and the environmental impact of VIPs is comparable to the impact of polystyrene. The energy demand and environmental impact of mineral wool per insulated area is about 50 % lower. However, the study also analysed the potential for improvement in the production process for VIP's. VIPs produced under optimized conditions for the production of fumed silica and opacifiers would bring the environmental impact of VIP's into the range of that of glass wool.

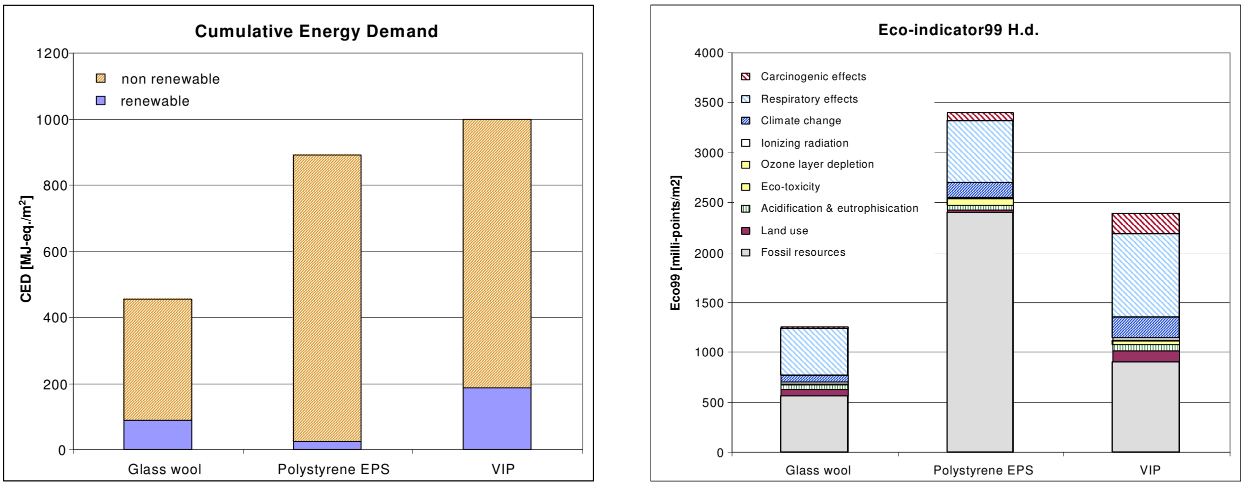

Figure 3: Comparison of the environmental impacts of glass wool, polystyrene and VIP insulation with an insulation value U of 0.15 W/(m^2·K) [Schonhardt 2004].

Look out

Economic trends will offer increasing opportunities for vacuum insulation technologies:

- The cost of energy is increasing and therefore a good insulation is becoming more important for everybody. Building regulations will require higher insulation standards.
- The prices for real estate are escalating. Optimised space use is becoming more and more important.
- Building renovations are becoming more important. The possibilities for traditional insulation and the space available are often limited.

VIPs are presently the only alternative to minimize space requirements for insulation. The biggest challenge is to convince the building industry and investors that the advantages are higher than the risks. Two measures seem to be most important besides good products and quality control:

- Training courses for architects and craftsmen to familiarize them with this new technology and to reduce prejudices.
- Standard sizes of VIPs, 20 and 40 mm thick, widely available (on stock) at standardized prices.

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Modelling of Heat Transfer in Nanoporous Silica - Influence of Moisture

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This work is interested in the modelling of the thermal behaviour of nanoporous silicas. These highly porous materials are suitable for the manufacturing of Vacuum Insulation Panels given that the exceptionally small size of their pores permits to reduce drastically the conductive heat transfer in the gas phase when a primary vacuum is applied. Nanoporous silicas have been widely studied experimentally. Researchers of the "Commissariat à l'Energie Atomique", of the Building Scientific and Technical Centre (CSTB) of Grenoble and the Bavarian Center for Energy (ZAE Bayern) have already underlined some typical characteristics of the thermal behavior of nanoporous silicas :

- Under ideal conditions, equivalent conductivities lower than 5 mW/m/K could be reached when a primary vacuum is applied
- Radiative heat transfer may be significant if the silica matrix is not opacified
- Due to their structure and hydrophilic characteristics, nanoporous silicas are prone to water adsorption which considerably degrades their insulating abilities,

All these conclusions were drawn from experimental investigations. Actually, very few studies have already dealt with the theoretical modelling of their thermal characteristics from their nanometric structure. That is the reason why we have developed a model of heat transfer based on a simplified representation of their structural morphology which permits us to analyse the contributions of each heat transfer modes (gaseous conduction, solid conduction, radiation) to the total heat transfer.

The coupled radiation-conduction heat transfer is treated using a simultaneous resolution of the Energy Equation and the Radiative Transfer Equation. The effective conductivity of the medium is computed by means of a Finite Element Method while its monochromatic radiative properties are calculated assuming that only silica particles are present and that they scatter radiation independently. The model can take into account the presence of condensed water at the surface of silica particles as well as the possible contact area between neighbouring particles. The results of the model permits us to investigate the evolution of the equivalent thermal conductivity of the nanoporous silicas with different parameters related to their structural characteristics (density, particle size, contact area between particles …) or to the external conditions (pressure, water content …). They notably indicate in which conditions the silica should be used in order to maximize their insulating performances.

The results of the model are compared with experimental results previously published and show good agreement. In particular, the bad influence of the presence of condensed water and of the contact area between touching particles on the conductive heat transfer are clearly confirmed theoretically.
This demonstrates the important role played by the adsorbed water on the thermal performances of this very absorbent material.
The study also reveals that, for materials with common densities containing silica particles alone, the radiative heat transfer is significant and noticeably degrades the insulating performances of the material. Thus, the addition of opaque particles to the solid matrix is indispensable.

Modifications of a Pyrogenic Silica Exposed to Moist Air

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Pyrogenic silicas are among the best candidates as core materials for vacuum insulation panels (VIP). Nevertheless, such highly divided materials exhibit high specific surface areas and consequently, gaseous adsorption, especially moisture, must be considered [Zhuravlev, 2000]. Thermal conductivity measurements indicate clearly a strong drop in the insulation capacity when VIPs are exposed to moist atmospheres [Quenard/Salle, 2005]. As in the field building materials a service life of 20, 50 (or more) years is expected, it is of the utmost importance to assess the evolution of the surface chemistry and of the silica microstructure induced by water adsorption. Consequently, the surface chemistry and the microstructure stability of this family of silica have been studied in climate conditions. The pyrogenic silica HDK T30 (from Wacker) has been chosen as main test material for ageing under moist atmospheres from 20°C-44%RH (Relative Humidity) up to 60°C-95%RH. This silica is made of spherical particles of 10-15nm in diameter and has a BET specific surface area (S_{BET}) of $273 m^2.g^{-1}$. Climatic test chambers and saline solutions have been used to fix the storage hygrometries and temperatures. Two other silica nanometric powders were also studied: Aerosil 200 (pyrogenic) and LS500 (precipitated) both from Degussa.
The water uptake has been recorded using gravimetric measurements. At a fixed temperature, higher the relative humidity, higher the mass uptake is. Thermogravimetric results indicate that the hydroxylation of the silica is associated with an increase in silanol surface concentration. Hence, the adsorbed water modifies the surface chemistry of the silica implying an increase in its hydrophilic capacity.
At 20°C no variation in S_{BET} of HDK T30 is observed up to 50 days whatever the humidity. But decreases of its S_{BET} occur continuously with time at 60°C and, higher the humidity, higher is the decrease. A mechanism of a dissolution-reprecipitation process driven by differences in solubility between surfaces of different curvatures could explain this phenomenon [Iler 1979]. The result is an increase in the neck size and an aggregation phenomenon.
Measurements of Young's modulus have been carried out. Whatever the ageing conditions, an increase in elasticity modulus occurs continuously with time, but the comparison of the different curves reveals two trends: (i) at a fixed temperature, the Young's modulus increases with the humidity and (ii) at a fixed relative humidity, the Young's modulus increases with the temperature. It is the resulting hydroxylation of the surface which is at the origin of the observed increase in Young's modulus as hydrogen bonds between particles may be formed in larger amount. The aggregation phenomenon of the primary particles also contributes to the rigidity.

At last, a linear correlation between the silanol surface concentration and the physisorbed water surface concentration has been established at 20℃-44%RH.

[Zhuravlev, 2000] ***The surface chemistry of amorphous silica – Zhuravlev model***, Colloids and surfaces A, 173, pp. 1-38

[Quenard/Salle, 2005] ***Mico-nano porous materials for high performance thermal insulation***, *In 2nd symposium on nanotechnology in construction, 2005, Bilbao, Spain*

[Iler 1979] ***The chemistry of silica***, Wiley, New York.

Influence of Water Content on the Thermal Conductivity of Vacuum Panels with Fumed Silica Kernels

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Vacuum insulation panels (VIP) made from fumed silica show thermal conductivities of less than $5*10^{-3}$ W/(mK) under absolutely dry conditions. The important question of service life and durability of VIPs is determined by the influence of moisture on their thermal conductivity. To investigate this topic thermal conductivity was measured depending on moisture content. The results confirm the increase of about $0,5*10^{-3}$ W/(mK)) per mass % of water found in [Schwab 2005]. But in addition the experiments show an irreversible increase of the thermal conductivity of about $2*10^{-3}$ W/(mK). This increase is caused by shrinkage and structural changes of the silica kernels. The shrinkage and structural changes based on the influence of moisture combined with the atmosphere pressure. There was no further effect measured after exposed VIP varying climate. In a further step the moisture distribution within VIPs depending on temperature gradients was measured and calculated. In order to describe the movement of water within VIPs an effusion based model combined with liquid transport in the inner surface of the silica kernels was developed. An additional investigation dealt with the use of desiccants in VIPs. It showed nearly complete absorption of moisture and a reduction of the moisture caused increase of thermal conductivity. With desiccants applied we found only low shrinkage and structural changes of the silica kernels. Thus it could be shown that by adding a desiccant, the negative effects of moisture in VIPs can be avoided.

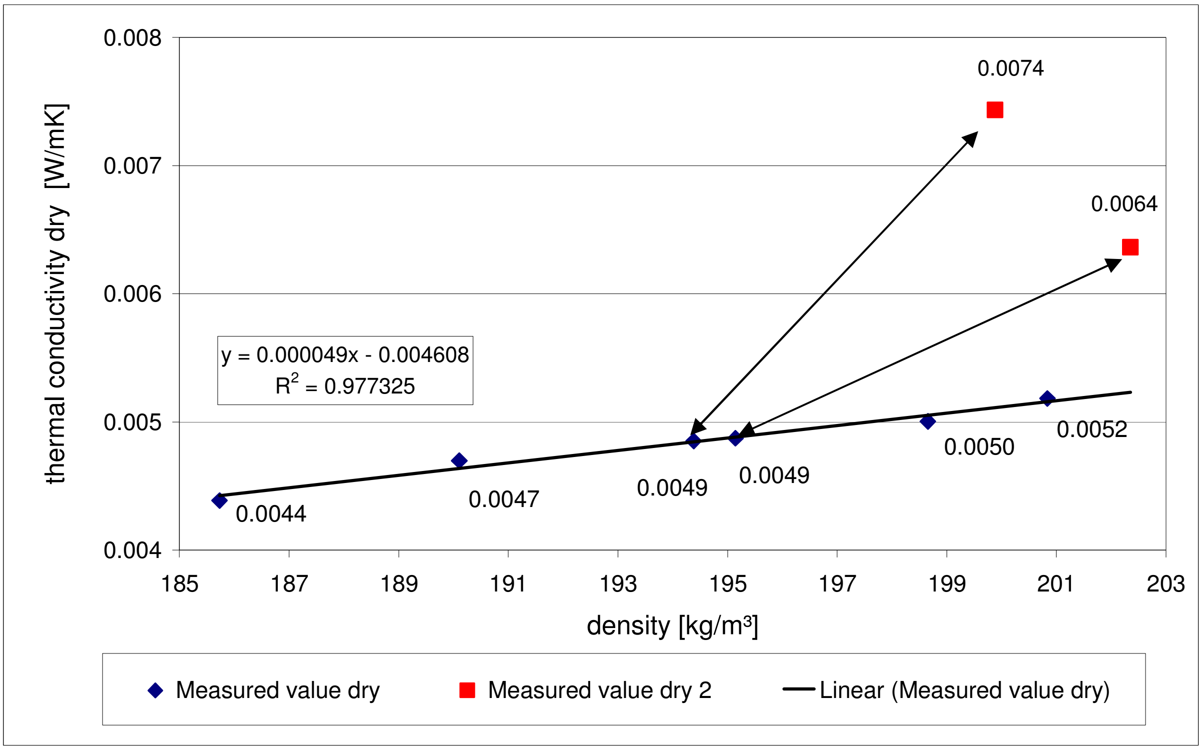

Figure 1: The diagram shows the increase of thermal conductivity due to structure changes of the silica kernels caused by moisture. The red squares refer to VIP samples that have been exposed to moisture and then dried again. The relation between density and thermal conductivity that was stated for the unaltered VIPs does not apply any more.

[Schwab 2005] **Dependence of thermal conductivity on water content in vacuum isolation panels with fumed silica kernels,** H. Schwab, U. Heinemann, A. Beck, H.P. Ebert, J. Fricke: Thermal envelope and building science, 2005

Acknowledgement

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Heat Transfer in Insulation Materials Based on Evacuated Glass Bubbles

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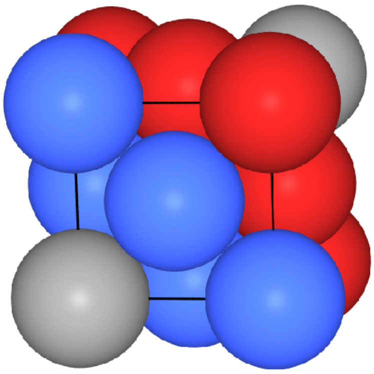
Heat insulation of buildings is an increasing demand not only due to the discussion of the climate change. The most efficient possibility is the usage of vacuum. Here, a general difficulty is the housing of the vacuum. There exist different approaches to seal in the vacuum: large-scale solutions like vacuum insulation panels and micro-scale solutions like evacuated glass bubbles. The advantage of the vacuum insulation panels lies in the excellent isolation properties. Its application in construction industry is restricted by its predefined size and the fact that even small injuries destroy the insulation effect of the whole panel. On the other hand the micro-scale approach with glass bubbles leads to a kind of porous material which is less efficient than large-scale vacuum solutions, but much more robust against local injuries and can have attractive insulation properties compared to standard products like glass wool.

The aim of this paper is the mathematical modelling and simulation of porous insulation materials using glass bubbles. Based on homogenisation techniques the heat transfer coefficient which is the essential property of the insulation material is determined.

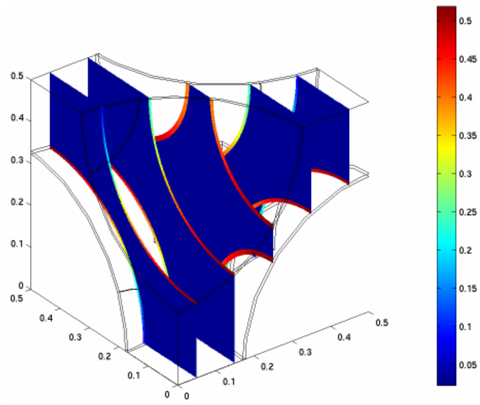
We consider an insulation material composed of evacuated glass bubbles and air. For the approximation of the heat conductivity two different homogenization approaches were used: a Triple-Cubic-Cell-model (TCC) and a Face-Centred-Cubic-model (FCC). For the TCC-model the glass spheres were replaced by glass cubes and an analytical approximation for the homogenized compound was derived as

$$\lambda_{compo} = \left(\frac{1-(v_{glass}+v_{vac})^{1/3}}{\lambda_{air}} + \frac{(v_{glass}+v_{vac})^{1/3} - v_{vac}^{1/3}}{(1-(v_{glass}+v_{vac})^{2/3})\lambda_{air} + (v_{glass}+v_{vac})^{2/3}\lambda_{glass}} + \right.$$
$$\left. + \frac{v_{vac}^{1/3}}{(1-(v_{glass}+v_{vac})^{2/3})\lambda_{air} + ((v_{glass}+v_{vac})^{2/3} - v_{vac}^{2/3})\lambda_{glass} + v_{vac}^{2/3}\lambda_{vac}} \right)^{-1}$$

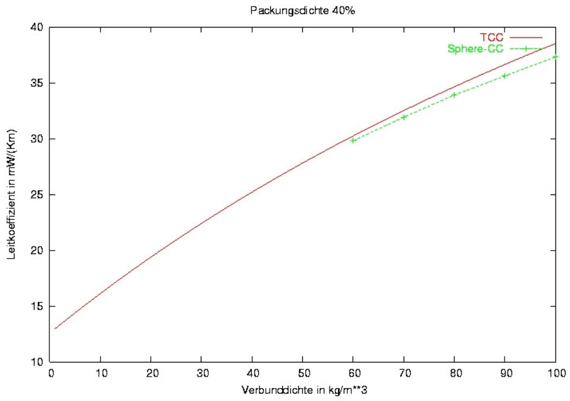
where different λ are the heat conductivities of the composite material, glass, vacuum, and air. v denotes the relative volume fraction of these materials (glass, vacuum, air). This kind of approximation is proven by detailed numerical simulation of the heat transfer in a periodic cell of the micro structure using a FCC-model (see picture 1 and 2).



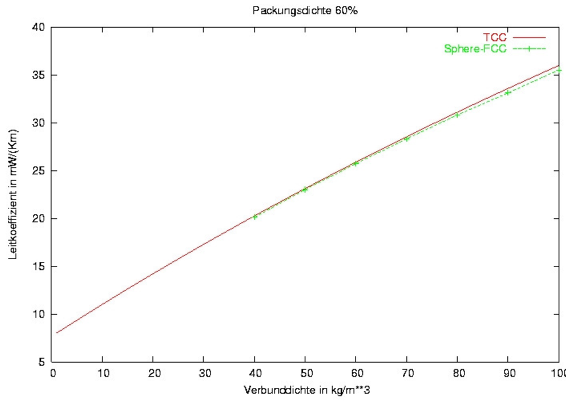
Picture 1: Sphere Face-Centred-Cubic-model (FCC)



Picture 2: Heat Flux simulated with the FCC-model



Picture 3: Comparison between TCC- and FCC-model (volume fraction of glass bubbles 40%)



Picture 4: Comparison between TCC- and FCC-model (volume fraction of glass bubbles 60%)

Both models are in good agreement as shown in pictures 3 and 4. The TCC-model gives an upper bound for the heat conductivity. Using the TCC-approximation formula we will discuss the influence of the different components like the glass shell and the inner gas or vacuum of the glass bubbles together with the structure and properties of the surrounding matrix.

Beside conductive heat transfer radiative effects are considered and estimated. The theoretical results are validated by different measurements of the effective heat transfer of fillings with existing glass bubbles which are not evacuated. Additionally the pressure resistance of glass bubbles with new specifications can be estimated mathematically using data of existing glass bubbles.

These modelling and simulation techniques are used to design new virtual insulation materials based on evacuated glass bubbles.

Polymer Foams: From Macroscopic to Nanoscopic Structure

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Nowadays, only four percent of mineral oil is converted into plastics. But almost 90 percent of mineral oil is used for the production of energy of which a large proportion is used for transport and heating purposes. The increased use of plastics for thermal insulation and in the automotive industries offers a considerable potential for saving energy. More than 50 years ago, BASF has invented Styropor®, an expandable polystyrene (EPS) which is today widely used for insulation purposes. BASF has further improved the classic EPS and has introduced Neopor®, an expandable polystyrene (EPS) which contains graphite, which considerably enhances the insulating capacity. All these products are based on a blowing process leading to materials with large pores (>10µm).

For physical reasons, this process can not be used when low-density foams with much smaller pores are needed (<500nm). Such foam materials require new synthetic strategies. The idea of preparing foams with nanometer-sized pores is not new: 70 years ago, so called aerogels using sol-gel chemistry of silica have been introduced. The aerogels available nowadays exhibit very low density (<150g/L), high porosity (>90vol%), and pores around 20-50nm. However, their preparation requires special and expensive conditions, such as supercritical drying, which strongly limit the development of such materials at a large industrial scale.

Thus, we are interested to explore synthetic pathways toward supramolecular nanomaterials with pore size in the several 100 nm range that show the potential to be used in a broad range of applications. We present the numerous challenges associated with the various syntheses including different supramolecular templating approaches in which microemulsions or colloidal particles are used to tailor the pore size of oragnic sol-gel based nanomaterials.

Trilobal Polyimide Fiber Insulation for Cryogenic Applications

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Fibrous insulations have a long history in applications at low temperatures [Kaganer 1969]. For example, they have been used for the thermal insulation of space applications, such as solar arrays, antennas, optical platforms and support structures for cryogenic tanks [Bansemir 1998]. Furthermore, fibre insulations were used for space suits of astronauts to assure safe extravehicular activities [Paul 2003]. For ground applications fibrous insulations are applied to avoid heat entry into cold devices (e.g. superinsulated liquid gas containers).

In principle, all fiber insulations try to enlarge the path length that heat has to travel from the warm side to the cold. For this reason it is desirable to maximize the thermal contact-resistance R_{ct} between the fibers as well.

In this work, the thermal conductivity of an evacuated specimen made of polyimide fibers is presented. Measurements of thermal conductivity by using a guarded hot plate apparatus show a (extreme) low value of smaller than $0.25 \cdot 10^{-3}$ $W(mK)^{-1}$ at temperatures of 120K under vacuum condition. The low thermal conductivity can be explained by the special cross-section shape of the fiber (see fig.1). The predominant form of the fibre is called "trilobal", because of its three-arm-build-up/structure. This structure leads to a very high thermal contact resistance between the fibres. Furthermore, the material is non-woven and has no NPI (needles per inch). As a result, there is no direct path for the heat transport by conduction through the specimen and the thermal conductivity is decreased even further.

Existing theoretical models [Paul 2003, Stark 1991, Büttner 1984] for the heat transport in fibrous insulations cannot sufficiently describe fibrous materials with non-cylindrical cross-sections. In this work, a modification for the heat transport model described in [Kaganer 1969] will be presented and compared to the original model. The results of the theoretical calculations are discussed in comparison to experimental results of thermal conductivity measurements performed with a guarded hot plate (GHP) apparatus at temperatures in the range from 120K to 420K (see Fig.2). (A description of the experimental setup can be found in [Heinemann 1995]).

Furthermore, the modified model is used to optimize a thermal insulation consisting of trilobal fibers. A variation in the specimen density takes effect on the thermal conductivity of the structure as well as on the heat transport by radiation. However, these two parts run into opposite directions. A higher density of the specimen reduces the contribution of the thermal radiation, but decreases the thermal resistance of the structure, and vice versa. The modified model is now used to find the theoretical optimum density for the lowest total thermal conductivity of the insulation.

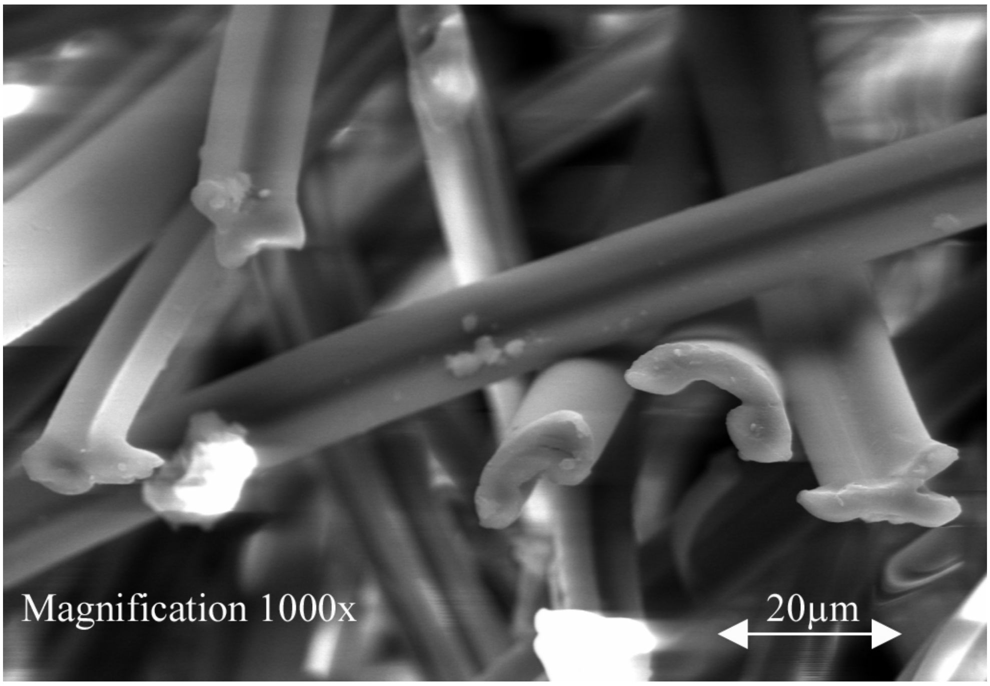

Figure 1: Picture of the investigated specimen, taken with a scanning electron microscope.

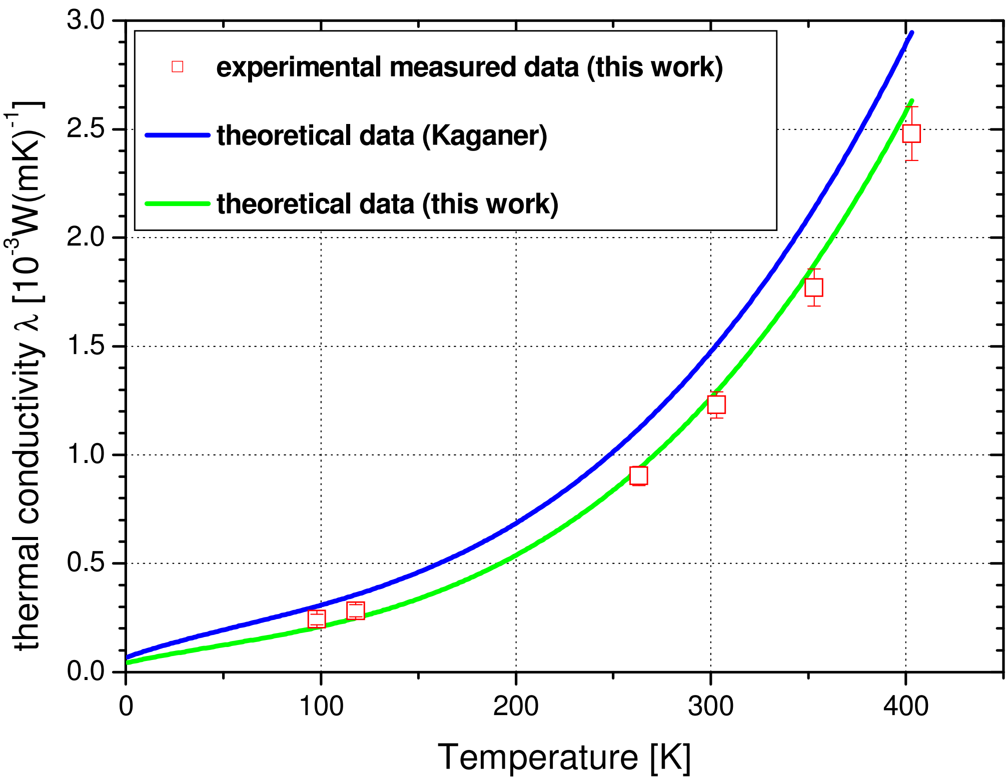

Figure 2: The diagram shows the thermal conductivity of the investigated polyimide specimen depicted as a function of temperature. The results of the model described by Kaganer and of the modified model are compared to the experimental results of measurements with a guarded hot plate apparatus.

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New POLO Concept to Manufacture VIP Barrier Film Laminates Based on Hybrid Barrier Layers

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Vacuum insulation panels (VIP) have the potential to reduce the thickness of building insulation by a factor of ten. They consist of a porous matrix encapsulated by a liner of foils, which is evacuated down to a final pressure below one mbar. Metal foils have the disadvantage of high thermal conductivity spoiling the u-value of the VIP at the borders and edges. More suitable are polymeric films equipped with barrier coatings reducing the permeation of water vapour and air by some orders of magnitude clearly below 10^{-2} $cm^3/(m^2*d)$ for oxygen and 10^{-3} $g/(m^2*d)$ for water.

The most critical component of a Vacuum Insulation Panel (VIP) is the envelope, which is responsible for the maintenance of the vacuum inside the panel. Normally polymer laminates are used which contain metallized polymers or aluminium foils as barrier layer. As with all polymeric films, the transmission rate for water vapour (WVTR) for these laminates was found to be several orders of magnitude greater than those for oxygen (OTR) or nitrogen: The units used for WVTR is $g/(m^2 \cdot d)$ and for OTR $cm^3(STP)/(m^2 \cdot d)$ and today products do have WVTR and OTR in the same range but 1 g H_2O equals 1244 cm^3.

State-of-the-art film laminates used in VIP applications are combined of 3 metallized films. There are 2 main concepts in the market one is based on 3 metallized PET films in layer stacks, the other one uses 3 different films each with another function, but finally fulfilling the main duties like barrier against water vapour and gases more or less, mechanical strength and Infrared reflectivity. In both cases the laminates have to be covered by flame resistant films on both sides as always in building applications. The POLO concept consists of only one film with a layer stack of 3 to 4 barrier layers of alternating vacuum coated inorganic and lacquered hybrid polymer layers. An especially designed concept and special effects within the layers stack lead to better barrier properties as in state-of-the-art film laminates. Furthermore by using only one film for the barrier properties, there is a clear advantage with regard to material reduction and basically a reduction of the amount of production steps to manufacture a full barrier laminate for VIP applications. This will lead to a clear reduction of the costs of the laminates.

The results of barrier measurements on film laminates of the project and the relation of the permeation through the film to corner and edge effects will be presented. First transparent films for translucent VIPs have been manufactured and also shown encouraging results.

Measuring extremely low permeation rates is challenging and very time-consuming. A fast measurement tool was developed to derive water vapour transmission rates from helium transmission measurements. The effects of corners and edges on water vapour and on oxygen transmission rates were also determined. Measurements on panels stored in different climatic conditions gave detailed information on permeation rates for air and water vapour as a function of temperature and humidity including all the effects of edges, corners and processing.

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Ultra High Barrier VIP Laminates – New Solutions to Tougher Requirements

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The developing VIP industry requires high barrier laminates with more features, and more challenging specifications. VIP laminates are required to minimize permeation rates of gases through the skin and through the sealed edges, to have poor heat conductivity (low thermal bridge), and to be resistant to mechanical and corrosive damage. Panels used for the thermal insulation of buildings must also have very low flammability in order to comply with the strict regulations of the construction industry.

During the last few years, many VIP manufacturers have started using less expensive core materials that demand more effective encapsulation solutions. Highly efficient barrier levels are also necessary for very long term applications such as the thermal insulation of buildings. In many cases, Al foil based laminates are not the best choice because they create substantial thermal bridges, especially with small size panels.

In order to avoid thermal shorts, the thickness of the Al barrier layers has to be reduced by more than an order of magnitude, whilst still keeping permeation at extremely low levels. This is achieved by thermal vacuum deposition of tiny nano-crystallines of Al (100nm average size) on polyester films, and lamination of several metallized films together. The nano structure of the Al crystallines plays a critical role in determining how effective the MVTR levels of the films are. Microscopic pinholes created in the metallization and the web handling processes contribute substantially to the permeation levels of oxygen and nitrogen in particular. Propriety deposition techniques recently developed by Hanita provide an impressive three-fold reduction in MVTR levels, and enable the replacement of Al foil based laminates by metallized films in more highly demanding applications.

This impressive improvement of the skin barrier has magnified the relative importance of edge diffusion through the seals. With ultra high barrier metallized films, the edge diffusion through the 50µ thick polyethylene seal layers can be responsible for more than 50% of gas permeation into the encapsulated panels, particularly by oxygen and nitrogen. Several options to replace the standard seal layers by high barrier seal layers will be discussed.

Another important factor that has a strong effect on the permeation rate is the amount of stress applied to the envelope along wrinkles, and along the edges and corners of the panels. These mechanical stresses stretch the plastic substrates of the laminates, causing micro gaps between the Al crystallines, and pinholes in the case of Al foils. The polycrystalline Al layers produced with the new vacuum deposition techniques are shown to have better response to these stresses.

Substantial barrier improvement has been achieved by adding external BOPP films to the laminates. The extra BOPP layer increases the rigidity of the laminate, reducing the stress levels on the Al layers by not allowing the laminate to fold over the edges with small radii of curvature. It was found that by making the laminates stiffer, substantial improvement to the actual barrier properties of the envelope can be achieved. The BOPP layers also provide very good mechanical protection from post-production mechanical damage, and eliminates the costly and time consuming need for wrapping the panels with tapes or foams before shipping and installation.

Flame retardancy is also a very important feature when dealing with the construction industry, because the panels have to meet strict non-flammability standards. Several solutions to achieving flame retardant laminates will also be discussed. A further topic discussed concerns the use of Al foils in the envelopes with negligible effect on the thermal bridge, whilst at the same time substantially improving barrier levels.

In summary, the new requirements from VIP laminates are: ultra high skin and seal layers; low thermal conductivity; mechanical robustness; very low corrosion rate; and flame retardancy. These requirements can be met by the new generation of tough, efficient ultra-high barrier metallized laminates.

Aluminium Metallised Bi-Oriented EVOH Film for Vacuum Insulation Applications

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Kuraray Co., Ltd. has developed EVOH (ethylene vinyl-alcohol copolymer resins) barrier films for use in barrier laminates for vacuum insulation panels (VIPs).

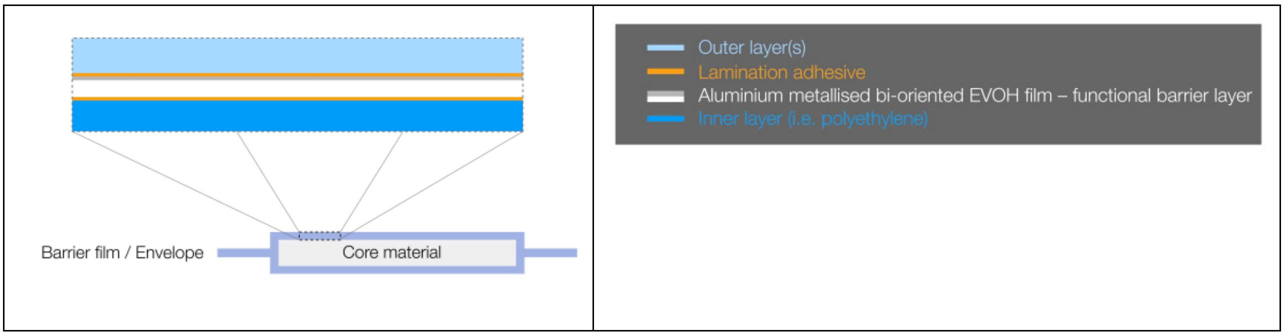

Figure 1: Vacuum insulation panel with a barrier laminate that contains a VM-BO-EVOH

Aluminium metallised bi-oriented EVOH films (VM-BO-EVOH) allow the vacuum insulation panel (VIP) industry to expand their application area and to take their technology one step further.

VM-BO-EVOH films offer a low permeation to gases and water vapour, combined with a very good resistance to manipulation (flex crack resistance and pinhole resistance). VIPs produced with barrier films containing VM-BO-EVOH will not be damaged during handling and transport.

The aluminium metallised layer provides an excellent water vapour resistance. Any reduction in gas barrier property of the metallised layer is counterbalanced by the superior barrier properties and excellent flex crack & pinhole resistance of the EVOH film. The EVOH bi-oriented base film has outstanding gas barrier properties exceeding those of other barrier plastics.

Films	**Gas Transmission Rates of Selected Polymers at 25°C and 0% RH (cc.20µm/m².day.atm)**			
	N_2	**O_2**	**CO_2**	**He**
EVOH bi-oriented film(1)	-	0,15	-	-
EVOH 32 mol% ethylene(2)	0,017	0,27	0,81	160
EVOH 44 mol% ethylene(3)	0,13	1,23	7,1	410
Oriented PA6	12	38	205	2.000
PET	8	54	110	3.100
Oriented PP	730	3.400	9.100	-

(1) EVAL™ film EF-XL *(2) EVAL™ F101B* *(3) EVAL™ E105B*

Table 1: Gas transmission rates of selected polymers (measured following ISO 14663-2)

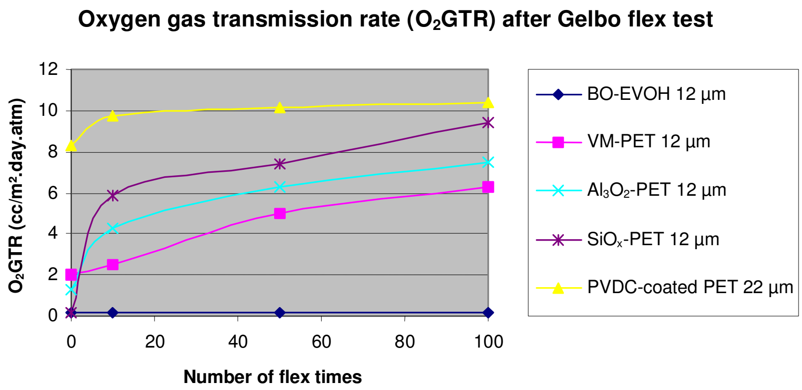

Figure 2: Resistance to manipulation of selected barrier films (flex crack resistance)

In Japan VIP barrier films with EVAL™VM-BO-EVOH are already used in: refrigerators, vending machines, hot water cookers, cold shipping boxes and refrigerated trucks. Recently VM-BO-EVOH was also used at the bottom of a bath to improve its heat retention.

About Kuraray and EVAL Europe

Kuraray Co., Ltd. has long been a leader in high gas barrier technology and development. The company is the first and foremost producer of EVOH (ethylene vinyl-alcohol copolymer resins) under the name EVAL™ and the manufacturer of KURARISTER™. The company was established in 1926 in Kurashiki, Japan. Today, the Kuraray Group consists of about 70 companies, employing around 7,000 people worldwide.

EVAL Europe nv was founded as a wholly owned subsidiary in Antwerp in 1997 to supply the European, Middle Eastern and African markets with EVAL™. EVAL Europe nv has all the necessary expertise to locally serve European customers from its Technical and Development Centre. The first EVOH production site in Europe doubled its production capacity in October 2004 to 24,000 tons per year.

EVAL™ resins are used for food packaging, construction and building, automotive and cosmetics applications.

Application of Vacuum Insulation at Temperatures above Ambient

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Most current large volume applications for vacuum insulation panels are for operating temperatures at or below ambient temperature. These include refrigeration, controlled temperature packaging, and building applications. The well-reported exceptions to this are the use of silica VIP's in hot water pots and rice cookers in Japan. Although most current applications are characterized by maximum temperature differences across the VIP of less than 40 ^{o}C or so, many higher temperature applications can have temperature differences of 100 to over 200 ^{o}C. Because of the higher temperature gradients, the potential for energy savings, as well as increased value of a VIP to the customer, can be much greater than for applications below or near ambient. There are many large volume applications with temperatures above ambient on at least one side of the insulation. These range from apparel (~35 ^{o}C hot side) to tank-type hot water heaters (~60 ^{o}C) to condensate (110-130 ^{o}C) to steam lines (150+ ^{o}C). The hot side for applications such as chemical/hydrocarbon process piping, oil/intermediates transportation, electronics, fuel cells, solar energy, ovens, and process equipment can cover the temperature range from ambient to >150 ^{o}C.

Employing VIP's at higher than ambient temperatures raises a number of new operational requirements that arise from the higher temperatures including:

1) Accelerated permeation of gases and vapours though vacuum barriers and seal materials,

2) Reduced performance/more stringent requirements for desiccants and some getters,

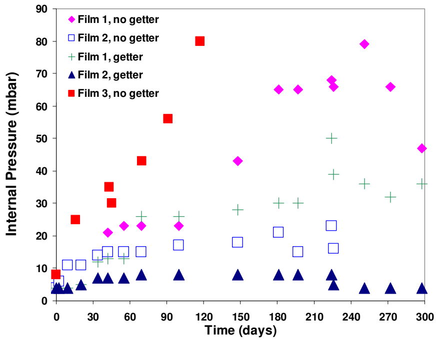
3) Degradation of core/barrier, problematic as getters/desiccants are not designed for these temperatures.

4) Different core requirements as radiation and the gas mean free path change,

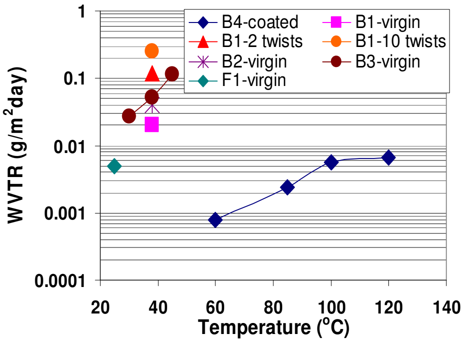
5) Thermal/mechanical stress for VIP/surroundings related to differential thermal expansion

Many of these problems are enhanced when one attempts to make thin (2-6 mm) VIP's because of the increased surface area to volume and seal area to volume ratios. In this paper, we discuss a multi-pronged approach to develop and commercialize VIP's for above ambient temperature applications.

At higher temperatures, either water vapor or O_2/N_2 permeation can be the main culprit in performance degradation depending on both hot and cold face temperatures, ambient humidity, VIP size, VIP construction method, core material and barrier material[i]. We currently have a series of panels produced with various commercial VIP barrier (metalized and foil) films and different getters/desiccants in long-term (10+ months) testing at 80 ^{o}C (see graph). At 80 ^{o}C, the permeation of water is ~100 times faster and oxygen/nitrogen is ~10 times faster than at ambient temperature. To further accelerate testing, 12 mm thick panels were employed. Because of the limitation of commercial films for high temperature applications, we have been pursuing the commercial development of higher barrier films that do not use foil or metallization. These films, during extended testing at high temperatures (65 to 140 ^{o}C) offer water vapor transmission rates which are less than $1x10^{-2}$ g/m^2/d when measured at 140 ^{o}C. In comparison, typical VIP films rarely reach values this low at 38 ^{o}C. Extrapolating those high temperature results to 38 ^{o}C indicates a factor of 100 lower water permeation rates as compared to current barriers. We note that this is through the film and does not account for seal diffusion. Multiple strategies for mitigating seal permeation will be discussed.



At higher temperatures, the challenges for gettering are not just water vapor and oxygen/nitrogen but also solvent from the adhesives in barrier films as well as outgassing and/decomposition products from the core material. Plastic foams obviously have no place in high temperature applications and fiberglass may be used but very careful consideration to the type of fiberglass, the presence and type of any sizing, and the pre-treatment of the fiberglass core are all important. Of course, the fact that fiberglass must be maintained at pressures 100x lower make these problems even more difficult. For silica cores, not just the presence of adsorbed water but the possibility of water vapor production due to silanol condensation at high temperature/long time must be considered. Additionally, any additives such as infrared opacifiers and structural material must be evaluated for outgassing. Most getter/desiccant companies only provide ambient temperature data. For higher temperatures, data must be provided by the supplier or measured independently.



It is well known that the trade-off between radiative transport, and solid and gas phase conduction is temperature dependent. For silica/carbon, the carbon content should be increased as the average temperature increases. From the extinction coefficient and solid phase conductivity, a model will be presented showing how the carbon content should be varied for different hot/cold face temperatures.

Thermal stress resulting from differential thermal expansion can be accounted for in the system design. Key points are the panel dimensions and methods to make thermal gradients across the panel more uniform. This is more serious problem for applications that go through many hot-cold cycles. Repeated thermal cycling over a wide range can clearly cause stress cracking of metalized barriers.

Despite the many *potential* problems, of using VIP's at high temperatures, they are in use for a range of applications including hot water heaters, electronics, fuel cells, and piping systems. Examples will be discussed as well as how further ongoing improvements in barrier technology will enable a new generation of above ambient temperature vacuum insulation products.

Optimization, Design, and Durability of Vacuum Insulation Panels

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New materials and structures are currently being developed to meet the new requirements for energy saving via building thermal insulation. Although the new technological solutions may present very interesting initial properties, their durability has yet to be quantified. Building materials must indeed last for tens of years, both for cost efficiency and environmental consideration.
A concept was recently proposed that relies on the best theoretical thermal insulator: the vacuum. The new porous materials, with amazing initial insulation performances when maintained under vacuum, are likely to bring excellent thermal properties while the performance of the acoustic properties remains limited. The development of these composites has to be undertaken simultaneously from the point of view of the core material, the protective packing and the structural siding. In other words the development of these composites should take into account the design, the materials selection and ageing all together.
The present work is focussed on the study of the permeability and durability of polymer/metal multilayers developed for packaging super insulators. It aims at developing characterization techniques with the help of simple films, namely polymers covered with thin aluminium layers. Various characterizations were carried out on these binary systems in their initial state. As a result, some basic properties/structure relationships could be proposed relating mechanical strength and permeability to the detailed architecture of the multilayer. Structural markers were identified such as the presence of holes within the aluminium layer as detected in optical microscopy. These heterogeneities considerably alter the barrier and mechanical properties of the films.
Accelerated ageing tests were performed in order to identify the mechanisms governing the evolution of the markers and thereby, of the macroscopic properties.

Thermo-Mechanical Behaviour of Barrier Envelopes and Heat Seals

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In recent years, the interest in vacuum Insulation has considerably increased and the need for volume efficient means of insulation has led to the development of new techniques among which vacuum insulation panels (VIPs) are one of the promising products. Vacuum insulation panels are thermal insulators that combine high thermal performance with limited material thickness due to a very low centre-of-panel thermal conductivity. This very low thermal conductivity is achieved by evacuating the core material to a gas pressure below 1 mbar and by adding so-called opacifiers to the initial mixture of the core material constituents. To maintain this state of vacuum for a period as long as practically desired, a high barrier laminate is enveloped around the core material. This barrier laminate nowadays mostly consists of either a laminated metal-polymer foil (for instance with a 6 to 12 μm thick aluminium layer or a 25 to 100 μm thick stainless steel layer) or a laminated metallised polymer film of approximately 30 to 100 nm thickness in total. If this barrier envelope is subjected to mechanical stresses due to a cooling down from room temperature to cryogenic temperature (liquid natural gas) or due to solar radiation, failure of this envelope may endanger the application of VIPs. Moreover, the mechanically weakest spot in the barrier envelope is the heat seal at which point two envelope parts are welded together. In this respect, it is important to realise that on the one hand the geometric shape of the heat seam provides stress concentrations and on the other hand this seam itself consists of the weakest material of the composite laminate, polyethylene. This paper therefore presents results of thermo-mechanical tests on several types of commercially available barrier laminates conducted in the framework of the EU/Craft research project VACI (project number: COOP-CT-2003-508026), a joint project which developed vacuum insulation for application around LNG-ducts.

The objective of this research has been to test materials suitable for application as barrier laminate for vacuum insulation panels. Two types of barrier laminates have been tested. The first type is typified as a metal-polymer laminate of which two makes were tested; the second type is a metallised polymer barrier film of which again two makes were tested. The samples for testing the strength, strain and Young's modulus of the laminates were cut out of large sheets of film material into rectangular samples of 12.5 mm wide and 230 mm long according to ASTM E345 type 2 specimens [ASTM, 2002]. For testing the heat seal strength, the foils are cut into samples of about 10 cm wide and 30 cm long and folded to be sealed afterwards. The sealed samples are then cut into samples of 20 mm wide so that tensile samples of 20 mm wide and minimal 200 mm long are left with the heat seal in the middle. The tests have been performed at 21°C and at approximately -130°C to determine the properties of the seam and between -150°C and +70°C to determine the general thermo-mechanical behaviour of the barrier laminates. With regard to the seams, specimens of six different laminates with the seams produced at different seal bar pressure, hot seal temperature and sealing time conditions have been tested.

Figure 1: **Ultimate tensile strength as function of temperature for laminates 1 and 4. The broken lines are just added for eye-guidance. hl stands for 'from room temperature to measurement temperature', while lh stands for 'from measurement temperature to room temperature'.)**

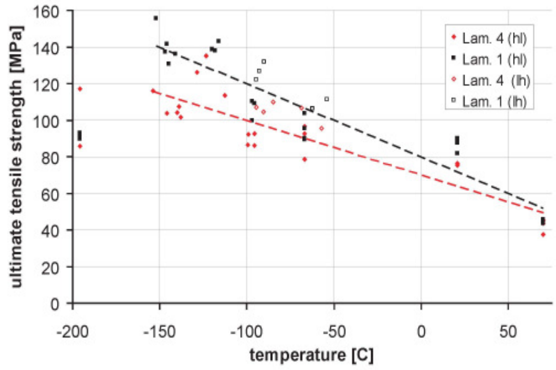
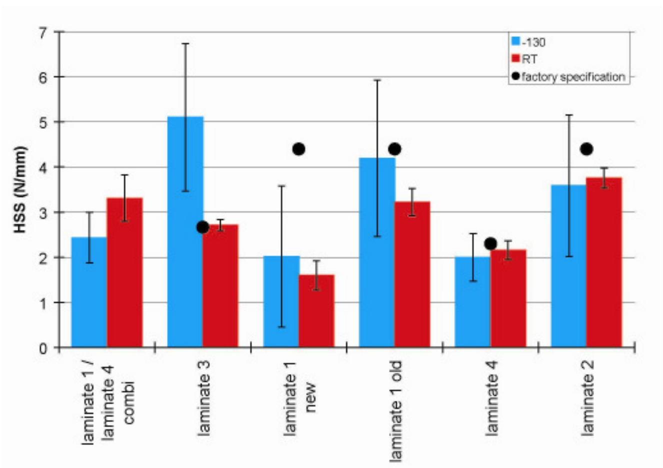


Figure 2: **Overview of the Hot Seal Strength of all tested laminates at room temperature and at -130°C. The black dots denote factory specification at room temperature if available.**



Figures 1 and 2 show some of the results of the tests for the general thermo-mechanical behaviour of the strength of a metal foil based laminate (lam. 4) and a metallised film based laminate (lam. 1) (Figure 1) and for the strength of the seam at both cryogenic and room temperature. As can generally be seen, the strength of the barrier laminate increases for decreasing temperature. This also applies to some heat seals, not all however.

Based upon all tests, it is concluded in the paper that the strength and the Young's modulus of the tested laminates increase with decreasing temperature; that their ductility however decreases, if the temperature decreases from room temperature to approximately 223 K, but increases again if the temperature is lowered further. Moreover, the strength of heat seals at room temperature and at 143 K is presented together with the influence of sealing temperature and hot seal time on this strength. In general, it can be concluded that within certain boundaries the sealing parameters (temperature, time and pressure) can be chosen freely. Moreover, it is concluded that the choice of barrier material in the

VIP production process must be made based upon service life considerations rather than on thermo-mechanical considerations since the differences in mechanical properties are small.

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Finite Element Analysis of Bending Barrier Films

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A critical component of all vacuum insulation panels is the barrier film. Performance of barrier films are typically measured in oxygen transmission, OTR, determined by test method ASTM D3985 and water vapour transmission, WVTR, determined by test method ASTM F1249-90. The testing is typically performed on flat undamaged film samples. In use, barrier films experience bending at many locations including the edges of the panel and the bending and taping of the seal flaps. At each International Vacuum Insulation Symposia there has been one or more papers dealing with barrier film design and performance. Some also note the potential for damage to the barrier in normal use. The DuPont Teijin Films paper presented in 2001 presented numerous mechanisms for damage to barrier films. Microscopic studies of barriers subjected to tensile strain, long term creep under load, thermal stresses, and external factors such as dust inclusion in the barrier and abrasion of the barrier were all studied. A recent paper "Applications of Vacuum Insulation Panels in Extreme Environments" by Kevin Roderick, Brian Glover and Douglas Smith presented at the 7th International Vacuum Insulation Symposium, shows that manipulation of the barrier film can result in failure or locally increased diffusion. Our own studies of failed panels where the failure cause was not obvious (no cuts, scratches, bad seals, etc.) using helium mass spectrometry to identify the areas that leak has shown no failures in the barrier covering the flat surface of the panel. All leaks occurred in the corners or edges of the panel. Interestingly almost all were at the end of the panel where the core is pushed up against the barrier and opposite the chamber seal flap.

Present barriers are carefully designed to provide outstanding barrier performance when not subjected to the above conditions. Many barriers now have a multitude of layers which allows for local fault tolerance of any one layer and still provide outstanding performance. The weak link appears to be the structural design of the barrier films. Many barrier layers are specifically design to be very thin to minimize the lateral diffusion inside the barrier film. This approach was presented in a paper by this author at the 7th International Vacuum Insulation Symposium. Most barrier films are composed of the barrier layers and the heat seal layers. Typically the heat seal layers are LDPE or HDPE, both at fairly low modulus "yielding" materials. Thus the barrier layers, often PET, take almost all the load and therefore can be locally highly stressed. It should be noted that the typical damage to the barrier is not over a large area or long line. It is microscopic points that locally yield by several hundred percent. The DuPont paper discussed above shows microscopic photos of such areas in the barrier.

The primary focus of this paper is the discussion of tools to analyze a barrier film structure and provide structural barrier design guidance. This author believes that barriers need to be structurally designed as well as designed for barrier properties. To gain a better understanding of barrier film stresses and strains, a technique has been developed to use Finite Element Analysis (FEA) to model the bending of barrier films. Only recently have FEA computer programs developed where the detail and needed boundary conditions can be imposed to easily analyze the complex barrier film behaviour. The computer model is detailed enough to include each layer of the barrier film with it's particular material properties and provide the detailed stress and strain for each layer. Several different barrier film configurations were analyzed including one configuration where an additional layer was added to the barrier film to offer abuse resistance and carry most of the loads which damage the actual barrier layers. The modelling showed the local strain in the area of the bend and some potential means of reducing the strain in the critical barrier layers of the barrier film. In one configuration the strain in the actual barrier layers was reduced by about 65%. An attempt was made to connect the amount of strain of the barrier to increased OTR and MVTR. The results were used to predict the potential impact on pressure inside a vacuum insulation panel. The very detailed layer by layer stress and strain information from the computer modelling and the ease with which new barrier configurations can be modelled should provide one more tool in designing new improved barrier films.

Temperature Dependent Permeation of Water Vapour through Barrier Foils

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Polymeric materials are used as water-vapour barriers, or substrate materials for barrier coatings in food packaging, photovoltaic devices or OLEDs and as embedding materials for solar cells or as containers for vacuum isolation materials. Their permeation properties determine the level of water in the polymers and inside the devices. The water can cause corrosion and/or detoriation of functional properties of the devices. The temperature of solar devices and the ambient water vapour concentration vary over time according to the solar radiation and the ambient climate. Temperature dependent permeation and diffusion properties are needed for a modelling of the water concentration over time in order to predict the long-term behaviour and the service life of such devices.

The paper describes the measurement of the temperature dependent permeation coefficient for polymeric foils, different combinations of polymeric foils and inorganic barrier coatings enforced by additional sol-gel based ORMOCER® coatings, or inorganic barrier coatings and initial results of modelling the service lifetime by integrating time-series of in-use conditions.

We used a set-up based on a mass-spectrometer for the measurement of the water-vapour permeation. The sample film is mounted on ultra-high-vacuum flanges of upto 300mm diameter by means of a butyl sealant and UHV-metal sealant and exposed to controlled temperature between 20°C and 90°C and a fast increase of the humidity until a set partial pressure is reached. The progress of the humidity content in the volume behind the sample film, which is initially filled with argon under atmospheric pressure is monitored by a quadrupole mass spectrometer and is used for evaluation of diffusion and permeation coefficients.

The results are used for modelling the humidity concentration by means of numerical models based on FEM algorithms with time-dependent border-conditions resulting from long term climate monitoring.

Insulation System of Foil Covered Vacuum-Insulation-Elements for Operational Plants under Cryogenic Conditions

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In the field of building-insulation flat-shaped VIPs are commonly installed. They are fit for a temperature-gradient of about 40°C – 50°C. In difference to that application bended elements are needed for the insulation of operational equipment, which operates with remarkably higher gradients. To approve that those bended elements, which have been developed during an EU-funded project, are fit for an operation under cryogenic conditions, it was reasonable to make tests under conditions close to reality.

Operational plants are characterized by nets of piping, which beneath the cylinder-shaped strait pipes consist of a large variety of fittings as e. g. valves, elbows, supports, T-pieces, reductions, flanges etc., most of them of non cylindrical shape. The operating temperatures of these plants, which produce e.g. liquid natural gas (LNG) go down to the boiling temperature of methane (-162°C). The range of diameters varies between 25mm to over 1000mm with a maximum between 100mm and 200mm.

This in mind a test bed was designed and build, which principally consists of a pipe loop comprising two different diameters (approx. 100mm and 200mm) and supports, hangers, elbows, T-pieces, flanges and reductions. The temperature inside the pipe loop can be set at any temperature down to -192°C through the regulated injection of a spray of liquid nitrogen. The speed of cooling can likewise be controlled over a wide range. There is provision for monitoring the temperatures on the surface of the pipe as well as the interior, even of a multilayer insulation system, and also measurement of the heat flow rate through the insulation. The tests approved that bended VIPs of different shape are easily to be fastened on the pipe loop, even the elements of the multilayer system fitted together without irregular gaps. Even at the hangers and supports there were no mechanical influences on the elements due to the low temperatures. There were no unexpected or irregular temperature drops at the joints. The average heat flow rate was determined at about 20 W/m2 and a comparison of the qualities of the tested insulation system with conventional systems clearly shows the potential in this kind of insulation.

Vacuum Insulation Panels (VIP) in Energy Efficient Cooling Appliances for Improving the Environment of our Children's World

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In February 2007 the Intergovernmental Panel on Climate Change (IPCC) published the Fourth Assessment Report in which the changes of the climate system for the period 1906 – 2005 are described. According to the report the global atmospheric concentrations of carbon dioxide, methane and nitrous oxide have increased markedly as a result of human activities since 1750. The carbon dioxide is the most important anthropogenic greenhouse gas, whose atmospheric concentration has arisen from a pre-industrial value of about 280 ppm to 379 ppm in 2005. [IPCC 2007]

The furnishing of above 39 million household customers in Germany with electrical equipment increases. Communication technology and entertainment technology as computer, television and telephone are responsible today for ten percent of consumption of electricity. In year 2005 the total consumption of private households accounted for 140 billions kWh. This nearly corresponds with 26 percent of the total consumption of electricity. Refrigerators and freezers cause more than 30 percent of consumption of electricity in households today. [VDEW 2006]

Since 1998 certain electrical household appliances have to be marked with the EU-Energy-Label in Germany. The legal basis for that labelling is the EU directive 94 / 2 / EG, dated January 21st, 1994, and the national energy consumption label regulation (EnVKV) based on the mentioned EU directive.

For that reason, at least the European market leaders in the field of refrigerators and freezers for households did some research and development projects to detect the energy saving potential using vacuum insulation panels (VIP) as part of the appliance insulation. In one of these projects, in which the company Porextherm Dämmstoffe GmbH was involved too, the starting-point was to install the VIPs once on inner surface of the outside walls of the appliance cabinet and once on the plastic liner of the appliance. With these two different philosophies for installing the high efficient vacuum insulation panels, the influence of surface coverage by VIPs relating to outer surface of the appliance was investigated. The vacuum insulation panels were placed in the door, the side walls, the back wall, the bottom and the top. With reverse heat leakage (RHL) measurements at a temperature of 27°C inside the cabinet and -20°C in the environment of the appliance the effectiveness of the VIPs were determined. For each design of VIP installation three appliances respectively cabinets were tested. Six thermocouples inside the cabinet and six thermocouples on the outside checked the temperatures and controlled the radiated power of the heaters just above the bottom of the appliance to guarantee constant measurement conditions.

The scenario I with VIPs on all described places on the inner surface of the outside walls of the appliance cabinet delivered at a maximum surface coverage of 70.2 % relating to outer surface of the appliance a RHL reduction of 32.5 %. Scenario II with VIPs on the plastic liner of the appliance delivered at a maximum surface coverage of 74.4 % relating to outer surface of the appliance a RHL reduction of 35.8 %. These results mean that the energy consumption of the test appliance can be reduced by using vacuum insulation panels to improve the heat insulation of the cabinet in the range of 20 to 25 %.

In case, that the roughly 29 millions refrigerators and freezers in Germany, which are at least 10 years old, will be replaced by high efficient appliances, an amount of approximately 8.500 GWh of electricity per year could be saved. With a conversion factor of 660 grams carbon dioxide (CO2) per kWh this amount of electricity corresponds to circa 5.5 million tons of CO2 per year. [Scholz 2007]

A really great potential to improve the environment of our children's world!

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Vacuum Insulated Passive Thermal Packaging Solutions

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Thermal packaging solutions for pharmaceutical industry generally consist of a well insulating material and a heat or cold storage medium to obtain and keep a certain temperature during transport. Today the demands on the performance of thermal packaging products for pharmaceutical industry rise more and more: many biotechnological products based on sensitive proteins require a strict temperature control between +2°C and +8°C and a so called one season packout. This means that there is no difference in the summer or winter setup of the thermal packaging. Typical materials in previous years are expanded polystyrene as insulation material and water bottles or gel packs for thermal storage. The latter had to be partly chilled and partly frozen and then to be arranged in a well defined way in order to obtain the requested temperatures. This led to heavy weight systems with low performance, a considerable failure rate due to temperature excursions (system errors) and human failures due to the complicated arrangements.

Modern thermal packaging solutions need a higher performance and do not allow any temperature excursions and thus require new techniques. In these cases VIP insulated containers have proven to provide an excellent performance and to fully meet the demands of pharmaceutical industry on next generation temperature controlled shippers. va-Q-tec designs and produces such high performance containers in a large industrial scale: from carton based one way shippers to rigid and robust air freight containers. In all cases the systems are constructed with a multi layer wall consisting of shock absorbing layers, stabilizing layers and VIPs. The inner volume of the containers contains one type of so called phase change materials (PCM) which provides a high level of thermal energy storage at a desired temperature requested for the safe shipment of the product. Such PCMs are typically salt solutions for temperatures below 0°C and organic materials like paraffin for positive temperatures.

All va-Q-tec containers are well qualified with respect to energy consumption and certain external temperature profiles. The necessary energy is provided by a defined amount of the PCM materials around the product to be shipped. The very sensitive energy balance within such high performance containers requires a strict quality control of all components used: a measurement and detailed control of the accumulated thermal energy content in the PCM bottles (called “accus”) and a measurement of the VIPs internal gas pressure after production, during assembly of the container and in many cases shortly before use. The latter is provided by the va-Q-check system, which is now part of many Standard Operating Procedures (SOP) of Pharmaceutical Industry. A one by one check after VIP production is a key for a reliable VIP application in many industries.

Based on profound thermal knowledge, experimental and numerical simulation techniques and a VIP material toolbox va-Q-tec provides solutions which fit exactly to the customers demands. In general va-Q-tec uses three types of VIP core materials: polyurethane foam, microfleece and pressed silica powder. Whereas the lightweight polyurethane foam is mainly used for one way packaging applications, microfleece is used for ultra thin walls and silica powder is used for longterm reusable products.

A high end example for the va-Q-tec packaging technology is the va-Q-tainer, which is an air freight container mostly used for the save transport of valuable pharmaceutical goods. The two main functional elements of the va-Q-tainer are the efficient VIP insulation and the PCM plates which are placed inside the container around the goods. The temperature performance of this container is excellent: Shipments up to more than a week at an exact inner temperature can easily be obtained at almost any ambient temperature profile (Fig.1). Even self recovering properties can be observed at certain ambient profiles. At present the passive va-Q-tainer is probably the most reliable transport tool for pharmaceutical bulk shipments.

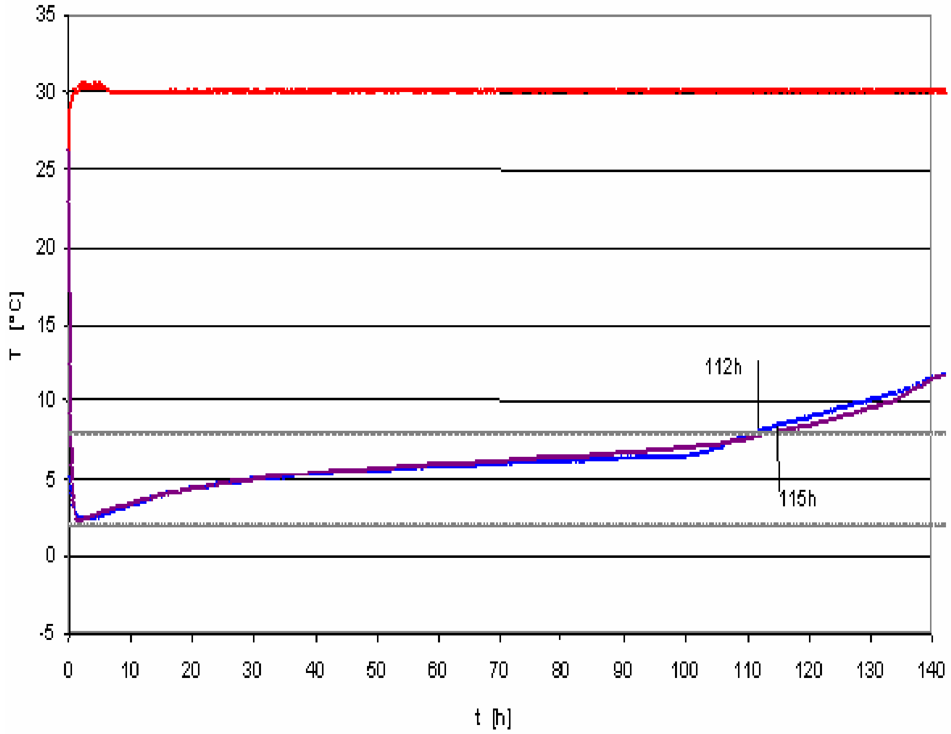

Fig.1: va-Q-tainer performance: Stable inner temperature (product temperature) between +2°C and +8°C for more than 100 hours at +30 °C ambient temperature.

Newly Designed Vacuum-Insulation for Big Pipes and Pipelines

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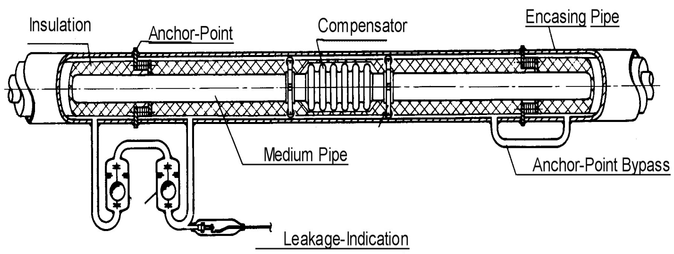
It is well known, that very low λ-values in the range of 0,004 W/m·K or less can be reached by using micro- or even nano-porous filler-materials. Today these so-called **s**upported **v**acuum-**i**nsulations (SVI) are in use in different applications – mostly with low or medium requirements regarding compressive stress, handling and evacuating.

Steel-**i**n-**s**teel pipelines (SIS) with an evacuated ring-space between the inner medium-pipe and the encasing pipe are well-known since the early 1960-ies [1]. The main application for this so called "Stahl-Mantel-Rohr" (SMR= SIS) is the district-heating, especially the transportation of hot (up to 400° C) or hazardous media over long distances. The space between the two tubes is mostly filled with low-compacted glass- or mineral-fibres; additionally the space is under light, continues vacuum of about 1 mbar. At mean-temperature of 100°C λ-values in a range of 0,02 W/m·K can be reached with such an insulation (which is about 50% of the specific heat-transfer-rate of the mineral-fibre at atmospheric pressure).

Old Design as shown in Ref.1



Ongoing Design of a SIS [3]

Figure 1: Steel in Steel Pipes (SIS) (Ref.1)

As this type of vacuum-insulation is not made to bear higher loads, the medium-tube has to be hold up by specially designed supports – which represent more or less heat-bridges.

New applications for SIS require much better insulating-characteristics – for example in deep-sea pipelines for the transportation of crude oil from off-shore fields, or even much more the transportation of liquefied natural gas (LNG with a temperature of –160°C), but also in the field of district-heating better features of the insulation are desirable sometimes. In case of big pipes (inside diameters in the range of 200 up to 1000 mm and distances of several kilometres) we have to keep in mind that the kind of manufacturing as well as the impact-loads have their own character and not every filler-material – as we know it from VIP-applications – can be used in such double-walled pipes.
The main aims of the R&D-project at FERNWÄRME-TECHNIK GmbH in Celle had been:

- low λ-values of less than 0,005 W/m·K (at a temperature-difference of more than 200°C) to have thinner insulations and smaller encasing pipe to lower costs for materials and passing the line
- high bearing pressure for the insulation-/ filler-material so that it can be foregone the special bearings
- easy handling of the filler-material during the mounting of the tubes

- easy to evacuate, even in case of water penetrating into the pipe throughout passing and assembling the line.

Different types of insulations-material (compacted powder, highly compacted micro-glass-fibres, bulk material of open celled mineral-foam and combinations of these) as well as several structures (with and without bearings) had been tested in a model experiment especially designed for this project.

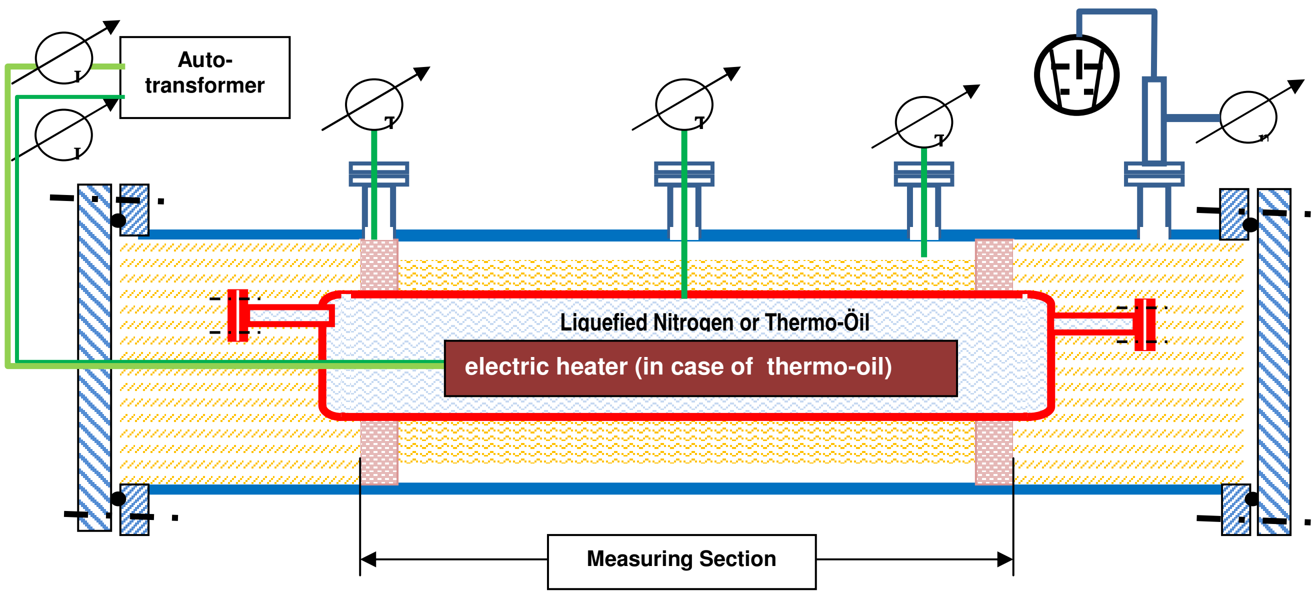


Figure 2: Design of the Measuring Section as used in the Tests for -196° up to 300°C

Good properties had been found by using high-strength glass-board-shells, which leads to low λ-values over the whole temperature-range of possible applications (-200°C up to 500°C), high stress-resistance and good handling-attributes during assembling and evacuating.

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ISBN 3-8169-2196-5 expertverlag 2003

[NN] FW Product Brochure SIS

Measuring Heat Transfer through Evacuated Glazing

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One attractive possibility to essentially improve the thermal insulation properties of a glazing is to evacuate the space between the glass panes [Weinläder 2005]. The low gas pressure eliminates heat transport due to convection between the glass panes and suppresses the thermal conductivity of the remaining filling gas. The glass panes can be prevented from collapsing by using a matrix of spacers (Figure).

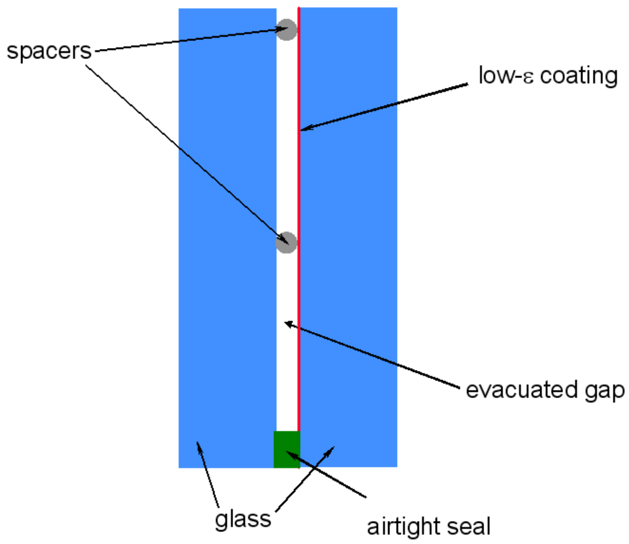

Figure 1: Diagram of a vacuum insulation glass with 2 x 4 mm float glass (system thickness < 9 mm).

These spacers, however, increase heat transfer between the glass panes. To quantify this effect, heat transfer through samples of evacuated glazing was experimentally determined. Samples were prepared with different kinds of spacer materials and spacer distances. The measurements were performed with a guarded hot plate apparatus [Heinemann 1995] under stationary conditions and at room temperature. The measuring chamber of the guarded hot plate was evacuated to $< 10^{-4}$ hPa. An external pressure load of 1,000 hPa, i.e. atmospheric pressure, was applied on the samples to ensure realistic system conditions. Radiation heat transfer between the glass panes was minimized by preparing every sample with one low-ε-coated glass pane. In a first step, comparison measurements without any spacers allowed to determine the amount of radiation heat transfer. With these data, the measurements with spacers could be corrected to separate the effect of the spacers on thermal heat transfer. The influence of the thermal conductivity of the spacer material as well as the distance between the spacers and spacer geometry (e.g. spheres, cylinders) was experimentally investigated. Pressure dependent measurements showed a great influence of external pressure load on the heat transmission coefficient (Figure 2) due to a variation of the thermal contact resistance between the spacers and the glass panes.

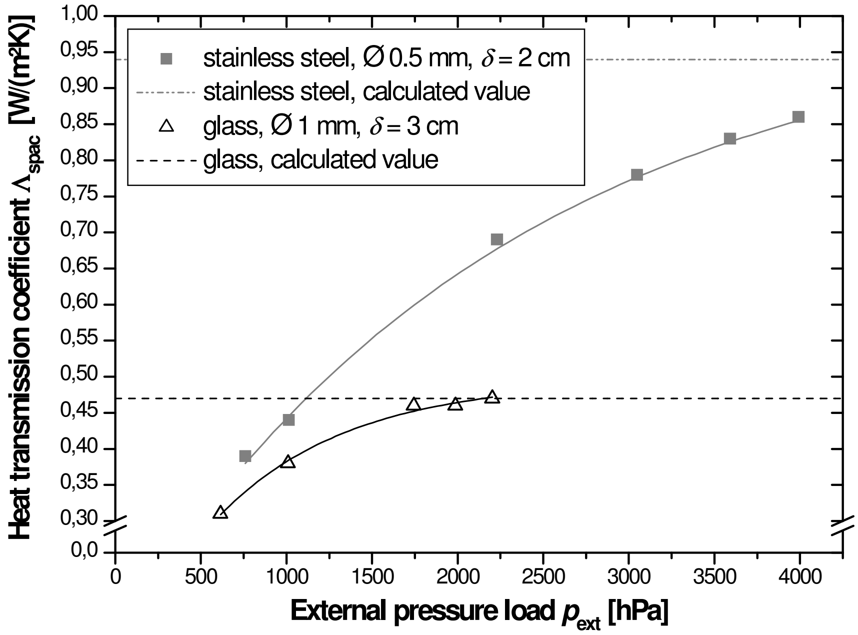

Figure 2: Measured heat transmission coefficients Λ_{spac} for cylindrical spacers made of glass and stainless steel as a function of external pressure load. The dotted lines show the calculated values of Λ_{spac} for a thermal contact resistance of 0 m^{2}K/W. δ is the spacer distance.

Finally, a test of an evacuated glazing system with thermally optimized spacers yields a total U-value of 0.58 W/(m^{2}K) when a low-ε-coating with $\varepsilon \approx 0.06$ is used. Using better low-ε-coatings, which are already commercially available ($\varepsilon < 0.03$), U-values < 0.5 W/(m^{2}K) are achievable with evacuated glazing.

Acknowledgements

The scientific investigations have been carried out within the research project "Vacuum Insulation Glass - VIG", which was supported by the German Federal Ministry of Economics and Technology (2004-2006, FkZ 0327366). During this project, the feasibility of Vacuum Insulation Glass has been shown. A current research project, also funded by the German Federal Ministry of Economics and Technology (FkZ 0327419), is focusing on developing a manufacturing process for serial production of VIG. This is to be completed by the end of 2010 (more information: www.vig-info.de).

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Transparent Aerogel Windows – Results from an EU FP5 Project

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Department of Civil Engineering (BYG) at Technical University of Denmark (DTU) was project manager of a recent EU FP5 project and on behalf of the consortium; some of the results are presented. Overall, monolithic silica aerogel was further developed with respect to the production process at pilot-scale, its properties and the application as transparent insulation material in highly insulating and transparent windows.

An industrial pilot facility for production of precursors for the aerogel production has been established and proved to be able to deliver the required amount and quality of precursor for lab-, medium-, and large-scale production. And intensive studies of ageing possibilities for strengthening the wet gels to achieve a more robust gel and thus less risk of cracks in the final aerogel sheet have been carried out and an understanding of the connection between strength and other material properties have been elaborated. This study has resulted in a reduction of the ageing time from 8 days to 1 day. Theoretical studies by means of CFD simulations of the super critical CO_2 flow during the drying phase in the autoclave have been used for optimisation of the drying process.

The aerogel production process has been optimised and tuned so monolithic silica aerogel sheets are produced with more than 85% crack free sheets per batch (12 sheets of 55 cm x 55 cm per batch). Furthermore the production time has been reduced to 1/3 of the initial production time through detailed theoretical and experimental analyses of especially the supercritical washing step included in the drying phase. At the same time the production plant have been modified to recycle most of the chemicals involved in the production process.

A large number of aerogel glazing prototypes have been made with partly evacuated aerogel in between two layers of low iron and anti reflection treated glass panes with an airtight edge seal solution based on multi-layered plastic foil developed for VIP. The edge seal solution shows only a very limited thermal bridge effect. The final glazing has a total solar energy transmittance about 87% and a U-value of 0.7 W/(m^2·K) for about 14 mm aerogel thickness, which for a 20 mm thickness corresponds to a U-value of approximately 0.5 W/(m^2·K). No other known glazing exhibits such an excellent combination of high solar transmittance and low heat loss coefficient.

At a Danish location and North facing, the energy balance for such a prototype glazing is calculated to be about 30 kWh/m^2 for the heating season whereas the best commercial available glazing has an energy balance of –10 kWh/m^2. Looking at single family houses, at two different insulation levels, the results of the comparison of the same two glazings are shown in table 1.

Building insulation level	Space heating demand [kWh/year]	
	Triple glazing	Aerogel glazing
Danish building code	6220	5040
Passive house	2070	1380

Table 1: Calculated energy consumption for space heating in two single family houses insulated to the Danish building code and to the passive house respectively with either argon filled triple glazing (U-value = 0.6 W/(m^2·K), g-value = 0.46) or with evacuated aerogel glazing (U-value = 0.5 W/(m^2·K), g-value = 0.75).

The most forward application would be as daylight components, but also for insulation panels with or without vacuum. However, it is believed that the vision through the aerogel glazing can be further improved and hence it can be applied as ordinary glazing.

Optimisation and Testing of an VIP Exterior Thermal Insulation Composite System (ETICS)

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The integration of VIP into a practical exterior insulation finish system has to consider both, insulation optimisation using the possibilities of VIP technology and practical applicability of the delicate system. Within our research project we developed in combination with the companies Maxit Deutschland GmbH and Porextherm GmbH a system which needs only few standard sizes for typical wall coverage, which may be size-adapted to a certain extent at the building site, and which shows minimum thermal bridge effects. The system is called the *LockPlate®-System*.

The system consists of VIP-panels enveloped with EPS. The geometry and thermal optimisation of the system has been developed using 2D-thermal simulation software. From single panels to the complete system a comparison between measurements using a hot-plate apparatus and the thermal simulations ensures the validity of the results. We show results for the standard system (basic VIP thickness 30mm thickness) and the passive house system (basic VIP-plate 40mm thickness). The clever idea is to cover the thermal bridge area with a lock plate incorporating a VIP also.

Figure 1: Schematical view of LockPlate®-System covering a wall using different baseplates and components (red=horizontal lock plate; blue= vertical lock plate) and production of the EOTA test wall

The system has been tested for stability utilising an EOTA test wall. The test had been successful, leading to the next project phase using the system at a demonstration house. The layout of a wall with windows covered with ETICS may be rather complex. For the VIP system a method for determining the average U-wall of the wall has been developed. T- and X-joints have been investigated experimentally. The results of experiments and simulation will be shown in the paper.

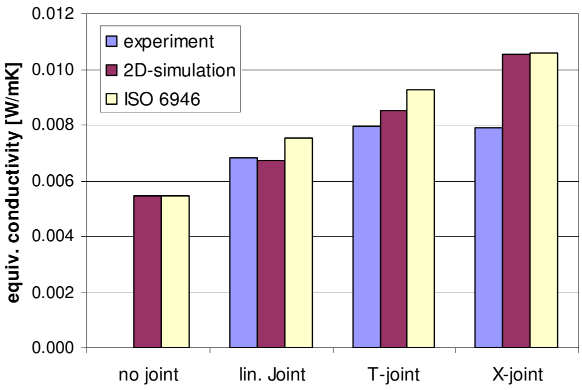

Figure 2: Results for equivalent conductivity of 30mm VIP-layer in ETICS depending on joint

Figure 2: VIP-ETICS-facades of demonstration house Giengen/Burgberg

Depending on the complexity of a real wall with windows and doors, the calculation of the equivalent thermal conductivity of the system is a tedious task in principle. A more detailed calculation using the linear thermal conductance of several thermal bridges within the system is compared with a simplified method according to DIN EN ISO 6946.

[DIN EN ISO 6946] ***DIN EN ISO 6946***, Bauteile - Wärmedurchlasswiderstand und Wärmedurchgangskoeffizient – Berechnungsverfahren, Deutsche Fassung EN ISO 6946:1996 + A1:2003

Development of Prefabricated Floor-to-Ceiling Insulation Elements with Integrated VIPs

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In 2006 the road-side facades of three small multi-family houses in Hofheim am Taunus were insulated with prefabricated floor-to-ceiling sized elements with VIPs and integrated windows. A special mounting system was developed to apply the insulation elements on the walls. The process of prefabrication and on-site installation was recorded in a documentary film.

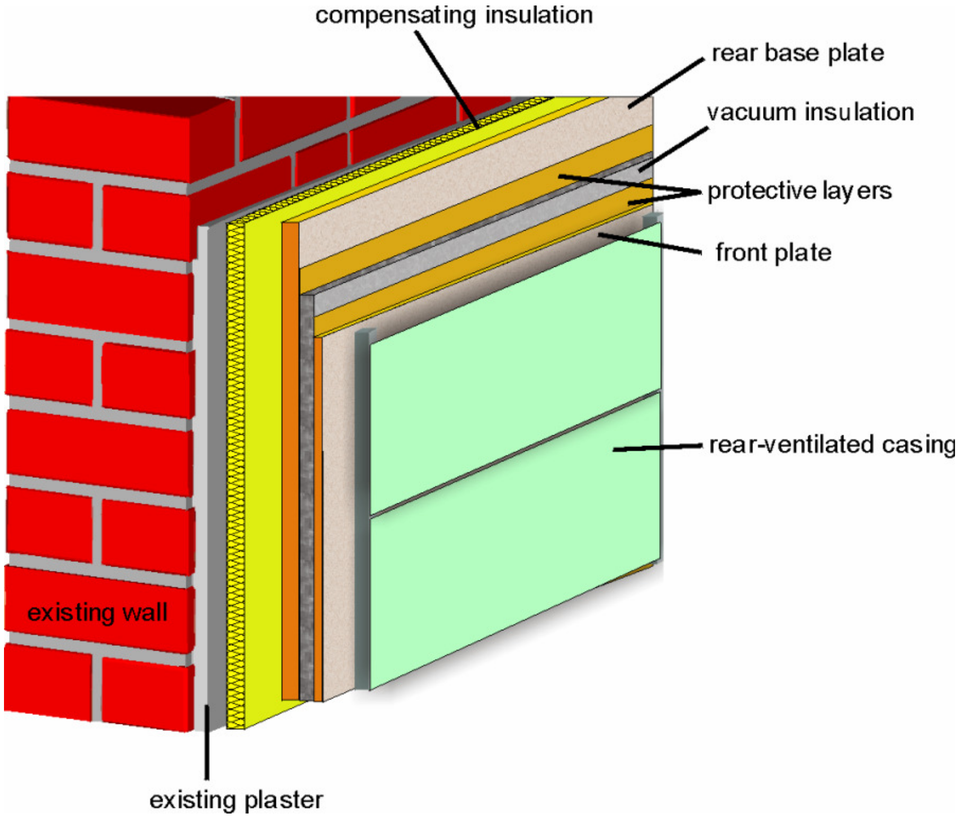

Figure 1: Cross-section of the element

Heat bridge analyses were carried out to reduce the additional heat loss through the fixing elements crossing the insulation layer. Parameter surveys of the 3D punctual fixing elements show the influence of thickness and material choice. In the final design the punctual elements raise the total U-value by about 15 %. A further increase of 25 % results from the joints between the VIPs and the elements. Special solutions were developed for the attachments of the elements to the other walls, to the roof and to the perimeter. The total U-value of the wall amounts to about 0.15 W/(m²K) (assuming a thermal conductivity of the VIPs of 0,005 W/(mK), that means without considering ageing) or circa 0,19 W/(m²K) (thermal conductivity of 0,008 W/(mK) in consideration of ageing).

Figure 2 gives an impression of the prefabrication process. The first vacuum insulation panel is being put to the element's rear base plate

Figure 2: Prefabrication of the insulation elements

Figure 3 shows the mounting of the elements at the buildings in Hofheim (still without casing which was installed afterwards). There are 4 elements per building with 14 VIPs and one window per element.

Figure 3: Mounting of the elements

The monitoring of the 168 VIPs installed at the three facades showed that a small number (about 3 % of the VIPs) were damaged during the assembly or mounting of the elements. The ongoing research project is carried out by Institut Wohnen und Umwelt (Darmstadt), Hofheimer Wohnungsbau GmbH, Planungsgruppe Drei (Mühltal), Ingenieurbüro Gathmann, Reyer und Teilhaber (Bochum), Variotec Sandwichelemente GmbH (Neumarkt) and Institut für Fenstertechnik (Rosenheim). It is funded by the German ministry of economies (via Projektträger Jülich) and by the Hessian ministry of economies.

Immediate Prospects for Vacuum Insulation in the British Site Built Housing Sector

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The Modern Masonry Alliance is sponsoring Ian Abley on an Engineering Doctorate at the Centre for Innovative and Collaborative Engineering at Loughborough University. The CICE is committed to advanced training and research in engineering and construction management. The theme of the EngD is **Better Built in Masonry**, with a focus on residential construction, and Ian will conclude his research in July 2011. The aim is three-fold, relating to the three scales of housing design:

Better Masonry Housing Technologies
To develop architectural ranges of advanced masonry wall constructions capable of achieving the highest performance standards required in the *Code for Sustainable Homes*, with the long structural design lives that bricks, blocks, and stone provide, while reducing the £/m2 of construction.

Better Masonry Housing Typologies
To show how masonry homes may anticipate the periodic upgrade of kitchens, bathrooms, toilets and utility rooms to accommodate the emerging building services foreseen in the *Code for Sustainable Homes*, while improving the m2/dwelling with larger internal and external space standards.

Better Masonry Housing Topologies
To consider streamlined and locally responsive approaches to residential development in relation to *Planning Policy Statement 3 – Housing* issued by central government, impacting on the density of dwellings/hectare within land use, spatial and infrastructural planning, and the £/hectare of land.

www.audacity.org
www.modernmasonry.co.uk
www.lboro.ac.uk/cice/

Britain built 196,000 homes in 2006, which barely met annual household growth. There is a growing appreciation that housing production must increase to meet demographic change, and additionally to replace the most dilapidated of the existing housing stock at a rate of more than 1% per annum. With a stock of just under 26 million homes, there is an emerging view that housing production must increase to 500,000 homes per year. This call for increased production is welcomed by the construction product manufacturing sector, and by many involved in arguing for reform of the land use planning system. (Heartfield 2006)

At the same time there is scepticism that Britain lacks the productive capacity for such a productive effort, suffers from a “skills shortage”, and is too concerned with the value of existing housing for there to be much prospect of housing supply being increased. (Barker 2004)

This paper will argue that since December 2006 the *Code for Sustainable Homes* (CLG 2006) will make it imperative that the sceptics are proved wrong. It is now clear that within the next decade the British house building sector shall have to increase the performance of all new housing to achieve a U value of 0.1 W/m2K through floor slabs, walls and roof, with a U value of 0.8 W/m2K at windows. This requires an air-tightness of 1.0 m3/hr/m2, and a disciplined integration of building services to ensure that the air-tightness is not compromised during periodic refitting of kitchens and bathrooms. Good thermal performance will require a transformation in domestic building services systems, and a reliance on mechanically ventilated heat recovery systems.

While these regulatory changes will require repetitive production of pre-approved designs, high standards of workmanship, and a more systematic approach to the design of housing as an upgradeable structure, the energy efficiency of new housing will stand in great contrast to the existing building stock upon which the property market is based.

As thermal performance is improved, and walls can no longer allow building services penetrations to occur without pre-planning for air-tightness, the market for vacuum insulation will develop. This will be forced by the need to improve the net to gross floor area ratio in new housing built to the *Code for Sustainable Homes*. New homes shall have to be larger, and construction thinner.

Space in the home will become as important as energy efficiency in the housing market, and business models will be developed by the construction product manufacturers interested in building the structure and the envelope of spacious and efficient housing. Their aim will be to secure market share through the planning process, establishing local economies of scale within administrative localities in which high performance housing has been pre-approved.

This will be most advanced in the site built masonry sector, where load-bearing brick, block and stone provides protection to vacuum insulation panels over the life of the structure. The technical challenge will be whether vacuum insulation manufacturers can demonstrate that their products will last the life of masonry construction.

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Thin Wall Technology: Building Cladding Using Vacuum Insulation

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There is increasing interest in using vacuum insulated panels (VIP) for building cladding. Very low U-values can be achieved with panels less than half the thickness of conventional polyurethane composite panels. The economic case for installing such cladding has also been presented using the net present value technique [Ogden 2005].

However, large, practical metal/VIP cladding systems have yet to be established. This paper presents selected aspects of work carried out as part of a UK Government funded project on advanced cladding systems in association with Corus and the Steel Construction Institute. It examines the problems encountered and possible strategies for resolving these problems.

Many of the design issues concern the reconciliation of thermal and structural properties:

- The relative thinness of VIP panels is such that the span to depth ratio is more severe and as result it is difficult to resist applied forces whilst maintaining conventional deflection limits and spans.

- Composite action of the type relied on in conventional steel/aluminium and polyurethane systems where the insulation material transmits longitudinal shear is difficult to achieve using vacuum bag based cores and the performance of these has proven unpredictable particularly in terms of their ability to recover shape in post load conditions.

- The build-up of panels is such that vacuum bags can be close to the external panel surface and so be subjected to thermal shock and consequent durability problems.

This paper describes detailed thermal analyses together with results of laboratory testing for load-deflection characteristics. It also presents some of the strategies presently being explored to resolve these technical design issues and questions whether conventional deflection limits are appropriate for vacuum based technology.

Demand for higher insulation levels is certain to increase, with ‘super-insulated’ cladding becoming a reality in the near future. Low U-values (high R values) will require increasing levels of insulation thickness, with conventional panels having to be 150mm or more to meet the requirements. It is in the area of ‘super-insulation’ that VIP-based cladding holds the key advantage of low thickness, and it was decided to concentrate on this in the development work.

Thermal conduction modelling has been used to show that a working panel of 1000 x 1500mm incorporating stiffening, foam encapsulation and inner VIP elements can achieve a U-value of under $0.2W/m^2K$ for a total thickness of 60mm (including edge effects).

The imperative to resist wind forces without excessive deflection is a major design issue. Whilst thin panels can be engineered to have very high levels of ultimate strength, sufficient to carry high wind loads, deflection is likely to be problematic. Research has therefore addressed this problem from two perspectives:

1. Minimising deflection by the effective design of the panels. This has involved the development of proprietary solutions that are beyond the scope of this paper.

2. Re-evaluating how much stiffness is required to produce serviceable building envelopes. Conventional cladding elements engineered to deflection criteria such as span/360 are significantly stiffer than the glazed areas within and around them. Examples exist of glazed elements designed to span/50 deflection criteria. This suggests that more flexible panels may well be acceptable that would take fullest advantage of the thinness of vacuum insulation systems.

Prototyping has been undertaken with the collaboration of the Centre for Joining Technology at Oxford Brookes University to understand the issues for production and to provide samples for structural testing.

Static deflection tests have shown that the panel design is capable of meeting the necessary deflection criteria for building cladding without the transference of stress to the VIP element within. Previous testing has shown that VIP cannot transfer shear stress without damage to the film and subsequent rupture, and that a strong carrier system would be needed. Further work will involve dynamic deflection testing to ensure that a realistic lifecycle is achievable.

Although the VIP is protected by a layer on conventional polyurethane, lifespan of the core could be much increased by minimizing the thermal cycling during use. Cladding can reach surface temperatures of over 70ºC in direct sunlight, an effect that is detrimental to both finish and core. Working with a well-known manufacturer of industrial coatings, it has been established that surface temperatures can be considerably reduced by introducing selective reflection in the near infrared part of the solar spectrum without compromising the range of coating colours available.

A complete cladding solution has been developed, with panels spanning horizontally between wind-posts, with glazing interfaces as required, or spanning vertically as floor-ceiling panels in conjunction with vertical glazing. Through-fixings would introduce unacceptable thermal bridging and might endanger the integrity of the vacuum panel, so a method of back-fixing has been developed which hold the panels in place from behind on a variation of the spider configuration often used with structural glazing. This mounting system has the added advantage of reducing the effective span of the panel by over 20%, hence making the deflection criterion less onerous.

The paper concludes that a viable cladding system using vacuum insulation technology is already commercially feasible and that research has shown the way forward to a practical high volume product for commercial and domestic buildings.

[Ogden, 2005] **VIP cladding panels for buildings: applications and conceptual solutions,** Prof RG Ogden and Mr CC Kendrick, 7th International Vacuum Insulation Symposium, Zurich 2005.

Sound Reduction of Vacuum Insulation Based Facade Panels

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The most important advantage of using VIP is the reduction of the thickness of the insulation layer in building panels used in façade constructions.

But the characteristics of the thermal insulation layer affects the sound insulation of panel. For example the thickness and the core material of a sandwich building panel also affects acoustical resonance and coincidence phenomena and by that the sound insulation.

VIP consists of a core material panel which is enclosed by a multi-layer envelope film (the gas barrier). A favourable core material is pressed powder board made of fumed silica with a specific mass of 190 kg/m3 and a porosity of 0,93 [1].

Under vacuum conditions with a pressure of approximately 1 mbar the core is sealed in a gas barrier. Because the core is restricted in its movements this will influences the mechanical properties, see table 1. The dynamic Young’s modulus is measured in accordance with ISO 9052 and a calculation of the dilatational resonance. Due the absence of air in the VIP the dynamical stiffness of the core decreases.

Sample	Flexural modulus in MPa[1)]	Dynamic Young’s modulus in MPa[2)]
VIP vacuum	36.1 ± 5.9	0.25 ± 0.03
VIP damage	16.8 ± 3.1	
Core atm.	7.1 ± 3.1	0.49 ± 0.06

Table 1 Experimental determined elasticity modulus of fumed silica VIP (Va-q-tec)
[1)] **The flexural modulus is converted for panel dimensions 1,25 x 1,50 m^2**
[2)] **In accordance with ISO9052**

Applied as insulation filling the sound absorption of a VIP is an important quality. Figure 1 shows the sound absorption coefficient of 20 mm VIP measured in a reverberation room. Above all the curve shows an absorption mechanism through resonance of the barrier.

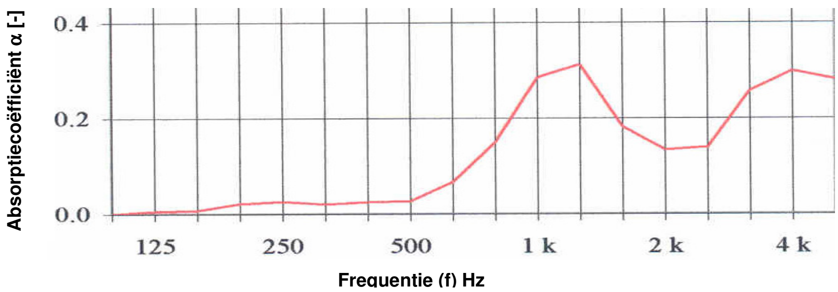


Figure 1 Sound absorption coefficient of VIP under vacuum conditions

As a reference is chosen a traditional sandwich panel with a core of 80 mm Styrofoam and 3 mm Trespa face sheets (panel A). Sandwich panel B with a core of 20 mm VIP and 3 mm Trespa face sheets has equal thermal resistance. This panel is measured with VIP intact (panel B1) and with VIP damaged (panel B2).
Also a panel can be composed as a double leaf panel just like double glazing. The panel consist of 3 mm Trespa face sheets which are connected through 20 x 20 rigid PUR laths; panel C1 with vacuum and panel C2 with vacuum damaged VIP panels as filling.
The dimensions of all the panels are 1250 x 1500 mm^2.
The results, expressed in the weight sound transmission loss R_w are given in table 2.

Panel		**m in kg/m^2**	**R_w in dB**	**C in dB**	**C_{tr} In dB**
A	reference panel, core 80 mm Styrofoam	10,7	25	-2	-3
B1	sandwich panel, 20 mm VIP intact	11,9	27	-2	-4
B2	sandwich panel, 20 mm damaged	11,9	28	-1	-3
C1	double leaf panel, frame 20 x 20 mm rigid PUR, filling 20 mm VIP intact	12,5	25	-1	-3
C2	double leaf panel, frame 20 x 20 mm rigid PUR, filling 20 mm VIP damaged	12,5	28	-1	-4

Table 2 Weighted sound transmission loss in accordance with NEN-EN-ISO 717-1

More or less the sound transmission loss of a sandwich panel is determined by the mass law. Negative deviances are the result of resonance and coincidence phenomena of which the dilatational frequency and the panel coincidence frequency are important.

In general terms the differences between R_w of the several panels are not striking. Remarkable is that the panels with VIP damaged have a sound transmission loss that is 1 to 3 dB higher than the corresponding panel with VIP intact. The panels with VIP are equal or better than the reference panel.
For the reference panel in according with the calculated dilatational frequency f_d is 2100 Hz.
For the VIP panel B1 f_d = 725 Hz so the dilatational frequency moves approximately one octave to the lower frequency range. For the 3150 Hz one-third-octave band the panel coincidence effect becomes visible.
In general terms there is an improvement of R_w of 2 dB due the increase of the weight (from 10,7 to 11,9 kg/m^2) of the panel with the VIP core (1,2 kg/m^2) and the shifting of f_d to the lower frequency range.
The damage of the vacuum, panel B2, causes a decrease of the mutual connection of the different layers of the sandwich panel with as result a shift of f_d to the lower frequency range in combination with a decrease of the sink. The panel coincidence frequency moves to higher frequencies. The resulting increase in R_w is 1 dB.

Figure 2: Measured sound transmission loss of reference panel (A) and VIP sandwich panel (B1)

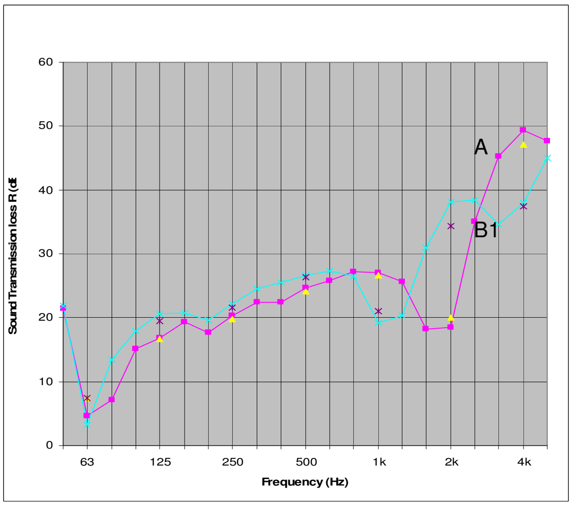
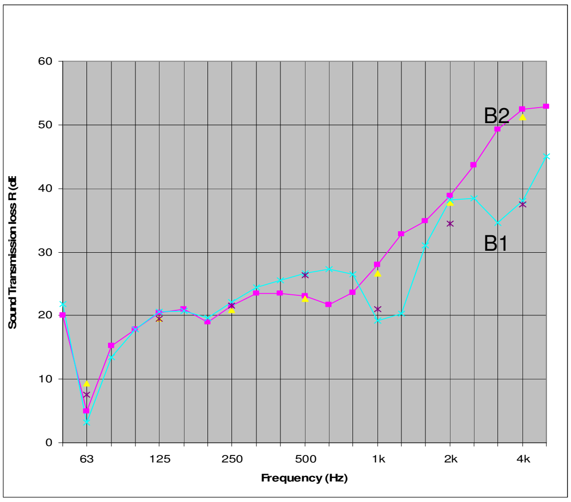


Figure 3 Measured sound transmission loss of VIP sandwich panel with (B1) and without (B2) vacuum conditions



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In Situ Performance Assessment and Service Life of Vacuum Insulation Panels (VIP) in Buildings

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In recent years the vacuum insulation panel (VIP) has been introduced into the building industry [IEA 2005]. VIP is a space saving alternative to conventional thermal insulation thanks to its 5 to 8 times higher thermal resistivity. Since gas permeation through the envelope barrier may drastically reduce the insulation efficiency, aging effects and service life expectation are crucial aspects of those high performance insulation assemblies [Schwab 2005, Simmler 2005]. In the present paper, performance data from two installed VIP areas in Swiss buildings are reported. One object is a VIP insulated flat roof, from which data have been collected over more than 2 years. VIP performance characteristics in terms of internal pressure and mass increase due to water vapour permeation are determined periodically by opening the sealed test area and subsequent measurement in the laboratory. The other location is a freezing room with a floor insulation built with VIP in March 2006. Because these panels are not accessible, the internal pressure is measured in situ by means of permanently installed heat flux detectors [Caps 2005]. In addition, temperature and relative humidity data on the surfaces and joints of VIP insulation layers as well as climatic boundary conditions are recorded continuously at both test sites. The results are compared with laboratory aging data obtained at constant conditions by linear and Arrhenius weighting of the dynamic boundary conditions. Justified by satisfactory agreement for the monitoring period in the flat roof application, a similar approach is applied for the prediction of the thermal performance after an installation time of 25 years.

The observed pressure increase (see Figure) may again be converted into a degradation of the thermal resistance. With a constant rate p_a = 0.6 mbar/yr, the increment of the thermal conductivity due to pressure increase after e.g. 15 years is just $0.3{\cdot}10^{-3}$ W m^{-1} K^{-1} or about 7 % of the initial value. Depending on the application, significant increments of the initial thermal conductivity must be taken into account. While the increment in cold and dry environment may be less than $0.5{\cdot}10^{-3}$ W m^{-1} K^{-1} in 25 years, it may reach $3{\cdot}10^{-3}$ W m^{-1} K^{-1} in building envelope components in the presence of regular moisture and temperature loads. In addition, thermal edge effects must be accounted for [Ghazi 2004]. Nevertheless, predicted long-term design values around $8{\cdot}10^{-3}$ W m^{-1} K^{-1} confirm the big potentials of VIP in building applications.

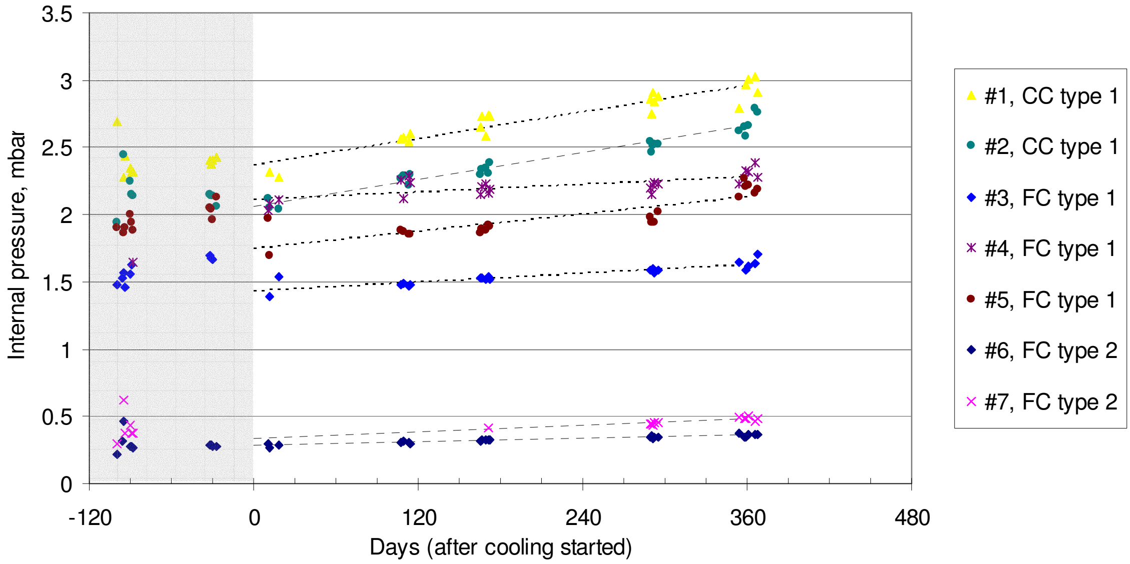

Figure: **Preliminary results from in-situ measured internal pressure of VIP floor insulation in the cooling / freezing chamber. The dotted lines indicate the respective linear trends with roughly between 0.1 and 0.6 mbar/yr.**

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Poster Presentations

Investigations on Highly Insulated Membrane Wall Constructions

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The work conducted and laid out here has been initiated by the Author's work on his PhD-thesis with the title 'Applications of Vacuum Insulation Systems in the Building Envelope - Technological, Physical and Architectural Aspects' [Cremers 2006]. Herein, opaque, translucent and transparent vacuum insulation systems have been studied and for the first time classified with regard to their potential for the application in the building envelope. Therefore, approved and conceivable solutions have been typologically recorded and exemplified. The thesis also places emphasis on the following aspects:

- Study on new mat-like vacuum insulation systems proposed by the author
- Characterisation of non load-bearing, highly insulated and very slim wall constructions
- The potential of vacuum-insulation-systems for temporary thermal protection
- Evaluation of linear thermal bridges within single-leaf VIP constructions

One of the main experimental studies has been on very slim wall constructions as presented already in [Cremers 2005]. For the thesis, different alternatives have been developed and presented but only one of the variants has been built and examined as a prototype model at Technische Universität München.

Working at SolarNext AG in Rimsting now which is a Hightex Group Company the author is now in a position to examine the most interesting of the presented alternatives in a more detailed and elaborated way as Hightex is one of the world leaders in structural foil and membrane constructions. The variants examined here are stabilised by membranes on both sides in parallel, the inside and the outside - basically following the ideas of Frei Otto from the 1950s that he named 'Buckelzelte' (Buckled tents), see fig. 1 [Roland 1965].

The principle section of the wall-type examined is given in fig. 2. Façades made with membrane or foil materials are still very rarely found as architectural applications but offer great future potential as they require an absolute minimum of material (in mass) and there is a big variety of new high performance fabrics and foils available (particularly Fluorpolymers). Therefore, the combination of the potential of the best performing insulation material (concerning the ratio of slimness and insulation) with the best performing envelope material (with regard to the ratio of the qualities required and the resulting mass involved) seems to be highly promising. The result would be nothing less than a new type of building envelope.

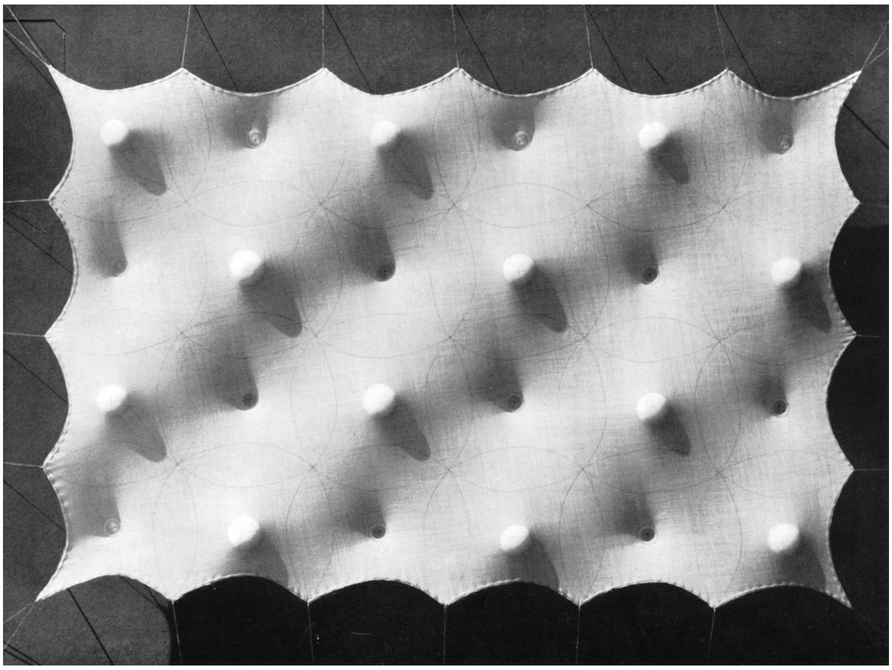

Figure 1: Principle of 'Buckled' Membrane Constructions as shown by Frei Otto [Roland 1965]

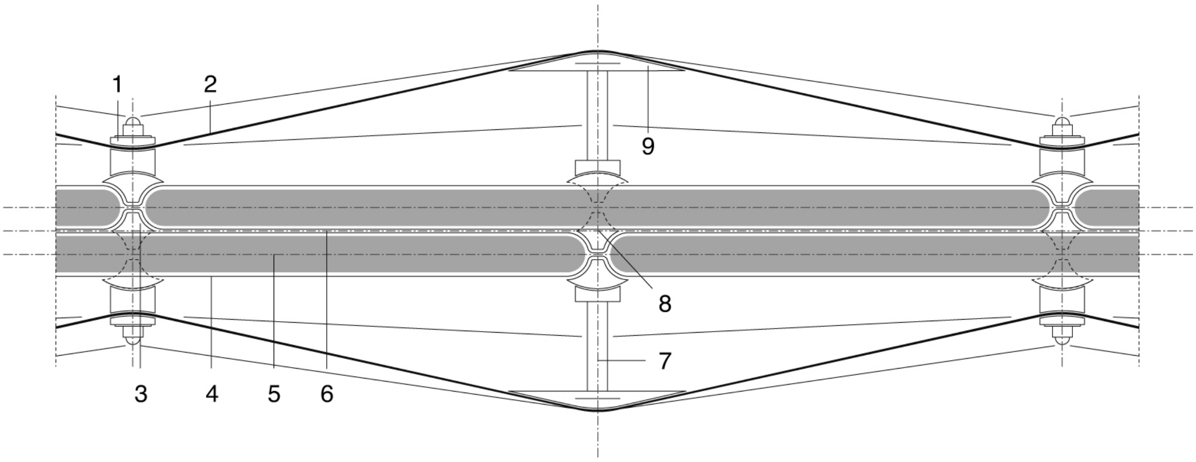

Figure 2: Principle section of investigated membrane wall constructions [Cremers 2006]

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Calculating the Thermal Conductivity of VIP

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In the recent years VIP with envelopes made of polymeric high barrier films and with a pressed powder filling have been introduced into the building market. In these applications the high thermal resistance should be maintained for at least 20 to 50 years. Up to now there are no thermal resistance or thermal conductivity data of real panels available over such long periods. To assure the durability for this long time, nevertheless, the expected increase in thermal conductivity with time has to be calculated. Thus, measurements are performed for a short period – generally about six month – and the resulting increase will be extrapolated in time.

For this type of VIP degradation of the thermal performance with time is caused on the one hand by penetrating dry air and on the other hand by incoming water vapour. For pressed fumed silica boards a relatively high gas pressure typically in the order of 100 mbar may be tolerated before thermal conductivity starts to increase significantly. Within the scope of durability prediction an increase in internal gas pressure can be detected much faster and more sensitive than an increase in thermal conductivity. Thus repeated measurements of the internal total gas pressure – e.g. performed by the foil lift-off method – are often the bases for calculations of the expected increase in thermal conductivity with time. Besides the influence of permeating dry air also the impact of initial water content – both adsorbed by the filler material and as water vapour in the pores – and its variation with time have to be considered for prognoses of the thermal behaviour. Therefore, repeated weighting has to be carried out, too.

Thus, to calculate the thermal conductivity of VIP, the increase in pressure caused by the dry gases and the varying water content of the kernel with time must be known as well as the initial water content after production.

In this paper such a data set will be presented. In contrast to the common practice, the increases of mass and gas pressure are measured over a longer period (up to two years) and the increase of the thermal conductivity itself is measured, too. The measurements are performed on VIP stored at different climatic conditions. In Figure 3 there are the three measures (thermal conductivity, internal gas pressure and mass) over time exemplarily shown for a panel.

Finally, the measured thermal conductivity will be compared with the thermal conductivity calculated from the measured data of gas pressure and mass [Schwab et al. 2005] (see eq. (1)) and the accuracy will be discussed.

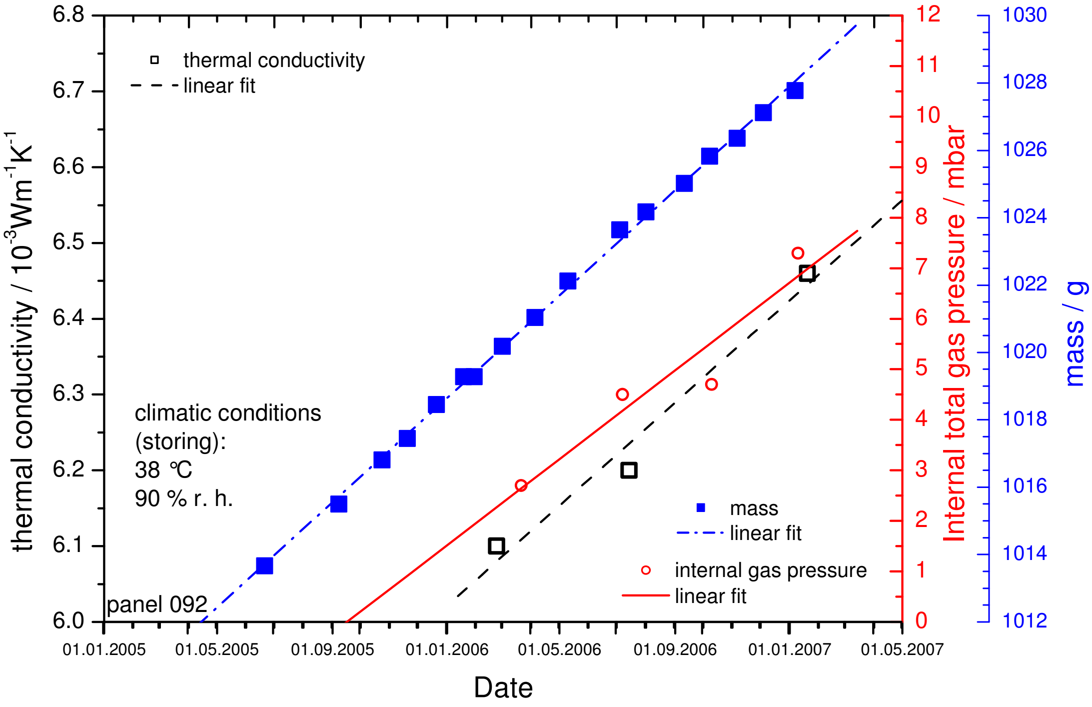

Figure 3: Increase of the thermal conductivity (squares; left ordinate), the internal total gas pressure (circles; first right ordinate) and the mass (filled squares; second right ordinate) with time. For each measure a linear fit is shown, too. The panel (092) was stored in a climate chamber at 38°C and 90 % relative humidity.

The calculation of the thermal conductivity is given in Equation (1):

$$\lambda(t) = \lambda_o + k_p \cdot (\partial p/\partial t) \cdot t + k_X \cdot a \cdot \varphi_a \cdot \left[1 - \exp\left(-\frac{t}{a \cdot \varphi_a} \cdot \dot{X}(t=0)\right)\right], \tag{1}$$

with the core dependent constants k_p and k_X , the slope of the sorption isotherm a and the external relative humidity φ_a.

Therefore, the following measures have to be performed:

	λ_o	thermal conductivity at the beginning,
	$(\partial p/\partial t)$	increase in internal gas pressure over time (sum partial pressures of the dry gases) and
	$\dot{X}(t=0)$	derivative of water content with respect to time in the panel at the beginning.

The water content X is defined as

$$X = \frac{\Delta m_{water}}{m_{core,\,dry}}, \tag{2}$$

and is given in mass-%.

Acknowledgment

The project „Energieoptimiertes Bauen, Teilkonzept 1: Aufbau einer Koordinationsstelle für die nationalen Tätigkeiten zum ECBCS-Annex 39 „High Performance Thermal Insulations for Buildings“ (HiPTI) der Internationalen Energieagentur (IEA) und Qualitätskontrolle von Vakuumisolationspaneelen [0327321E]“ is funded by the BMWi (German Federal Ministry of Economics and Technology) in Berlin.

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Radiative Properties of Silica Nanoporous Matrices

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Nanoporous superinsulating materials are currently the subject of much attention because of their awesome thermal insulation properties [Goyhénèche *et al*, 1999]: up to five times better than air, generally regarded as an excellent thermal insulator, when they are placed under primary vacuum. These materials are made of nanoporous matrices of amorphous silica nanoparticles, fibres to provide mechanical reinforcement and micrometric particles to improve opaqueness in the infrared wavelength region. Our aim is to determine experimentally and to model the radiative properties of such nanoporous materials, which are semi-transparent media in the considered wavelength range. In the simplified approach presented here, we consider the nanoporous matrix alone.

To measure the spectral transmittance and reflectance properties, we used two different spectrometers covering an overall spectral band of [250 nm ; 25 µm] and equipped with integrating spheres that collect hemispherically the radiation travelling through or reflected by the samples. These samples were made by compacting powders of 10 nm diameter particles (supplier: german company Wacker) and were of different thicknesses. The porosity of each sample was about 90%. Using the radiative transfer equation formalism and a parameter identification technique based on the Newton-Raphson algorithm, we determined the spectral radiative properties (*i.e.* the extinction coefficient and albedo spectra) of the nanoporous matrix from the experimental values of the spectral hemispherical transmittances and reflectances. For the resolution of the radiative transfer equation, we assumed one-dimensional radiative transfer in an absorbing, scattering, non-emitting semi-transparent medium with azimuthal isotropy.

The experimentally determined radiative properties of the nanoporous matrix were then compared to the results of the well-known Mie theory [Van de Hulst, 1957]. As the primary particles used to prepare the samples were hydrophilic silica particles, we had to take into account the water contribution, so we used a coated sphere model [Bohren *et al*, 1983] (a water coating thickness of 2 Å was retained). The only way that we found to get a good agreement between the theoretical and experimentally obtained radiative property spectra was to consider a particle diameter of 55 nm instead of 10 nm (figure 1). Consequently, from the point of view of the interaction with electromagnetic waves, our material behaves approximately as a cloud of uniform size particles of about 55 nm diameter. Although this value is significantly different from the diameter of the primary particles, it is not an absurd value: indeed, during the silica powder fabrication process, the primary nanoparticules of 10 nm diameter fuse together to form larger units of approximately 120 nm hydrodynamic equivalent-sphere diameter [Wacker]. If we assume that the porosity of these aggregates is the same as the one of the matrix, the volume of silica contained in such an aggregate is equivalent to the volume of a dense silica sphere of 55 nm diameter. Hence, we can venture the hypothesis that the nanoporous matrix scatters as a cloud of primary scatterers, the primary scatterer being here the aggregate obtained during the production process.

In order to confirm this hypothesis, we are currently working on the Discrete Dipole Approximation (DDA) [Draine *et al*, 1994] [Okamoto, 1995] [Yurkin *et al*, 2007] to compute the radiative properties of an aggregate. The DDA is a flexible method that allows to compute the absorption and scattering properties of irregular targets (particles of complex shapes, clusters of spheres) approximated by arrays of point dipoles. DDA calculations require the localization of the dipoles in space and the evaluation of their polarizabilities. Concerning the polarizabilities, since we apply the DDA on a cluster of spherical particles that are small compared to the wavelength, we may treat each particle as a single dipole using the a_1-term method. This method has been shown to be superior to the other polarizability prescriptions for a cluster of spherical monomers replaced by single dipoles [Okamoto, 1995]. The dipole moments within the cluster result on the one hand from an incident electromagnetic field that activates them, and on the other hand from the interaction between them; once these dipole moments are solved, it is possible to determine the radiative properties of the cluster.

Prior to DDA calculations, the dipoles must be localized in space. To obtain valuable results, the material structures on which DDA calculations are performed must be representative of our nanoporous material in terms of porosity (≈ 90%), specific surface area (≈ 250 $m^2.g^{-1}$) and fractal dimension (≈ 1.8 according to the literature [Legrand, 1998]). As no tomographic characterization is currently possible at that length scale, we have resorted to the numerical generation of structures with the help of the Diffusion Limited Cluster-Cluster Aggregation algorithm [Meakin, 1983] [Kolb *et al*, 1983]. We have integrated the water contribution in the relative dielectric permittivity function and hence in the polarizability function of the particles with the help of the Maxwell-Garnett mixing rule. We have generated clusters of 170 particles of 10 nm diameter with the equivalent of 2 Å thick water coatings. The number of 170 particles was chosen in order to form clusters of 120 nm equivalent diameter and of 90% porosity. The satisfactory correspondence between the experimental and simulated radiative properties spectra (figure 2) is quite encouraging, and is a first step toward a reasonable representation of the material organization within our nanoporous matrices.

Summary and perspectives

We have determined the spectral radiative properties of silica nanoporous matrices from experimentally obtained reflectances and transmittances using a parameter identification. These data have been compared to the Mie theory assuming a uniform diameter distribution of 10 nm for the particles. To get a good agreement between the experimental values and the Mie theory, we had to increase the particle diameter up to 55 nm.

From the very little we know about the silica powder, we have proposed an explanation that seems to be confirmed by the first DDA calculations. Nonetheless, these results must be toned down because they are based on the use of a structure with a given fractal dimension, that is close to what is usually found in the literature. As many other different fractal dimension values can be found, depending notably on the particle size and volume fraction, fractal dimension measurements of our samples are in progress using X-ray and neutron scattering techniques.

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[Yurkin *et al*, 2007] **The discrete dipole approximation: an overview and recent developments**, Journal of Quantitative Spectroscopy and Radiative Transfer (2007), DOI: 10.1016/j.jqsrt.2007.01.034

Figures

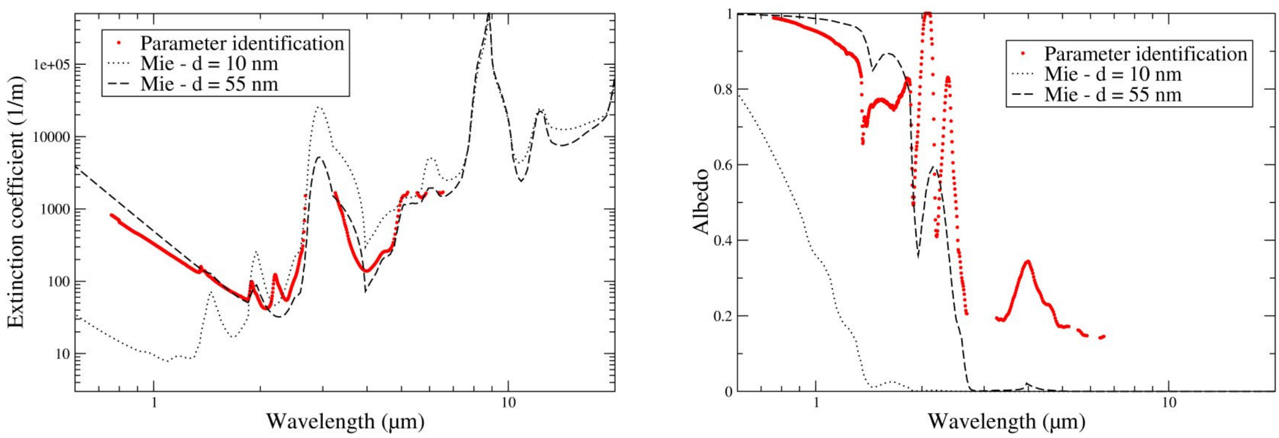

Figure 1: Comparison of the experimental extinction coefficient and scattering albedo spectra (red dots) to the results of the Mie theory for two particle diameters. Data used for the Mie calculations: particles of 10 nm and 55 nm diameters coated with 2 Å of water, solid volume fraction = 10%.

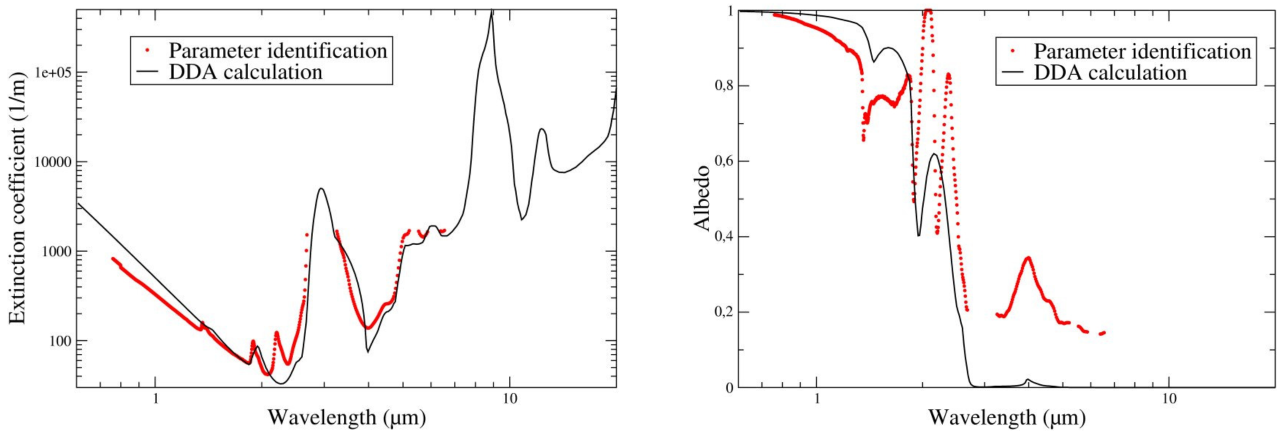

Figure 2: Comparison of the experimental extinction coefficient and scattering albedo spectra (red dots) to the results of a DDA calculation for an aggregate of 170 particles of 10 nm diameter.

Numerical Simulation of Vapour and Gas Transport into a VIP Panel

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The quality of high-barrier films is decisive for the lifetime of a VIP system. If gas and vapour pressure within the core material raise to unacceptable levels depending on the core material pore size distribution, the vacuum is destroyed and the thermal conductivity within the VIP rises. Usually water vapour transmission rates WVTR and oxygen transmission rates OTR are being optimised for guaranteeing a long service life time. However this is not the only factor of influence. Sorption and wetting processes within the core material have to be taken into account as well. The boundary conditions due to temperature and humidity variations with the built environment have to be known.

In order to understand the rather complex transport processes and their interactions a numerical simulation model has been developed. The following parameters are being considered in the model:

- gas and water vapour permeability coefficients dependent on temperature
- adsorption and desorption processes within the core material
- increase of thermal conductivity due to humidity and gas pressure
- possibility to incorporate line defects of barrier films (e.g. due to edges, folding)
- panel dimensions
- different gases oxygen, nitrogen and water vapour
- changing boundary conditions inside and outside

The numerical model has been coded in Fortran and uses a relaxation technique to enable convergent iterations. In order to check the model experimental testing of VIP panels has been performed in controlled climate chambers varying temperature and relative humidity in cyclic tests. The internal pressure of the VIPs has been recorded qualitatively with RFID sensors.

Depending on data used for barrier films, core material, geometry, line defects we get rather different results. An overview will be presented in the paper as well as some interesting effects. For example, due to the higher permeability of oxygen compared to nitrogen, the percentage of gas pressures due to individual gases change. However in practice, water vapour and humidity is the main factor increasing the thermal conductivity of the VIP.

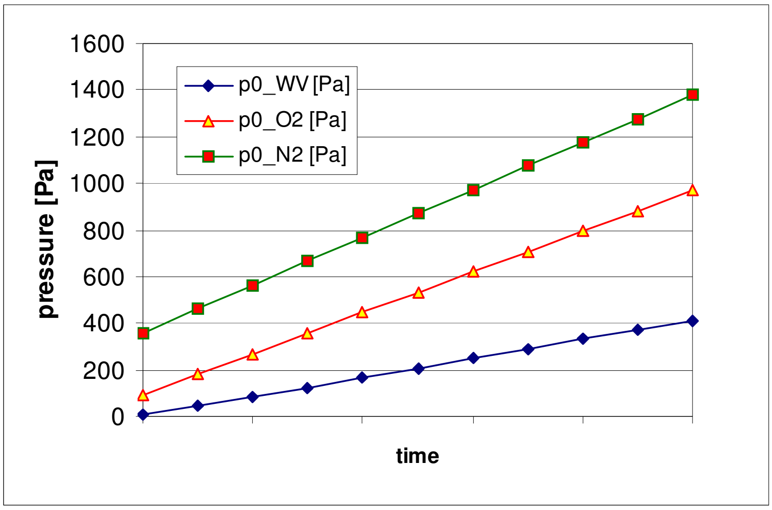

Figure 1: Qualitative result for gas pressure increasing over years

The model cannot on one hand be used for trying to predict the increase of gas partial pressures and core humidity over the years, using the boundary conditions of temperature and humidity occurring in real building constructions. These can be measured or simulated with multidimensional hygrothermal simulation software as e.g. WUFI or DELPHIN.

On the other hand the testing in the laboratory e.g. in climate chamber can be simulated as well. The time dependence of gas pressure due to the effects of permeation, sorption and desorption as well as the local distribution of core humidity can be predicted.

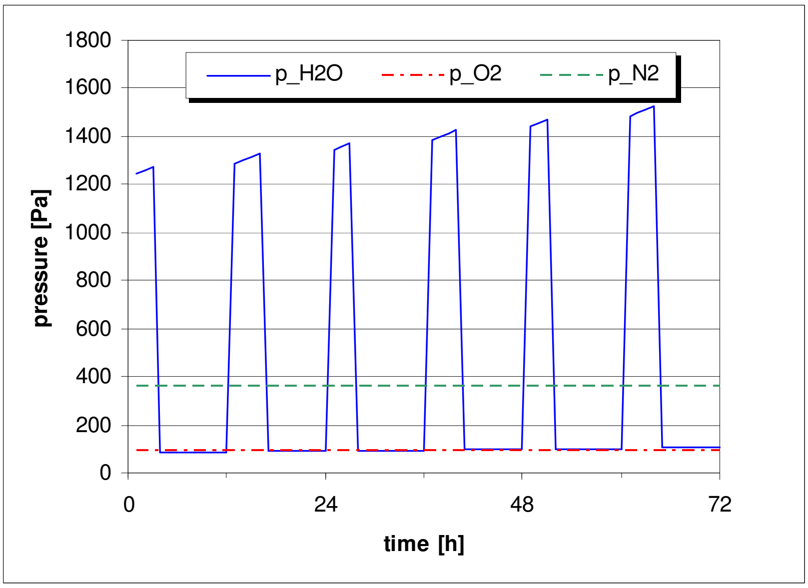

Figure 2: Simulated time-dependence of water vapour pressure during a cycling test alternating between 25°C and 60% r.h. and 80°C and 80% r.h.

Simplified Analytical Models for Service Life Prediction of a Vacuum Insulation Panel

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Because of the desire for sustainability and obligations due to international protocols and treaties, primary energy generation with fossil fuels needs to be reduced drastically. Since increasing the thermal performance of building skins with conventional insulators would enlarge the thickness of these skins to beyond thicknesses that are practically desirable, alternative more efficient thermal insulation materials, like vacuum insulation panels (VIPs) have caught the attention of the building sector. Vacuum insulation panels consist of a core material and a barrier envelope to keep this vacuum for as long as possible or desirable. In this state of vacuum, the thermal conductivity of the product is reduced significantly to a value of about $4{\cdot}10^{-3}$ $W{\cdot}m^{-1}{\cdot}K^{-1}$, as a result ideally outperforming all conventional gas-filled thermal insulators by a factor 5 to 10 [Caps et al., 2001].

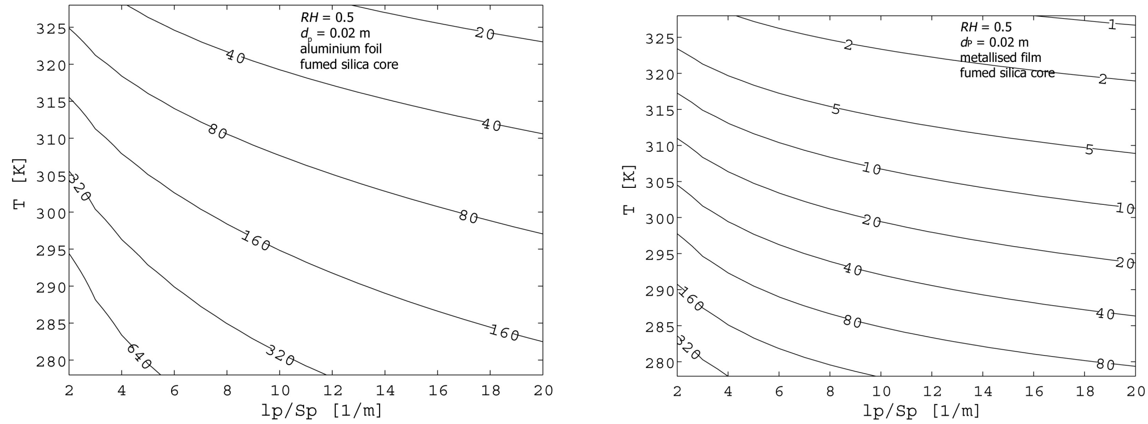
This barrier envelope, however, is not completely gas and water vapour tight, as a result of which atmospheric gases and water vapour will migrate into the core material, slowly but gradually increasing its thermal conductivity (thermal conductivity ageing). The rate at which gas pressure and water content will increase depends on the barrier quality of the envelope, i.e. oxygen transmission rate and water vapour transmission rate, and of the barrier and production quality of the seal. The service life of a VIP can now be defined as the time that elapses from the moment of production until the moment the thermal conductivity has increased to a limit value, often set at $8{\cdot}10^{-3}$ $W{\cdot}m^{-1}{\cdot}K^{-1}$ [Simmler and Brunner, 2005].

For estimating this service life, physical mass balance and transport equations can be used in conjunction with permeation data obtained from laboratory or field measurements. Simmler and Brunner [2005] and Schwab [2004] showed how to estimate service lives based upon this method by determining the thermal conductivity as function of time. To determine the service life using these equations is accurate, as far as the measurements are accurate, but requires an iterative procedure. Based upon these models, it is possible to derive analytical equations for rapid estimation of the service life without first calculating and plotting the thermal conductivity of the core material as a function of time. Depending on the type of equation, several semi-experimental parameters need to be determined from laboratory measurements on VIPs for different barrier envelope and core combinations. This paper therefore derives and presents the aforementioned service life prediction models and determines the semi-experimental parameters for VIP combinations of a metallised and an aluminium-based high barrier envelope and a core material of fumed silica and PU-foam.

The simplified service life prediction models are based on the following proportional relations:

$t_{SL} \sim d_p$ Since the panel volume is the product of the panel thickness and surface area, the service life is linearly proportional to the panel thickness.

Figure 1: service life t_{SL} [yr] of a VIP with a fumed silica core and a metallised film (left) or an Al based foil (right) as function of panel size and temperature for a panel thickness of 20 mm at 50% RH.



$$t_{SL} \sim \frac{1}{T} e^{\frac{E_a}{R}\left(\frac{1}{T}-\frac{1}{T_0}\right)}$$

Since both WVTR and GTR of the barrier depend on temperature according to an Arrhenius type equation and if the water vapour saturation pressure curve is assumed to be linear with temperature within in a small temperature interval, t_{SL} depends on temperature according to the equation beside.

$$t_{SL} = f\left(\frac{l_p}{S_p}\right)$$

Moreover, since both WVTR and GTR can be separated into a part involving the edge transmission and a part concerning the area-related transmission, the ratio l_p / S_p (panel perimeter length to surface area ratio) plays an important role, too

Among others based upon these relationships and using experimental data from Simmler and Brunner [2005] and Schwab et al. [2004], simplified closed analytical service life prediction models have been determined for a VIP with a core of rigid polyurethane foam and for a VIP with a core of compressed fumed silica board. It must be noted that the maximum deviation between the advanced model and the approximation model can be as large as about 17%. These large deviations however only occur for a value of λ_{lim} which lies relatively closely to λ_0. For λ_{lim} > 0.008 $W \cdot m^{-1} \cdot K^{-1}$ deviations go to below 8%. Based upon the models and experimental data, it is possible to create service life plots with the service life as function of temperature, service life limit, panel thickness and/or panel size. Figure 1 shows two examples of service life plots with the service life of a VIP with a fumed silica core and a metallised film (left) or an aluminium based foil (right) as function of panel size and temperature for a panel thickness of 20 mm at 50% RH from which t_{SL} can easily be determined.

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Analytical Models for Predicting Thermal Bridge Effects due to VIP Barrier Envelopes

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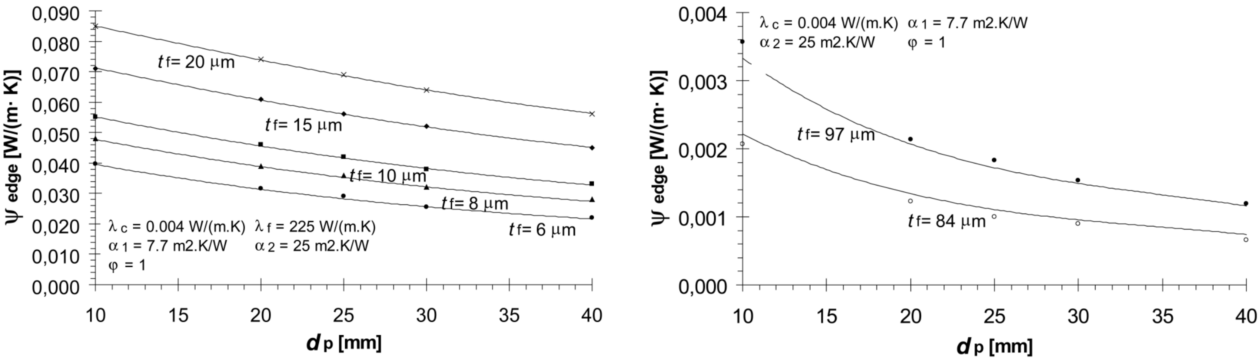
Because of a necessity for sustainability and thus for a reduction of the amount of primary energy generated with fossil fuels, vacuum insulation panels have recently caught the attention of practitioners in the building industry. Vacuum insulation panels (VIPs) are thermal insulators with a very low centre-of-panel thermal conductivity, as a consequence requiring limited thickness for achieving a certain thermal performance. A VIP of only 20 mm, for instance, performs in the centre-of-panel region thermally equally well as a mineral fibre board of approximately 195 mm or a polyurethane foam board of about 120 mm; a reduction of thickness of a factor 5 to 10 thus [Brodt, 1995; Caps et al., 2001]. Their effective thermal conductivity, however, may be raised significantly owing to large additional heat fluxes caused by a continuously enveloping high barrier laminate, necessary to maintain the vacuum for as long as practically required. In case of aluminium foil based barrier laminates (6 µm) or metallized film laminates (97 µm), the effective thermal conductivity of a VIP of 600x600x20 mm^3 can be increased by a mere 105% or 7% respectively [Tenpierik and Cauberg, 2007]. For metal foil based barrier envelopes this effect thus is highly significant

Several researchers have already studied this thermal bridge effects. All of these studies have in common that they increased the knowledge on the thermal edge effect and proved that especially for metal-based barrier envelopes this effect needs to be considered when speaking of the overall thermal performance. None of these studies however theoretically showed which factors are of importance in determining the heat flows through the edge of a VIP. In this contribution therefore analytical models are presented which on the one hand allow rapid estimation of the VIP overall thermal performance and on the other hand show the influence of material and geometric parameters on this performance.

The models presented in this contribution show that the linear thermal transmittance, which represents the amount of heat being transferred through the edge of a VIP, depends on the thermal conductivity, λ_f, and the thickness, t_f, of the barrier envelope (or barrier envelopes if both sides of the panel have a different laminate), the thermal conductivity, λ_c, and the thickness, d_p, of the core material and the seam configuration (thermal conductivity, λ_e, and relative thickness of the edge, φ). The analytical models are validated through numerical simulations. The simulations have been performed for a VIP with a thermal conductivity of the core material of 0.002, 0.004, 0.006, 0.020 and 0.040 $W \cdot m^{-1} \cdot K^{-1}$ and with an aluminium foil based, a stainless steel foil based and a metallized film based high barrier laminate. Each core and envelope combination is computed for several panel thicknesses and envelope thicknesses. Figure 1a and b give two examples of a comparison between analytical model and numerical simulation results.

Figure 1: Comparison of numerical data (markers) and analytical model (continuous lines) of the linear thermal transmittance as function of panel thickness for a VIP with a aluminium high barrier foil (a) or a metallized barrier film (b) with a centre-of-panel thermal conductivity of $4{\cdot}10^{-3}$ W·m^{-1}·K^{-1}.



As can generally be seen from these figures, the difference between the analytically calculated and numerically simulated results is small, as a result of which the analytical model presented can be used as a tool for rapid estimation of the linear thermal transmittances due to continuously enveloping thin high barrier laminates. For a VIP with a 6 μm thick aluminium based foil and a centre-of-panel thermal conductivity of $4{\cdot}10^{-3}$ W·m^{-1}·K^{-1}, for instance, this deviation is -0.0002 W·m^{-1}·K^{-1} (-0.4%), -0.0002 W·m^{-1}·K^{-1} (-0.7%), 0.0000 W·m^{-1}·K^{-1} (0.1%) and -0.0004 W·m^{-1}·K^{-1} (-1.8%) for a panel thickness of 10 mm, 20 mm, 30 mm and 40 mm respectively. Even if a low thermal conductivity barrier, like a three-layer metallized film, is applied, deviations between analytical and numerical results are small as well: -0.0003 W·m^{-1}·K^{-1} (-6.7%), 0.0000 W·m^{-1}·K^{-1} (-3.3%), -0.0000 W·m^{-1}·K^{-1} (-2.8%) and -0.0000 W·m^{-1}·K^{-1} (-2.4%) for a panel thickness of 10 mm, 20 mm, 30 mm and 40 mm respectively.

As is shown in the paper, these very small deviations not only occur for low centre-of-panel thermal conductivities but also for higher thermal conductivities and for stainless steel barrier envelopes. Moreover, it is shown that the models are sufficiently able to cope with seams near the edge of the panel, with additional insulation layers adjacent to the VIP and with VIPs having envelopes combining different laminates; and that the inaccuracy of the models is less than about 5% for idealised barrier films, within the limitations specified. The inaccuracy of the model for more realistic seam containing barrier envelopes is less than approximately 9%. Using the presented models then, enables VIP designers, architects, building engineers and scientists to estimate the overall thermal performance of a VIP and of building panels and to systematically improve the thermal performance of VIPs.

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A Vacuum thermal insulation structurally stiffened by air pressure

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The present work introduces a new vacuum insulation, which is patented by the author [Yeganeh 2004]. In this insulation, pressurized air is used for inflating and stiffening the load-carrying structure in order to prevent scrunching the envelope. By deflating the structure vacuum is produced in the empty space between layers. With this design the vacuum insulation can be produced by flexible materials thus could be foldable in non-operational conditions, when the structure is deflated. In operational condition the structure will be stiffened by entering high pressure air, so the structure would be able to carry the atmospheric load. Figure 1 shows the configuration of the proposed insulation.

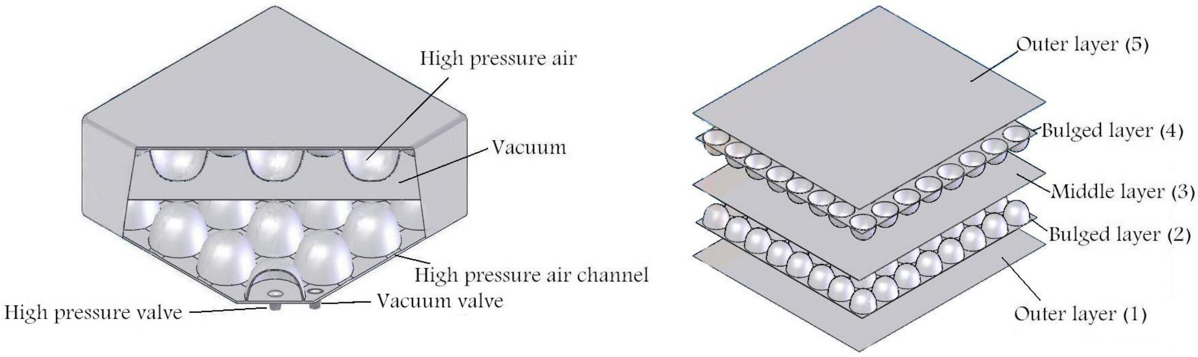

Figure 1: Exploded view of the proposed vacuum insulation

As it could be seen from Figure 1, a sheet of this insulation has different layers. Flat layers are positioned at two outer sides and the center of the insulation and two bulged layers between these layers are attached at the contact surfaces. These layers are made of impermeable and flexible envelope. It is noted that if pressurized air of the bulges are evacuated, the insulation will be scrunched due to the atmospheric pressure acting on outer surfaces. This ability causes the insulation to have small volume in non-operational condition, which makes easy its transportation. In order to make the insulation operational, pressurized air has to be entered into the structure through the proper valve. The high pressure valve is depicted in Figure 1. The other valve in this figure is vacuum valve. Through this valve the remaining air of the vacuum container would be evacuated.

It is well known that in vacuum insulations the insulating effect will depend upon the extent of the vacuum, as well as the configuration of the remainder of the structure, including the amount of continuous structural contact between the opposing surfaces. Such structural contact will result in heat conduction between the surfaces. To investigate the effect of such parameters on thermal characteristics, the proposed insulation is investigated using FEM software ANSYS 10.0. The state of stress in the structure under the atmospheric and inside pressure loading is also investigated.

In the proposed insulation, bulges are main parts of the load-carrying structure. The bulges' area to total area determines the required inside pressure of structure to inflate the insulation. This ratio is the main parameter affecting the thermal efficiency of insulation. In other words the greater inside pressure of structure leads to a smaller required bulge area, which yields to a greater vacuum area and therefore higher thermal efficiency. In the case presented here this ratio is equal to 4, which means the inside pressure of structure is 0.4 MPa (four times the atmospheric pressure). The minimum area of bulges to total area of the insulation must be determined in a way that the structure could carry the load of atmospheric pressure. The main dimensions are considered as follows:

Radius of the bulge's root: 8 mm
Minimum required bulge's radius: 5 mm
Height of the bulge: 10 mm
Center to center distance of the bulges: 17.7 mm

The barrier material is considered to have the mechanical and thermal properties as Mylar "350SBL300", marketed by DuPont [Dupontteijinfilms 2007]. This barrier material is flexible and has low thermal conductivity. Characteristics of Mylar "350SBL300" is as follows [Dupontteijinfilms 2007]:

Modulus of elasticity: 510 MPa
Yield stress: 25 MPa

The structural analysis result indicates that the maximum magnitude of the von Misses stress is equal to 19 MPa, which is produced in the junction zone of the bulge's peak and middle layer. Considering the yield stress of material (25 MPa), it could be concluded that mechanical strength safety factor of the proposed insulation is about 1.3.

The main phenomenon responsible for heat transfer in the proposed insulation is heat conduction through the medium and pressurized air within the structure. Therefore in this investigation for simplifying calculation only the conduction is considered and the other modes of heat transfer are neglected. For calculating the thermal conductivity of insulation uniform heat fluxes with opposite signs (0.01 W/mm^2 and -0.01 W/mm^2) are applied to outer surfaces. The temperature of the lower surface of the insulation is considered constant and equal to 25 ^oC, and the problem is solved in steady state condition. The result shows that the temperature of the outer surface is equal to -5^oC. The area of the considered unit is equal to 78.3 mm^2 and its thickness is equal to 24.14 mm. Since the temperature difference between two surfaces of the insulation is 30 ^oC, the thermal conductivity of the insulation is approximately 0.001 W/(mK).

Considering the obtained results it is concluded that the proposed insulation has proper mechanical and thermal characteristics.

[Yeganeh 2004] *M Yeganeh,* ***A Vacuum Thermal Insulation Structurally Stiffened by Air Pressure,*** *No. 29342, Iran's patents registration organization, (2004).*

[Dupontteijinfilms 2007] ***www.dupontteijinfilms.com***

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