Insulation through vacuums

High performance thermal insulation for building envelopes and windows

A service from FIZ Karlsruhe
Straight to the point

What works for thermos flasks can also be used for thermally insulating buildings: insulation by means of a vacuum. For this purpose, panels made of compressed silica powder, which is an extremely porous material, are enclosed in a largely gas- and water vapour-tight envelope made of special high-barrier films or stainless steel and evacuated. The thermal insulation provided by these vacuum insulation panels (VIPs) is five to ten times that achieved by conventional insulation systems. This means that vacuum insulation requires a correspondingly lower thickness of insulation material to achieve the same insulating effect, which is highly beneficial when there are space constraints or high thermal insulation requirements.

Although VIPs offer new, highly efficient solutions in building, they also require new forms of collaboration and planning. In contrast to conventional insulation technology where the material can be cut to size on site, with these insulation elements it already needs to be determined whether standard sizes can be used and the sizes that are required for custom-made elements during the design phase. Furthermore, the elements are, from a mechanical point of view, relatively fragile: if the envelope is damaged, the vacuum can ‘escape’ and the thermal insulation effect is reduced. In recent years, vacuum insulation systems for the construction industry have been tried, tested and further developed in various research projects. In 2008, the first construction products using VIP systems were granted building regulations approval in Germany. In ViBau, a research area forming part of the energy-optimised construction (EnOB) research initiative run by the German Federal Ministry of Economics and Technology, various research institutes and companies are working on further improvements to the technology. The focus is currently on quality checks and quality assurance as well as on monitoring commercial applications used in building practice.

Parallel to this, research is also being conducted on glazing systems using a vacuum in the space between the panes, whereby it is essential to have a gas-tight edge seal. In order to be able to bear the pressure load of the ambient atmosphere, suitable spacers also need to be found for the inter-pane cavity. The development of a highly efficient window frame completes the system.

This Themeninfo brochure explains the principles behind this new thermal insulation technology, its potential applications and its unique features. Examples from practice demonstrate possible applications in new-build schemes and refurbishments.

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Improving thermal insulation

A well-insulated building ensures comfortable living conditions and low energy costs. If, however, increasing thermal insulation demands lead to increasingly thick wall structures, not every building developer is amenable to this. This is understandable given that the space required for this is generally very costly. However, the new, high performance vacuum insulation panels offer new prospects.

Since the first German Thermal Insulation Ordinance (WSVO) was introduced in 1977 in response to the oil crisis, the insulation requirements for building envelopes have increased continually. Whereas the 8-cm-thick insulation required for facades by the 1995 amendment to the WSVO was still something unusual for architects and builders, today insulation systems twice as thick are now almost a matter of course in new buildings. And the bar is being raised even further. With the European Union’s aim of introducing an almost zero energy standard for new buildings by 2020, the requirements for thermal insulation are growing with the thickness for the necessary insulation. If such a standard is to be met with conventional thermal insulation materials made of mineral fibre, polystyrene, polyurethane, foam glass or cellulose, this could require thicknesses of up to 40 cm. That in turn requires space, which is usually expensive and is not even always available for refurbishments.

This means that the thermal insulation values required for energy-based reasons are not always so easy to realise in practice. Particularly with the refurbishment of old buildings, retrofitted insulation often leads to geometric problems or unattractive design consequences. For example, the existing roof overhang may not be sufficient for the planned additional thickness or the insulation layer creates deep window openings with unfavourable incident light and unsuitable fields of view – the so-called loophole effect. If the facade directly abuts on the pavement, the retrofitted insulation is usually not allowed to protrude to any great extent. And in the case of internal thermal insulation, the amount of living space lost ought to be kept to a minimum.

High performance insulation materials and components offer space-saving solutions in this respect, which in turn offer new technical and design possibilities. One approach is to provide the insulation with vacuum insulation panels. These flat, evacuated panels were developed in the 1970s for use in cooling and refrigeration equipment and have now been adapted to meet the requirements of the construction industry. With correct planning and careful deployment, they provide very good thermal insulation values with a slim construction.

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The development of heating energy requirements and thermal insulation thicknesses over time. Source: RUBIN / Ruhr-Universität Bochum

Fig. 1 This mini-building with vacuum insulation integrated within the sandwich structure shows the possible gain in space: if conventional insulation materials were to be used to provide the same level of thermal insulation for this building volume of just 75 m², only 17 m² instead of 25 m² would be usable. Photo: Dipl.-Ing. Manuela Skorka, Neuried

Fig. 2 Development of heating energy requirements and thermal insulation thicknesses over time. Source: RUBIN / Ruhr-Universität Bochum
Vacuum insulation: Material and manufacture

Vacuum insulation panels improve the thermal insulation effect not by using thicker materials but through further reducing the thermal conductivity. If the gas pressure inside the panel is sufficiently reduced, the heat transferred by the gas is almost entirely eliminated. This means that even very thin structures can achieve excellent performances. However, the technology poses considerable challenges in terms of the materials and processing.

According to DIN 28400 Part 1: “A vacuum is the state of a gas when the pressure of the gas in a container and thus the particle density is lower than outside or when the pressure of the gas is less than 300 mbar, i.e. lower than the lowest atmospheric pressure on the earth’s surface.” The principle that an “air-free” volume provides good insulation is utilised by the thermos flask, which was already invented at the end of the 18th century. This is because lowering the gas pressure within a volume (evacuation) suppresses gaseous thermal conduction. A sufficiently vacuum-tight envelope—whereby a thermos flask uses stainless steel, aluminium or glass—prevents the gas pressure from exceeding a critical amount.

Cylindrical containers, such as those used for thermos flasks, are by their very nature highly resistant to pressure. In order, however, to transfer the highly efficient insulation technology to flat panels, as is required for insulation in the construction industry, special filler materials or structures for the cavities are required. These must be able to withstand the external atmospheric load pressure of 1 bar, which corresponds to a weight load of 10 t/m². A VIP therefore mainly consists of a panel-shaped, pressure-resistant core material and a sufficiently vacuum-tight envelope.

Criteria for filler materials

For a material to be considered suitable as a core for vacuum insulation, it must be possible to evacuate it and its overall thermal conductivity should be as low as possible. A completely open structure is required. Since the filler material must be able to withstand the mechanical pressure load, a higher density is usually required than would be the case if the same type of material were used in conventional, non-evacuated insulation. In addition to having a low solid-state thermal conductivity, the infrared radiative heat transfer is also reduced by as much as possible. Given the low overall thermal conductivity of the evacuated system, this component has a relatively greater impact. The addition of infrared opacifiers such as carbon black, iron oxide and silicon carbide helps here. Because the gas is largely evacuated, the gas thermal conductivity is insignificant.

The extent to which the gas pressure has to be lowered in the VIP elements substantially depends on the size of the pores. The finer they are, the lower the requirements placed on the quality of the vacuum. Depending on the core material, this lies between 0.1 and around 20 mbar (rough vacuum). Not only does this vacuum pressure have to be achieved during the manufacture of the elements but it also has to be maintained during the entire lifespan. Depending on the filler material, this places different demands on the impermeability of the envelope.

Choice of materials for the filling

Possible core materials include open-cell polymer foams (e.g. special polyurethane or polystyrene foams), glass fibres, loose powder or powder pellets (e.g. from silica), and aerogels. Foams and glass fibres require a high quality vacuum with a gas pressure less than 1 mbar. With
Heat transfer in thermal insulation materials

The aim of thermal insulation materials is to reduce the transfer of heat caused by temperature differences. The thermal conductivity is the significant material parameter: the lower it is, the better the insulating effect.

Convection, a form of heat transfer that is linked to the transport of a gas or a liquid, is a very effective mechanism. It is used, for example, in the circulation of water in heating systems. Suppressing this is the primary task of thermal insulation, which is also optimally fulfilled by conventional thermal insulation materials thanks to their fine-celled structure.

The second thermal transport mechanism is thermal conduction, in which individual atoms or molecules transfer heat to neighbouring atoms or molecules. This mechanism can be found not just in solids but also in quiescent liquids and gases. Since the thermal conductivity of gases is generally considerably lower than for solids, thermal insulation materials are highly porous. Plastics are particularly good at reducing the amount of heat conducted via the solid structure. With such highly porous thermal insulation materials, it is nevertheless the heat conducted by the gas in the cavities that dominates the overall thermal transport (proportion greater than 60%). The type of gas and – with nano-structured materials – the gas pressure in the pores considerably influence not just the heat conducted by the gas but, as a result, the overall thermal transport.

A third, frequently underestimated contribution to the thermal transport is provided by infrared radiation. This transport mechanism does not depend on the presence of matter at all. All surfaces emit thermal radiation in accordance with their own temperature, whereby they also absorb and scatter incident radiation. The transport of infrared radiation in a porous system is influenced by the density (and structure) of the material: the higher the density, the more it is attenuated – the requirements for diminishing it are therefore exactly contrary to the requirements for reducing the solid conductivity. Additives – so-called infrared opacifiers – help diminish the infrared radiation transport even more for a given material density.

Conventional thermal insulation materials achieve thermal conductivities between 0.030 W/(m K) and 0.040 W/(m K). In order to improve the thermal insulation properties, a particular focus is on reducing gaseous thermal conductivity. One possibility is to use heavier gases with a lower thermal conductivity than air. Polyurethane foams filled with heavy gas achieve thermal conductivities less than 0.022 W/(m K). However, permeating air causes the thermal conductivity to increase over time. Another approach is to make the structure so fine that the gas particles under atmospheric pressure collide not so much with one another but with a diverse number of walls. To achieve this, the pores must be smaller than a few tenths of a micrometre in size. Nano-structured fumed silica or aerogels have measured values as small as 0.015 W/(m K).

Vacuum insulation is taking a different approach: lowering the gas pressure largely eliminates thermal conduction via the gas. The thermal conductivity of evacuated thermal insulation materials loaded with atmospheric pressure therefore ranges between 0.002 W/(m K) and 0.008 W/(m K).

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**Thermal insulation materials in comparison**

| Thermal conductivity [10⁻³ W/(mK)] | 0 | 5 | 10 | 15 | 20 | 25 | 30 | 35 | 40 | 45 | 50 |
|-----------------------------------|---|---|----|----|----|----|----|----|----|----|----|----|
| Foam glass                        |   |   |    |    |    |    |    |    |    |    |    |    |
| Rock/glass wool                   |   |   |    |    |    |    |    |    |    |    |    |    |
| Polystyrene foam                  |   |   |    |    |    |    |    |    |    |    |    |    |
| Polyurethane foam                 |   |   |    |    |    |    |    |    |    |    |    |    |
| Silica/aerogels                   |   |   |    |    |    |    |    |    |    |    |    |    |
| Evacuated insulation              |   |   |    |    |    |    |    |    |    |    |    |    |

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**Fig. 4**: Thermal conduction in conventional thermal insulation materials: Thermal conduction via the solid pore walls (yellow arrow), thermal conduction via the filling gases (blue arrows) and thermal radiation between the pore walls (red arrows). The contribution made by convection within the pores (green arrow) is negligible.

**Fig. 5**: An enclosed volume of approximately ten litres: Conventionally insulated (white) and insulated with VIP of the same insulation quality (silver). Photo: ZAE Bayern
the particularly finely structured fumed silica and aerogels, a gas pressure of just 10 to 50 mbar is sufficient to substantially suppress the gaseous thermal conductivity. The overall thermal conduction only doubles when there is a residual gas pressure of typically around 100 mbar (Fig. 8). Since there is no single filler material that combines all advantages, the choice of VIP filling depends in particular on the physical properties of the envelope and the type of application.

The thermal conductivity of nano-structured fumed silica is only roughly half that of conventional thermal insulation materials, even in non-evacuated, atmospheric condition with 0.018 W/(m K). In addition to the comparatively low requirements regarding the impermeability of the envelope, the fact that the vacuum envelope still provides a minimum of thermal insulation for preventing mould formation in the case of complete failure predestines this material for manufacturing durable vacuum insulation elements for the construction industry.

Silica is made from artificially manufactured silicon dioxide (SiO$_2$), which in its natural form is most commonly found as sand. Nano-structured fumed silica is mostly produced as a by-product in silicon wafer production. Silica is non-toxic, easy to recycle, incombustible and does not cause harmful emissions. In addition to its low sensitivity to increasing gas pressure, a further advantage of its fine structure is its considerable ability to absorb water vapour that can permeate through the envelope in small amounts. In contrast to coarser materials, nano-structured powders can be easily compressed to form panels and can therefore be easily handled in the VIP manufacturing process.

**Criteria for the envelope materials**

Whether a material is suitable as an envelope principally depends on its gas impermeability. In terms of the life expectancy of a VIP, its impermeability to water vapour is also important. In addition, a low thermal conductivity is also decisive in order to keep the thermal bridge effect as low as possible along the edges of the panels. Because of the mechanical loads that occur during construction, the envelope materials should also have sufficient puncture resistance.

**Choice of materials for the envelope**

The envelope materials used for thermos flasks, namely stainless steel, aluminium and glass, are also generally suitable for flat vacuum insulation panels. In combination with filler materials such as foams and fibres, it is actually only these materials that achieve the required high gas impermeability that is required for durable products. In practice, manufacturers mostly use aluminium-metallised high barrier plastic laminates, aluminium composite films and stainless steel films or sheets to provide the VIP envelopes.

- **Three times metallised high barrier laminates**
  This rather inelegant name actually provides a rather good description of the multilayer structure of these films. They consist of several layers of polymers that are characterised by their low thermal conductivity and high durability. Because the barrier effect provided by pure polymer films is nowhere near sufficient for use in VIPs – in particular to protect against water vapour – additional layers made of aluminium, aluminium oxide or silicon oxide increase the impermeability. Because it is not possible to produce perfect and faultless barrier layers in the vapour deposition process, several of these are required – typically three in building construction.
With the high barrier laminates, it is solely the inner layers that are metallised. The outermost layer has to protect against environmental and ambient influences, whereas the innermost layer acts as a sealing material. Depending on the underlying conditions and the requirements for the VIP, polyester, polyamide, polypropylene and polyethylene are used for the individual layers. Polyethylene is mostly used for the sealing material and occasionally polypropylene.

The greatest advantage of this multi-coated, multi-layered plastic laminate is its low thermal conductivity. Because the overall thickness of the aluminium layer in the entire assembly is only around 100 nm, the metal does not significantly influence the effective thermal conductivity of the VIP. However, if aluminium is deployed as the barrier layer, the vapour-deposited films are susceptible to corrosion under certain conditions.

- Aluminium composite films
Aluminium composite films for VIPs consist of an aluminium film with a layer thickness between 6 and 12 μm in the middle and two plastic films on the outer surfaces. The advantage of such a metallic envelope is its high gas impermeability. The disadvantage is the strong flow of heat through the edge of the panel, which reduces the effective thermal insulation of the VIP. The thicker the metal layer and the smaller the panel, the greater the edge effect.

The manufacture of VIPs
The manufacture of vacuum insulation panels substantially corresponds to the vacuum packaging technology used in the food industry. The main differences relate to the dimensions of the VIPs and the increased demands regarding the permitted residual gas pressure (vacuum). Depending on the production process, the core is first of all cut to any desired format from pre-pressed panels or a special press mould is required for each panel size, which reduces the flexibility in the production process. The core is then encapsulated in a correspondingly sized envelope. The VIP is generally evacuated in a vacuum chamber. The size of the chamber determines the maximum possible dimensions of the panels (e.g. 2 m x 1 m).

Portrayal of vacuums in history
The Greek philosopher Aristotle (c. 384 – 322 B.C.) proposed the theory that nature abhors empty spaces, which he described as "horror vacui" (lat.: horror of emptiness), whereby empty spaces always try to suck in gas or liquids. According to Christian theology, a "gap" in God’s creation was unthinkable.

Otto von Guericke (1602 – 1686), who was a diplomat, scientist and mayor of Magdeburg, refuted this theory with an impressive experiment: 16 horses, eight harnessed in one direction and eight in the other, were unable to pull apart a sphere made of two metal hemispheres void of air. Guericke therefore proved that materials are not sucked in by vacuums but are pushed in by the ambient pressure.

For the experiment he used two hemispheres made of approximately 2-cm-thick copper sheet with a 60 cm diameter. The rims were smoothed with fine sand and placed together to form a sphere. Using the vacuum pump developed by him, he was able to largely remove (evacuate) the air from inside the sphere. The pressure of the ambient atmosphere now pressed the two halves together. From 1657 onwards he repeated this experiment with differently sized spheres and a different number of horses – at that time horses provided the strongest tractive force available.

These days vacuum technology is a proven and long-established technology that has become indispensable in diverse industrial processes and research techniques. In industrial production, its range of uses extends from annealing and melting metals to vapour depositing metals and drying processes for different materials. In physical- and chemical-based investigations, mass spectrometers, particle accelerators and electron microscopy all make use of vacuums.
VIPs for the market

In order to launch new construction materials on the market, not only must their functional efficiency and practicality be proved but various other parameters must be clarified as well. A substantial aspect is, for example, fire protection. Particularly with vulnerable vacuum insulation, durability and quality assurance also play an important role for its long-term success.

There are currently no generally approved technical standards for vacuum insulation panels (e.g. DIN standards). Therefore in order to use them in accordance with the respective building regulations of the various German federal states, they have to have a “allgemeine bauaufsichtliche Zulassung” (national technical approval – abZ). If no abZ is available for the product, it is necessary to obtain approval in individual cases in accordance with the respective federal state building regulations, which is a costly and time-consuming process. However, four manufacturers now offer VIP products with an abZ – and the trend is increasing:

• va-Q-tec AG, Würzburg
• Porextherm Dämmstoffe GmbH, Kempten
• Variotec Sandwichelemente GmbH & Co. KG, Neumarkt/Oberpfalz
• Vaku-Isotherm GmbH, Rossau.

The VIP products that have an abZ are listed in the “Verzeichnis der allgemeinen bauaufsichtlichen Zulassungen, Zulassungsbereich Baustoffe und Bauarten für den Wärmeschutz” (Directory of national technical approvals for construction products and types of construction for thermal insulation) published by the Deutsche Institut für Bautechnik (DIBt).

Each national technical approval specifies the object being approved, its area of application, its properties and the composition of the construction product. It also stipulates the manufacture, packaging, transport, storage and labelling as well as the necessary quality assurance measures. For designers, decisive are the design and measurement stipulations, in particular the design value for the thermal conductivity to be used, the minimum thermal insulation and the respective fire protection classification. An abZ is generally issued for five years and can be revoked.

Fire protection

All VIPs with a national technical approval are classified as normally inflammable (Construction Material Class B2 to DIN 4102). In accordance with fire protection requirements, unprotected VIPs can only be installed in the external walls of the building envelope up to a height of seven metres. Laminating the elements with corresponding protection layers enables them to be used up to high-rise limit (Construction Material Class B1).

Recycling and ecological balance

With VIPs that have already been rejected in the factory or on the building site because they are damaged, the core material can be directly used again by grinding and...
Vacuum insulation offered many advantages with the energy-oriented refurbishment of this mid-terrace house (approaching the passive house standard). Especially with terraced houses, retrofitted, thick external insulation causes geometric, structural and visual problems in terms of the stepped joints to the unrefurbished adjoining homes. Here the use of thin, supplementary insulation with VIPs in the roof slopes enabled the roof height and the short, continuous roof overhang to be maintained. The exterior walls were clad with a 9-cm-thick outer skin consisting of VIPs integrated between timber battens and new windows that open to the outside. The use of VIPs also provides efficient thermal insulation for the low basement ceiling. The problem of thermal bridging created by the party walls to the neighbouring homes was successfully solved by inserting VIP elements into 25-cm-deep vertical channels.

For the prototypical, new-build design for the double-family house, the structural design and the insulation with VIPs ensure a passive house standard with an extremely slim appearance. The facade of the two-storey, prefabricated solid timber structure consists of Swedish red spruce cladding on top of a VIP substructure, with solar collectors integrated under prismatic glass on the south elevation. In addition to the external wall, vacuum insulation is also used in the monopitch roof above the upper storey and in the exterior doors. Particularly the consistently designed timber structure as well as the high quality, separable materials have ensured an ecological, functional and economically optimised overall result. The slim wall structures create 15 m² of additional living space.

In both projects it is possible to replace aerated VIP elements at any time. The installation between the timber battens and metal rails enabled standardised element sizes and simplified assembly. The unprotected VIPs were installed in the respective substructure without any problems using compri-bond sealant tape along the edges. However, when these prototype buildings were constructed in the year 2000, there were still considerable but solvable problems with the delivery conditions and the quality assurance.
Although highly efficient, slim insulation systems based on VIPs have considerable appeal, they are also viewed with considerable scepticism: Does the vacuum envelope actually remain intact during its handling on building sites? Is the quality of the vacuum in the panels permanent? The aim of the VIP-PROVE project was therefore to increase confidence in the VIP technology. The project covered not only the monitoring of existing, predominately commercial buildings using VIPs but also the development of documents for training and further educating specialist designers, architects and trade specialists as well as the processing and dissemination of information, especially via www.vip-bau.de.

The monitoring of 26 buildings showed that, on average, around 12% of the surface areas are in all probability aerated – at first glance a rather sobering result. However, if three of the buildings where there seems to have been a fundamental failure are removed from the statistical evaluation, the proportion of problematic panels is less than 5%. It should also be taken into account that with the majority of the buildings, this was the first time that the designers and builders had come into contact with this unusual insulation technology, i.e. the mentioned rate ought to be considerably undercut in future if corresponding care is taken. A particularly positive aspect is that even repeated checks did not reveal any other abnormal deficiencies over time for whatever reasons. Even in applications where the VIPs have been in use for more than 10 years, the only deficiencies were with the panels classified right from the beginning as “probably aerated”.

A particularly critical aspect therefore seems to be the handling on the building site. Once the VIPs are installed, the high thermal insulation evidently remains reliable for many years. That would be expected from the extensive scientific investigations that have been previously conducted and the experience gained from the first test and demonstration projects.

Quality assurance and testing procedures

Because VIPs only provide optimum thermal insulation if the vacuum is intact, this technology requires – and to a much greater extent than with conventional thermal insulation materials – a quality assurance and monitoring system for the entire manufacturing and processing stages.

The national technical approvals from the DIBt in themselves prescribe strict, factory-based production inspections and regular monitoring from external parties, whereby in some cases it has to be checked daily whether the raw materials, properties, dimensions, thermal conductivity, compressive strength and internal pressure comply with the specifications stipulated in the respective approval.

Manufacturers who are members of the ‘Vacuum Insulation Panel Product Group’ within the Güteschutzgemeinschaft Hartschaum e.V., an European quality assurance association for thermal insulation products, even subject their products to additional controls that go beyond those required by the national technical approvals. Products that pass the testing procedure can be furnished with the quality mark according to RAL-GZ 960.

One manufacturer, however, is taking a different approach. A special, patented sensor enables him to carry out relatively precise controls of each individual panel with relatively little effort.

Although the production takes place under controlled conditions, with trained personnel, and ensures a high product quality, the transport, storage on the construction site and, in particular, the handling on site present a particular risk for VIPs. The DIBt has therefore stipulated in its national technical approvals for VIP products that the installation of VIP elements may only be carried out by trained personnel, i.e. personnel who are sufficiently experienced to know how to handle VIP elements carefully.
Vacuum insulation as a problem solver

VIPs are currently substantially more expensive than conventional thermal insulation materials with the same U-values. 2-cm-thick VIPs generally cost between EUR 50 and 100/m², whereby there is also a greater outlay in terms of the planning, installation and quality assurance. They are particularly worth using:

- When there is insufficient space available for conventional insulation, e.g. with existing buildings bordering pavements or with basement ceilings
- When the use of slim VIPs makes it possible to dispense with elaborate additional measures such as shifting doors and window lintels, or when insulating roof terraces or foundation slabs
- In order to achieve as much usable space as possible from a given floor area and in accordance with specified U-values, e.g. in urban areas with high land prices or on small, awkwardly shaped sites
- For design reasons, e.g. in order to maintain the geometrical proportions with refurbishments, with roof dormers, with closed elements in mullion- and-transom structures and with listed buildings

New residential and office building

Pool Architekten, Martin Pool, Munich

Fig. 23 The six-storey residential and office building in Munich-Lehel with seven apartments and six office units across a total floor area of 1,350 m² achieves a heating requirement of just 22 kWh/m² p.a. Photo: Sascha Kletzsch, Munich
Fig. 24 The thermographic image does not show any deficiencies. Photo: ZAE Bayern
Fig. 25 Large glass surfaces on the building’s rounded corners – where there is least shading – are designed to maximise solar heat gain. Photo: Michael Heinrich, Munich

The residential and office building in Munich is the first large-scale building to be entirely insulated with VIPs. The main motivation for deploying VIPs was the economic advantage of having more space as a result of using slim facades. The increased solar gain and the improved views as a result of thinner jambs and reveals were also reasons.

The VIP insulation, which has a thickness of just 2 cm, is combined with a strengthened 8-cm-thick plaster base panel. This composite thermal insulation system provides the mechanical and weather protection for the VIPs and provides an insulation cover for thermal bridges at fixing points and connections. With conventional thermal insulation materials, a layer thickness of 25 cm would have been necessary to achieve a comparable thermal insulation value.

The structural system newly developed for this project is based on an already existing system with a national technical approval for a TICS with PU insulation on a frame construction. It was possible to supplement this with relatively little effort by gaining individual approval for the VIPs. Other systems have essentially failed because of the cost and time spent on testing procedures that are required for approval in individual cases.

The building was awarded the German Building Physics Prize in 2005, received a commendation in the 2006 Bavarian Energy Prize awards and was awarded the dena “Energy efficiency and good architecture” prize in 2009.

This building was also monitored as part of the VIP-PROVE project. Of the 750 m² of installed VIPs, approximately 450 m² were accessible for taking thermographic images. Not one of these panels was classified as aerated.

Fig. 21 Application areas (blue) include facades (internal and external), parapets, floors, ceilings, roof terraces and recessed balconies. Source: FHNW
Fig. 22 : VIPs enable the subsequent insulation of floors with low structure heights. Photo: Fraunhofer IBP
Installation versions with vacuum insulation

Vacuum insulation panels are available on the market in various standard formats. Modular sizes are intended to simplify the planning and avoid custom-made elements. Special formats or fitting pieces, for example with notches for fixing elements, anchors or similar fixtures, are even more expensive and require advance planning during the production.

VIPs are available for the construction industry in non-laminated and laminated versions or integrated into prefabricated building elements. It is likely that construction products and systems with integrated VIPs will become increasingly available on the market.

- **Unprotected VIPs**
  Pure vacuum insulation panels from various manufacturers have proved themselves in construction for a decade now. In addition to their slim shape, the fact that they can be easily controlled, at least until they are installed, is another advantage in using them. With corresponding planning, individual panels can be replaced should they fail. Faulty VIPs can be easily recycled or correctly sorted and disposed of. Their big disadvantage is that the panels are extremely fragile given the harsh conditions that prevail on construction sites, and they require a professional installation team.

- **Laminated VIPs**
  In order to make the panels more robust and/or to adapt them to specific application areas, some manufacturers laminate the VIPs from the start on both sides. The materials used for the lamination include conventional thermal insulation materials similar to TICS for the outer insulation, timber and hard-plastic panels for the interior finishes, and even supplementary rubber layers to provide additional impact sound insulation when used for flooring.

  Laminated VIPs provide relatively good mechanical protection and, provided that they are also laminated along their edges, can also be adjusted on site in terms of the size. The additional layer of course makes the elements somewhat thicker and also makes it more difficult to inspect them.

- **VIPs integrated into building elements**
  Prefabricated building elements with vacuum insulation for facades or roofs are available as sandwiched timber structures, precast concrete elements or elements based on the insulation glass principle. Individual building elements such as doors, lintels and roller shutter housings are also available on the market. The fragile VIPs are installed in these prefabricated elements with a considerable degree of precision and under controlled conditions in the factory. This considerably reduces the risk of damage. With corresponding planning, it is also possible to eliminate the need for expensive fitting pieces and tolerance zones that would have to be filled with conventional thermal insulation on site. Another attraction of prefabricated elements is their slimness and lightness. In mullion-transom structures, this enables transparent elements to be combined with opaque, highly insulating elements of the same thickness as part of a unified installation and fixing system.

  With prefabricated elements, the currently available procedures do not enable the vacuum in the installed VIPs to be subsequently checked as this requires free access to the surface of the VIP film.
In practice

Refurbishment of a children’s day care centre

Institut für Gebäude + Energie + Licht Planung (IGEL), Wismar

For the refurbishment of a children’s day care centre built using precast concrete, which was conducted as part of a research project funded by the German Federal Ministry of Economics and Technology, the windowless end walls were deemed suitable for the use of VIP insulation, which was one of its first large-scale refurbishment applications. For this purpose, two different systems were tested and compared.

On the west elevation, VIPs from a commercial provider were integrated in a standard composite thermal insulation system (2 cm vacuum insulation with a 3 cm PS laminate). This approach enabled the U-value to be improved from the original 1.25 W/(m²K) to 0.18 W/(m²K). For the east elevation, prefabricated VIP facade elements were newly developed that are designed to make it possible to replace defective or damaged VIPs. High-strength ceramic panels on the exterior each protected four VIPs. Because of thermal bridges in this structural system, the U-values in the wall were only (mathematically) reduced to 0.34 W/(m²K).

As part of the VIP-PROVE project, the two designs were tested in terms of their practicality and durability. The newly developed elements on the east side of the building have been shown to be not fully mature in technical terms. In addition to some aerated VIPs (approx. 5%), the thermographic images particularly reveal the thermal weak points in the joints between the facade elements.

Considerably less pronounced are the thermal bridges with the system on the west elevation. Two panels and three smaller fitting pieces on a house corner were identified in the images from 2006 as aerated. Checks carried out three years later did not show any others to be defective.

In portrait

The certifying engineer and the architect – two expert opinions

Christoph Sprengard, a certifying engineer from the Department of Building Physics and Building Components at the FIW München, carries out measurements and calculations on VIPs, national technical approval tests on behalf of manufacturers and is also involved in research projects for optimising VIPs.

“For many years, the FIW München has supported the manufacturers of VIPs in developing new products. We measure and calculate the thermal and mechanical properties of products as part of the tests conducted for national technical approvals. The very fact that there are national technical approvals in itself shows that VIPs have now developed beyond the experimental stage. New developments show reliably low thermal conductivities after their manufacture. Even the currently applied accelerated ageing procedures show only very slight changes, which would indicate the good durability of the panels in their installed condition. This has enabled the design values for thermal conductivity to be continually lowered in recent years, and with most manufacturers it is now around 0.007 W/(m²K). Even if a panel fails and is aerated, 0.020 W/(m²K) can still be expected, which is sufficient to provide the minimum required thermal insulation. This is enough to prevent condensation and mould developing on walls and ceilings behind the aerated panels. The thermal conductivity and mechanical properties of the approved panels are regularly monitored by third parties, which helps to ensure the panels’ level of quality.”

Architekt Florian Lichtblau and his brother Wendelin have run their architectural practice Lichtblau Architekten BDA for more than 20 years, focussing on practice, research and teaching sustainable construction.

“When we first founded our office together in 1987, we covered a daring glazed roof with translucent thermal insulation (TTI), survived the experiment unscathed and as a consequence sourced and initiated many other new “building elements”, including vacuum insulation. ZAE Bayern approached us back in 1998 with the request to support the research project with two prototypes. We agreed. Since then there’s hardly a project that we have realised without new VIP details. As responsible designers, we always take structural precautions to ensure that the installation of the elements can be reversed. The better crafted and simpler the building element, the quicker and cheaper damaged VIPs can be replaced if required. We think that the future holds enormous potential for development, in particular with the current research involvement in the field of industrial prefabricated module facades for highly efficient building refurbishments. In combination with timber construction, vacuum glazing and the integration of solar technology etc., we can foresee the development of exciting concepts as part of a sustainable reshaping of the building stock. We call that ’the second chance for architecture’.”

Fig. 29 The energy consumption, structural condition and poor access and circulation within the building made the refurbishment necessary. Photo: IGEL, Wismar

Fig. 30 Vacuum insulation is concealed behind the blue ceramic panels. Photo: IGEL, Wismar
Building with vacuum insulation

Vacuum insulation needs to be precisely thought out and detailed right from the initial planning phase. Not only is it necessary to take the building physics aspects into account but the required panel sizes must also be determined and a layout plan drawn up. On the building site, the deployment of the fragile VIPs needs to be precisely planned, ranging from their transport and storage to the installation and coordination with other trades on site.

In order to decide whether and in which areas vacuum insulation panels are suitable for a building project, the client and all those involved in the planning must be aware of the properties and special characteristics of VIPs. VIP manufacturers and suppliers should be involved in the design process from the earliest possible stage. If no national technical approval is available for the intended application, it will be necessary to apply for individual approval for using the VIPs. That requires sufficient forward planning.

Design values, thermal bridges and vapour diffusion

The design value for the thermal conductivity that are stipulated in the national technical approvals and that need to be used by the designer take into account not just the ageing but also the thermal bridging effect caused by butt-jointed VIPs. A small ‘failure rate’ due to aerated VIPs is also included in the calculation. The thermal bridging effects caused by anchors and fixing elements that can only be applied in the joints between two panels need to be taken into account separately. Double-layered, offset installation of the VIP insulation panels or an additional cover layer of conventional thermal insulation material that is just a few centimetres thick help to reduce increased thermal flow across any possible gaps in the joint area between the panels.

In comparison with standard thermal insulation materials, vacuum insulation is extremely impermeable to water vapour and therefore, from a hygric point of view, generally less critical than conventional thermal insulation solutions. In case of doubt, specialists should analyse and assess the planned structure using computer programs that simulate the building physics (e.g. WUFI, DELPHIN).

Inspections and the replacement of aerated VIPs

Although aerated panels cannot be repaired, they still provide twice the thermal insulation effect as conventional thermal insulation materials of the same thickness. In accordance with the stipulations provided by the corresponding national technical approval, the structure should be so designed that even if all panels are aerated, the minimum required thermal insulation is provided in order to prevent mould forming. In order to ensure the high quality of the vac-
uum insulation solution, the panels should be visually and tactually inspected before and after their installation. If by means of skilful planning it is possible to utilise panels that have just a few different sizes or even just standard dimensions, this will make it easier to replace any faulty VIPs with panels of the corresponding size. Otherwise, re-manufacturing and re-supplying replacements will delay the construction timetable. Since it is usually difficult to replace defective panels once the insulation structure is completed, particular care must be taken when handling them.

Bills of materials and layout plans

Since VIPs cannot be adjusted in size on site, the fixed panel sizes must already be determined during the detailed design stage. Reducing the different panel sizes facilitates their processing. Bills of materials and layout plans must be drawn up as early as possible in close collaboration between the designers and the VIP suppliers. The layout plans must be drawn up after conducting precise measurements on site, taking into account the production tolerance for the panels of around 2-3 mm. All penetrations and fixing points must be precisely determined during this phase in conjunction with the various specialist trades involved. This may require specially customised VIPs.

VIPs on the building site

There is a considerable risk that the VIP envelope could be damaged during transport, storage or installation – particularly on the corners and edges. Exposed nails, protruding burr from the substructure, stones or sand, or even knocks against the corners, are enough to damage the vacuum envelope and thus aerate the VIPs. Correspondingly labelled and sufficiently secure storage areas should therefore be provided on the building site. Base and cover layers in the structural assembly made of soft, flexible material, such as just a few millimetres or centimetres of polystyrene foam, considerably reduce the risk of damage.

The proper handling of VIPs therefore requires considerable care – and trained personnel. The training must be carried out by the VIP manufacturer in accordance with the national technical approval. VIP manufacturers and various skilled trades have therefore joined together to form networks for this purpose.

Constraints affecting their installation

Before installing VIPs, it is essential to ensure their compatibility with the other construction materials. Various adhesives or an alkaline substructure, such as fresh concrete, have proved critical in the past.

User information

If VIPs are not installed in a manner that prevents subsequent damage, tenants, owners and workmen should be informed and – for example by means of warning labels – notified about the fragile content of the building structure.

Quality check

- The VIP elements should be visually inspected on delivery. The high barrier film must tightly seal the supporting core.
- The VIP elements must not be mechanically damaged through sawing, cutting and drilling.
- The substructure on which the VIP elements are laid must be smooth and must not have any edges or burring.
- The VIP elements must also be sufficiently protected against damage during their period of use, e.g. through covering them with cladding.
Vacuum-insulated glass

In thermal terms, glazing still forms the weak point in buildings. The heat transfer coefficient of highly insulating triple-glazing systems of between 0.5 and 0.7 W/(m²K) is still five times higher than for opaque facades designed to the passive house standard. Insulation glass with a vacuum in the inter-pane cavity would not only provide better insulation but would also be slimmer and lighter. Researchers have already developed prototype glazing systems and subjected them to detailed testing. Work is now being carried out to make the products and production technology ready for mass production.

A vacuum in the inter-pane cavity instead of inert gases – this idea could help glazing systems make a considerable leap forward in terms of their development. Whereas the transition from double-glazing to triple-glazing improves the insulation by having a greater system thickness – more helps more –, vacuum-insulated glass (VIG) provides a qualitative improvement: the elimination of gaseous thermal conduction in the inter-pane cavity. This enables $U_g$ values of 0.5 W/(m²K) to be also achieved with double-glazed assemblies with system thicknesses less than 10 mm. Vacuum glazing would therefore not only be considerably slimmer and lighter, it would also provide two to three times more insulation than conventional insulation glass. To realise this, the gas pressure in the inter-pane cavity has to be evacuated to a level less than $10^{-3}$ mbar, i.e. a millionth of the atmospheric pressure.

Technical challenges

In order to produce vacuum glazing that is competitive in Europe, the researchers had to develop a sufficiently airtight, thermally stable edge seal as well as visually, thermally and mechanically suitable support pillars that can absorb the atmospheric pressure on the inter-pane cavity.

- **Edge seal**
  Not only must the edge seal remain airtight throughout the window’s service life, it must also absorb any changes in size caused by the considerable temperature deviations between the outer and inner pane that occur as a result of the excellent thermal insulation. Although glass is in itself well suited, it is too rigid, which would cause considerable mechanical stresses even with low temperature differences. The developers were able to solve this problem, however, by using thin metal foil. Its elasticity balances out the temperature-related stresses. It is soldered to the glass pane and then welded in a vacuum chamber on both sides so that it is gas-tight. This assembly achieves $U_g$ values of 0.5 W/(m²K).

- **Support pillars**
  To prevent the pressure of the ambient atmosphere from pressing the panes together, they have to be kept apart by using tiny support pillars in a regular grid. The size of the support pillars, the spacing between them and the thermal conductivity of the materials used influence the overall thermal loss from the vacuum glass. Whereas small support pillars with compact surface areas are better in terms of the appearance and thermal performance of the vacuum glass,
Vacuum glazing for all cases

Windows, facades or roofing for new and old buildings – these will be the main application areas for VIG, but its use in solar collectors, vehicles and refrigerators is also conceivable. In addition to standard designs made of float glass, it is also possible to produce safety glazing using toughened or laminated safety glass as well as thermal insulation and solar control glazing. Although VIG is comparable to conventional double-glazed thermal insulation glass units in terms of the energy transmittance and light transmission, its simultaneous excellent thermal insulation enables higher solar gain.

Still being researched

Gas-tight sample panes have already been produced at a laboratory scale and their mechanical stability has been confirmed. The work is now focussing on developing the joint and production processes for mass-producing VIG systems. The production in a vacuum chamber eliminates the need for evacuation pieces that still disrupt visibility with the Asian glazing systems. A demonstration plant for testing the individual process stages is now in operation. New testing procedures have been developed to confirm that the maximum resilience and durability of the VIG test panes are comparable with conventional glazing systems.

With large-scale production technology, VIG glazing is expected to cost around 100 euros per square metre in the long term, i.e. no more than the price for conventional triple glazing. The fully developed production technology is planned to be available by the end of 2012.

Vacuum glass on the market

Nippon Sheet Glass Co. (Japan) and Qingdao Hengda Industry Co. (China) already offer VIG for the Asian market in the form of double-glazing systems with heat transfer coefficients of around 1.1 W/(m²K). The relatively high heat transfer coefficients are caused by the rigid edge seal made of glass solder. If the insulating effect were better, the thermal stresses would cause the edge seal to fail.

Thanks to their double-glazed assembly, the Asian systems are very lightweight and slim, being just 10 mm thick. The support pillars are hardly visible. However, the production system chosen by the manufacturers requires the use of evacuation pieces within the field of view. With EUR 50 to 80/m² (ex factory), the costs are somewhat greater than for conventional insulating glass units with comparable Uₚ values.

The Uₚ values achieved with the Asian VIG systems can also be attained by commercial insulating glass units in Europe with a considerably thicker but standard pane assembly. The narrower system thickness provides a positive selling point in the Asian market. There the vacuum-insulated glass can replace the widely used single pane glazing in the existing frames.

German manufacturer Velux has also been offering for some time a 24-mm-thick energy saving vacuum pane with a Uₚ value of 0.7 W/(m²K), in which a VIG panel has been integrated within a double-glazing assembly.
A suitable frame

Parallel to vacuum glazing, suitable frame structures are also being developed: an optimal frame for vacuum glazing should cover the thermally bridging edge seal, be slim and have good thermal insulation properties. With profiles made entirely of polyurethane, the researchers are relying on a completely new technology. This innovative system is also suited for conventional triple glazing.

The thermal insulation values of conventional window frames are considerably worse than those achieved with the best glazing systems, whereby even passive house frames rarely achieve $U_f$ values less than 0.7 W/(m²·K). The downside here is that these are inelegant systems with larger profiles and fittings and with increased installation depths.

In developing the frame, the researchers adopted new approaches in regard to the materials and manufacture. Instead of pressing the profiles from aluminium or extruding them from PVC as has been common up to now – methods that provide little scope for optimisation – the core of the new frame is made by filling foam into a mould and then covering this foam core with a plastic layer.

In detail

The new frame entirely consists of just one material: polyurethane (PU), whereby a thin layer of form-stable and weatherproof solid polyurethane material encases the insulating core made of foamed PU. Whereas the core ensures excellent thermal properties, the casing provides good mechanical and structural stability. Moreover, it provides freedom of design: there are virtually no limitations to how the surfaces can be glued and painted. Since the frame is manufactured from just one single material, there are not any problems with its later disposal; besides, PU can be recycled.

This frame achieves the necessary stability without steel or aluminium reinforcement. This also results in a lower weight and lower thermal insulation values. With triple-glazed insulated glass in the standard size of 1.23 m x 1.48 m, such a window achieves a $U_w$ value of 0.8 W/(m²·K), while VIG even achieves 0.7 W/(m²·K). The new profile is therefore comparable to passive house window frames, but weighs less and is considerably thinner with a frame depth of just 90 mm. The newly developed frame also provides a solution for the thermal weak point of vacuum-insulated glass – namely the metallic edge seal – by providing a large insertion depth. The profile can be fitted with glass ranging from 9 to 50 mm in depth and is suitable for both new-build and refurbishment schemes. As regards the installation of these windows, there are no differences compared with conventional frame systems. For example, the distances between the screw connections are similar to those for conventional windows.

For facade systems that are up to several storeys in height, such a pure plastic profile cannot be used since it does not provide any load-bearing function. For this reason a thermally optimised mullion-and-transom structural system has been developed based on aluminium supports.

New approaches in manufacturing

The new system has consequences for the production and further processing. Special machines are necessary for foaming, casting and coating. Window manufacturers buy the material in six-metre lengths and then cut these down according to their needs. In contrast to conventional frames, profiles made entirely from polyurethane cannot be welded; instead the corners, frames and glazing are bonded together with a newly developed adhesive. The manufacture of the new profile can be integrated into an existing production process, providing an additional profile option.

Pilot production and initial discussions with system manufacturers are currently underway. The production technology for manufacturing polyurethane profiles will already be available in 2011.
### Overview of thermal characteristic values for frames and windows

<table>
<thead>
<tr>
<th>Frame Type</th>
<th>$U_f$ value $[W/(m^2K)]$</th>
<th>$U_{w}$ value $[W/(m^2K)]$ for standard window size $1.23 \times 1.48 m$</th>
<th>$U_{w,eq}$ $[W/(m^2K)]$ taking solar thermal gains into account</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard aluminium window frame</td>
<td>1.8</td>
<td>1.5</td>
<td>0.69</td>
</tr>
<tr>
<td>Standard PVC window frame</td>
<td>1.4</td>
<td>1.4</td>
<td>0.39</td>
</tr>
<tr>
<td>Optimised PVC window frame</td>
<td>1.1</td>
<td>–</td>
<td>0.17</td>
</tr>
<tr>
<td>Passive house window frame</td>
<td>0.7 to 0.8</td>
<td>Approx: 0.8</td>
<td>0.00</td>
</tr>
<tr>
<td>New window frame (TopTherm 90)</td>
<td>0.68</td>
<td>–</td>
<td>0.07</td>
</tr>
</tbody>
</table>

**Highly insulating frames**

The highly insulating frames currently available have heat transfer coefficients of between 1.1 and 0.7 W/(m²K). There are also cases where slightly lower values are achieved. $U_f$ values of between 0.7 and 0.8 W/(m²K) are possible using improved spacers. However, this also leads to increased installation depths. Values of around 120 to 130 mm apply for passive house window frames.

The following categories of frame can be identified:

- Extruder frame profiles made of PVC with interior steel reinforcement and several air chambers. Additional PU foam elements can further improve the thermal insulation performance of the frame.
- Wooden frame with core insulation or as a sandwich structure with an insulating middle or exterior layer. The insulating material is either PU integral foam, PU recycled material (Purenit), Styrodur or soft-fibre insulating material. The arrangement of the insulating layers differs among the various manufacturers. There are also wood-aluminium windows available with a PU insulation core.
- Aluminium frames where the frame shell is filled with a PU insulation core.
- Other developments: foam-filled plastic profiles where the steel reinforcement is replaced by profiles strengthened with glass fibre; wooden frames which are combined with externally fitted profiles that are strengthened with wood fibres.

**Vacuum Insulation in the Construction Industry (ViBau) research area**

The development of highly efficient thermal insulation elements for building envelopes has been promoted for many years with funding from the German Federal Ministry of Economics and Technology as part of ViBau, a research area forming part of the energy-optimised construction (EnOB) research initiative. Whereas the focus was initially on developing and conducting basic tests on the evacuated elements, their feasibility in practice was later tested and demonstrated. Parallel to this, individual components were optimised and systems for practice-oriented system integration were developed and tested. In addition, special methods for the quality control and assurance were also developed. Now that the first VIP products have been granted national technical approvals and have become commercially available, their functionality in general construction practice is being monitored as part of scientific accompanying research. The intention now is to foster greater public awareness of the potential and special features offered by this innovative thermal insulation technology and to anchor this knowledge in the training and continuing education of specialist designers and practitioners.

With the vacuum-insulated glazing that does not require any considerable rethinking among the designers, the next step is now being taken to progress from the prototypes to mass production. It is not expected that this will lead to any special issues in terms of the planning and application.

Further information on this topic is available at [www.enob.info/vibau/](http://www.enob.info/vibau/).
Outlook

The vacuum insulation technology for the construction sector has been continually further developed in recent years. Products for different application areas have been increasingly granted national technical approvals. Previous construction and refurbishment projects show that vacuum insulation is interesting for highly efficient new-build schemes, as a problem solver – particularly with old buildings – and in terms of the architectural design possibilities it offers. However, the use of fragile, custom-made elements requires particular care during both the planning and handling on the construction site. In relation to this highly efficient insulation technology, the prevention of thermal bridges takes on even greater significance than is already the case with conventional insulation technology. Standardised solutions such as integrating VIPs in prefabricated sandwich elements or in coatings made of conventional insulation foam are possibilities that not only provide additional protection for the VIPs but also counter the thermal bridging problem.

Vacuum insulation panels are still relatively expensive, whereby the cost of the filler material – particularly the finely structured fumed silica – substantially determines the price. The use of more cost-effective alternatives would require, however, even more airtight vacuum envelopes. One conceivable approach would be to further develop the special high barrier plastic laminates that are currently used. Another approach is to use materials that by their very nature are considerably more gas-tight and which are anyway used in the building element as part of the vacuum envelope (glass or metal coverings). New envelope concepts offer not only the possibility of reducing costs but also the prospect of mechanically less sensitive products.

Once the products developed during research are ready for the market and have proved their durability, the prospects for vacuum glazing are also good: with costs comparable to triple glazing but with an added weight advantage and the ability to use energy efficient window frames that are less elaborate, vacuum glazing could well replace triple glazing.

More from the BINE Information Service

- New window frame: High thermal insulation value, low weight. BINE-Projektinfo 09/09
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- Vacuum glazing: When inert gas is replaced by a vacuum. BINE-Projektinfo 01/08
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- Building refurbishment – Children’s day care centre. BINE-Projektinfo 10/06
- Gebäude sanieren – Gemeindezentrum. BINE-Projektinfo 08/06

Literature (in German)

Lehrmittel für die Aus- und Weiterbildung von Fachplanern, Architekten und Handwerkern. (Script and PowerPoint presentations developed as part of the VIP-PROVE project). Download: http://www.vip-bau.de/d_pages/lehrmittel/lehrmittel.htm

Newspaper articles, conference papers, project reports and further publications on this topic are available at www.vip-bau.de under Further Reading.


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