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Energy in Buildings and Communities Programme

International Energy Agency

Long-Term Performance of Super-Insulating-Materials in Building Components & Systems

Energy in Buildings and Communities Programme

Bijan Adl-Zarrabi, Pär Johansson (Editors)

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Long-Term Performance of Super-Insulating-Materials in Building Components & Systems

Report of Subtask III: Practical Applications

Retrofitting at the Building Scale – Field scale

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Preface

The International Energy Agency

The International Energy Agency (IEA) was established in 1974 within the framework of the Organisation for Economic Co-operation and Development (OECD) to implement an international energy programme. A basic aim of the IEA is to foster international co-operation among the 28 IEA participating countries and to increase energy security through energy research, development and demonstration in the fields of technologies for energy efficiency and renewable energy sources.

The IEA Energy in Buildings and Communities Programme

The IEA co-ordinates research and development in a number of areas related to energy. The mission of the Energy in Buildings and Communities (EBC) Programme is to develop and facilitate the integration of technologies and processes for energy efficiency and conservation into healthy, low emission, and sustainable buildings and communities, through innovation and research. (Until March 2013, the IEA-EBC Programme was known as the Energy in Buildings and Community Systems Programme, ECBCS.)

The research and development strategies of the IEA-EBC Programme are derived from research drivers, national programmes within IEA countries, and the IEA Future Buildings Forum Think Tank Workshops. The research and development (R&D) strategies of IEA-EBC aim to exploit technological opportunities to save energy in the buildings sector, and to remove technical obstacles to market penetration of new energy efficient technologies. The R&D strategies apply to residential, commercial, office buildings and community systems, and will impact the building industry in five focus areas for R&D activities:

- Integrated planning and building design
- Building energy systems
- Building envelope
- Community scale methods
- Real building energy use

The Executive Committee

Overall control of the IEA-EBC Programme is maintained by an Executive Committee, which not only monitors existing projects, but also identifies new strategic areas in which collaborative efforts may be beneficial. As the Programme is based on a contract with the IEA, the projects are legally established as Annexes to the IEA-EBC Implementing Agreement. At the present time, the following projects have been initiated by the IEA-EBC Executive Committee, with completed projects identified by (*):

Annex 1: Load Energy Determination of Buildings (*)
Annex 2: Ekistics and Advanced Community Energy Systems (*)
Annex 3: Energy Conservation in Residential Buildings (*)
Annex 4: Glasgow Commercial Building Monitoring (*)
Annex 5: Air Infiltration and Ventilation Centre
Annex 6: Energy Systems and Design of Communities (*)
Annex 7: Local Government Energy Planning (*)
Annex 8: Inhabitants Behaviour with Regard to Ventilation (*)
Annex 9: Minimum Ventilation Rates (*)
Annex 10: Building HVAC System Simulation (*)
Annex 11: Energy Auditing (*)
Annex 12: Windows and Fenestration (*)
Annex 13: Energy Management in Hospitals (*)
Annex 14: Condensation and Energy (*)
Annex 15: Energy Efficiency in Schools (*)
Annex 16: BEMS 1- User Interfaces and System Integration (*)
Annex 17: BEMS 2- Evaluation and Emulation Techniques (*)
Annex 18: Demand Controlled Ventilation Systems (*)
Annex 19: Low Slope Roof Systems (*)
Annex 20: Air Flow Patterns within Buildings (*)
Annex 21: Thermal Modelling (*)

Annex 22: Energy Efficient Communities (*)
Annex 23: Multi Zone Air Flow Modelling (COMIS) (*)
Annex 24: Heat, Air and Moisture Transfer in Envelopes (*)
Annex 25: Real time HVAC Simulation (*)
Annex 26: Energy Efficient Ventilation of Large Enclosures (*)
Annex 27: Evaluation and Demonstration of Domestic Ventilation Systems (*)
Annex 28: Low Energy Cooling Systems (*)
Annex 29: Daylight in Buildings (*)
Annex 30: Bringing Simulation to Application (*)
Annex 31: Energy-Related Environmental Impact of Buildings (*)
Annex 32: Integral Building Envelope Performance Assessment (*)
Annex 33: Advanced Local Energy Planning (*)
Annex 34: Computer-Aided Evaluation of HVAC System Performance (*)
Annex 35: Design of Energy Efficient Hybrid Ventilation (HYBVENT) (*)
Annex 36: Retrofitting of Educational Buildings (*)
Annex 37: Low Exergy Systems for Heating and Cooling of Buildings (LowEx) (*)
Annex 38: Solar Sustainable Housing (*)
Annex 39: High Performance Thermal Insulation Systems (*)
Annex 40: Building Commissioning to Improve Energy Performance (*)
Annex 41: Whole Building Heat, Air and Moisture Response (MOIST-ENG) (*)
Annex 42: The Simulation of Building-Integrated Fuel Cell and Other Cogeneration Systems (FC+COGEN-SIM) (*)
Annex 43: Testing and Validation of Building Energy Simulation Tools (*)
Annex 44: Integrating Environmentally Responsive Elements in Buildings (*)
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Annex 47: Cost-Effective Commissioning for Existing and Low Energy Buildings (*)
Annex 48: Heat Pumping and Reversible Air Conditioning (*)
Annex 49: Low Exergy Systems for High Performance Buildings and Communities (*)
Annex 50: Prefabricated Systems for Low Energy Renovation of Residential Buildings (*)
Annex 51: Energy Efficient Communities (*)
Annex 52: Towards Net Zero Energy Solar Buildings (*)
Annex 53: Total Energy Use in Buildings: Analysis & Evaluation Methods (*)
Annex 54: Integration of Micro-Generation & Related Energy Technologies in Buildings (*)
Annex 55: Reliability of Energy Efficient Building Retrofitting - Probability Assessment of Performance & Cost (RAP-RETRO)
Annex 56: Cost Effective Energy & CO2 Emissions Optimization in Building Renovation
Annex 57: Evaluation of Embodied Energy & CO2 Equivalent Emissions for Building Construction
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Working Group - Energy Efficiency in Educational Buildings (*)
Working Group - Indicators of Energy Efficiency in Cold Climate Buildings (*)
Working Group - Annex 36 Extension: The Energy Concept Adviser (*)

Summary

More than 80% of the energy consumption will be influenced by the existing building stock. Accordingly, building renovation has a high priority in many countries. Furthermore, several studies have shown that the most efficient way to curb the energy consumption in the building sector (new & existing) remain the reduction of the heat loss by improving the insulation of the building envelope (roof, floor, wall & windows). All since the first oil crisis in 1973-1974, the national building regulations require improvement of the thermal performance of the building envelope to significantly reduce the energy use for space heating. Following the regulations, the energy efficiency of new buildings has improved. In Europe, targeting to an average U-value close to 0.2 W/m2·K is optimal. Using traditional insulation materials this means an insulation thickness of about 20 cm. Thus, the thickness of internal and/or external insulation layers becomes a major issue of concern for retrofitting projects and even for new building projects in cities. Therefore, there is a growing interest in the so-called super-insulating materials (SIM). The scope of the present work covers two different types of SIMs:

- Advanced Porous Materials (APM), where the gaseous heat transfer is hindered significantly by the fine structure in the sub-micrometre range, and
- Vacuum Insulation Panels (VIP), where the contribution of gaseous conductivity to the total heat transfer is suppressed by evacuation.

For Advanced Porous Materials (APM) one might distinguish between

- porous silica e.g. based on fumed silica, and
- aerogels.

For Vacuum Insulation Panels (VIP) one might distinguish between:

- different core materials: fumed silica, glass fibre, PU, EPS, others;
- different envelopes: metalized film, aluminium laminate, stainless steel, glass, or combinations;
- with or without a getter and/or a desiccant.

The objective of this Annex 65 Subtask 3 report is to define the application areas of SIM and to describe the conditions of the intended use of the products. Indeed, it's clear that the requested performance of the SIM will strongly depend on the temperature, humidity and load conditions. For building applications, storage, handling and implementation requirements are also described. Common and specific numerical calculations will be performed at the building scale to assess the impact of SIM on the performance of the building envelope.

SIM was used in almost all building components with different environmental condition (boundary condition) and in different climate zone. The moisture and temperature conditions in building components can cause moisture/temperature induced stresses and the stresses can cause damage in sensitive super insulation material e.g. VIPs. Thus, to convince the conservative market of construction, it needs, in addition to laboratory measurements, real condition/environmental measurements of commercially realized objects (new buildings as well as refurbishments) under several years of operation.

The long-term performance of super insulation materials has to be determined based on case studies in field and laboratory. Full scale experiments provide knowledge of practical and technical difficulties as well as data for service life estimation. For certain conclusions to be drawn from the case studies, monitoring is essential. Unfortunately, monitoring is only performed in few case studies. In this report these experiences are gathered and evaluated from a long-term performance perspective.

APMs have been commercially successful in the building industry in niche applications typically with space restrictions since the early 2000s. Therefore, over the last years, a number of state-of-the-art reviews have focused on applications of advanced porous materials, such as aerogels, used as thermal insulation in buildings. VIPs, on the other hand, have also been used in other applications than buildings, such as refrigerators and transport boxes. The different applications areas have been identified by numerous researchers. However, in most studies of VIPs available in the literature, it was only the thermal performance of the assembly that was investigated. However, also the moisture performance is important to consider since changes to existing structures will influence the risk for moisture damages.

In the Annex, the gathered case studies cover a wider range of SIM i.e. aerogel blankets, AB, (7 case studies), silica-based boards, SB, (3 case studies) and VIP (22 case studies). The aim was to gather information from projects where SIMs were used in different assemblies. Some of the projects have been monitored, i.e. sensors were installed to monitor the temperature, relative humidity or heat flux through the assemblies, while only three have been followed up, i.e. where a third party have analysed the results of the monitoring. The case studies are presented and specific and general conclusions from each application are made.

The case studies showed that aerogel blankets are possible to install in up to five layers (50 mm) without too much difficulty. The evaluations showed that the performance of the aerogel blankets was maintained over the evaluation period. For VIPs, it is difficult to evaluate the performance when installed in the wall. In one of the case studies in the report, the external air space made it impossible to identify the different panels by thermography. Only indirect methods, like evaluation of the measured temperatures in the wall, can be used to follow the long-term performance of the panels. In another case study, hybrid insulated district heating pipes were installed at two locations in a district heating system with temperatures up to 90°C. Measurements during the period 2012 to 2015 showed no sign of deterioration of the VIPs and the temperature profile over the pipes was constant. An existing masonry wall was insulated with VIP-foam sandwich (XPS-VIP-XPS). It showed satisfactory and promising performance for a period of six years (2011-present). The analysis of the data obtained from continuous temperature monitoring across each insulation layer indicated the aging of VIP remains insignificant.

In the framework of IEA EBC Annex 65 a common simulation-based procedure was introduced with the scope to identify potential critical hygrothermal working conditions of the SIM, which were identified as main drivers of the ageing effect. The study highlights that some physical phenomena (such as thermal bridging effects, the influence of temperature on the thermal conductivity and the decay of performance over time depending on the severity of the boundary conditions) should be carefully evaluated during the design phase in order to prevent the mismatch between expected/predicted and the actual thermal performance.

As general guidelines to mitigate the severity of the operating conditions of VIP, a list of recommendation are in the following summarised:

- For the external wall insulation with VIP in solar exposed façade, the adoption of ventilated air layer could dramatically reduce the severity of the VIP operating conditions. Alternatively, light finishing colour are warmly encouraged to mitigate the surface temperature.
- The protection of VIP with thin traditional insulation layer is always encouraged.
- The application of VIP behind heater determines high value of surface temperature field which could potentially lead to a fast degradation of the panel. A possible solution to mitigate the severity of the boundary conditions could be the coupling of VIP with a radiant barrier, or the protection of VIP with thin insulation layer when it is possible.
- In roof application, light colour (cool roof), performant water proof membrane, ventilated airspace and gravel covering layer (flat roof) represent effective solutions to mitigate the severe exposure.
- In presence of wall subjected to high driving rain, it is preferable to adopt ventilated façade working as rain-screen to prevent the water absorption.

Furthermore, to provide designers, engineers, contractors and builders with guidelines for the applications of vacuum insulation panels (VIPs) and Advanced Porous Materials (APMs) examples are given of methods that may be used to verify the quality and thermal performance of SIMs after installation. A comprehensive account of transport, handling, installation and quality check precures are presented. The main purpose of the descriptions is to promote safe transport, handling and installation. In the case of VIPs the primary issue is that of protecting the panels whereas the main concern for APMs is the safety in handling of the material.

During the work of the Annex several questions regarding the long-term performance of SIMs on the building scale have been identified and discussed. Four main challenges were identified:

- Knowledge and awareness among designers concerning using SIM
- Conservative construction market
- Cost versus performance
- Long-term performance of SIMs

Finally, SIMs for building applications have been developed in the recent decades. Theoretical considerations and first practical tests showed that VIP, especially those with fumed silica core, are expected to fulfil the requirements on durability in building applications for more than 25 years. Both VIPs and APMs have been successfully installed over the past 15 years in buildings. However, real experience from practical applications exceeding 15 years is still lacking, especially when considering third-party monitoring and follow up of demonstrations

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Appendix B: VIPs performance and operating conditions at building scale for the service life planning

Abbreviations

Table 1: List of frequently used abbreviations

Abbreviations	Meaning
APM	Advanced porous material
ASTM	American Society for Testing and Materials International, an international standards organization
CEN	European Committee for Standardization (Comité Européen de Normalisation)
DHW	Domestic hot water
EE	Embodied Energy
EN	European Norm
EPBD	Energy Performance of Buildings Directive
EOTA	European Organisation for Technical Approvals
GHP	Guarded hot plate
HFM	Heat flow meter
IEA-EBC	Energy in Buildings and Communities Programme of the International Energy Agency
ISO	International Organization for Standardization
LCA	Life cycle Assessment
LCI	Life cycle Impact
LCIA	Life cycle impact analysis
λ	Thermal Conductivity [W/(m K)]
NZEB	Nearly zero energy building or nearly zero emissions building
SIM	Super Insulating Material
ST 1	Annex 65 Subtask 1: State of the Art on Materials & Components - Case Studies
ST 2	Annex 65 Subtask 2: Characterisation of materials & components - Laboratory Scale
ST 3	Annex 65 Subtask 3: Practical Applications – Retrofitting at the Building Scale – Field scale
ST 4	Annex 65 Subtask 4: Sustainability – LCC, LCA, EE – Risk & Benefit
UEATc	Union Européenne pour l'Agrément technique dans la construction a grouping of 18 approval bodies in Europe
U-value	Thermal transmittance of a building element [W/(m^{2}K)]
VIP	Vacuum insulation panel

Definitions

Definitions of energy performance according to EN 15603:2008 (Official Journal of the EU, 19.4. 2012, p. C 115/9):

- **Thermal conductivity:** The amount of heat per unit time per unit area that can be conducted through a plate of unit thickness of a given material, the faces of the plate differing by one unit of temperature.
- **Energy need for heating or cooling:** Heat to be delivered to or extracted from a conditioned space to maintain intended temperature conditions.
- **Energy need for domestic hot water:** Heat to be delivered to the needed amount of domestic hot water to raise its temperature from the cold network temperature to the prefixed delivery temperature at the delivery point.
- **Energy use for space heating or cooling or domestic hot water:** Energy input to the heating, cooling or hot water system to satisfy the energy need for heating, cooling or hot water respectively.
- **Embodied energy:** The total energy required for the extraction, processing, manufacture and delivery of building materials to the building site.
- **Primary energy:** Energy found in the nature that has not been subject to any conversion or transformation process. It is energy contained in raw fuels and other forms of energy received as input. It can be non-renewable or renewable.

Definitions of building life cycle according to ISO 14040:2006:

- **LCA:** Life cycle assessment: compilation and evaluation of the inputs, outputs and potential environmental impacts of a product system throughout its life cycle.
- **LCIA:** Life cycle impact assessment: phase of life cycle assessment aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts of a product system.

Vocabulary for building and civil engineering works according to ISO 6707-1:

- **Construction works:** Everything that is constructed or results from construction operations that has the provision of shelter for its occupants or contents as one of its main purposes, usually partially or totally enclosed and designed to stand permanently in one place.
- **Building element:** Major functional part of a building (e.g. foundation, floor, roof, services)
- **Material:** Substance that can be used to form products or construction works.
- **Product:** Item manufactured or processed for incorporation in construction works.
- **Component:** Product manufactured as a distinct unit to serve a specific function or functions.
- **Assembly:** Set of related components attached to each other

1 Introduction

1.1 General context

In the building sector, space heating (SH) and domestic hot water (DHW) remain the most important energy users [1]. Since the first oil crisis, the implementation of Building Regulations [2] through a combination of higher efficient systems and improved thermal performance of building envelope leads to a significant reduction in the per capita energy requirement for SH. The potential of energy saving has been estimated to be close to the energy consumption in the transport sector [3] and the current challenge is to make this potential a reality. This goal can be reached by developing net zero energy building (NZEB) as defined in the Annex 52 [4] and promoted in the Energy Performance of Buildings Directive (EPBD) recast in 2010 [5]. However, more than 80% of the energy consumption will be influenced by the existing building stock [1]. Accordingly, building renovation has a high priority in many countries. Furthermore, several studies [6,7,8] have shown that the most efficient way to curb the energy consumption in the building sector (new & existing) remain the reduction of the heat loss by improving the insulation of the building envelope (roof, floor, wall & windows).

Since the first oil crisis in 1973-1974, the building regulations require improvement of the thermal performance of the building envelope to significantly reduce the energy use for space heating. Following the regulations, the energy efficiency of new buildings has improved.

In recent years most of developed and developing countries have upgraded or introduced new building energy codes or regulations (IECC, ASHRAE, NECB etc.). Moreover, global green building movement, supported by Net-Zero, LEED, Passive House etc., have also become major drivers for energy efficient buildings. However, in most industrialized countries, new buildings will only contribute 10% to 20% of energy use by 2050 whereas more than 80% of the energy use will be related to the existing building stock of today [1]. Therefore, renovation of the existing buildings has a high priority in many countries. Hence, the existing buildings represent the major challenge as these represent such a high proportion of the energy use and they will remain for many decades to come. Furthermore, several studies [6,7,8] have shown that the most efficient way to curb the energy consumption in buildings (new and existing) is by the reduction of heat losses by improving the insulation of the building envelope (roof, floor, wall and windows).

A step beyond the current thermal performance of building envelope is essential to fulfil the world-wide intended energy reduction in buildings. In Europe, targeting to an average U-value close to 0.2 $W/m^2{\cdot}K$ is optimal [9]. Using traditional insulation materials this means an insulation thickness of about 20 cm. Thus, the thickness of internal and/or external insulation layers becomes a major issue of concern for retrofitting projects and even for new building projects in cities. Furthermore, the thickness of the insulation material is also essential in the domestic hot water systems as well as in refrigerators and freezers. Therefore, there is a growing interest in the so-called super-insulating materials (SIM). The scope of the present work covers two different types of SIMs:

- Advanced Porous Materials (APM), where the gaseous heat transfer is hindered significantly by the fine structure in the sub-micrometre range, and
- Vacuum Insulation Panels (VIP), where the contribution of gaseous conductivity to the total heat transfer is suppressed by evacuation.

For Advanced Porous Materials (APM) one might distinguish between

- porous silica e.g. based on fumed silica, and
- aerogels.

Porous silica is produced e.g. in flame process (fumed silica); aerogels are produced in a sol-gel process.

The insulation performance of these materials can be as good as about twice that of conventional insulation materials. Handling and workmanship might be similar to conventional insulation materials. Therefore, they can be cut and adapted to the needs on-site.

For Vacuum Insulation Panels (VIP) one might distinguish between:

- different core materials: fumed silica, glass fibre, PU, EPS, others;
- different envelopes: metalized film, aluminium laminate, stainless steel, glass, or combinations;
- with or without a getter and/or a desiccant.

The insulation performance of these elements is practically about two to five times that of conventional insulation of the same thickness. Handling and workmanship is quite more similar to windows or façade elements. VIP cannot be cut without losing the benefit of the vacuum. Thus, an exact planning is required to fit to the geometrical sizes of the application. Either standard sizes may be used or special sized and/or shaped VIP must be custom-made. Sensitivity against puncturing of the envelope and increased heat transfer at the edges are characteristics common for façade assemblies but very unusual for standard insulation products used for buildings.

1.2 Challenges for SIMs in construction works

To accelerate the introduction of SIMs on the construction market there are some challenges that must be overcome. The first challenge is the cost versus performance ratio. The thermal performance of SIMs is practically two to five times better than conventional materials. However, the price of 1 m^2 of SIM generally is between 4-15 times higher than conventional insulation materials for the same U-value. Thus, the payback period on an investment with the same thermal performance may be extended. However, there are valuable savings of space when less area is needed for the building elements which leads to an increased rental income [10]. There can also be technical reasons to select a SIM, i.e. when conventional insulation materials are not a practical alternative or for architectural reasons.

The second challenge is the long-term performance of SIM. The service life of a building is 25-100 years. The SIMs for building applications have been developed in the recent decades. Theoretical considerations and first practical tests showed that VIP, especially those with fumed silica core, are expected to fulfil the requirements on durability in building applications for more than 50 years [11, 12]. However, real experience from practical applications ranges up to around 15 years for VIPs [13] and even less for the APMs. Moreover, construction techniques and compositions of SIMs are also changing over the years. Thus, the long-term performance of SIMs in buildings should be assessed.

The third challenge is that the construction market is a conservative market, regulated by numerous codes and standards, and thus, introducing new products takes a long time. However, for VIPs standardization work is ongoing in CEN/TC 88/WG 11 for Europe and in North America VIPs are covered by ASTM Designation C1484-10. Moreover, in Europe several products have had technical approval (ETA) which have now been transformed to technical assessments for several products.

The fourth challenge is knowledge and awareness among designers concerning using SIM. Due to their nature, VIPs can’t be adapted in size on-site by e.g. cutting. Thus, there is an additional effort for planning since standard sizes or custom-made VIP must be ordered in advance. The VIPs are also sensitivity to mechanical puncturing of the envelope. Therefore, special care is necessary during installation. There may be a need for certification of craftsmen and need of special training.

1.3 Objectives of IEA-EBC Annex 65

The activities of IEA EBC Annex 65 have the following objectives:

- to make a state of the art of a decade of development of SIM by the industry and of applications in the building sector,
- to develop experimental & numerical tools to provide reliable data (properties & durability) for manufacturers and designers,
- to write guidelines for secure installation,
- to support standardisation and assessment procedures,
- to improve knowledge and confidence of the supply chain regarding SIM, thanks to sustainability analysis,
- to foster a wider public acceptance of SIM in the future by communication.

As an introduction to the field, Subtask 1 has focused on development of a state-of-the-art report. The activities in Subtask 2 contained several measurement methods for determination of thermal properties of SIM in laboratory. The long-term performance was also determined by using accelerated ageing methods. Generally, determination of long-term performance (25 to 100 years) of novel building materials is done by using accelerated laboratory measurements and verified with limited shorter real case or real environment measurements. The evaluation becomes more important when the SIM can be used in a variety of building elements e.g. floor, walls, roofs, pipes, etc. The objectives of Subtask 3 were focused on gathering and analysing data obtained from case studies in real conditions and real environment. In Subtask 4 methods for assessment of the overall sustainability of SIMs through the evaluation of LCA, and LCC of superinsulation materials over the entire life cycle (production, use and end-of-life) was developed and utilized.

1.4 Objectives and structure of Task 3

The activities in the task are separated in three actions:

a) Mapping of the Use Conditions (Components & Assemblies),

b) Performance at the Building Scale (Experiments & Simulation), and

c) Practical Applications focused on Retrofitting

The objective of this task is to define the application areas of SIM and to describe the conditions of the intended use of the products. Indeed, it's clear that the requested performance of the SIM will strongly depend on the temperature, humidity and load conditions. For building applications, storage, handling and implementation requirements are also described. Common and specific numerical calculations will be performed at the building scale to assess the impact of SIM on the performance of the building envelope.

This report starts in Chapter 2 with a summary of the report of Subtask 1 'State of the Art on Materials & Components – Case Studies' where different SIMs are introduced. In Chapter 3, the use conditions for different buildings and building assemblies are presented together with previous and new case studies of long-term performance of SIMs in practice. In Chapter 4, a methodology for assessment of the performance at the building scale is given in. Recommendations for how to implement SIMs practically at the construction site is presented in Chapter 5. The final conclusions and outlook are presented in Chapter 6.

2 Super-Insulation Materials on the construction market

2.1 Description of SIM

In general, heat transfer forced by a temperature gradient may be separated to three different physical heat transfer mechanisms:

- convection, a transport mechanism which is related to the transport of gases or liquids,
- conduction, the energy transfer between neighbouring atoms or molecules in the solid, liquid or gaseous phase, and
- radiation, long-wave infrared radiative heat transfer even in vacuum.

First task of any porous thermal insulation material at room temperature is to suppress convection, the most efficient heat transfer mechanism. Second task is to attenuate radiative heat transfer. As the thermal conduction of gases is much smaller than that of liquids and solids thermal insulation materials usually are highly porous. Optimisation of air-filled thermal insulation materials balances between radiative heat transfer and thermal conduction via the solid skeleton. Nevertheless, the conductivity of the gas in the hollow spaces is the dominant heat transfer path (see Figure 2-2). Thus, further improvements are achieved by:

1. modification of the gas - heavy gases have a lower conductivity than air - e.g. in closed-cells polyurethane (PU) foam with blowing agent,
2. reducing the size of the hollow spaces down to the mean free path of the gas molecules in the order of about 100 nm (at 25°C, atmospheric pressure), so that the heat transfer of the gas molecules is hindered by numerous collisions with the solid structure (nano-structured aerogels or fumed silica), or
3. removing the gas by evacuation. Unlike cylindrical vessels like thermos flasks, in flat evacuated elements, a filler material is necessary to bear the external atmospheric pressure. The so-called vacuum insulation panels or VIPs thus in principle are composed by an envelope and a filler or core material.

The scope of the present work covers two different types of so-called super insulation materials (SIM):

- Advanced porous materials (APM), where gaseous heat transfer is hindered significantly by the fine structure in the sub-micrometre range (see the third group in Figure 2-2) and
- Vacuum insulation panels (VIP), where contribution of gaseous conductivity to the total heat transfer is suppressed by evacuation (see the fourth group in Figure 2-2).

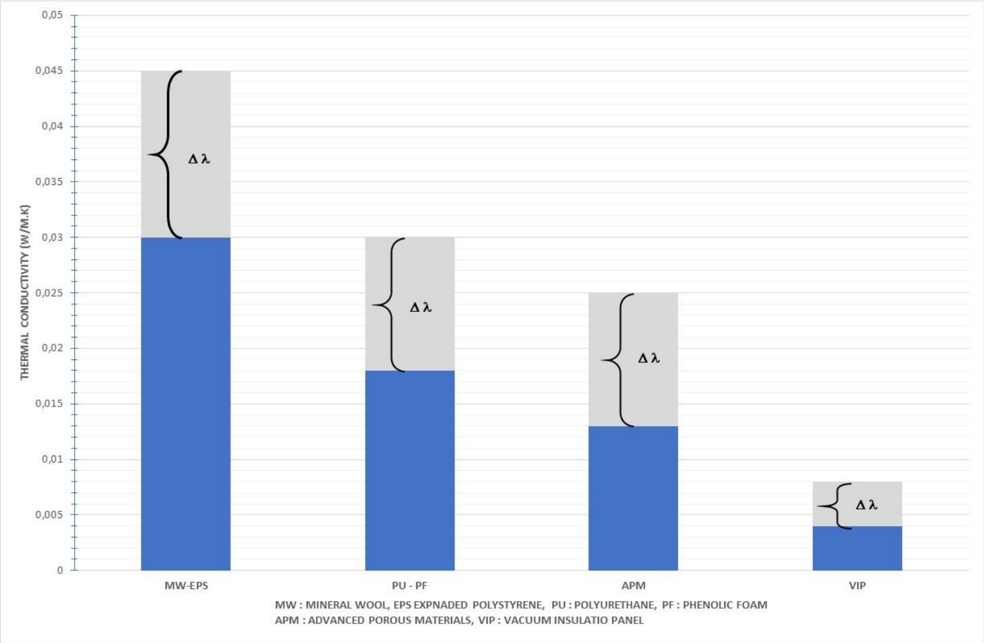

Figure 2-1: Comparison of the thermal conductivity of different thermal insulation materials used for buildings. The blue bar indicates the spread of different products commercially available.

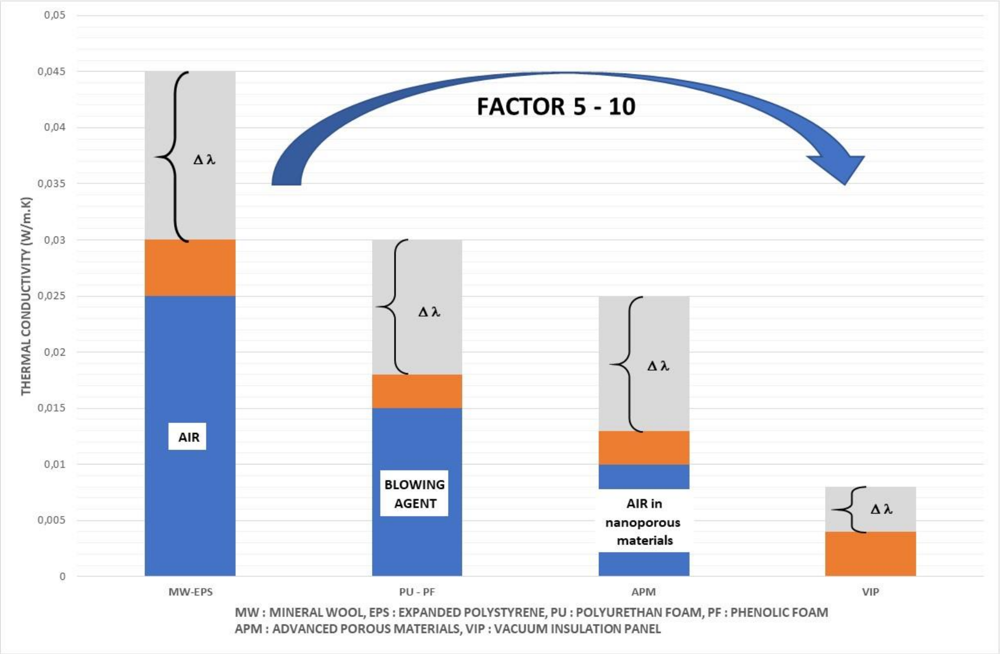

Figure 2-2: As Figure 2-1. Additionally the yellow bar indicates the contribution of the gas to the total heat transfer. It becomes obvious, that significant reductions in the total heat transfer are related to the gas [14].

Some historical review was given by Fricke and Emmerling [15] for aerogels, and Fricke et al. [16] for VIP. One of the first publications on aerogels and the relation between heat conductivity and structure in silica aerogel is from Kistler [17] and [18]. A systematic study on the heat transfer and the contribution of the different paths was given by Kaganer in 1966, translated from Russian to English by Israel Program for Scientific Translation in [19].

For further information, please refer to Subtask I - State-of-the-Art and Case Studies report, Chapter 2.

2.2 Advanced Porous Materials

For advanced porous materials (APM) one might distinguish between

- porous silica e.g. based on fumed silica and
- aerogels.

Porous silicas are produced e.g. in flame process (fumed silica); aerogels are gained by a sol-gel process.

The total thermal conductivity of APM is about half of that of conventional insulation materials. Handling and workmanship could be like conventional insulation materials. Therefore, they can be cut and adapted to the needs on-site.

Advanced porous materials (APM) can be described by their morphology. The raw materials consist of a nano-scaled open porous structure with a high-levelled porosity (up to 97%, the most common ones between 90 to 94%) and a solid body built as a network of connected particles and pores in the range of 20 nm. They are known as light materials with density in the range of 50 to 250 kg/m³.

APM for thermal superinsulation applications consist primarily of two families:

Firstly, lightweight solids or granular material derived from sol-gel processing, in which the liquid component of the gel has been replaced by air. These may be available as monoliths, granules, fibre reinforced mats, bonded, or packed between to composite sheet.

Secondly, materials based on synthetic amorphous silica packed boards received from hydrophobised pyrogenic (fumed) silicon dioxide.

For further information, please refer to Subtask I State-of-the-Art and Case Studies report, Chapter 3.

2.3 Vacuum insulation panels

Vacuum insulation panels (VIP) represent a state-of-the-art high-performance thermal insulation solution. The pristine non-aged centre-of-panel thermal conductivity value for a VIP can be as low as 2 to 4 mW/(m·K) depending on the core material. Declared values for the thermal conductivity, which also account for thermal bridge effects and ageing e.g. within 25 years, typically are between 7 and 8 mW/(m·K) for VIPs with fumed silica cores. VIPs enable highly insulated solutions for building applications, both for construction of new buildings and for renovation of existing buildings, and hence may be a measure to reduce the energy usage in buildings without having to employ thick building envelopes.

For vacuum insulation panels (VIP) you might distinguish between:

- different core materials: fumed silica, glass fibre, PU, EPS, others;
- different envelopes: metallised film, aluminium laminate, stainless steel, glass, or combinations;
- with or without a getter (vapour absorbers) and/or a desiccant.

The total thermal conductivity of these VIP is about a fifth to one-tenth of that of conventional insulation. Handling and workmanship are quite similar to windows or façade elements. VIP cannot be cut without losing the benefit of the vacuum. Thus, an exact planning is required to fit to the geometrical sizes of the application. Either standard sizes may be used or special sized and/or shaped VIP must be custom-made. Staggered double layer pattern could be used to reduce the edge thermal bridge effects. Sensitivity against puncturing of the envelope and increased heat transfer at the edges are characteristics common for façade elements but very unusual for standard insulation products used for buildings.

For further information, please refer to Subtask I State-of-the-Art and Case Studies report, Chapter 4.

3 Mapping of the Conditions (Components & Assemblies)

SIM was used in almost all building components with different environmental condition (boundary condition) and in different climate zone. Generally, insulation materials are used for fulfilling sustainable energy demands in buildings. However, the insulation materials can be exposed to mechanical loads e.g. insulation in a flooring. Furthermore, moisture and temperature in building components can cause moisture/temperature induced stresses and the stresses can cause damage in sensitive super insulation material e.g. VIPs. Thus, to convince the conservative market of construction, it needs, in addition to laboratory measurements, real condition/environmental measurements of commercially realized objects (new buildings as well as refurbishments) under several years of operation.

The long-term performance of super insulation materials must be determined based on case studies in field and laboratory. Full scale experiments provide knowledge of practical and technical difficulties as well as data for service life estimation. For certain conclusions to be drawn from the case studies, monitoring is essential. Unfortunately, monitoring is only performed in few case studies. In this Annex 65 Subtask 3 “Practical Applications – Retrofitting at the Building Scale – Field scale” these experiences are gathered and evaluated from a long-term performance perspective.

3.1 Previously reported studies in the literature

Previously reported studies concerning SIMs have focused on a variety of topics and areas of applications. In this report we aim to give a state-of-the-art update on different case studies previously reported in the literature and broaden the knowledge by presenting new case studies that were collected through the network and working group of the Annex. It was found that APMs have been studied since the 1930’s for a variety of applications and have found commercial success since the early 2000s in the building industry. VIPs, on the other hand, have been used in other applications than buildings, such as refrigerators and transport boxes, thus modifying these for construction was performed faster than for APMs.

3.1.1 Advanced Porous Materials

Since the early 2000s many case studies and applications to come installed. APMs have been commercially successful in the building industry in niche applications typically with space restrictions since the early 2000s. Therefore, over the last years, several state-of-the-art reviews have focused on applications of advanced porous materials, such as aerogels, used as thermal insulation in buildings [20, 21, 22, 23]. This shows there is a large interest in the materials. The most common aerogel-based products are opaque aerogel infused blankets, granulate aerogels (generally hydrophobized), and translucent monolithic aerogel plates. For further information on the types of aerogels, please refer to Subtask I State-of-the-Art report, Chapter 3.

Good knowledge of the hygrothermal properties are fundamental to predict the relation between the performance at the material, component and building scale. The aerogel-based products, such as blankets, are in general vapour permeable and has a low liquid water absorption. Additionally, the thermal conductivity is stable at dry and moist condition up to 90% relative humidity, and above for some products [24]. If free water saturation of the pores is reached, the thermal conductivity rises. This condition is seldom fulfilled when blankets are used in buildings. In general, the increase of the thermal conductivity is small due to the low water content of the moist material, but it depends on the hydrophobic nature of the aerogel-based insulation. The temperature range normally found in constructions with internal, but also external retrofit, does not significantly affect the thermal conductivity of the products. For further information on the material characteristics, please refer to Subtask 1 State-of-the-Art report, Chapter 2 and Subtask II report, Chapter 3.

Previous studies of the installation and design of APMs targets all kind of materials listed above. Aerogel-based blankets, where aerogel is coupled with a fibrous matrix, have been used in buildings for both internal and external insulation of the walls since the early 2000s. One of the advantages is the easy application thanks to their flexibility. Some examples of these systems for internal and external retrofit can be found in e.g. [25, 26].

The hydrophobicity of the APMs and the stability and durability, demonstrated during laboratory testing, confirm the suitability for exterior retrofit, which can be applied with tailor-made renders. One of the earliest reports on applying aerogel-based blankets as exterior insulation for old buildings with massive walls, showed the effective thermal improvement by means of IR thermography and in-situ measurement of the U-value [27]. The flexibility of the blankets was a major asset as the old stone walls did not have a regular shape and in this case a rigid insulation would be much more difficult to apply. An important fact is that the effective thermal conductivity of the aerogel-based blankets on site is slightly higher than the values given by the supplier. This is due to application of render and finish and the intermixing with the blanket. Furthermore, numerical hygrothermal modelling showed that even with an initially wet wall (equilibrium with 90% relative humidity i.e. 3.9 kg/m^3 water content) the retrofitted wall will dry out to half of the initial water content within 4 years. This shows the importance of choosing gluing layers that are vapour open to allow the drying out of the inner layers. Finally, the external appearance of the 130 years old building could be kept unchanged. This was clearly visible when compared to the non-retrofitted reference building. IR thermography during the cold period was used to quantify the temperature difference on the exterior surfaces of the two buildings.

The KUBIK building, Derio, Spain, is a full-scale experimental R&D infrastructure to demonstrate energy efficient technologies, focused on the development of new products and systems [28]. A relatively large test cell on the second floor of the KUBIK test building was selected for testing aerogel based composite insulation system for inner retrofit. A monitoring campaign was performed in 2014 over 6 months. According to the researchers, the measurements provided thermal conductivities of the aerogel board within the range of the thermal conductivity measured at laboratory scale; 15-17 mW/(m·K). Unfortunately, no data in terms of moisture are available from this study.

In another previously reported study, the behaviour of prototype aerogel-based blankets used for interior insulation have been monitored for roughly 1 year after installation on an existing wall (Milan, Italy), considering the effect of moisture. After model validation [29], a HAM simulation was carried out to determine the long-term (10 years) performance with different thickness of the insulation, two different climatic contexts and two different types of masonry [30]. The results point out the well-known critical aspects of an interior retrofit of existing traditional masonry constructions. Adding layers with high thermal resistance on the inside reduces the temperature and increases the relative humidity in the existing wall. The risk of interstitial condensation in the HAM simulations is largest for insulation thicknesses of more than 5 cm, high indoor moisture load but for shorter time periods. This condensation is due to the balance between vapour diffusion and capillary liquid transport in the porous materials. In winter, at non-isothermal condition, vapour transport is from inside to outside (due to the partial pressure gradient) and liquid-moisture transport goes into the opposite direction (due to RH gradient). In other words the vapour inside the room passes easily through the very vapour open insulation and reaches condensation behind it, on the contrary the liquid stored behind the retrofit does not easily go to the internal side, due to the hydrophobic nature of insulation. For that reason wall dries off slower and the the risk of thermal transmittance increasing over time is not due to the water storage inside the insulation layer itself, but rather inside the existing wall. It was demonstrated that changing the type of finishing layer and choosing the right gluing material helps to avoid moisture retention, even when the boundary conditions are critical. The interior surface temperature and moisture trend after the interior retrofit was always satisfactory and below critical values in the simulation results.

Hydrophobized granulate aerogel can be added also to mortars for obtaining insulating renders [31]. The hygrothermal behaviour over time of the aerogel-based insulating render was monitored and analysed [32, 33, 34]. Stahl et al. [35] applied an aerogel based rendering to the whole external façade of an inhabited historic mill in Sissach, Switzerland, maintaining the old character of the building. The reduction of energy demand for heating, avoiding also moisture accumulations between the applied rendering and the original wall were demonstrated in the project. As the authors declared, temperature and moisture measurements at critical sites showed no trespassing of the threshold for damages. The measured temperature does not go below the dew-point temperature between the original wall surface and the applied rendering and no deterioration or detachment of the rendering occurred. The hygrothermal simulations showed that even if the walls are wet they will dry out as the aerogel-based render is vapour permeable and does not induce moisture accumulation over a long period of time.

Another investigation on the usage of rendering containing aerogel for energetic refurbishment of half-timbered walls has been reported by Stahl [36]. The aerogel rendering was used also as infill of the half-timbered wall and its influence on the moisture accumulation in the wooden parts. Furthermore, samples of the aerogel render was cut out of the wall after being subjected directly to the climate of Duebendorf, Switzerland, for 1.5 years, and their thermal conductivity measured. It was found that these values correspond to the thermal conductivity of the aerogel render at approximately 75% relative humidity.

Several investigations concern also aerogel glazing systems [37, 38]. Buratti and Moretti [39] investigated the performance of both monolithic and granular aerogel for the glazing system. The experimental campaign carried out on an aerogel window prototype at lab scale confirmed the estimated results, showing lower thermal transmittance (-23%) than a conventional window (such as a double glazing with a low-e layer). Monolithic aerogel is better for light transmission, thermal insulation and solar factor. Granular aerogel glazing can also improve the sound insulation of the building envelope. According to the researchers a 55% reduction in the heat losses was achieved by monolithic aerogel, with only a 25% reduction in light transmittance compared to a conventional window. For the granular systems, the reduction was about 25% in heat losses, but 66% in light transmission. In that case no long-term evaluation is available. Gao et al. [40] presented an overview of examples for building integration of aerogel glazing: a single-family house with aerogel glazing (Villa Holmenkollen, Oslo); the Rama 1000 supermarket at Kroppanmarka with 220 m^2 aerogel glazing panels; Levanger primary school, in Norway, where the entire second floor was built with aerogel glazing for upper windows and normal clear glass glazing for low windows; Sandvika knowledge centre in Oslo, where the roof was integrated with aerogel glazing.

3.1.2 Vacuum insulation panels

The different applications areas have been identified by numerous researchers. In 1999-2002 an investigation commenced by the US Department of Housing and Urban Development evaluated the market potentials for VIP in residential buildings in the US [41]. 27 different constructions were evaluated which resulted in ten alternatives of which five were chosen as most promising based on their respective annual market potentials. These were manufactured housing floor panels (45.4 km^2), exterior doors (9.3 km^2), garage doors (3.1 km^2), manufactured housing ceiling panels (45.4 km^2), and attic access panels/stairway insulation (approx. 1 million access panels on the US market).

The IEA Annex 39 investigated the possibilities to use VIP in buildings during [42] 2002-2005. In total 20 constructions were analysed in respect of the consequences on energy use, thermal bridges and moisture performance:

1. Floor and ceiling insulation (Zug/Switzerland)
2. Interior and dormer window insulation (Zürich/Switzerland)
3. Terrace insulation (Kerzers/Switzerland)
4. Floor insulation in a cold and deep-freeze room (Winterthur/Switzerland)
5. Non-load bearing wall sandwich elements (Landschlacht/Switzerland)
6. Parapet insulation in window element (Basel/Switzerland)
7. Façade insulation with prefabricated panels (Binningen/Switzerland)
8. Façade insulation (Nuernberg/Germany)
9. Insulation of outside walls, roof and door (Munich/Germany)
10. Insulation of the building envelope (Munich/Germany)
11. Insulation of a wall heating system (Wernfeld/Germany)
12. Jamb-crossbar construction (Erlenbach/Germany)
13. Integrated façade element with radiator (Wuerzburg/Germany)
14. Insulated prefabricated concrete elements (Ravensburg/Germany)

15. Façade insulation (Bersenbrueck/Germany)
16. Façade insulation with polystyrene-lined VIP (Trier/Germany)
17. Façade insulation (Munich/Germany)
18. Floor insulation (Kempten/Germany)
19. Floor insulation (Schaffhausen/Switzerland)
20. Renovation with insulation under underfloor heating (Gemuenden/Germany)

Unfortunately, few of the case studies mentioned above have long-term monitoring results on neither temperature nor moisture conditions several years after construction. This may be caused by that many of the projects are practical demonstration projects that have been monitored only a short time after the VIPs were installed. After commissioning, there is normally small interest among building owners to participate in monitoring schemes since the results will probably not benefit them. Therefore, other means of follow-up of the long-term performance have to be used to get insights in a bigger number of different VIP applications, including also some of earlier ones. Heinemann and Kastner [43] used infrared thermography to investigate 19 buildings insulated with in total 3 224 m^2 VIPs, a few years after the construction finished. The objective was to evaluate the performance in real practical application. Thus, most of the investigated objects were realised commercially. Additionally, also the very first experimental object, a refurbished gable façade in Nuremberg, was reviewed. Three objects stood out in the investigation with more than 15% of the VIPs damaged. In one of these objects it was assumed that errors were made in the design by installing unprotected panels close to an uneven plaster surface. In another project, photos from the construction site showed that the VIPs had been stored and handled improperly by the construction workers. In some of the very first objects, an alkaline glue was used which is not recommended today since it will deteriorate the aluminium in the VIP laminate leading to a reduced service life. In the 16 buildings remaining after the worst objects had been removed, 1 999 m2 VIPs had been installed. The total percentage damaged VIPs was 4.9% in these objects. Thermography repeated over several years did not yield any hint for an additional unexpected failure mechanism. Thus, it was assumed that failures are due to improper installation. The conclusion of the study was that the percentage of damaged panels installed in a construction is low, if the recommendations by the producers are followed.

A Norwegian investigation by Grynning et al. [44] concluded that the building traditions in other parts of the world (Scandinavia, North America, Asia) are different from the traditions in central Europe. Many of the first constructions with VIP are in Switzerland and Germany where the use of timber constructions is less common. For example, Norwegian single-family houses are almost exclusively built using timber frame constructions with a ventilated roof. This means that the conclusions from the Swiss and German studies cannot be applied directly to these buildings without more evaluations. Several assemblies where it could be possible to use VIP in Norway were identified:

- Prefabricated sandwich elements
- Continuous insulation layer in non-load bearing walls
- Thin timber frame walls
- Floors and compact roofs
- Retrofitting of buildings with limited available space

- New buildings in areas with high ground costs
- Doors and windows
- Insulation of terrace floors where even connections are important

A number of studies of long-term performance of VIPs were gathered by Johansson [13]. He concluded that in most studies of VIPs available in the literature, it was only the thermal performance of the assembly that was investigated. However, also the moisture performance is important to consider since changes to existing structures will influence the risk for moisture damages. The focus on energy performance is beneficial for short term improvements in the building envelope but could prove costly on long term. The VIP laminate is comparable to a vapour barrier in regards of vapour transfer. This may cause problems around the panels if the connection between them is insufficiently sealed. Moist air could be transported through the layer and into the cold parts of the construction. In some cases, sealing tape has been used to increase the air tightness of the connections. Another option is to use an additional layer of vapour retarder to ensure a vapour tight layer.

One of the most predominant building elements where VIPs have been used is in flat roofs. At Empa researchers have monitored a roof construction in Zurich, Switzerland, containing VIPs since 2004. After 2 years, seven of the panels were removed from the roof and the pressure and weight increase were measured. These showed that the pressure in the VIPs had increased by 2.1 mbar/year for 50x50 cm VIPs on average after 2 years [45]. The same flat roof was reopened in 2013 after 8-9 years operation. Some of the installed VIPs were transported to the laboratory for measurements of the thermal conductivity. Brunner and Ghazi Wakili [46] found that the thermal conductivity indeed had increased after 8.8 years to 6.6 mW/(m·K) respective 7 mW/(m·K). This is an increase of 65-75% from the initial thermal conductivity of 4 mW/(m·K), but still well below 20 mW/(m·K) which is the thermal conductivity of the core material at atmospheric conditions.

One of the 20 constructions studied by [42] was a protected heritage building, with a protected façade, in Nuremberg, Germany. The retrofitting was finished in 2000 and Heinemann and Kastner [43] investigated the building again in 2001, 2003 and 2008 with infrared thermography. The exterior of one of the gable walls was retrofitted with VIPs as shown in Figure 3-1. The 15 mm thick VIPs were secured between horizontal plastic rails that were fastened in an exterior 35 mm thick layer of EPS. A vapor barrier was attached between the VIPs and the existing wall. The calculated U-value of the wall was improved from 0.7 W/(m^2·K) to 0.19 W/(m^2·K) which would increase to 0.32 W/(m^2·K) if the panels were damaged. The infrared thermography showed a temperature difference of 0.7°C between the centre-of-panel and the edge [42]. As can be seen in Figure 3-1 one panel underneath the two windows was damaged already in 2001. A second panel had an increased surface temperature in 2008 which indicated that it had been filled with air. However, the remaining VIPs seem to be in good condition after 8 years of operation [43].

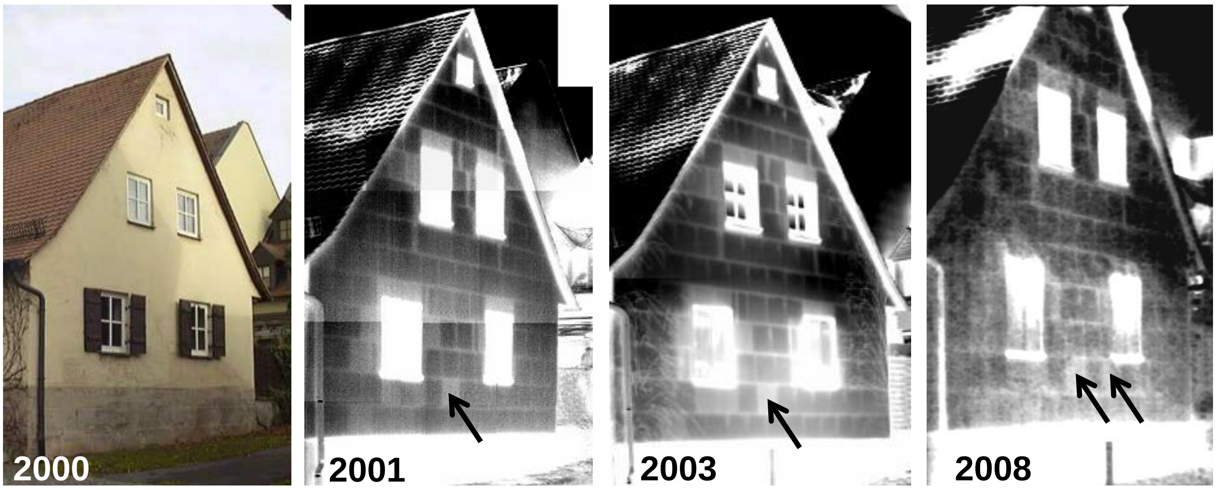

Figure 3-1: The gable of a listed building was retrofitted on the exterior with 15 mm VIPs using a special plastic rail system. The wall was afterwards investigated using thermography. From left: 2000, 2001, 2003 and 2008 (Photo: ZAE Bayern; [43]).

Another façade where VIPs had been used was studied by Brunner et al. [47]. The VIPs were surrounded by a layer of EPS on all sides where plaster had been applied on the exterior. One day the façade had blisters and cracks in the plaster. When the plaster was removed, 17 out of the 88 VIPs in the façade had been filled with air. The internal pressure in some of the remaining evacuated VIPs was measured and found to be above 200 mbar. Brunner et al. [47] found that the reason for the failures was that the metallization process in the production of the metalized multi-layered polymer laminate had failed. The resulting laminate had many defects in the aluminium layers resulting in a large air and moisture permeability. When solar radiation increased the temperature on the surface of the VIPs the internal pressure increased rapidly, and the VIPs were blown up. This problem can be avoided in the future by careful inspection of the laminate before used as VIP envelope.

More information of case studies with SIMs in building applications can for instance be found in [13, 42, 43] and from home pages such as [48, 49, 50]

3.1.3 Conclusion related to the previous studies

In the report by Binz et al. [42] the closing word on quality assurance is that actions are needed in this field. They also recommend systematic measurements of the internal pressure of the panels at the producer so that defective specimens can be tracked down and crucial processes identified. In the past producers had quality assurance problems at the production plants which meant the quality on the products varied. Nowadays, the production is standardized with mainly high-quality control procedures at the production plant. However, it has still to be made sure that the VIPs applied in a building do not get damaged during the handling and installation processes. Due to lack of proper tools for the required measurement tools are not suitable for quality control in the whole process chain. During the last years improved measurement techniques and new kind of sensors have created better possibilities.

From the study by [43], the main conclusion is that as long as the VIPs are not damaged at installation, about 95% of the VIPs will maintain their vacuum. Thus, the installation of the VIP is the critical process. The technology seems to function properly for all assemblies. Unusual, not expected ageing phenomena or even destroying mechanisms could not be detected, even for the oldest application (> 10 years), with infrared thermography.

Therefore, the starting point for this Annex work is that

- The long-term performance (25-100 years) cannot be entirely determined due to lack of data for longer period than 10 years. However, as seen above, there were few claims concerning the malfunction of VIPs in construction.
- APMs have found commercial success in most traditional building insulation applications, due to the cost position relative to other materials typically these applications have been focused in areas of space restriction or in areas of very high-performance requirements.
- APMs are suitable for building application, demonstrating vapour permeability, low liquid water absorption and almost stable thermal conductivity even at moist condition of insulation (up to ≈ 90% RH and above). The materials are robust and well suited to the building site handling conditions.
- The hydrophobicity of the APMs and their stability and durability, demonstrated during laboratory testing and by in-situ monitoring, confirm the suitability for exterior and interior retrofit, used as both aerogel blanket and aerogel insulating render.
- For the optimum inner retrofit in critical climatic contexts, attention should be paid to the thermal resistance and consequently thickness of insulation during the design phase, to avoid moisture retention within the existing wall. This analysis should be coupled to the right characterization of the diffusive properties of the APMs and the right choice of the gluing and finishing layer.
- The performance of a VIP should be controlled at construction site before assembling of the VIP, since transportation and storage on site can be crucial processes.
- Workmanship in construction site should be improved. The improvement covers handling of VIP during construction and knowledge about which type of material can be used in vicinity of the VIP.
- Thermal performance of a VIP is the main technical function for reduction of energy demand. However, the thermal performance can be reduced if VIPs in a component are not assembled in a way that prevent undesired air and moisture transfer e.g. sealing between two VIPs and connection between VIPs and frames.
- VIPs sandwiched between semi rigid insulation boards appear to be less failure on the construction site and may have a longer service life.

3.2 Current studies gathered in the Annex

Several case studies related to using SIM in buildings and building elements were gathered during this Annex. The aim is to increase the knowledge bank by presenting these case studies that were collected through the network and working group of the Annex The case studies cover a wider range of SIM i.e. aerogel blankets, AB, (7 case studies), silica-based boards, SB, (3 case studies) and VIP (22 case studies). The aim was to gather information from projects where SIMs were used in different assemblies. Some of the projects have been monitored, i.e. sensors were installed to monitor the temperature, relative humidity or heat flux through the assemblies, while few have been followed up, i.e. where a third party have analysed the results of the monitoring. A summary of the case studies is presented in Appendix A. The case studies are distributed on several different building envelope components and includes new construction and renovation projects, as presented in Table 2.

Table 2: Number of case studies and total area of SIMs divided on the building envelope component where SIMs were installed.

SIM	Building envelope component	Number of case studies	Total SIM area (m^2)
APM: Aerogel blankets, AB	New wall	2	280
	Renovation wall	5	2,347
APM: Silica boards, SB	New wall	1	-
	Renovation wall	2	-
VIP	New wall	8	5,655
	New roof	2	15,045
	Renovation wall	7	70,298
	Renovation roof	1	13
	Lab scale wall	3	30
	District heating pipes	1	N/A
Total	-	32	93,668

The case studies are in different climate and locations. Table 3 presents the case studies based on their location and Table 4 based on the reported climate conditions.

Table 3. Number of case studies and total area of SIMs divided on country.

Country	Number of case studies	Total SIM area (m^2)
Canada	1	-
China	3	70,000
France	1	40
Germany	7	495
Greece	1	16
Italy	2	9
Japan	4	2,803
Korea	3	17,750
Sweden	3	95
Switzerland	2	200
United Kingdom	4	233
USA	1	2,000
Total	32	93,668

Table 4. Number of case studies and total area of SIMs divided on climate conditions (where reported).

Climate conditions	Number of case studies	Total SIM area (m^2)
Cold / wet	12	2,632
Oceanic, mild	3	20,096
Medium tempered	9	68,125
Total	25	90,826

3.2.1 Case studies Aerogel Blankets (AB)

There are 7 case studies where aerogels have been used. Of these, one wall renovation in New York City, USA stands out with 2,000 m^2 aerogel blankets (AB). In the following, a selection of the case studies is presented. A summary of the U-value before and after renovation (when applicable) is given in Table 5.

Table 5. U-value before and after renovation for the 8 case studies using AB.

City, Country	U-value before (W/m^2K)	U-value after (W/m^2K)	Total SIM area (m^2):	SIM thickness (mm):
Marktredwitz, Germany*	-	0.24	200	50 (AB)
Nottingham, UK	-	-	80	20 (AB)
Milan, Italy	0.97	0.7/0.52	7	6/20 (AB)
Oberhallau (SH), Switzerland		0.48	200	18 (AB)
London, UK	2.1	0.15	80	30 (AB)
Watford, UK	2.1	0.3	60	30 (AB)
New York City, USA	2.6	0.5	2,000	20 (AB)

**Too little information and no third-party follow up of the construction after the project finished, therefore not included in the following presentation.*

3.2.1.2 Nottingham, United Kingdom

Figure 3-2: Test house in Nottingham, UK [51].

Contact (org) University of Nottingham

Application area New wall

Project description

The project monitored a test family house in Nottingham, UK. Both theoretical & practical evaluations were carried out. With the use of just 20 mm of aerogel blanket a 63% reduction in the measured heat loss through the wall was observed. The project demonstrated the how the energy efficiency could be improved using aerogels in slim wall designs. The project demonstrated the conformity of theoretical design and practical measurements. Prototype house built solely for monitoring real life energy efficiencies. The walls in the test house were monitored before and after the installation using heat flow meters to determine actual physical heat loss before and after insulation installation.

SIM m^2 80

Follow up Yes

References Cuce et al. [51]

3.2.1.3 Milan Italy

Figure 3-3: Building no.14, Politecnico di Milano, conference room [29].

Contact (org) Polimi and Empa for EASEE Project

Application area Renovation wall internal

Project description

The EASEE project (2013-2016) aimed at developing and producing innovative and easy to implement solutions, to be combined according to the characteristics of the existing building to be retrofitted. A part of research activity was related to develop prototype insulating materials for the inner retrofitting: an aerogel based laminated board and an aerogel-based wallpaper compared to a perlite based board. They have been installed with specific renders and gluing materials. The facade used as demonstration is a south-east oriented cavity wall, belonging to the academic building, which has been retrofitted to measure the performance in terms of transient U-value, considering also the effect of moisture. The wall has been monitored in continuous before and after retrofitting for a year and a half and the monitoring is still on-going. Data have been acquired by means of a wireless communication system. Humidity and temperature sensors have been installed on the external and internal surface, behind the insulation and inside the air cavity. Heat flux meters have been installed on the internal surface of the wall partitions. Furthermore, inside and outside air temperature and humidity data are collected. A solar pyranometer has measured the irradiance on the south-east facing wall. To have a complete climatic data set at boundaries, data collected from the weather station, placed on the roof of the building, have been added, including the rain measured on the horizontal surface, wind speed and direction, and long wave radiation.

The analysis comprised of both monitoring and numerical HAM modelling (WUFI), by means of comparison between simulation and measurement. A parametric analysis permitted both the validation of assumptions made for numerical simulations and the identification of the most affecting variables.

The average U-value of the wall before retrofit was 0.97 W/m^{2}K and after the retrofit the average U-value is 0.52 W/m^{2}K for the aerogel board (20 mm thick) and 0.70 W/m^{2}K for the aerogel wallpaper (6 mm thick), a U-value reduction between 30% and 50%.

The moisture and temperature trend measured over time through the wall proves the expected performance of these insulation systems, considering the thin layers of insulation and the vapour permeability.

SIM m^2	7 m^2 (3.5 m^2 of aerogel laminate board / 3.5 m^2 of aerogel wallpaper)
Follow up	Yes
References	[24, 29, 52, 53]

3.2.1.4 Oberhallau (SH), Switzerland

Figure 3-4: Old mill renovated in Oberhallau, Switzerland [54].

Contact (org) Amstein + Walthert AG

Application area Renovation wall external

Project description

The thick stone walls of an old mill building from 1608/09 were insulated from the outside with a double layer of aerogel sheets, to reduce the heat losses while maintaining the external appearance of the building (monumental protection). To compare different possible solutions (e.g. outside vs. inside insulation), the following detailed analyses were performed by the means of specific software:

- 3D model of the thermal bridges (Antherm)
- dynamic simulation of the moisture transfer through the walls (WUFI)

This was the first multi-layer application of aerogel sheets, so the realisation had to be carefully planned together with the contractor and was first tested on a sample surface. Since then, thicker layers and multilayer applications have become standard and do not require special expertise anymore. Since it was a new and costly realization, it was only possible thanks to the determination of the owner and planners to adopt an innovative solution. In the years since the renovation, there was no need for further works on the external walls and the occupants are satisfied with the building performance.

The old mill was renovated and insulated on the outside. Aerogel insulation layer of 18 mm resulted in U-value of 0.48 W/(m^2K). Heat loss was reduced, the estimated heating demand savings of the building section insulated with aerogel amount to 25%.

SIM m^2 about 200

Follow up No

References [54]

3.2.1.5 London, United Kingdom

Figure 3-5: Victorian London terrace home [55].

Contact (org) Aspen Aerogels Inc.

Application area Renovation wall internal

Project description

An 1840 London terrace was completely refurbished using a variety of insulation materials ranging from traditional insulation to VIPs and Aerogels. The project was completed in 2013. The insulation materials were all internally applied as the building is in a conservation area. The building has been monitored for hygrothermal performance. The use of SIM was selected to maximise the internal living space, manage the hygrothermal performance and overall energy use reduction. SIM contributed significantly to the treatment of thermal bridges common to this type of building. Due to weather conditions prevalent in London and the use of internal insulation a major effort was made to measure and monitor the RH of the building envelop. AB insulation was used extensively to address thermal bridging common to this type of construction, challenging details such as the wall to intermediate floor cavities were addressed without increasing the risk of damage to the supporting timbers embedded in the wall. Continuous monitoring of relative humidity in building and walls using 15 embedded sensors starting in mid-May 2013 (mid-construction) and are on-going. The walls are behaving as expected for the construction type, exposure and climatic conditions and vapour permeable materials utilized.

SIM m^2 80

Follow up Yes

References [55, 56]

3.2.1.6 Watford, United Kingdom

Figure 3-6: Stable block in Watford, UK [57].

Contact (org)	Aspen Aerogels Inc.
Application area	Renovation wall internal

Project description

The Victorian stable block at the BRE centre in Watford, UK, was refurbished using internal wall insulation on to a solid wall. Aerogel blankets from Aspen were selected for one of the blocks. The project was part of the UK energy reduction programme ‘CERT’. The performance of the insulation was measured by Heat Flow Meter before and after the installation. The internal state of the rooms is continuously measured for humidity and comfort.

SIM m^2	60
Follow up	Yes
References	[57]

3.2.1.7 New York City, USA

Figure 3-7: Building on 1770 Davidson Avenue, Bronx, New York City, USA [58].

Contact (org) Aspen Aerogels Inc.

Application area Renovation wall internal

Project description

A multi-family solid brick 1920's building in New York City including 65 apartment units, was insulated with 20 mm AB. The building was a listed heritage project so only internal insulation was accepted. The project was an US Department of Energy sponsored project. Construction began in July 2012. The project was completed in December 2014. The work took place in unoccupied apartments. The owner reported no problems with the installation of the aerogel system and no shortcomings with the product other than price. Nothing unexpected arose for management or contractors during the project, and the contractor quickly and easily picked up techniques for handling and installation and reported no difficulties. The installation was monitored for installation performance but not followed up. The thermal performance of the walls covered with the aerogel system was compared to that of the untreated walls of the same base construction in the same building during the same period.

SIM m^2 2,000

Follow up Yes

Reference [58]

3.2.1.8 Conclusions for AB

Based on the information obtained through observations made in the case studies described above, several conclusions can be made:

- Aerogel blankets suits well to curved walls, due to development of 5-layer approach into laminated panel.
- Hygrothermal simulations tools was used in several of the projects as a design tool for insulation and to avoid condensation.
- Computational analysis and simulation were carried out using the monitored data for determine the U-value of the walls before and after and water content inside the layers.

- The RH was measured in the building fabric of the London terrace. The high vapour permeability of the aerogel materials clearly indicates a drying of the fabric over the cycles. The target energy reduction of 75% was achieved. The insulation was used for examples in the cavity wall/inner-floor without increasing the risk of damage to the supporting timbers embedded in the wall.
- The Watford building was retrofitted with single layer installation aerogel blankets. These are not used any more.

3.2.1.9 Insights and lessons learned for AB.

Based on the information obtained through observations made in the case studies described above, several insights and lessons learned were reported:

- Development of product design to achieve a proper installation.
- The project with the test house demonstrated the agreement between theoretical design and practical measurements.
- The realisation was planned and tested together with the contractor on a sample surface of the mill.
- Single layer installation aerogel blankets have more installation issues than the newer installation systems with panel lamination capabilities.

3.2.1.10 Follow-up issues for AB

In the Marktredwitz, Germany case study AB were used due to the curved wall shape of the office building. The five-layer solution initially was problematic to install, and this led to the development of a laminated panel, which is now the default selection for AB ETICS systems. The designers worked with WUFI design tool to ensure adequate insulation and condensation control. The installation was monitored for installation performance. Heat flow meters were used to check whether the design U-value of the wall was met, but the heat flow was not continuously monitored.

3.2.2 Case studies silica-based boards (SB)

There are 3 case studies with silica boards. A summary of the U-value before and after renovation (when applicable) is given in Table 6.

Table 6. U-value before and after renovation for the 3 case studies using SB.

City, Country	U-value before (W/m^2K)	U-value after (W/m^2K)	Total SIM area (m^2):	SIM thickness (mm):
Darmstadt, Germany*	2.1	0.35	-	30 (SB)
Pleiskirchen, Germany	-	-	-	80 (SB)
Rheinfelden, Switzerland	-	-	-	40 mm (SB), 30 mm (VIP)

**Too little information and no third-party follow up of the construction after the project finished, therefore not included in the following presentation*

3.2.2.1 Pleiskirchen, Germany (SB)

Figure 3-8: Refurbishment of a 150 year old farmhouse [59].

Contact (org) Evonik Resource Efficiency GmbH

Application area Renovation wall

Project description

Refurbishment of a 150-year-old farmhouse with 50 cm thick brick walls and no separate insulation. The refurbishment contained a pure mineral, open porous 8 cm interior insulation board. It consists of the hydrophobic core material with a thermal conductivity of 0.019 W/(m·K) which is embedded in an open porous, capillary active calcium silicate structure. The average thermal conductivity of the system is about 0.03 W/(m·K). The refurbishment was finished 2011. The monitoring is still going on.

SIM m^2 -

Follow up: No

References [59, 60]

3.2.2.2 Rheinfelden, Switzerland (SB)

Figure 3-9: Office and production site in Switzerland [59].

Contact (org) Evonik Resource Efficiency GmbH

Application area Renovation wall

Project description

The new insulation is a multilayer system with 30 mm VIP core and a 2 times 20 mm silica based board covering. After renovation the overall facade U-value, including the less insulated windows, achieved 0.18 W/(m^2·K)..

SIM m^2 400

Follow up: No

References [59, 61]

3.2.2.3 Conclusions for SB

Based on the information obtained through observations made in the case studies described above, several conclusions can be made:

- In the Pleiskirchen project (Germany), internal insulation was used on a 50 cm thick brick wall. The objective was to verify if there is enough interaction between the water vapour going through the open porous insulation, the condensate at the brick wall and the movable water capacity by capillary transportation. It was substantial for the owner to preserve the historical architecture and at the same time achieve a maximum thermal efficiency. The monitoring is still going on.
- In the Rheinfelden project (Switzerland), energy saving with about 40% with system of 30 mm VIP core and a 2 times 20 mm silica-based board covering. The minimal invasive construction work ensured the continuing work in the office during the renovation. It was substantial for the owner that the renovation caused no noise emission, no dust contamination and therefore no limitation for the workflow.

3.2.2.4 Insights and lessons learned for SB

Based on the information obtained through observations made in the case studies described above, several insights and lessons learned were reported:

- The thermal insulation system board can be cut by a common jigsaw. No special materials or tools are required to mount the insulation system to the wall.
- The system used in Switzerland was highly effective considering disturbances.
- A simple geometry, which repeats several times, helps to reduce costs for the insulation panel manufacture and installation.
- Since the U-value after renovation is very low in the core section, the thermal bridges need to be considered in detail. The increased temperature differences from the centre of the facade to the fastening points can cause condensation and therefore damages of the façade.

3.2.3 *Case studies Vacuum Insulation Panels (VIP)*

There are 22 case studies where VIP have been used and four of these have been followed up, i.e. where a third party have analysed the results of the monitoring. Of these 22 case studies, 2 are lab setups, 2 are field assessment in a wall and 1 is a district heating pipe monitored in field. In the following, a selection of the case studies is presented. A summary of the U-value before and after renovation (when applicable) is given in Table 7.

Table 7. Data available to quantify the energy performance before and after renovation for the 22 case studies using VIP (energy use or U-value).

City, Country	Energy Performance before	Energy Performance after	Total SIM area (m^2):	SIM thickness (mm):
Qingdao, China			20,000	20
Suzhou, China			-	14
Taicang, China			50,000	15
Fukushima, Japan*	550 kWh/year/room	485 kWh/year/room	2,576 (23 m^2×112 rooms)	8 (wall)
Shiga, Japan*	2.0 W/m^2K	1.0 W/m^2K (init), 1.3 W/m^2K (7 yr)	96	10
Osaka, Japan*	16.3 kWh/day	9.9 kWh/day	128	10 (wall, roof), 8 (floor)
Osaka, Japan**	2.29 W/m^2K	1.36 W/m^2K	3.3	10
Eitting, Germany			45	50
Bottrop, Germany*	72,000 kWh	900 kWh***	60	50
Rosenheim, Germany			110	46
Stuttgart, Germany			80	50

Gothenburg, Sweden (1)	158.7 kWh/m^2	127.5 kWh/m^2	83	20
Gothenburg, Sweden (2)			N/A	8-10
Stockholm, Sweden**			12	20
Nantes, France	250 kWh/m^2	115 kWh/m^2	40	40
Athens, Greece**			16	20
Turin, Italy**			1.8	25
London, UK*	3.03 W/m^{2}K	0.18 W/m^{2}K	13	40
Whitehorse, Canada			27	12
Seongnam, Korea	0.21 W/m^{2}K	0.16 W/m^{2}K	250	20
Jeju, Korea			2,500	30
Seoul, Korea			15,000	30

**Too little information and no third-party follow up of the construction after the project finished, therefore not included in the following presentation*

***Lab scale setup, therefore not included*

****Renovation of one-family house from the 60's into a 'Plus-Energy house'*

3.2.3.1 Qingdao, China

Figure 3-10: Wanda plaza where walls and roof were equipped with VIPs (Photo: Zhaofeng Chen).

Contact (org) Qingdao Yichen New Energy Co. Ltd.

Application area Roof, wall

Project description

A high-rise building was after 40 years of use renovated and the owner decided to transform it into a hotel. The hotel walls and roofs were insulated with VIPs. The energy use in the building was reduced by 35% after the renovation. The U-value rose by approximately 0.5 $W/(m^2 \cdot K)$ in 6 years. This change is due to the decrease in insulation performance of the VIPs and polyurethane foam, or reduced airtightness. Especially the performance change of the VIPs needs examination in more detail.

SIM m^2 20,000

Follow up No

Reference NUAA – Nanjing - China

3.2.3.2 Suzhou, China

Figure 3-11: Wall insulated with VIPs on the exterior (Photo: Zhaofeng Chen).

Contact (org) Nanjing University of Aeronautics and Astronautics (NUAA)

Application area Wall

Project description

The renovated buildings are commercial building. In this project, characterization of the material composition, procedures for installation method, as well as outlook have been investigated and discussed. The VIPs were installed on renovated commercial buildings in Suzhou City, China, to minimize the energy losses and condensation due to higher relative humidity. Unconventional VIPs were developed having a core material prefabricated with blind holes, known as Peephole-VIP. These VIPs have better adhesion compared to the conventional VIPs. For such a type of VIPs, the measured U-value was reported to be 0.8 $W/(m^2 \cdot K)$. However, the energy losses because of thermal bridging effect was high.

SIM m^2 N/A

Follow up No

Reference NUAA – Nanjing - China

3.2.3.1 Taicang, China

Figure 3-12: Wuxi video city with VIPs in the walls (Photo: Zhaofeng Chen).

Contact (org)	Nanjing University of Aeronautics and Astronautics (NUAA)
Application area	Walls

Project description

The application in the project realized an ultra-low thermal bridge effect and enhanced the VIP insulation efficiency, thus obtaining the lowest overall thermal conductivity. The project was a demonstration of high-end energy-saving products, performance in the international leading level, for China's energy-saving emission reduction. The project had important practical significance to showcase current foreign products in the construction in China.

SIM m^2	20,000
Follow up	No
Reference	NUAA – Nanjing - China

3.2.3.3 Eitting, Germany

Figure 3-13: Office building with 50 mm VIPs [62].

Contact (org)	Porextherm GmbH
Application area	New roof

Project description

Office building in passive plus energy house standard. A highly heat-insulated outer shell is needed to achieve the passive house standard. VIPs with a thickness of 50 mm were fitted around the entrance area.

SIM m^2	45
Follow up	No
References	[62]

3.2.3.4 Rosenheim Germany

Figure 3-14: FH Rosenheim's contribution to the Solar Decathlon Europe 2010 [63].

Contact (org)	University of Applied Sciences Rosenheim
Application area	Floor, roof, wall

Project description

The house was designed and build by students from FH Rosenheim for the Solar Decathlon Europe 2010. Emphasis was put on reducing energy consumption and on obtaining all the necessary energy from the sun. The house was developed for housing of two people. The layout enables flexible usage of living, working and sleeping area. The competition took place in summer 2010 in Madrid. Each participating team had to build their house at the contest venue. The House won 2nd place of the competition. The house from FH Rosenheim is now located at the zero-energy city Mietraching/Bavaria/Germany and is used for hospitality.

SIM m^2	110
Follow up	No
References	[63]

3.2.3.5 Stuttgart, Germany

Figure 3-15: House with walls and ceiling containing VIPs [64].

Contact (org) Porextherm GmbH

Application Floor, wall

Project description

The wall and ceiling areas were fitted with an insulation layer made of VIPs covered by XPS panels. The special characteristics of this version are the 3 mm XPS lamination for the protection and further attachments of the VIPs and the quick availability.

SIM m^2 80

Follow up No

References [64]

3.2.3.6 Gothenburg, Sweden (1)

Figure 3-16: 1930s building in Gothenburg with VIPs (Photo: Pär Johansson).

Contact (org) Chalmers University of Technology

Application area Renovation wall

Project description

The exterior wall listed 1930s multi-family building house was thermally insulated on the exterior with 20 mm thick VIPs. The calculated energy use for heating decreased by 24%. Temperature and relative humidity sensors were installed in the test wall and in a neighbouring (non-retrofitted) wall as reference. It was concluded that the hygrothermal performance of the test wall was substantially better than that of the reference wall.

SIM m^2 83

Follow up Yes

References [65, 66]

3.2.3.7 Gothenburg, Sweden (2)

Figure 3-17: District heating pipes monitored in field (Photo: Axel Berge).

Contact (org)	Chalmers University of Technology
Application area	District heating pipe

Project description

VIP have been used to add extra insulation to the supply pipe in polyurethane foam insulation district heating twin pipes. Calculations and laboratory measurements predict a decrease of the heat losses by 10-30 % compared to conventional polyurethane pipes. The pipes have been installed to a district heating network in Sweden to test the long-term performance under high temperature. No deterioration of the panels so far could be observed.

SIM m^2	N/A
Follow up	Yes
References	[67]

3.2.3.8 Nantes, France

Figure 3-18: Building in Nantes insulated with VIPs in floor and on the interior of the existing walls (Photo: POUGET Consultants).

Contact (org)	POUGET Consultants
Application area	Floor, Wall

Project description

Overall renovation of a building classified to the industrial heritage area in Nantes which prohibits the insulation on the exterior of the facades. 800 m^2 of office space for 3 homeowner companies wanting to demonstrate the ability to go a long way in reducing energy needs by combining the well-being of the occupants.

BEPOS pilot project Effinergie tertiary renovation.

BEPOS : Bâtiment Energie POSitive.

SIM m^2	40 m² for Wall & Floor
Follow up	Yes
Reference	Pouget Consultant – Nantes - France (IVIS Paris 2017 Symposium)

3.2.3.9 Whitehorse, Canada

Figure 3-19: Infrared image of the retrofitted wall [68].

Contact Phalguni Mukhopadhyaya, University of Victoria

Application area Renovation wall

Project description

A masonry wall of commercial building was retrofitted on the exterior face with VIPs (glass fibre-based core). VIPs were sandwiched between two layers of XPS. The strategically instrumented VIP retrofitted wall was constructed in 2009. Recorded sensor data and thermographic images till to date (January 2017) show no significant aging or failure of VIPs.

SIM m^2 27 m^2 for Wall

Follow up Yes (Ongoing)

Reference [68]

3.2.3.10 Seongnam, Korea

Figure 3-20: Seongnam residential building with 20 mm VIP (Photo: OCI).

Contact	Kongju National University
Application area	Wall

Project description

A new residential building was built which was insulated with 20 mm thick Vacuum Insulation Panels (VIP) on exterior walls.

SIM m^2	250 m^2 for Wall
Follow up	No
Reference	[69]

3.2.3.11 Seoul, Korea

Figure 3-21: MMCA with 30 mm VIP (Photo: MMCA).

Contact	Kongju National University
Application area	Roof

Project description

The National Museum of Modern and Contemporary Art (MMCA) Korea opened a new branch in Sogyeok-dong, Seoul, at the former site of the Defense Security Command. The building was built with 30 mm thick VIP on the roof. This project is perhaps the biggest building in the world in terms of installed VIP per area. It was easier to install VIP on the roof than on wall and ceiling.

SIM m^2	15,000 m^2
Follow up	No
Reference	[70]

3.2.3.12 Jeju, Korea

Figure 3-22: Jeju branch of Bank of Korea. (Photo: Jun-Tae Kim).

Contact Kongju National University

Application area Wall

Project description

The Jeju branch building of the Bank of Korea was built with 30 mm thick VIP on the exterior wall. The purpose of the building was to achieve a highly energy efficient building envelope that satisfy passive house standard (U-value) of 0.15 W/m^2K. This project was the first challenge for passive house standard using VIP installed on the exterior wall with granite finishing, in Korea.

SIM m^2 2,500 m^2

Follow up No

Reference [71]

3.2.3.13 Conclusions for VIP

Based on the information obtained through observations made in the case studies described above, several conclusions can be made:

- Eitting project: To find the exact number of panels, a dedicated planning software was used. Heat transfer coefficient of 0.13 W/m^2K could be realised around an entrance area, when 50 mm of VIP laminated on both sides with polystyrene was used. Approximate 22 cm in building height could be saved.
- Stuttgart project: A dedicated planning software was used when designing the application. The building was prefabricated and assembled on one day, a lot of planning was made on beforehand. The building materials in the building are fully recyclable, does not cause emissions and it is possible to build a house that produce more energy than it requires.
- Osaka project: The thermal performance of the VIPs in the test house, having low- and high-insulated rooms, was monitored and energy savings were calculated. The results showed good agreement between measured and simulated values. Improvement of thermal comfort was also validated.
- Gothenburg renovation project: The project showed that it is possible to maintain the aesthetics while the energy demand was reduced. Mineral wool was used in stripes between VIP's. In the final retrofit design 62% of the façade was covered by VIPs, 17% was covered with glass wool boards and the remaining 21% were windows.
- Bottrop project: A lot of space could be saved, 1 m^2 per 7 meters of wall.
- Gothenburg district heating pipe project: The performance of the pipes where increased by the addition of VIP close to the media pipe. This gives a large improvement on the thermal performance of the pipes. So far, the project has shown that there is no instant collapse of the vacuum panels.
- Whitehorse project: Aging of VIPs in extreme cold and dry climate appears to be very slow or insignificant, compared to the same under hot and humid conditions.

3.2.3.14 Insights and lessons learned VIP

Based on the information obtained through observations made in the case studies described above, several insights and lessons learned were reported:

- Gothenburg renovation project: Special care is needed at the construction site. Learning essential for the designers in the project. Optimization was possible regarding the thermal bridges caused by the mineral wool between the VIP's. A detailed technical drawing of where each VIP should be installed in the construction is needed before construction can start since the panels cannot be adjusted on the construction site. A scanning of the facade was used to produce the final drawings.
- Gothenburg district heating pipe project: COMSOL have been used to predict the influence from the VIP on the thermal performance of the pipes. The simulations can also give indications on how to place the panels.

3.3 Results regarding long term performance

The flat roof testing site in Switzerland (Chapter 3.1.2), the retrofitting projects in Gothenburg, Sweden (Figure 3-16) and Whitehorse, Canada (Figure 3-19), and the field station related to using VIP in district heating pipes (Figure 3-17) are the projects that actually have a continuous monitoring. The results of the follow-up of these projects are presented below. The results from the roof was presented already in Chapter 3.1.2.

3.3.1 Renovation wall, Gothenburg, Sweden (1)

The results of the retrofitting project, started 2010, indicate that the VIP fulfil their function after that they have been in operation for almost six years. The basis for the evaluations are measurements of the temperature and relative humidity (RH) performed in a multi-family building in Gothenburg retrofitted in 2010.

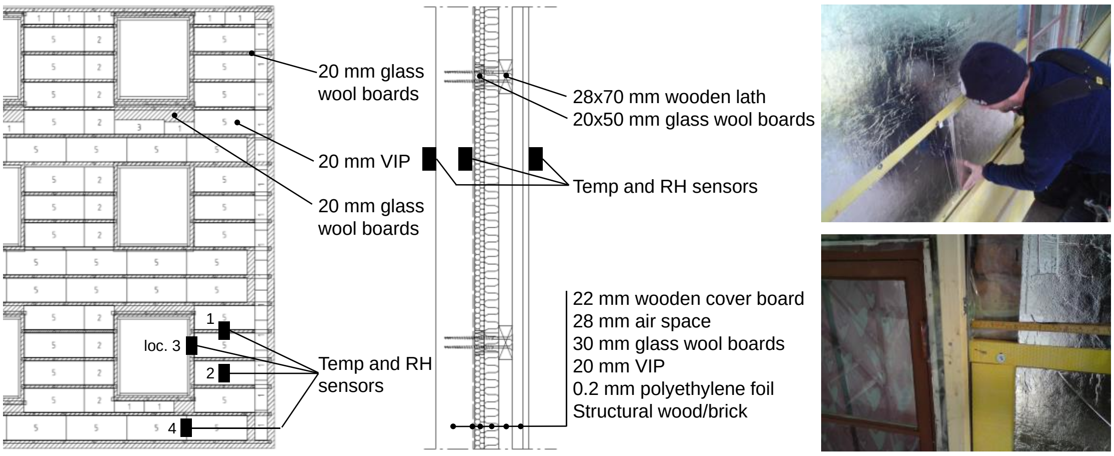

Figure 3-23: Left: wall layout after retrofitting with 20 mm VIPs and 30 mm glass wool boards. The location of the temperature and RH sensors in the wall are marked by the black boxes (not in scale); 1) behind the strips of mineral wool, 2) behind the centre-of-panel, 3) at the window frame, 4) behind the VIP-VIP joint. Right: installation of the VIP layer with the glass wool boards creating a thermal bridge between the VIPs themselves and between the VIPs and windows.

The hygrothermal performance is monitored by sensors integrated in the construction. The temperature and RH in the wall have been recorded during 5 years, from January, 2011, to December, 2015. The measurements in the wall during 5 years show no sign of deterioration of the VIPs and there is a low risk for condensation in the construction, see Figure 3-24. For easier readability, the 24-hour moving average indoor and outdoor temperature and RH were calculated for the presented results.

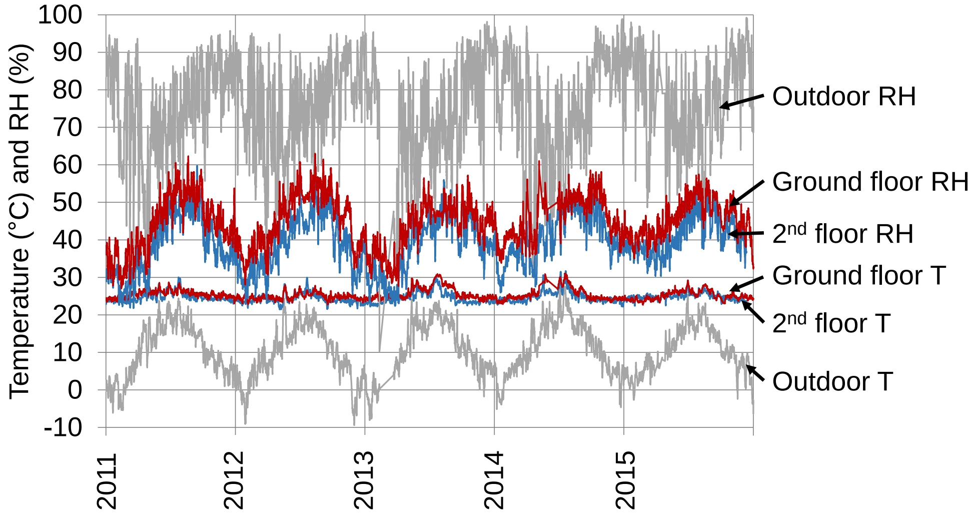

Figure 3-24: Temperature and RH presented as the 24-hour moving average in the apartments on the ground floor and 2nd floor, respectively, compared to the outdoor temperature and RH, for the period from January, 2011, to December, 2015.

The measurements were ongoing until the battery went out in 2018. The aim was to determine the long-term performance of VIPs in building applications. However, it is difficult to evaluate the performance of the VIPs when installed in the wall. In the retrofitting solution presented here, the external air space makes it impossible to identify the different panels by thermography. Only indirect methods, like evaluation of the measured temperatures in the wall, can be used to follow the long-term performance of the panels.

For more information, please refer to [65, 66]

3.3.2 *District heating pipe, Gothenburg, Sweden (2)*

The VIP in district heating pipes, 5 field stations, fulfil their function after about 5 years. The advantage of the study is that the operating temperature is about 80°C which can be counted as an accelerated aging with elevated temperatures for VIP in buildings. The main issue when using VIPs in district heating pipes is the high temperature in the pipes (up to 120°C). This has two possible consequences; the temperature could destroy the laminate leading to a collapse of the VIP, and the heat speeds up the diffusion of air through the laminate. The deterioration of the VIPs has been tested in a pilot site. Hybrid insulated district heating pipes were installed at two locations in a district heating system with temperatures up to 90°C. The temperature on the surface of the VIPs and in a reference pipe with only PUR foam has been recorded every hour. The positions of the thermocouples are shown in Figure 3-25. The measurements during the period 2012 to 2015 show no signs of deterioration of the VIPs and the temperature profile over the pipes is constant.

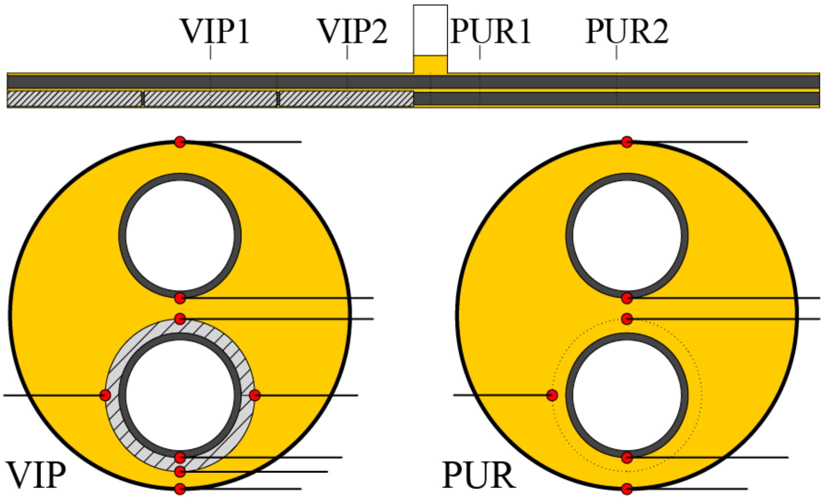

Figure 3-25: Description of the thermocouple placement for one of the field measurement pipes. Left: section of the hybrid insulation part. Right: section of the reference part with conventional PUR foam insulation. Each temperature point was measured at two positions along the pipe.

For more information, please refer to [67].

3.3.3 *Renovation wall, Whitehorse, Canada*

The VIP-foam sandwich (XPS-VIP-XPS) thermal insulation solution for retrofitting an existing masonry wall in the Canadian subarctic city – Whitehorse, Yukon has shown satisfactory and promising performance for a period of six years (2011-present). The analysis of the data obtained from continuous temperature monitoring across each insulation layer indicated the aging of VIP remains insignificant, see Figure 3-26. An infrared image of the retrofitted wall assembly taken almost every year after the installation has indicated that there is no damage or failure of VIPs. Moreover, this project has shown that many perceived challenges (i.e. handling, installation, etc.) relating to the application of VIPs in the construction industry have been addressed through careful planning and detailing. Ongoing in-situ temperature monitoring of this project provides valuable field data to be used for validating theoretical VIP aging predictions and laboratory accelerated aging test results.

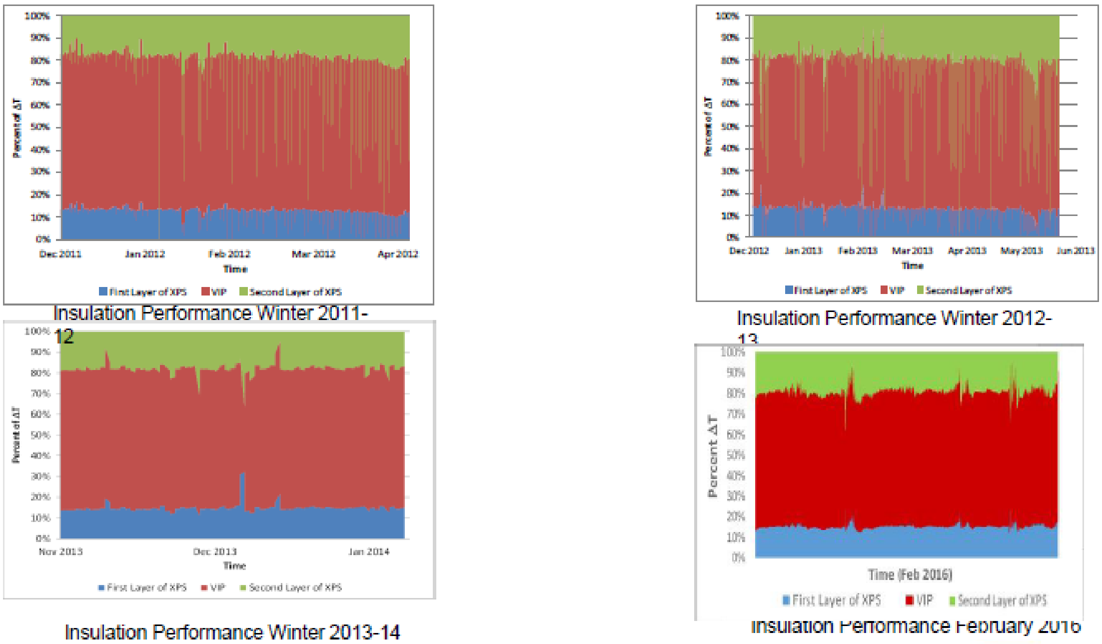

Figure 3-26: Insulation performance in the retrofitted wall in 2011-2016 [68].

For more information, please refer to [68].

When planning constructions different numerical assessment and evaluations are done in an iterative fashion throughout the design process. In next Chapter, a methodology for assessment of the performance at the building scale is presented based on hygrothermal calculation in different climate zones.

4 VIPs performance and operating conditions at building scale for service life planning

4.1 Disclaimer

The aim of this chapter is to present examples on how the hygrothermal behavior of different constructions can be evaluated using numerical simulations. The intention is to provide a course of actions that reveal the reliability of the designed construction. The analyzed constructions are based on local building traditions in the respective countries that may differ from the specific recommendations when using SIM. Furthermore the exposure conditions that have been used in the calculations are to be seen merely as examples and not as recommended use conditions.

4.2 Introduction and scope

The application of VIPs in the building sector is characterised by a series of issues which need to be properly investigated, to define their impact on the overall building thermal performances and to find potential technical solutions. The actual thermal performance of VIPs when they are applied in building envelope components could be very different from the one assessed with laboratory measurements. The following main phenomena influencing the performance of VIPs have been investigated in literature in the last few years:

- the thermal bridging effect determined by the relatively higher thermal conductivity of envelope and/or materials used to couple the panels;
- the ageing effect;
- the effect of temperature on the thermal conductivity of VIPs;

The thermal bridging effects in VIPs were widely analysed in literature at both material/component scale [72,73,74] and building scale [75,76,77,78].

A further phenomenon that can determine deviations between the theoretical and actual VIPs performance is the ageing effect. The ageing mechanism (due to the increasing of pressure and moisture content inside the panel over time) could produce a decay of thermal conductivity [79,80]. The link between VIPs ageing effects and service life in real building applications is still an issue to be solved. Several works were focused on the prediction of VIPs service life, and on the development of linear model for the determination of the increase in moisture content [81]. An aspect that can influence both the ageing process and the real thermal performance (and that needs to be properly investigated) is the effect of high working temperatures. When VIPs are exposed to the external environment they can reach quite high temperatures (e.g. in sun-exposed façade VIPs could work at temperatures higher than 60°C). Temperatures in the range 30 – 60°C (which are typical of many building applications) determine an increase of the thermal conductivity of VIPs [82,83] and can accelerate the ageing phenomenon.

4.2.1 Procedures for evaluation of VIPs performance in building applications

The evaluation of the VIPs thermal performance is not only characterised by the declared centre of panel thermal conductivity: several effects decrease the thermal performance of VIPs when they are applied to buildings. These effects should be carefully considered for building energy calculation, because they could determine a non-negligible divergence between predicted and actual building thermal performances.

In the following sub-sections, the main phenomena affecting the performance of VIP based building envelope components have been analysed.

4.2.1.1 Temperature effect on COP thermal conductivity of VIPs based envelop components

The average working temperature of an insulating material may influence its thermal conductivity. For traditional insulating materials the relationship between thermal conductivity and average temperature is almost linear with a positive slope (at least in the typical building temperature range). Whereas, in case of VIPs this correlation shows a non-linear trend (due to their nanoporous internal structure). Besides the local slope of the curve is typically higher compared to traditional insulating materials (e.g. [82] and [83]). For example Figure 4-1 shows that the centre of panel thermal conductivity of a 20 mm thick fumed silica VIP could range from 4.3 mW/(m·K) at 2.5 °C (VIPs external insulation in winter condition) to 6.1 mW/(m·K) at 52.5°C (VIPs external insulation in summer condition, or domestic hot water tank insulation), which corresponds to a λ_{COP} increase of about 42% (1.8 mW/(m·K)).

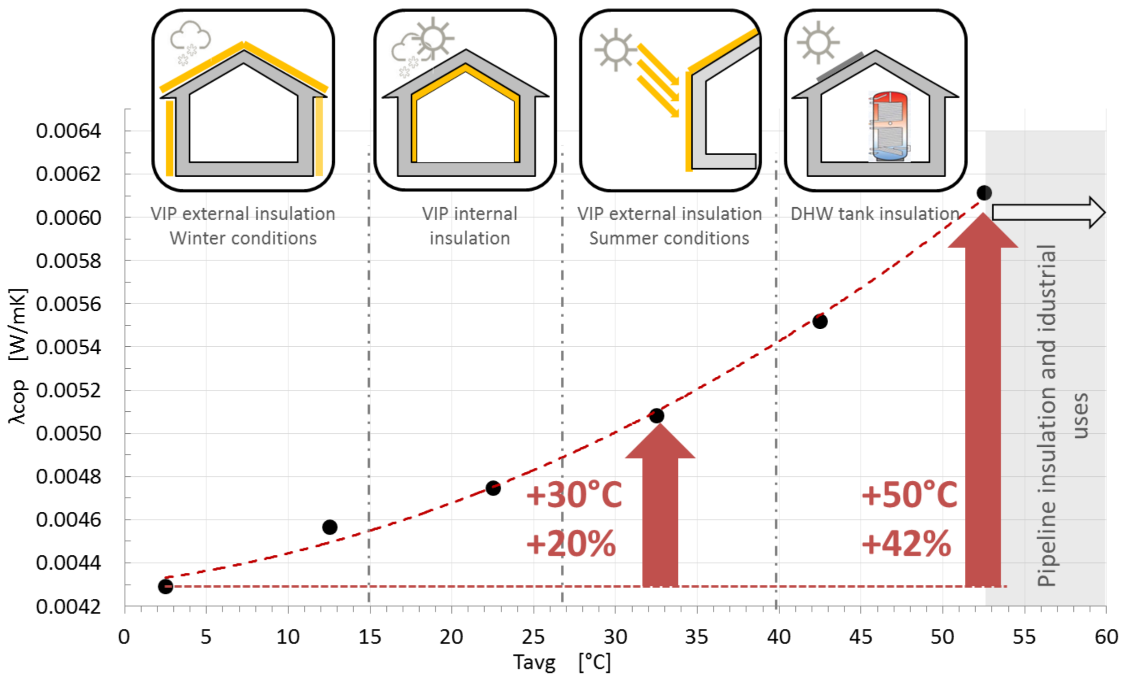

Figure 4-1: VIP centre of panel λ_{cop} depending on the mean testing temperature (20 mm thickness) [82]

Similar behaviour is shown by thicker panels (10 and 30 mm [82]).

In real building applications the VIPs insulating layer is usually placed inside a multilayer structure. Therefore, the variability of its COP thermal conductivity with the working temperatures might not have a sensible influence on the overall energy performance of the envelope component.

For this reason, to evaluate the effect on the energy efficiency of the variability of the λ_{COP} with the temperature, an annual energy balance was performed on a VIP insulated roof configuration (Figure 4-2).

Two different calculations were done: one considering a constant thermal conductivity at 10°C (using the measured values equal to: $\lambda_{COP\text{-}10mm}$ = 5.1 mW/(m·K), $\lambda_{COP\text{-}20mm}$ = 4.4 mW/(m·K), $\lambda_{COP\text{-}30mm}$ = 4.9 mW/(m·K)) and one with a λ-value variable with the temperature (adopting the function obtained in [82] and [83]). The climatic conditions of Torino were assumed for the evaluation (heating degree days = 2,617, heating design temperature value = -8°C, cooling design temperature value = 30.7°C [84]).

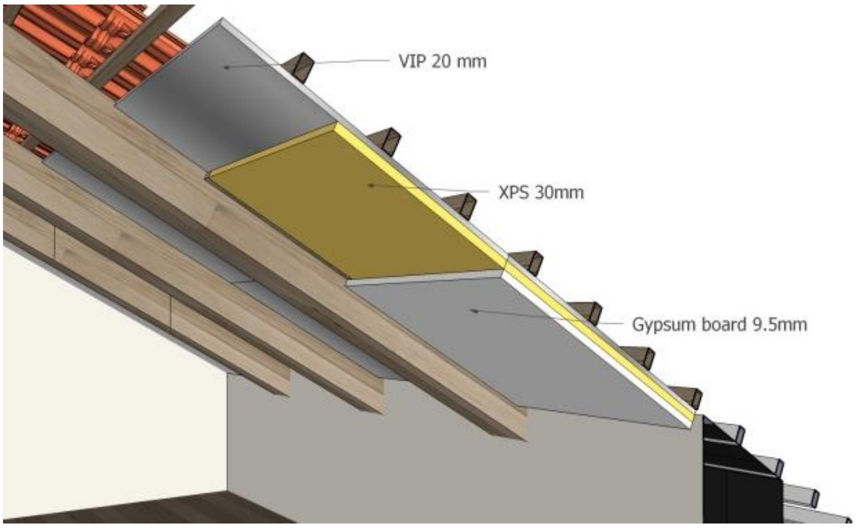

Figure 4-2: Roof configuration. This configuration is given as an example for simulation.

As shown in Figure 4-3, the variability of the λ-value has an almost negligible influence on the winter heat losses, for all the VIP thicknesses. During the summer period, instead the calculated heat loads are higher of about 14% if one considers a variable λ_{COP} instead of a fixed value.

Despite the effects on the energy balance are not so relevant (at least during winter season), the assumption of a variable λ_{COP} could have some consequences on other thermal aspects. Figure 4-4 shows the effects of the different values of the VIPs thermal conductivity on the interior surface temperature.

The assumption of variable values of VIP thermal conductivity determines an increase of the indoor surface temperature of the roof, during the daily peak, of about 0.6°C.

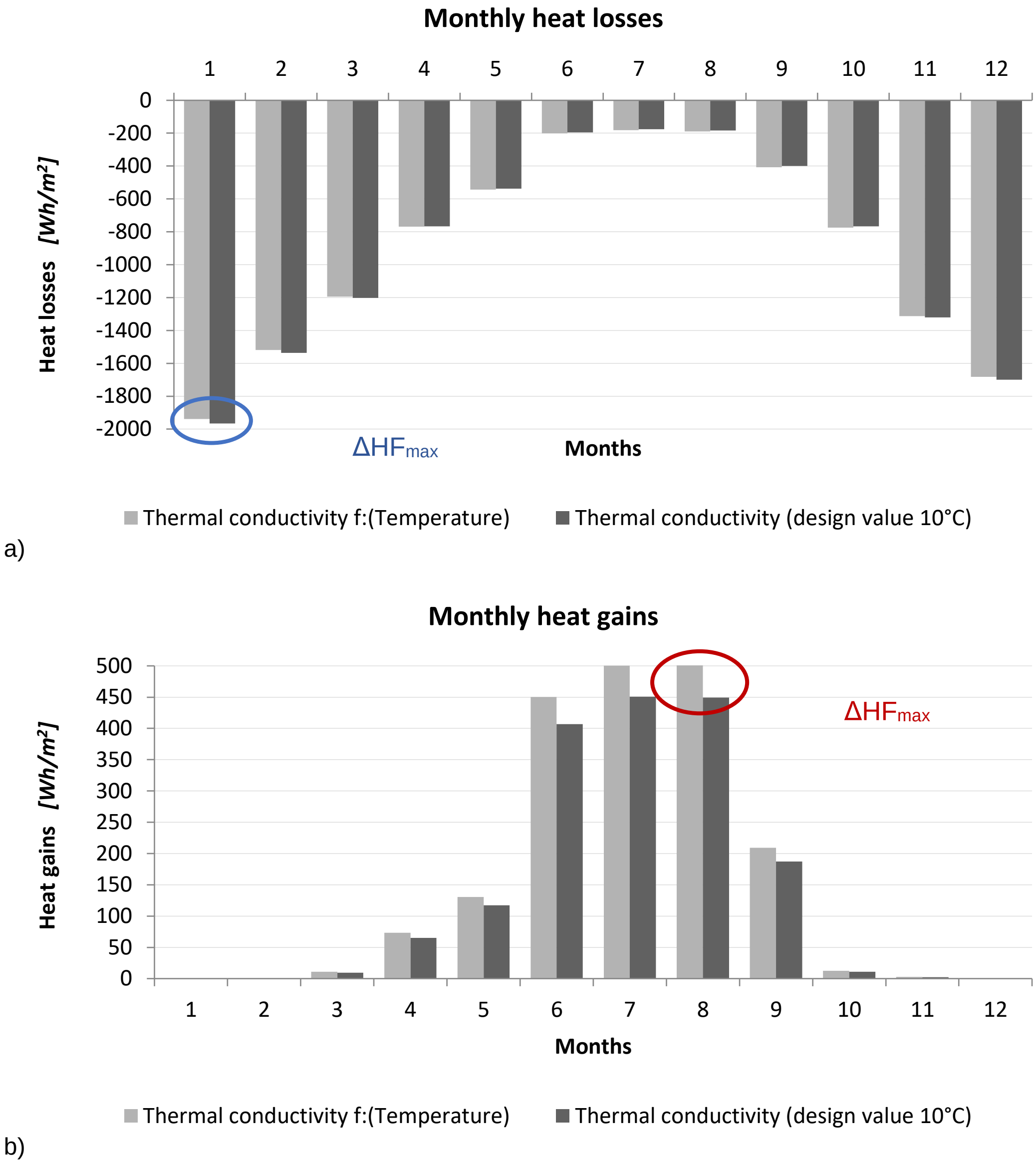

Figure 4-3: Energy balance: (a) Monthly heat losses; (b) Monthly heat gains (VIP thickness equal to 20 mm).

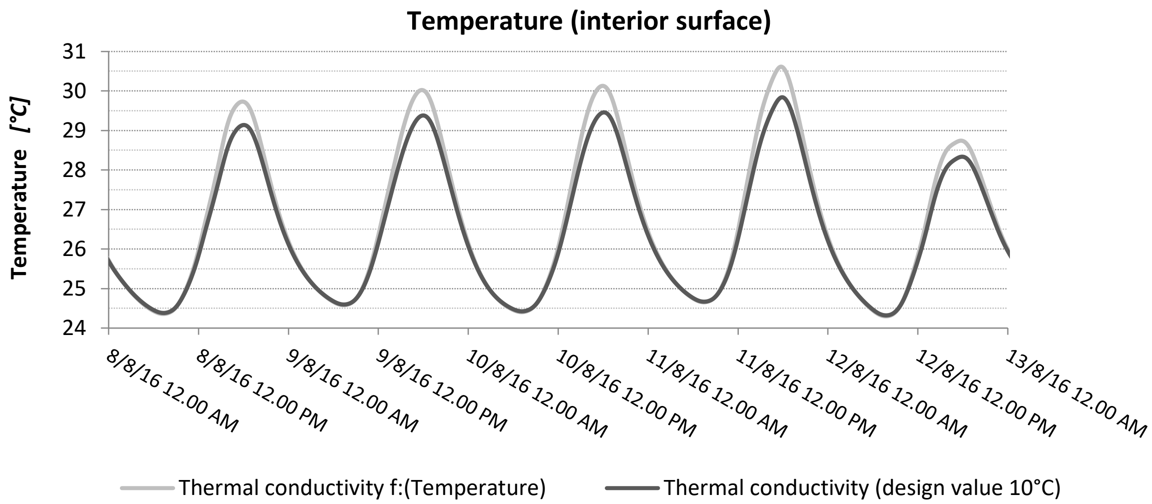

Figure 4-4: Effects of VIP thermal conductivities on the interior surface temperature.

4.2.1.2 The impact of thermal bridges on the performance of VIPs based envelop components

To correctly assess the actual VIPs thermal performances when they are employed for building applications, the thermal bridging effect between the panels needs to be properly accounted for (the higher the thermal resistance of the insulating material, the greater is the importance of thermal bridging effects).

In [76] the thermal bridging effects of VIPs applied on different multilayer walls were assessed considering different structural joint materials or air joints. The numerical simulations were done adopting a 2D model.

The analysis was performed for the following configurations:

- three wall typologies (solid wall, cavity wall and insulated cavity wall);
- two insulating configurations (interior side and exterior side of the wall);
- four possible extra insulation layers (0, 20, 40 or 60 mm thick) with a thermal conductivity λ = 35 mW/(m·K) ;
- three different VIP thicknesses (10, 20 and 30 mm);
- four different materials for structural joints (rubber, MDF, XPS and aerogel);
- three different widths of air gap for the air joint.

Figure 4-5 shows the linear thermal transmittances of the thermal bridge as a function of the wall total – additional - thermal resistance (R_i + R_e) in case of VIP 20 mm thick.

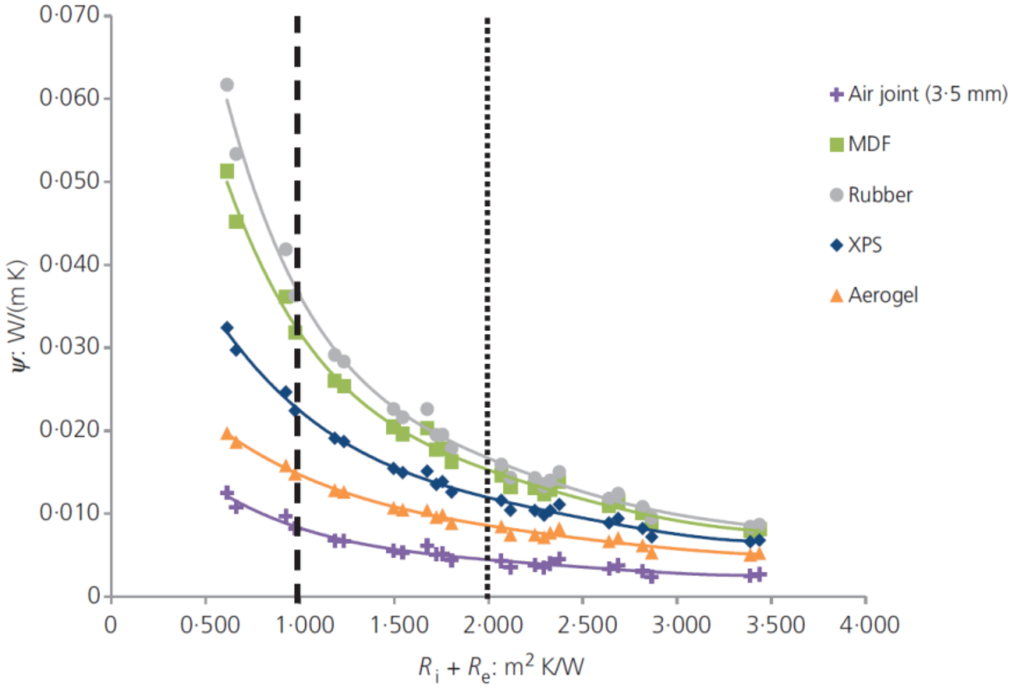

Figure 4-5: Linear thermal transmittances (ψ) as a function of total thermal resistance (20 mm thickness VIP) [76]. (Dashed vertical line: Ri + Re = 1 m²K/W - rough cavity wall; Dotted vertical line: Ri + Re = 2 m²K/W - cavity wall with 40 mm of extra insulation layer).

The higher the value of the additional total thermal resistance, the lower the entity of the thermal bridging effect. Consequently, highly insulating structural joints (XPS or aerogel-based) represent ideal materials for assembling VIPs in building applications, especially when the total thermal resistance of the bounding layers is high (i.e. R_i + R_e > 2 m²K/W).

Moreover, it is possible to see that the linear thermal transmittance values slightly decrease with the VIP thickness, particularly when the thermal resistance of the bounding layers becomes higher [76].

The study done in [76] was focused on analysing the influence of the thermal bridges at the component level. Nevertheless, another important issue that has a great impact on the overall energy efficiency in buildings, is related to the effect of the thermal bridges at the façade scale. Therefore, to investigate such phenomenon, the overall – average - thermal transmittance of a typical façade that makes use of VIP panels was assessed considering different types of structural joints. In detail, the coupling of VIPS and Aerogel Based Products (ABPs) was numerically analysed to assess the global average thermal transmittance of the façade. Moreover, the global average thermal transmittance was also assessed considering VIPs coupled with traditional insulating materials (EPS, MDF), considering both thermal and economic aspects. The comprehensive description of this activity is available in [85] where the thermo-physical studies were integrated with an economic analysis, aimed at assessing the influence of the different solutions on the overall cost.

For the sake of brevity only the relevant results are summarized in this report.

The main features of the modelled façade are (Figure 4-6):

- external masonry in solid wall;
- VIPs used as the external insulation layer (VIPs thickness = 10 mm and size 500 x 600 mm), and covered with a cladding plasterboard layer (10 mm thick);
- thermal bridges related to windows were neglected.

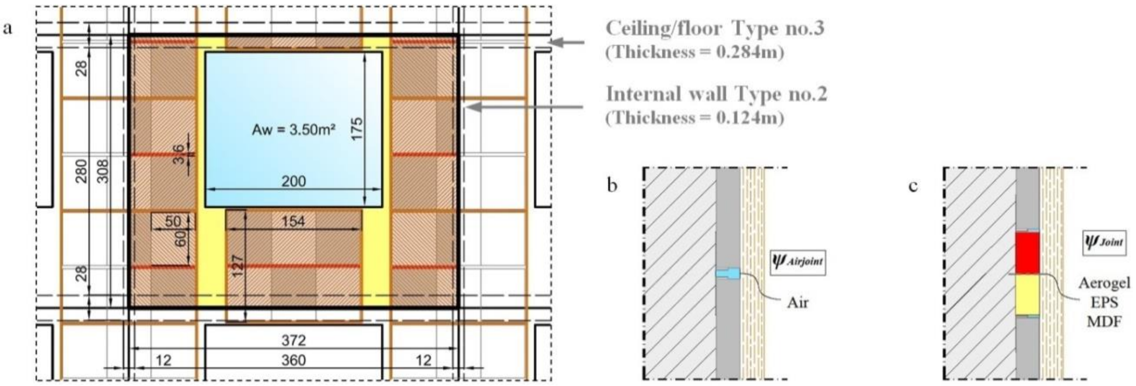

Figure 4-6: (a) Façade Features. Different joint materials: (b) Air; (c) Structural (aerogel, EPS, MDF) [85].

Simulations were repeated considering either structural joints or air joint, whose features were:

- structural joints made of either: aerogel, EPS or MDF, with 36 mm width (or more where necessary).
- air joints between two VIP panels directly coupled together (width ≈ 2 mm)

Considering as the reference values of the average thermal transmittance (U_{avg}) the one referred to the VIP + aerogel configuration, coupling VIPs and EPS lead to an increasing of the average thermal transmittance of the façade equal to ≈ 16%; the thermal performances in the case of MDF joints are still worse than the reference case (≈ 28% U_{avg} increasing), as shown in Figure 4-7. From an economic point of view, the use of EPS or MDF as structural joint, instead of aerogel, causes a reduction of the parametrical cost (PC) of about 12% and 11% respectively. The cost increasing due to coupling VIPs and aerogel assemblies is almost negligible if compared to the increasing of SIMs assembly insulating performances. This trend is due to the higher cost and quantity of VIPs in comparison to other materials used as joints.

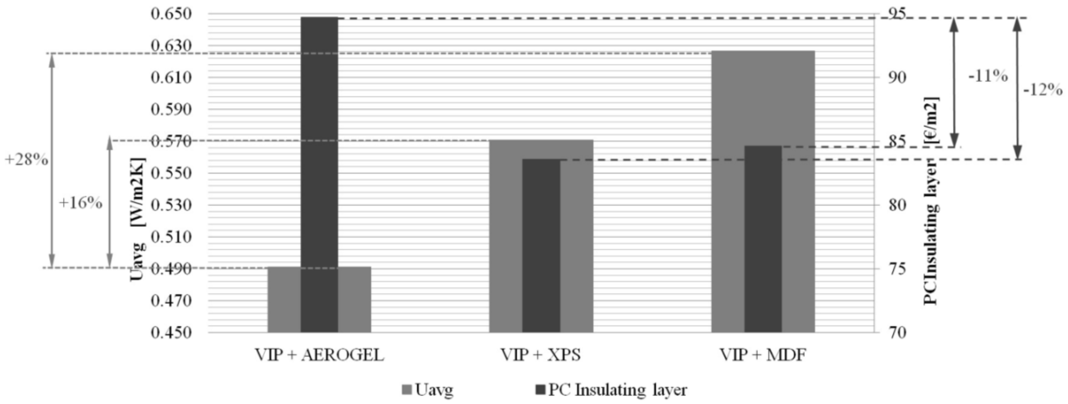

Figure 4-7: Façade parametrical cost and respective ΔU_{avg}-values for three different material joints (aerogel, EPS, MDF) [85]

In [76] a numerical analysis aimed at evaluating the performance of vacuum insulation panels (VIPs) at the building scale is performed. The building transmission heat losses (H_{tr}) and heating energy need (Q_H) were estimated for a typical building, considering three different thermal conductivity values of the VIPs layer inserted in the wall configuration above described [76]:

- the centre of panel thermal conductivity (λ_{COP});
- the equivalent thermal conductivity (λ_{eq}) to consider the thermal bridging effects;
- the practical equivalent thermal conductivity, ($\lambda_{eq,practical}$ = 7 mW/(m·K)), to take into account the thermal bridging effects in a simplified way by incrementing the centre of panel thermal conductivity.

Moreover, to consider the influence of different room typologies, four scenarios were considered. A room with:

- four external walls;
- one adiabatic wall;
- two adiabatic walls;
- three adiabatic walls.

(The floor and the ceiling were always assumed to be adiabatic.)

In Figure 4-8 the building heating energy need Q_H, normalised on net floor area as a function of the *S/V* ratio, is plotted. In case of 10 mm thick VIP the coupling joint material does not affect significantly the building heating energy need, while considering 20- and 30-mm thick VIP the effects on the building heating energy need are more evident.

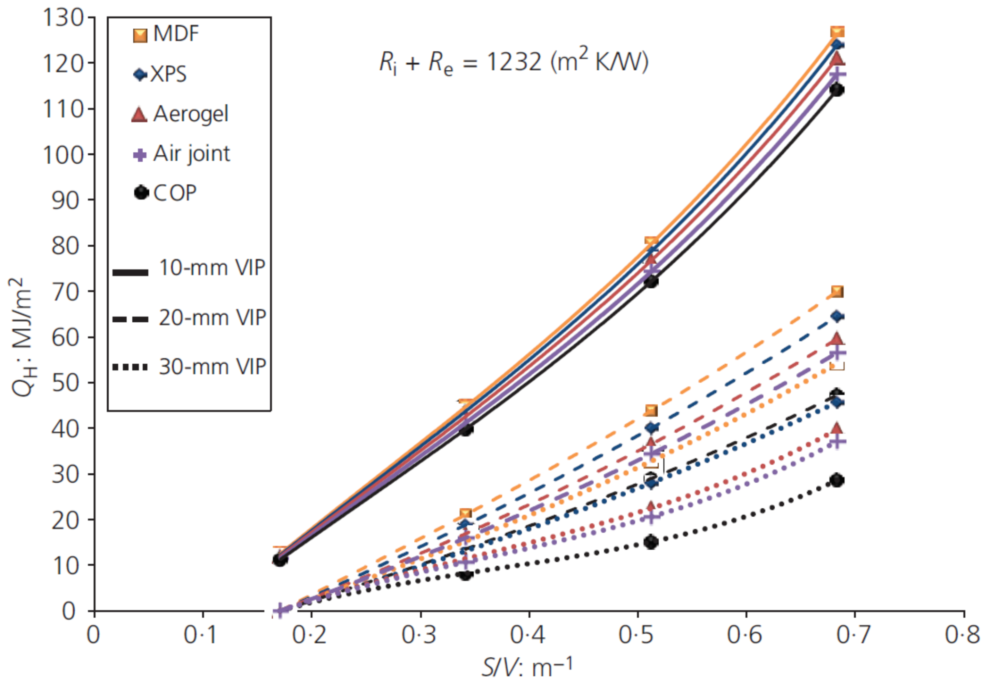

Figure 4-8: Building heating energy need as a function of different surface-to-volume ratio, *S/V* and different VIP thicknesses [76].

The percentage difference between H_{tr} calculated assuming for the VIP assembly λ_{COP} and λ_{eq} respectively are shown in Figure 4-9. The values of H_{tr} calculated considering the equivalent thermal conductivity is higher because it considers the thermal bridging effects. The ΔH_{tr} increases with the decrease of (R_i + R_e) and with the increase in the aspect ratio. Even though the percentage differences reach low values for high (*Ri* + *Re*) values, the thermal bridging effects can never be considered negligible.

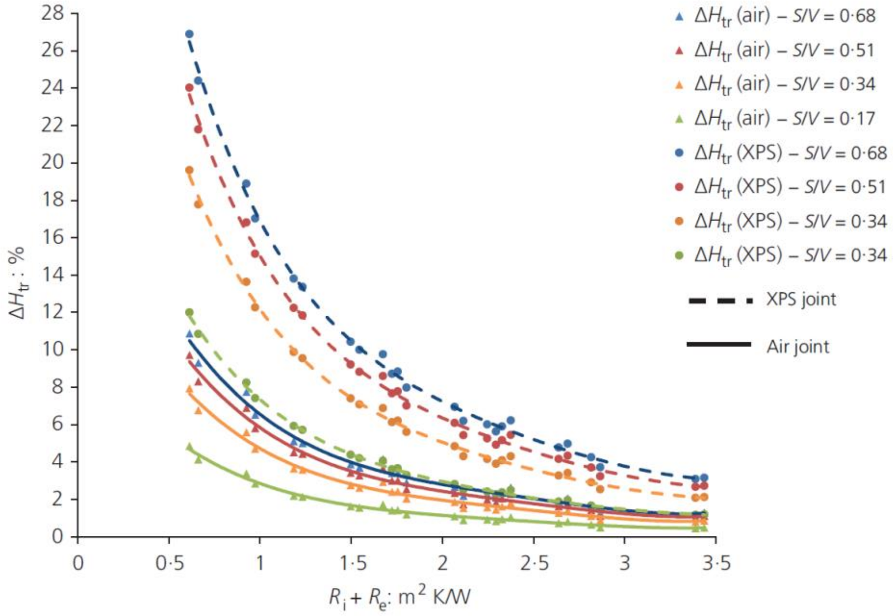

Figure 4-9: Percentage difference between H_{tr} calculated with λ_{cop} and λ_{eq} (XPS joint and air joint) [76].

Finally, Figure 4-10 shows the difference between H_{tr} calculated considering λ_{eq}-value for VIPs, and the one obtained considering the value of $\lambda_{eq,practical}$ which takes into account the thermal bridging effects in a simplified way. The percentage differences are always negative because $\lambda_{eq,practical}$ is always higher than λ_{eq}. For this reason, considering a practical equivalent thermal conductivity, an underestimation of VIP thermal performance can occur. Also, in this case, the percentage differences reach no negligible absolute values.

Consequently, the thermal bridging effects in VIPs strongly affect the heat transfer coefficient by transmission H_{tr}.

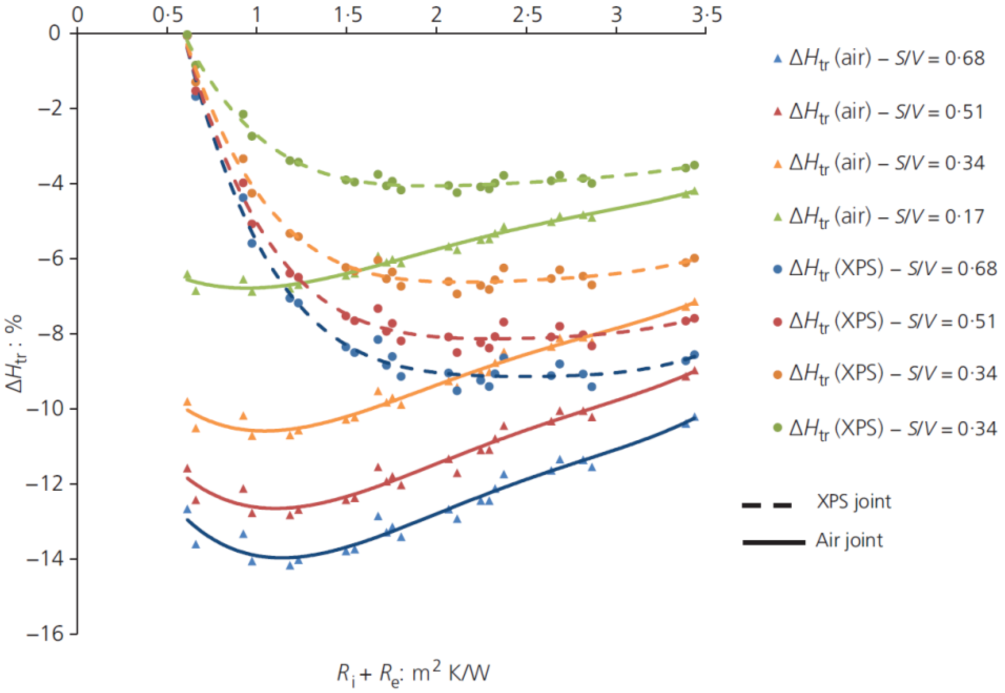

Figure 4-10: Percentage difference between H_{tr} calculated with λ_{eq} and $\lambda_{eq,practical}$ (XPS joint and air joint) [76].

The analyses demonstrate that H_{tr} can increase up to 50% when the thermal bridging effects are compared with an ideal insulation made of a homogeneous VIP layer. This case occurs with high VIP thickness, low joint thermal conductivity and low (R_i + R_e)-values. Therefore, it's possible to conclude that the thermal bridging effects are also significant at the building scale.

4.3 Common exercise: Evaluating conditions for service life assessment

Vacuum Insulation Panels represent one of the most promising innovative solution for building thermal insulation. Nevertheless, the VIPs service life may be limited if compared to buildings lifetime, depending on the boundary conditions. Several research investigations proved that the main factors influencing the VIPs lifetime are water vapour and gas permeations.

The permeation phenomena, in turn, are tightly linked to the severity of the conditions to which the panels are subject during their normal operation. Specifically, high temperature and high relative humidity may significantly accelerate the ageing. In the context of IEA EBC Annex 65 activities, a common simulation-based procedure was introduced to identify potential critical hygrothermal working conditions at the boundaries of VIPs, when they are inserted in different building components. A methodological framework was developed with the aim to estimate, for a comprehensive set of envelope configurations, the yearly profiles of temperature and relative humidity, considering different weather and indoor climate conditions.

This procedure makes it possible to assess the VIPs lifetime expectancy, providing general guidelines for the correct design of VIP based components, considering the actual working conditions. In this chapter a description of the proposed procedure related to different wall and roof configurations are described and critically analysed. The detailed results of simulation are presented in Appendix B.

The aims of this study are to:

- Highlight “critical applications/configurations” due to severe boundary conditions (high temperature and relative humidity).
- Identify possible solutions to mitigate the working conditions and to protect the SIM (e.g. introduction of additional layers, vapour barrier, repositioning of the SIM, renderings and cladding, etc.).
- Provide general guidelines for the correct design of building components which include SIMs (regarding various wall configurations, climatic conditions and orientations).
- Contribute to the definition of the “accelerated ageing test conditions in laboratories, considering different component configuration and climatic conditions (frequency distribution of temperature (T), relative humidity (φ) and water vapour pressure (p_v) around SIMs).

4.3.1 Methodology

The general working procedure proposed for the common exercise is based on the following steps:

- selection of typical configurations of walls, roofs and terraces around the world (only centre of wall configurations were considered, without accounting – at this stage – the influence of thermal bridges. Further investigations will be needed to address the thermal bridges);
- selection of boundary conditions for the analyses (external weather conditions and indoor temperature and relative humidity conditions);
- simulations at the building component scale aimed at assessing the time profiles of: temperature, *T,* relative humidity, φ, and partial pressure of water vapour, p_v, at the VIPs surfaces. These results may be then used for the evaluation of the expected service life of VIPs;
- results analysis, aimed at identifying the critical situations characterised by severe boundary conditions at the VIP surfaces.

4.3.1.1 Selection of typical configuration

Different building components were selected (walls, roof, terraces, etc.) according to the past/current building technologies of each country participant to the common exercise. The case studies are representative of the local typical constructions.

4.3.1.2 Selection of boundary conditions

Temperature and relative humidity of the indoor space were defined according to different technical standards (UNI EN 15026:2007 [[86]], ASHRAE 160:2016 [[87]], EN ISO 13788:2012 [88]).

When available, actual monitored data were assumed for the simulations.

The outdoor weather conditions include:

- outdoor temperature;
- outdoor relative humidity;
- direct, diffuse and global solar radiation;
- wind speed and direction;
- rainfall.

4.3.1.3 Simulation procedure and assumptions

Numerical analysis were carried out by means of 1D dynamic HAMs simulation tools. Figure 4-11 summarise the criteria used for the simulations.

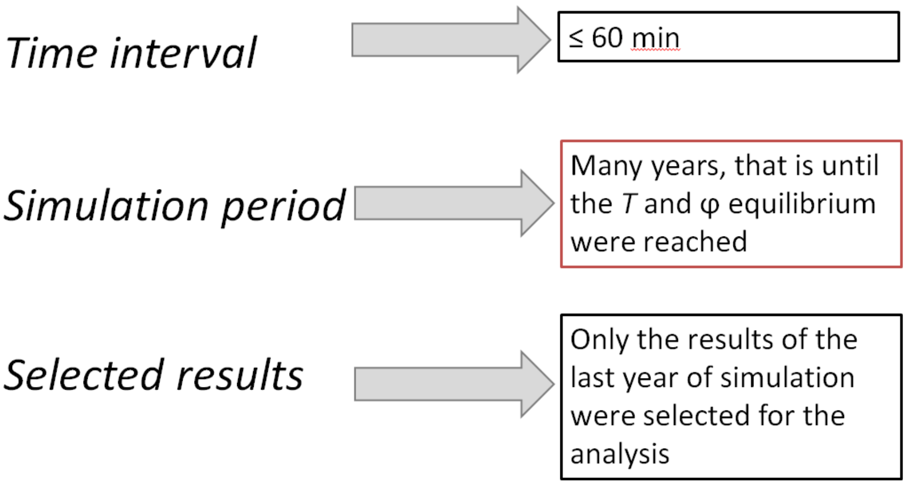

Figure 4-11: General simulation criteria adopted for the common exercise.

For minimizing the computational efforts, a series of assumptions and simplification were adopted (see e.g. Figure 4-12):

- VIP panels were modelled as an equivalent homogeneous layer, disregarding the actual structure which consists in an envelope and a core material;
- only 1D heat and moisture transport phenomena were considered (as already mentioned, at this stage, thermal bridging effects were neglected);
- the centre of panel thermal conductivity λ_{COP} of VIP was assumed for the numerical analysis;
- the water vapour permeability of the VIP layer was considered infinite.

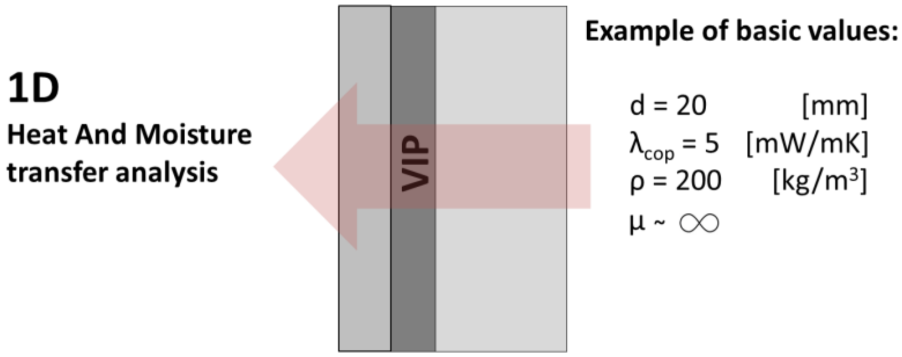

Figure 4-12: Example of assumption and basic values adopted for the simulations.

4.3.1.4 Design alternatives

Simulations were performed for different design alternatives considering those parameters that mostly affect the severity of the operating conditions, that are:

- location;
- orientation;
- external finishing colour (bright, medium, dark);
- indoor moisture load (low, medium, high);
- presence of vapour barrier;
- VIPs thickness.

4.3.1.5 Simulations outputs

Simulation results were post-processed to clearly identify the VIPs operating conditions.

In this report, for the sake of brevity, only the results of the most representative and/or critical design alternative for each case study are presented (e.g. darker surface, medium moisture load, etc.).

For each selected design alternative, two different graphical outputs are shown:

- charts of the T, φ and p_v profiles over the time (yearly);
- cumulative frequency distributions of T, φ, p_v.

The cumulative frequency distributions are graphically subdivided in four ranges of values from (*I*) to (*IV*). Where: (*I*) represents the less severe operating conditions and (*IV*) the worst (Table 4.1).

Table 4.1. Ranges of values of temperature, relative humidity and water vapour pressure. * For each range of severity p_v was calculated as the product of the relative humidity and the saturation vapour pressure at temperature T.

Range	**Temperature ranges *T* *[°C]***	**Relative humidity ranges ϕ *[%]***	**Water vapour pressure p_v *[hPa]****
I	T ≤ 30	ϕ ≤ 50	p_v ≤ 21.2
II	30 < T < 40	50 < ϕ < 60	21.2 < p_v < 44.4
III	40 < T < 50	60 < ϕ < 70	44.3 < p_v < 86.3
IV	T ≥ 50	ϕ ≥ 70	p_v > 86.3

Finally, summary tables give a resumed overview of the simulations output for all the possible design alternatives for the various configurations.

These tables show: the peak values (maximum temperature, relative humidity and water vapour pressure) on each side of the VIP panel, and the percentage of time for which, during the year, the VIPs are exposed to a certain class of severity (from *I* to *IV*).

4.3.2 Overview of the analysed configurations

Ten configurations in four different countries characterised by different climatic conditions were selected for the common exercise analysis (Figure 4-13), consisting in:

- 2 Flat roof configurations (Germany and France);
- 2 Wall external insulation (Italy and Germany);
- 2 Wall external insulation with ventilated façade (Sweden and Germany);
- 2 Internal wall insulation (France and Germany);
- 2 Pitched roof configuration (Germany and Italy).

The descriptions and results of each configuration are presented in Appendix B.

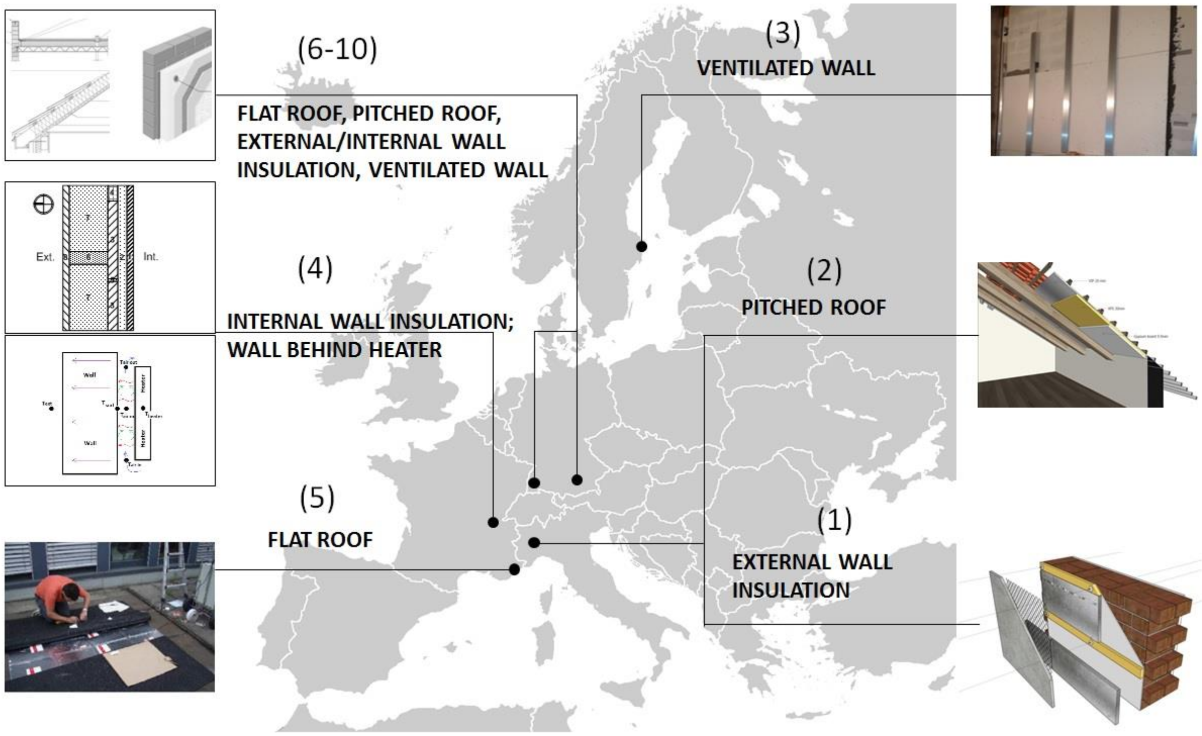

Figure 4-13: Case studies distributions and typologies.

4.3.3 Results and discussion

The descriptions and results of each configuration are presented in Appendix B.

4.4 Examples of service life evaluation

The time profiles of *T*, φ and p_v obtained in the previous sections give an information about the severity of the working conditions at which the VIP panels are likely to be subject during their use.

Therefore, they represent a basis to evaluate the expected service life of the product.

The service life is defined as the time in which the VIP thermal conductivity rises over a predefined limit ($\lambda_{lim,sl}$), no longer ensuring the expected insulating level. The VIP service life can be estimated considering that air and water vapour permeation through the envelope layer represents the main ageing phenomena that lead to the decrease of the panel core thermal conductivity (λ_c). (Degradation phenomena are clearly described in Section 4.5.3. Annex 65 Subtask 1 Report, [80, [89]]).

As explained in Yrieix et al. (2014) [[90]0], many methods for the service life evaluation exist. In this example of service life calculation, the applied method represents the most common practice (Simmler and Brunner 2005) [[91]], considering both the moisture impact and the dry air impact.

An estimate of the expected service life (t_l) can be done adopting the dynamic model proposed by Baetens et al. 2010 [92]

To exemplify the possible use of the time profiles of *T* and φ previously analysed, the Baetens model was applied to the configuration 1 investigated in Section 4.2.

Figure 4-14 : Procedure for estimating the VIPs service life. Figure 4-14 schematically shows the adopted procedure.

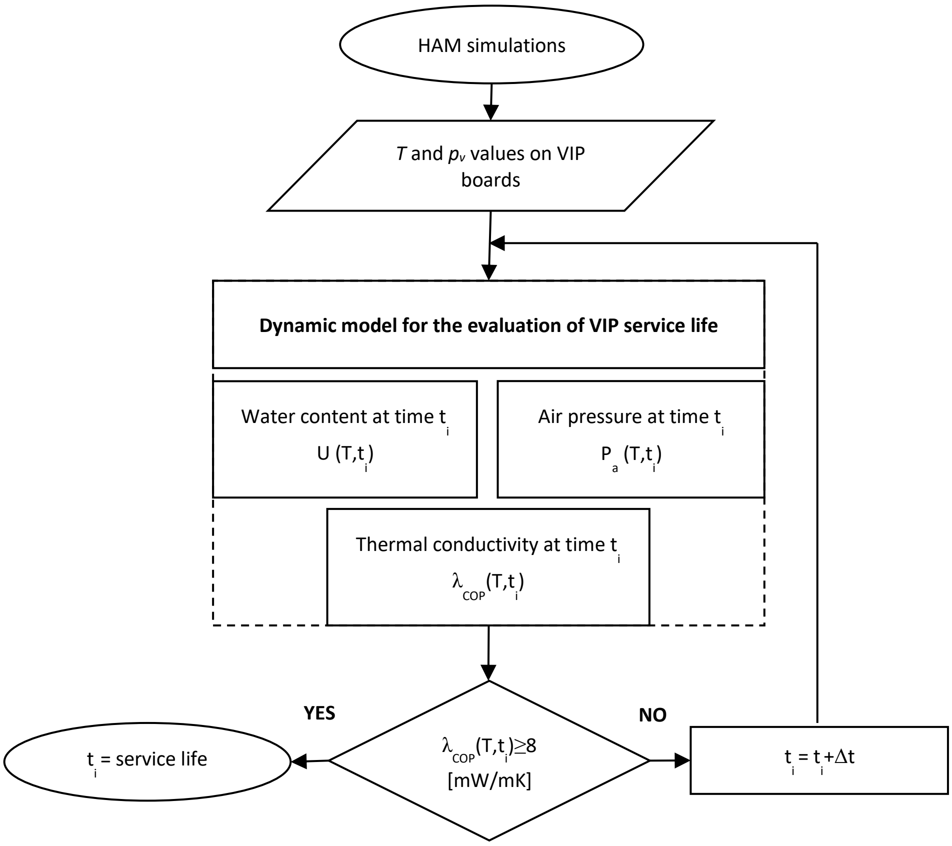

Figure 4-14 : Procedure for estimating the VIPs service life.

4.4.1 *Example of estimation of the expected service life - "Configuration 1 (Turin)"*

In order to exemplify the calculation of the expected VIP's service life, the design alternative represented by the dark-painted west-oriented vertical-wall subjected to high internal moisture load was selected (see Section 1.11.1 in Appendix B). The reason of such choice lies in the fact that this is the case that leads to severe boundary conditions. The analysis was carried out considering a VIP panel having a size of 500 x 600 mm and the calculations were repeated for two different thicknesses (20 mm and 10 mm). Moreover, different VIP envelope layers, characterized by different metallized films (MF1, MF3 and MF4), were considered.

In Figure 4-15 and Figure 4-16, the results of time evolutions of VIP air pressure, and VIP water content were respectively plotted for different metallized envelope film. Figure 4-17 shows the evolution of the centre of panel thermal conductivity over the time.

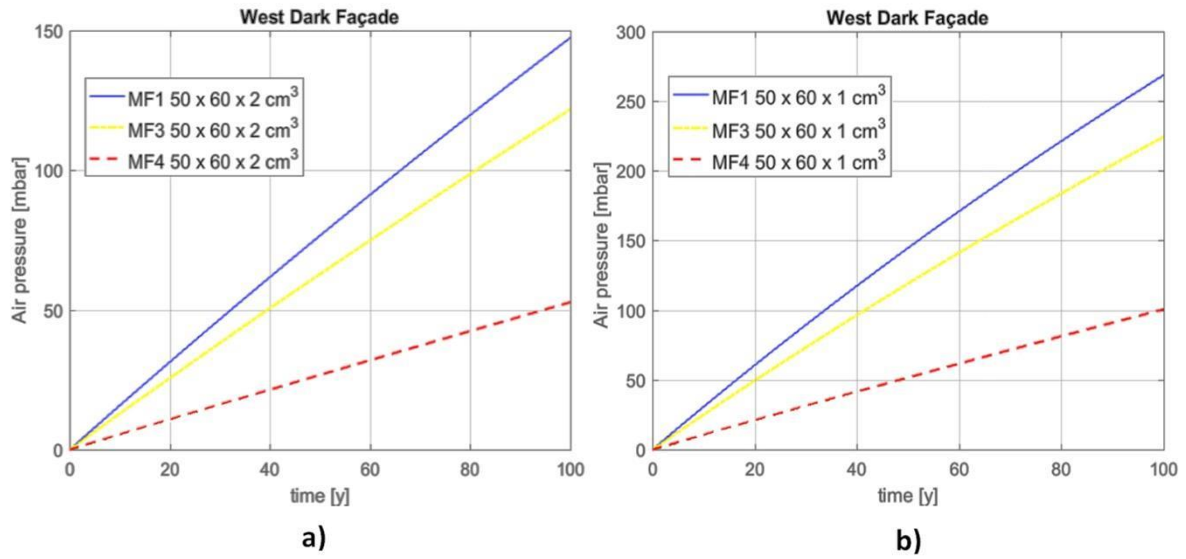

Figure 4-15 : Air pressure inside the VIP core over the time for a 20 mm thick VIP (a) and 10 mm thick VIP (b) , - west dark façade with 'high' internal moisture load.

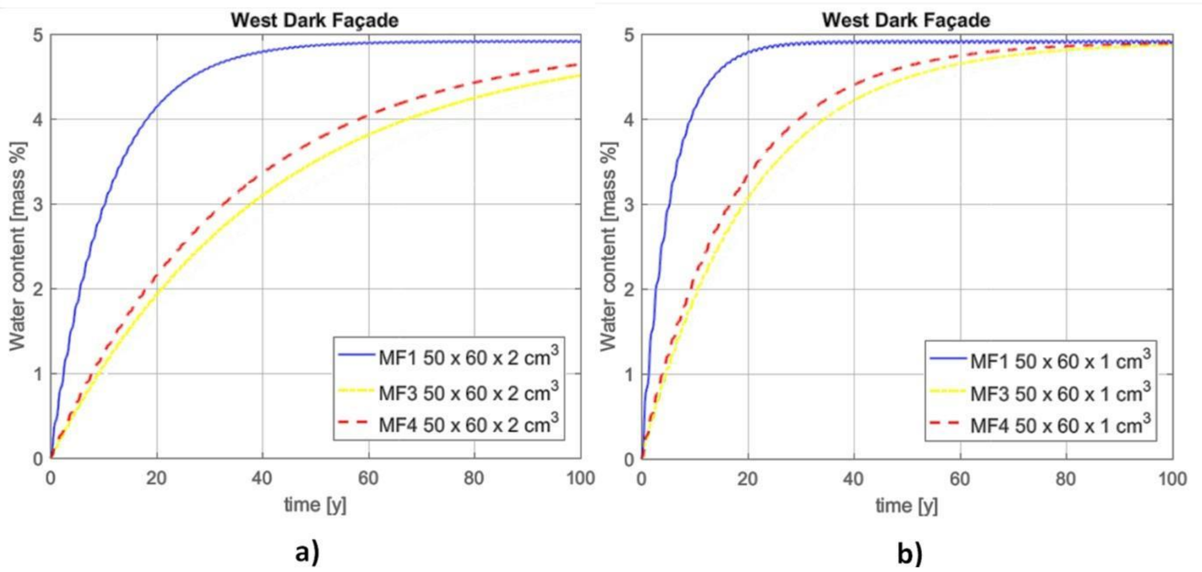

Figure 4-16 : Water content inside the VIP core over time for a 20 mm thick VIP (a) and 10 mm thick VIP (b) - west dark façade 'high' internal moisture load.

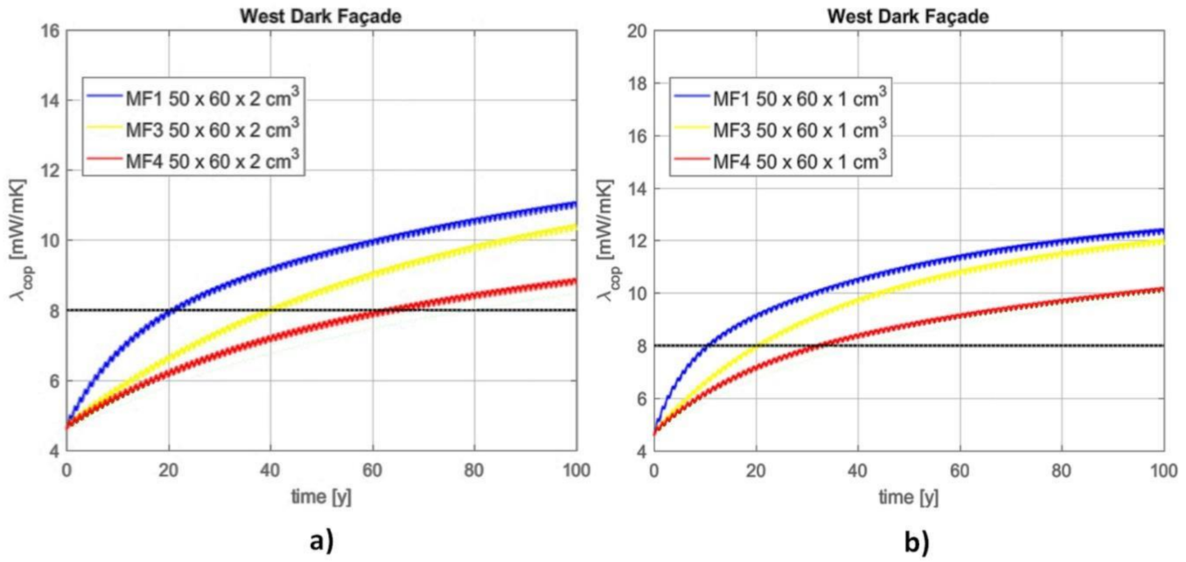

Figure 4-17 : Time evolution of panel core thermal conductivity λ_c as a function of the envelope for 20 mm
(a) and 10 mm
(b) thick VIP - west dark façade, with 'high' internal moisture load.

Figure 4-17 shows that the increase of thermal conductivity and, therefore, the expected service life are strongly dependent on the type of the metallized envelope film.

Considering a VIP panel having a thickness of 20 mm and a working period of 25 years, the relative increase of the thermal conductivity, compared to its pristine value, is of about 41% for MF4, 52% for MF3 and 80% for MF1 envelope.

It is also possible to see in Figure 4-17 that, assuming a $\lambda_{lim,sl}$ = 0.008 W/mK [91] the likely service life is of about 60 years for MF4, 38 years for MF3 and 20 years for MF1 envelope. These results highlight that the VIP durability is in line with the building lifetime, except for the MF1 envelope type. Nevertheless, it is important to observe that in case of thinner VIP panels (e.g. d = 10 mm) the estimated lifetime is practically halved (Figure 4-17 (b)).

4.5 Conclusions and lessons learned

Super Insulating Materials and, more particularly, Vacuum Insulation Panels are subjected to a series of issues both in design and operation phases that may affect their actual thermal performance. The study highlights that some physical phenomena (such as thermal bridging effects, the influence of temperature on the thermal conductivity and the decay of performance over time depending on the severity of the boundary conditions) should be carefully evaluated during the design phase to prevent the mismatch between expected/predicted and the actual thermal performance.

In the framework of IEA EBC Annex 65 a common simulation-based procedure was introduced with the scope to identify potential critical hygrothermal working conditions of the SIM, which were identified as main drivers of the ageing effect.

The climatic stress that acts on the surface of the VIP is dependent from the construction. Differences in the temperature on the external side are visible between the observed roofing and walling configurations. Roof configurations are likely to cause higher temperature on the outside. The moisture stress varies especially between the configurations where the VIP are installed between diffusion-tight layers (flat roof) or underneath layers of plaster (ETICS, internal insulation) that will lead to high moisture stress and the applications with ventilated or diffusion-open boundary conditions to the VIP surface (pitched roof, ventilated façade).

The influence of the location is partly visible. Especially for the configurations with diffusion open or ventilated boundary conditions to the VIP, the high driving rain load in west-orientation of Holzkirchen in combination with high internal moisture load shifts the distribution of relative humidity to higher values compared to the location in Freiburg with low internal moisture load.

The main outcomes of the presented common exercise have allowed a comparison among the effect of various exposure severity conditions for a wide range of VIP based construction applications in buildings (flat/pitched roof, wall with interior/exterior insulation, wall with ventilated façade, wall behind heaters, etc.). The exercise makes it possible to assert a series of final considerations:

- The hygric stress is in general higher for configurations with VIP placed in between high vapour diffusion tight layers. Especially when moisture loads, according to driving rain or air convection, penetrate the construction. A slower re-drying occurs and the mean relative humidity at the boundary layer of the VIP increases.
- Generally, for the same climatic conditions, higher maximum values of temperature were observed in roof applications in comparison to wall applications except for solar exposed dark finished walls.
- When VIPs are used for internal insulation applications are generally not affected by severe values of temperature. However, depending on the location, orientation and the surface solar absorbance, relatively higher annual average temperatures in comparison to external insulation applications (VIPs placed at the external side) may be reached.
- VIP placed behind heaters/radiators are exposed to very high temperatures that lead an overheating of the VIP indoor exposed surface which is detrimental to the service life and thermal performance of the VIP.
- Without vapour barrier, the influence of the indoor moisture load is relevant for both internal and external VIPs wall application.

As general guidelines to mitigate the severity of the operating conditions of VIP, a list of recommendation is in the following summarised:

- For the external wall insulation with VIP in solar exposed façade, the adoption of ventilated air layer could dramatically reduce the severity of the VIP operating conditions. Alternatively, light finishing colour are warmly encouraged to mitigate the surface temperature.
- The protection of VIP with thin traditional insulation layer is always encouraged.

- The application of VIP behind heater determines high value of surface temperature field which could potentially lead to a fast degradation of the panel. A possible solution to mitigate the severity of the boundary conditions could be the coupling of VIP with a radiant barrier, or the protection of VIP with thin insulation layer when it is possible.
- In roof application, light colour (cool roof), performant water proof membrane, ventilated airspace and gravel covering layer (flat roof) represent effective solutions to mitigate the severe exposure.
- In presence of wall subjected to high driving rain, it is preferable to adopt ventilated façade working as rain-screen to prevent the water absorption.

The above list has to be intended as guidelines for the early design stage. Nevertheless, heat and moisture simulation are always recommended as a verification method to prevent the operation of VIPs in severe hygrothermal conditions and to guarantee their long service life.

5 Practical Applications focused on Retrofitting: Guidelines for SIM installation

The aim of this Chapter of Subtask 3 is to provide designers, engineers, contractors and builders with guidelines for the applications of vacuum insulation panels (VIPs) and Advanced Porous Materials (APMs). It gives a comprehensive account of transport, handling, installation and quality check. The main purpose is to promote safe transport, handling and installation. In the case of VIPs the primary issue is that of protecting the panels whereas the main concern for APMs is the safety in handling of the material. Examples are given of methods that may be used to verify the quality and thermal performance of SIMs after installation.

5.1 Guidelines for implementation

The aim of this Chapter is to give an overview of different factors that are vital to the performance of SIMs and issues related to handling. The guidelines are concerned with VIPs as well as APMs that do not rely on vacuum. The framework of the criteria for VIPs is based on the recommendations by the German Federal Institute for Research on Building, Urban Affairs and Spatial Development [93] as well as the guidelines published by some of the VIP manufacturers while available observations and experimental results from the scientific literature are also referred to. Guidelines from manufacturers are the main source of information on APMs.

It is worth noting that 'European Technical Approval' reports cover the subjects of packaging, transport, storage and installation. Those reports commonly refer to 'instructions of the manufacturer' and according to the upcoming 'Guidelines for the certification of thermal insulation products' by the French Acermi [94], the manufacturer must, in accordance with a quality manual provide handling procedures to avoid any damage to the product.

5.1.1 Ordering and specifications

Previous publications point out that VIPs often have a long delivery time and that this may disturb the time schedule of a building project, not the least in the case of damaged panels and the subsequent ordering of replacement panels [93]. Exact part lists should therefore be made early in the process and would favourably include spare panels in case of damage. The design and a production process should facilitate the replacement of the VIPs for instance by allowing for dismounting of layers adjacent to the VIPs as well as the VIPs.

5.1.2 Packaging and transport

It is important that the panels are packed in a manner that does not allow for any movement in the box and that the edges of the panels are not subject to load. It is also recommended that the panels are separated with a layer of fleece and the transport cases should have some protection against mechanical shock while the transport pallets must be of adequate size. Furthermore, it is recommended to keep the panels in the packaging until use [93]. One of the manufacturers of VIPs has developed a special cardboard packaging for the transport of VIPs, see Figure 5-1.

Figure 5-1: Example of a special transport packaging provided by a manufacturer (Photo: Kingspan).

The problem of mechanical damage to the VIP envelope is well known and has been mentioned in research. Simmler and Brunner [95] concluded that the installation of unprotected VIP cannot be recommended and that pre-fabricated assemblies protecting the VIP are to be favoured. The adding of a protective outer layer is offered by a number of VIP producers. This protective layer may for instance consist of a thin layer of expanded polystyrene (EPS) or rubber granule layers, see Figure 5-2.

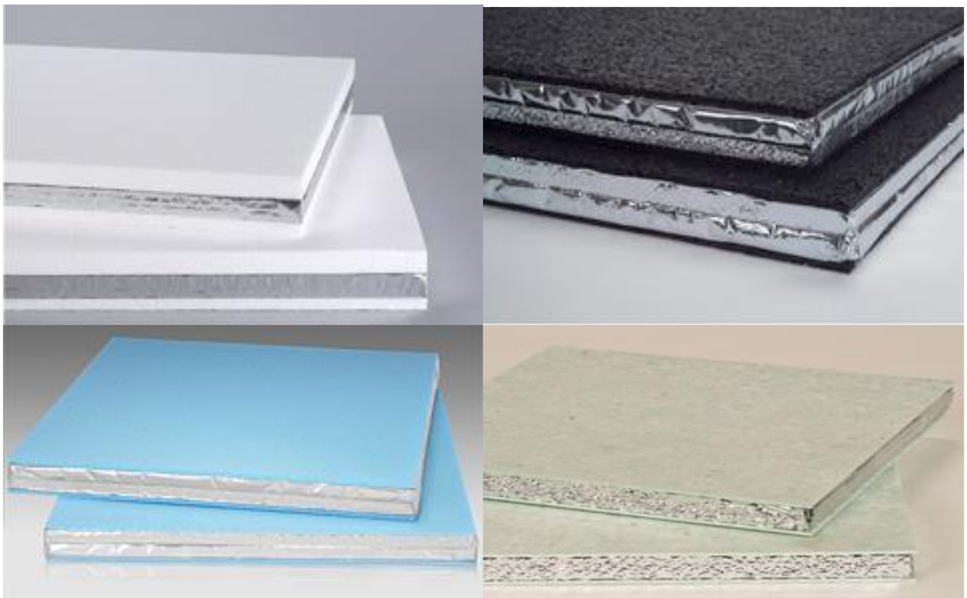

Figure 5-2: Panels with protective layer of expanded polystyrene (EPS), extruded polystyrene (XPS), rubber granule mat and recycling noise-reduction-sheet lining (Photo: Porextherm).

5.1.3 *Delivery and storage on site*

The panels should be inspected at delivery. Figure 5-3 gives an example of the visual instructions for detecting a faulted panel provided by one manufacturer of VIPs.

Figure 5-3: How to detect a faulted panel [96].

Another manufacturer of VIPs describes how a proper panel is relatively hard and the barrier film fits tightly, with a crinkly appearance while a damaged panel is softer and the barrier film is loose with slight bubble formation and without the distinctive crinkled appearance and provides a picture to illustrate the differences as shown in Figure 5-4.

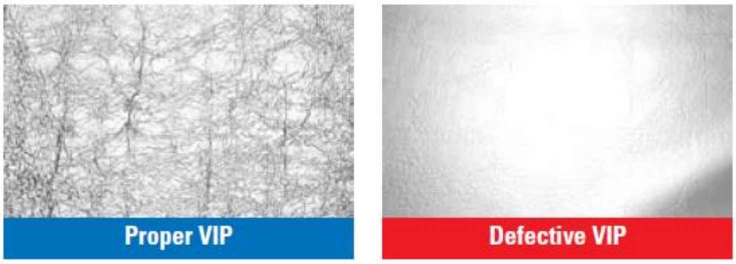

Figure 5-4: How to detect a faulted panel [97].

Wegger et al. [98] carried out climate ageing studies of VIPs with black fleece for fire protection that included cyclic loads of UV radiation, spraying with water, freezing and thawing. Severe deformation of the panels and delamination of the fleece cover of the panels were observed after 1 month and the authors concluded that the results are relevant for interim storage or exposed conditions of VIPs at construction sites and that the exposure of VIPs to extreme temperatures and UV-radiation on building sites should be avoided. Earlier work described in the report of Simmler et al. [99] gives an account of the maximum service temperatures of polymers commonly used in laminate envelopes but while various stabilizers to prevent UV as well as thermal aging are available for the polymers of the laminates it is advised that the exposure to UV radiation and excessive temperatures should be limited unless shown otherwise by testing. The oxidation of the aluminium layer in the laminates is also an issue even though an oxidized layer may act as a barrier for further oxidation. It has been argued that since accelerated oxidation is primarily observed at high relative humidity and temperatures around and above 80°C and that this is not critical in building applications [99] but those conditions might arise for unprotected panels at a building site and some producers recommend that the panels should therefore be kept indoors and packaged until used. Figure 5-5 gives an example of some of the warning labels from one VIP producer that illustrate the necessity to protect from moisture and direct sun.

Figure 5-5: Warning symbols for VIPs [97].

The panels should not be placed in direct contact with concrete or other alkaline substances as the pH-value of moisture or water in the environment must be kept below 8.5 [100] and [101]. It has also been shown that alkaline glues may cause corrosion at the edges of the panels [43]. The effects of various adhesives and concrete/screed constituents on the durability of the high-barrier envelope of VIPs were studied in the work of [102]. In general, VIP laminate envelops turned out to be very resistant to the substances studied in this project. However, damage to welded seams due to a long-term exposure to moist alkaline environments cannot be ruled out. According to the same study, temperature-related cyclic mechanical loads did not show any negative effects on the panels.

Contact with hot water may cause degradation of the PU layers of the laminates [103]. When it comes to exposure to low temperatures, the combined effect on the polymers and the aluminium can cause sheer stress and delamination of the laminate at around -20°C. This effect is enhanced by interstitial water-vapor condensation [74].

An elaborate discussion of service life and ageing is given in Section 4 of this report, and in Section 5 in the report of Subtask 2 of this Annex.

Powder boards of fumed silica are not flammable but commonly VIPs have a flammability label B2 according to DIN 4102 [104].

When it comes to stacking of the material at the building site, it is recommended that the directions of the producers be followed and in general stacking should be avoided unless it can be done in a manner that will not afflict bending load on the panels.

5.1.4 Chemicals: Glues, adhesives, cleaning agents

The use of adhesives reduces the need for mechanical fasteners and consequently the thermal bridges of the constructions may be diminished. Vacuum insulation panels should however not be used in association with solvent based adhesive systems the adhesive glue in direct contact with VIP laminates must not include chlorides, Ga, Tl, In, Sn and Pb according to the work of Garnier et al. [105]. In general, according to one of the leading manufacturers, panels that have been in contact with solvents or acids should not be used.

According to the technical documentation for VIPs, Adhesives cartridge glues such as MS polymer™ cartridge glues are suitable for the mounting of VIPs [106]. The applicability of a standard solvent free polystyrene adhesive has been demonstrated in a plus energy house in Bottrop, Germany [107].

5.1.5 Installation and Handling

Due to the fragility of the laminate, direct contact with rough surfaces should be avoided, as should dirt and particles on the surface of panels.

Figure 5-6: Warning symbols for VIPs [108].

The contact with any protruding or sharp objects of the structure, such as structural steel members or fasteners must be avoided. Furthermore, any load that could cause shear stress on the laminate should be prevented.

The report of the BBSR [93] states that warning labels are an important part of quality assurance as they can raise the awareness of people working with VIPs as well as other construction workers on the building site. The report suggests the marking of components with VIPs and proposes the use of a pictogram (Figure 5-7) from the work of Binz et al. [42] for this purpose. The pictogram warns for the use of sharp tools close to VIPs.

Figure 5-7: A pictogram for constructions with VIPs [42].

The report of the BBSR [93] does also mention the need for warning label for VIPs illustrating that the VIPs should not be treaded on, cut, sawed or drilled through. Figure 5-8 shows examples of such labels from one manufacturer of VIPs.

Figure 5-8 Warning labels for VIPs [97] (Porextherm, 2011).

Dimensional tolerances are provided by the manufactures and are typically in the range of a few millimetres but depend on the size of the panels. The tolerances should be allowed for in the design as the panels cannot be cut and may not be pushed into place. It is necessary that workers who work with the installation VIPs get proper training in the use of the panels and that are provided with adequate tools. The use of felt overshoes and felt covered boards with handles and load spreader might also be of great help when installing VIPs on horizontal trafficked surfaces as this will allow the workers to kneel on freshly laid VIP without causing dents and risking damage [42].

5.1.6 Other activities at the building site

The report of the BBSR [93] explains how construction activities on the building site may cause damages to VIPs. Other contractors on the buildings site must therefore be informed of the VIPs and some areas may at times have to be closed off to those not involved in the installation of the VIPs. The authors mention some of the categories of craftsmen that need be especially aware of VIPs on the buildings site, including installers of buildings services and electricity, tilers and drywallers, plumbers, window installers, roof layers, masons and carpenters.

5.1.7 Working environment

In the case of a broken panel the dust of the porous core may cause eye irritation, temporary drying and irritation of the skin, eyes, and mucous membranes. Inhalation of dust from handling may cause temporary upper respiratory tract irritation. Avoid therefore dust contact with eyes, skin and clothing and avoid breathing dust.

5.1.8 General summary of guidelines

In the absence of more specific guidelines from the producers the following table can give guidance for the installation of VIPs.

Table 2: Factor of exposure and recommendations from factory to installation.

Phase	Factor of exposure and recommendations
Packaging and transport	Panels should be protected until installation, either by using special packaging and/or protective layers.
Receiving and storage	The panels should be inspected at delivery It is recommended to store the panels indoors Avoid exposure to UV-radiation Avoid dampness on panels Avoid temperatures below -20°C Avoid temperature above 80°C Avoid load on VIPs that cause shear stress on the laminate Avoid stacking of VIPs unless following directions from the manufacturer
Installation	Installation should be carried out by trained personnel Inform workers on site Do not walk on the panels Avoid direct contact with rough surface, avoid dirt and particles on the surface of panels Avoid abrasion of the panels The panels should not be pushed into place The adhesive glue in direct contact with VIP laminates must not include chlorides, Ga, Tl, In, Sn and Pb. Do not place in direct contact to concrete or mortar or other alkaline substances. Avoid pH values above 8.5 Avoid contact with solvents and acids.

5.2 Advanced porous materials

Not all SIMs rely on vacuum and in comparison with VIPs those products are less prone to damage. Blankets and boards with aerogels and other silica based materials are examples among the expanding range of products that have a wide variety of applications. The most prominent difference in comparison with VIPs is that the products may be cut and sawed to size at the building site, much like traditional insulation materials. Aerogel blankets can be fixed directly with mechanical fasteners or a combination of mechanical fixing and adhesives [109]. Microporous boards of synthetic amorphous silica can be bonded with adhesives based on two-component acrylic resins or with silane-modified polymers or single-component hybrid adhesives that contain no water or solvent. After thermal activation of the surface at about 600°C it can also be bonded using water glass adhesives [110]. Several aspects concerning storage, handling and safety are worth mentioning while it must be noted that those issues are of concern for all building materials. Further information can be found in the technical documents and safety data sheets of the various producers.

5.2.1 Transport and storage

Aerogels and silica-based products should generally be stored in a clean, dry, and protected environment. Figure 5-9 shows an illustration from Aspen Aerogels [109] of how to store aerogel blankets, a fibre reinforced silica aerogel blanket insulation suitable for a range of applications. The producer states that material that has to be stored outdoors should be placed on pallets and thoroughly covered with a waterproof tarp or plastic sheeting and stored in its protective packaging until required thus and that direct exposure to the weather should be prevented.

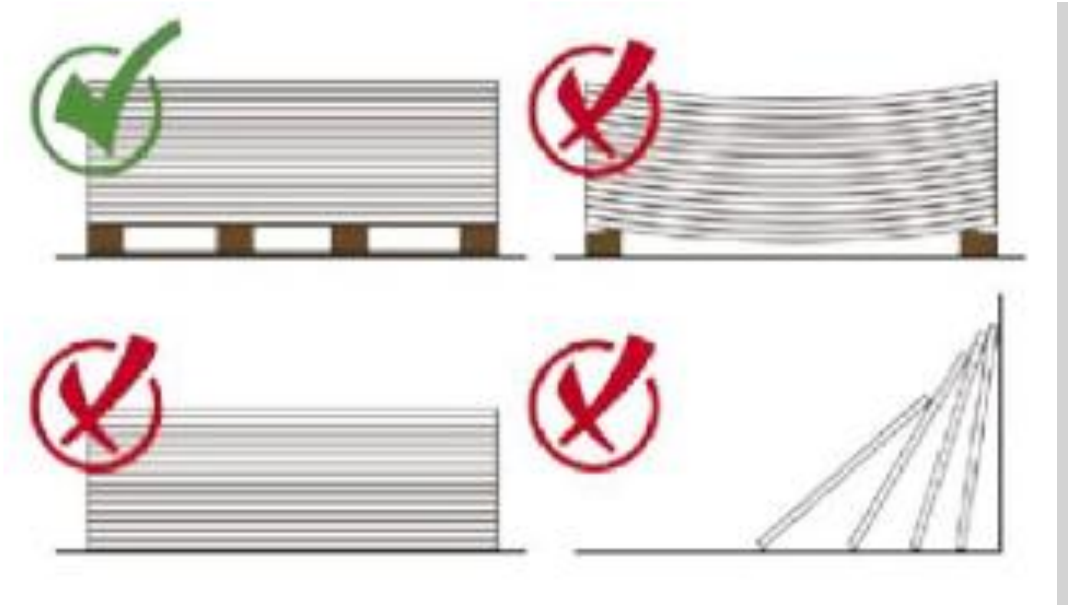

Figure 5-9: How to store aerogel blankets [109].

The producers of synthetic amorphous silica boards state that the insulation boards are to be protected by cardboard during transport and can be handled just like other insulation panels, apart from the low strength of the material which requires support for manual movement of individual boards [110].

5.2.2 Handling and safety

Aerogel is generally not a hazardous substance. However, the dust may cause mechanical irritation to the eyes and the skin and drying of the skin. Dust may also cause irritation of the respiratory tract [111], why inhaling aerogel dust should be avoided, primarily by providing appropriate exhaust ventilation at machinery and other places where dust may be generated while the use of an approved respirator may be necessary if local exhaust ventilation is not installed. It is also recommended to promptly clean up dust, preferably with dry vacuuming. Aerogel dust is hydrophobic and water is not an effective dust control agent [109]. It is also recommended to wear protection for eyes and face and dust contact with skin and clothing should also be avoided. Skin drying can be prevented through the use of protective gloves and the use of protective clothing. One manufacturer recommends daily washing of clothes and states that work clothing should not be allowed out of the workplace. Protective barrier cream should be used before handling the product while hands and other exposed skin should be washed with mild soap and water.

An important measure to minimize exposure is to use proper packaging, especially for cut-offs and waste. Furthermore, the products should be handled in accordance with good industrial hygiene and safety practice [111]. For more detailed and product specific information the reader is advised to consult the information of the material producers [109, 110, 111].

5.2.3 Installation

It necessary to employ competent building professional to install SIMs and any work related to constructions with SIMs, may it be plumbing or electrical installation. Some products may be damaged when subject to loading or unsupported foot traffic.

5.3 Inspection on site and post installation methods for quality control of SIMs

A number of methods can be used to test the in situ thermal performance of constructions with VIPs and other SIMs. The thermal performance can for instance be evaluated through measurements of the thermal resistance of the wall. The steady-state thermal resistance can be measured with a heat flow meter and thermocouples as described in ISO 8301-1991 [112] and ASTM C518-04 [113] . A heat flow meter can also be used to measure the thermal resistance by three different methods; the average, the storage and the dynamic as described in ISO 9869-2014 [114].

Infrared thermography can be used to measure the surface temperatures on a façade and can provide instant qualitative information about the defect of individual VIPs or faulty applications of other SIMs as these will constitute a thermal bridge in the façade. The method can be applied on large surfaces. The method requires that the panels are exposed or at least not covered with conductive massive material or ventilated façade covering [42, 65].

A number of special methods have been specially developed to verify the quality of VIPs after installation. An important aspect is that the installation of VIPs is carried out in a manner that allows for inspection. The radio frequency identification method identification technique (RFID) is a way of measuring pressure that relies on the identification of radio waves emitted by RFID tag placed in VIP and is fast and suitable for large number of VIPs [115, 116]. The pressure can also be measured by measurements of the thermal conductivity of thin fibre sensor fleece inside the panel and its relation to pressure increase, but the method is slow and requires multiple tests for accuracy [115, 116].

A thorough discussion of thermal conductivity measurements of VIPs can be found in Subtask 2 report of this Annex and a comprehensive account of quality assurance of VIPs, describing methods and standards for monitoring various technical characteristics of VIPs can also be found in [117].

6 Conclusions and further outlook

During the work of this Annex several questions regarding the long-term performance of SIMs on the building scale have been identified and discussed. Four main challenges were identified and here the aim is to give some clarity to what extent these have been resolved based on the information presented in this report and in other reports from this Annex.

6.1 Knowledge and awareness among designers concerning using SIM

There is an additional effort for planning since standard sizes or custom-made VIP have to be ordered in advance. Therefore, tailor made planning software have been developed for assemblies where VIPs are intended to be used. These CAD based software decrease the threshold for using the product and simplifies design. Also, the implementation of several products based on SIMs in commercial hygrothermal design tools, such as WUFI, helps increasing the awareness among architects and designers. However, care is necessary during installation since the VIPs are sensitivity to mechanical puncturing of the envelope. Therefore, there may be a need for certification of craftsmen and need of special training.

6.2 Conservative construction market

The building industry is generally conservative to new solutions and materials. The industry is regulated by numerous codes and standards, and thus, introducing new material takes a long time. The ongoing standardization on the material and product levels may trigger building components with SIMs integrated to be introduced on the market.

6.3 Cost versus performance

There are valuable savings of space when less area is needed for the building elements which leads to an increased rental income. There can also be technical reasons to select a SIM, i.e. when conventional insulation materials are not a practical alternative or for architectural reasons. This was investigated in-depth in Subtask 4 please refer to this report.

6.4 Long-term performance of SIMs

The SIMs for building applications have been developed in the recent decades. Theoretical considerations and first practical tests showed that VIP, especially those with fumed silica core, are expected to fulfil the requirements on durability in building applications for more than 25 years. Both VIPs and APMs have been successfully installed over the past 15 years in buildings. However, real experience from practical applications exceeding 15 years is still lacking, especially when considering third-party monitoring and follow up of demonstrations.

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