Aerogel materials for heritage buildings: Materials, properties and case studies

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**ABSTRACT**

Aerogels are open-porous, high-performance thermal insulation materials that can be used for very thin building insulation. So far, the application conditions of these materials and their potential in heritage buildings have not yet been described comprehensively. This review shows the technical properties of commercially available aerogel materials – such as blankets, boards and renders – and their use scenarios in heritage buildings, taking into account the heritage criteria of authenticity, integrity, reversibility and compatibility. Additionally, historic buildings that were refurbished using aerogels are presented. The study by theoretical evaluations and calculated U-values indicates that superinsulating aerogel materials have an exceptional potential in the refurbishment of heritage buildings. The presented examples show the feasibility of refurbishments with aerogel and the resulting improvements in terms of both comfort and thermal properties. Hence, aerogel materials are well suited to be used in preservation of heritage objects according to generally known rules and conditions of heritage preservation, thus contributing to the reduction of energy consumption in the building sector.

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1. Introduction

A significant amount of the energy consumption and the CO\textsubscript{2} emissions in Middle and Northern European countries is due to the heating of buildings. In Switzerland for example, more than one third of the domestic energy is used for room heat [1]. In particular, older buildings are often poorly insulated, resulting in both a high energy consumption and a poor thermal comfort within the building. The data in Fig. 1 shows that in the cities of Basel and Zürich, it is the buildings built before 1980, which have the biggest impact on the total energy consumption. In general, buildings from that time-span can contain several tangible values of architecture. If they are to be refurbished, the owner or the architect representing them might propose that these values should be conserved, or on the other hand, they might be protected officially by the local or national office for monument conservation. Improvement is possible with additional thermal insulation externally and internally, technologically with new efficient heating technologies and/or choice of appropriate heating program according to use of the building and its envelope construction. In these cases, refurbishment with standard methods and conventional insulation materials is often not possible or practical. This is because conventional insulation materials require the application of thick insulation layers which in many cases would alter the appearance of the building too much. Moreover, the usage of these materials themselves often does not conform with the requirements of heritage protection. Aerogel materials on the other hand are well suited in many cases to improve the thermal properties and the comfort of heritage buildings, as only thin layers are necessary and aerogel materials can screen diffusion open and water resistant/hydrophobic. The most commonly used insulation materials, on the other hand, require thick layers, can accumulate humidity (mineral wool) or are not water vapour diffusion open (EPS). Internal insulation represents a risk in the historic construction, because of creating new vapour barrier and shifting dew point towards interior. Vapour diffusion open materials, such as aerogel materials, allow for a higher flexibility in these circumstances compared to non-permeable materials.

Silica aerogels are highly porous materials with very low thermal conductivities in the range of 14 to 19 mW/(m·K) [4]. Because their pores are open, they are water vapour diffusion open and because they consist mainly of silica, they can reach good fire
ratings. Additionally, they are normally hydrophobic, i.e. water-repellent. With these properties, they are very well suited as thermal insulation materials in buildings in many different applications. Compared to conventional materials, they achieve the same insulating effect with about half the thickness. There are different types of silica aerogel materials available on the market, which will be described in more detail in Section 3. The making of aerogel in general, also for other applications, is well described in [5].

Heritage buildings constitute a special case of refurbishment where the public interest lies in the preservation of the building’s appearance and in the conservation of its substance. Aerogel materials have already been applied in this context and publications document these applications, partly including building monitoring [6–13].

Not all the potential benefits of the usage of aerogel in the context of cultural heritage have been described. The use conditions in heritage structures have not been provided in terms of the protection of cultural values of the object. In general, heritage buildings can be protected on several levels: international level (UNESCO heritage), national, regional and local.

The value of a historic building is not represented only by its appearance, but represents also the complexity of all present parts [14]. With the question of the energy demand of the building, the construction of the building envelope needs to be considered. At the same time, it is “physical holder” of building values, together with shape and floorplan, which may not be touched by additional insulation. For this reason, the present article examines the use of aerogel materials in the building envelope. Furthermore, today, a higher level of interior comfort is usually required in historical buildings. “Structures of architectural heritage, by their very nature and history (material and assembly), present a number of challenges in diagnosis and restoration that limit the application of modern legal codes and building standards.” [15]. Although heritage buildings represent an exception in energetic standards of building given by international documents [14,16], improved thermal building envelopes are desirable. With these, an appropriate indoor environment can be achieved, which on the one hand protects the building structure itself from unfavourable weather influences and on the other hand allows for a sustainable and adequate use. This, in turn, favours regular maintenance. Therefore, the protection of heritage buildings by their effective use is the goal of heritage preservation.

The present article summarises the conditions of use of commercially available aerogel products and systems in preservation of heritage together with selected examples of refurbished buildings, while other works of co-authors like [17] deal with not yet commercialized approaches. This present article shows the requirements of the materials, i.e. products and systems, for the preservation of cultural heritage. Regarding the available materials and the example buildings showing the successful application of aerogels, we focus mainly on Switzerland. This is:

- because for most aerogel material types the first full-scale building application was in Switzerland
- because aerogel application in buildings is higher in Switzerland due to a combination of relatively strict building energy requirements and high price levels, which make aerogels produced outside of Switzerland more affordable.

Also, high labour cost in Switzerland reduce the impact of material cost in the overall budget. Nevertheless, the price of high-performance insulation is still significantly higher than the price per U-value of conventional insulation products.

Based on interviews with aerogel manufactures, distributors and users, the different aerogel materials available on the market are compared and their technical properties are given. Their potential for applications in heritage buildings is assessed according to the criteria of heritage protection: authenticity, integrity, reversibility and compatibility. Subsequently, the principles of use of aerogel insulation materials in heritage buildings and a summary of their use conditions are given. Furthermore, the available materials and systems are compared, sorted and categorised into specific use positions. Also, potential benefits and harmful effects are examined. For the different aerogel materials, at least one application example in a historic building is given to illustrate the possibilities both with respect to heritage criteria and thermal properties.

2. Heritage principles

According to cultural heritage policy documents such as international charters [14,16,18] and cultural heritage conventions [19], the general principle of the addition of a new material, instead of the removal of authentic materials should be used. In the context of heritage preservation, the present article reviews the addition of aerogel insulation for improvement of the energy efficiency of

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1 The first aerogel render application was "Mühle Sissach", cf. Section 5.2 large scale application of translucent elements was the gym hall of the school "Buchwiesen" in Zürich [17] and the first large scale use of aerogel blankets on a building façade was done in “Müli Oberhallau”, cf. Section 5.1.
historic buildings. Furthermore, it provides the principles of its application. New additions to heritage buildings should be recognisable as different “on second sight”. They should not be so different that they stand out but they should be distinguishable from authentic material, so that in the future, added material can be removed from the original layers. Aerogel products are clearly distinguishable from historical building materials. Additionally, because of their good performance, the use of aerogel materials and products meets the general condition of minimisation of the necessary intervention [20,21].

Heritage policies and conventions require that the analysis and the proposal of an intervention are conducted, as in medicine, in a specific order of steps. These steps are: anamnesis, diagnosis, therapy and monitoring [14].

For heritage projects, “anamnesis” is represented by the knowledge of the history, the changes, and the influencing factors with respect to the object. Here, all the knowledge of the history of the building presented by archaeological and historical study should be included [16]. Also, all visible building stages should be taken into account. “Diagnosis” is represented by the knowledge on the technical status of the building, the technical diagnosis, the assessment of usability, of the construction and of the materials, the evaluation of cracks and faults and the identification of the historical cultural and architectural values through an expert opinion. “Therapy” consists of the methodological approach of preservation and conservation, of the proposal of preservation of the building and of construction actions for a refurbishment or of the monument preservation itself. The “monitoring” of influences, resulting in changes of the building should be conducted by the user and/or the monumental service. Having observed and documented influences, these can be included in future methodological and proposal corrections or another intervention for preservation.

As a complement to this methodology, a new step, “prevention”, can be added. Monitoring after refurbishment can be considered as a part of prevention, as well as regular maintenance: painting, replacement of damaged materials and regular inspection serving as prevention of future damage.

For non-heritage buildings, usually the only steps are “diagnosis” and “therapy”. Monitoring after refurbishment is mostly missing for non-heritage buildings. Nevertheless, these missing steps are suggested for the refurbishment process of all existing buildings.

Within the European H2020 project “Effesus” further guidelines and decision aids were developed which can be found in [22]. A decision support system is described in more detail in [23].

In the framework of the steps introduced above, for heritage preservation “No action should be undertaken without having ascertained the achievable benefit and harm to the architectural heritage” [14], except in cases of safeguard of heritage building structure. For this reason, the application of aerogel materials and their potential in the context of heritage are discussed in the next section.

3. Available products and systems and their properties

3.1. Properties of aerogel materials

Aerogel materials were first used in buildings in the early 2000s. The first application of aerogel blankets in buildings was in a former mill in Switzerland from the 17th century, that was refurbished in 2008 [24]. Since then, the number of available aerogel products has increased and the market for these materials has seen a strong growth in Switzerland. Aerogels have very favourable material properties for the application as building thermal insulation: low thermal conductivities between 14 and 19 mW/(m·K), strong hydrophobicity, low water vapour diffusion resistance and good fire ratings. For a given insulation performance, only about half the thickness is needed in comparison to conventional materials. Hence, aerogels are very suitable for the refurbishment of heritage buildings where little space is available or where a thick insulation would alter the appearance of the building drastically. A drawback of some aerogel materials such as blankets, boards and granules is that they produce dust during handling, making them less agreeable for users.

Aerogel materials, their properties and production have been reviewed by different articles [4,25,26], mostly focusing on the thermal properties of aerogels. The acoustic properties have been investigated mainly for granular beds with good sound dampening effects, depending on granule size [27,28]. The durability of aerogels was studied for granules [29] and blanket materials [30], with the finding that prolonged exposure to temperatures above 70°C at high relative humidity (>90%) can lead to a deterioration of the material, in terms of its hydrophobicity and thermal conductivity. As these temperatures are not typical for most building applications, this is not a concern.

3.2. Aerogel product types

Interviews with users and distributors of aerogel material have indicated that in Switzerland, the most commonly used aerogel materials are blankets, boards and renders, in this order. While exact numbers of applications are not available, well over 100,000 m² of façade have been applied with aerogel renders in Europe since 2013, with an average thickness of ca. 50–60 mm. The most commonly used aerogel materials are described in the following and some specimen are shown in Fig. 2. Technical properties of common products are given in Table 1. It is important to note that there are some copy-cat products of inferior performance on the market – mainly of Asian production. Hence, it is important to check the quality of a given material or to use well-known and controlled materials (Fig. 3).

3.2.1. Aerogel blankets

The most widespread aerogel product type in Switzerland, aerogel blankets, consists of a fibre fleece made from organic and inorganic fibres, into which the aerogel is embedded. The blankets are mechanically flexible and the best products have a very low thermal conductivity around 15 mW/(m·K) (Table 1). They are typically used as insulation material in architectural details such as roller shutter housings or window reveals, as interior insulation or as external thermal insulation for façades. Aerogel blankets are available as the product with maximal thickness of 10 mm.

3.2.2. Aerogel boards

Aerogel boards are more rigid and have greater thickness than blankets. They are produced by either gluing several layers of aerogel blankets together or by binding aerogel granulate into boards, usually with a laminate. In both cases, due to the addition of glue, the thermal conductivity of the boards is higher than that of the blankets around 16–19 mW/(m·K) (Table 1). Boards are used as interior insulation or as ETICS (External Thermal Insulation Composite System). The latter can be attached without the usage of dowels but is only intended for interior application and smaller areas on the exterior.

3.2.3. Aerogel renders

By binding aerogel granulate with inorganic binders, several render systems with thermal conductivities of around 28 mW/(m·K) have been developed, which is slightly below the thermal conductivity of conventional insulation blankets or boards and
### Comparison between ordinary refurbishment and heritage building preservation

| Product type | Refurbishment of existing building which is not listed as heritage | Heritage building preservation, listed heritage building |
|--------------|------------------------------------------------------------------|--------------------------------------------------------|
| blanket      | A Can be used where not enough space is available. | A Can be used where proportions cannot be changed (around windows, doors) or where not enough space is available. Flexible blanket for uneven surfaces. |
|              | I New construction layers can be proposed. The removal and replacement of original material is possible. Anchoring is allowed. | I Removal and replacement of original material and necessary anchoring points should be minimised.* |
|              | R Reversibility of the application is not required. | R Reversibility of the application is required. Possible addition to existing façade. Visual difference to original material is positive. |
|              | C The physical compatibility of used materials is relevant for durability. Vapour openness of façade not required. | C Physical compatibility with historical materials and techniques (vapour open, durable) is required. Vapour openness can be influenced by exterior render. Scientific proof of compatibility should be given.* |
| boards       | A Visual appearance of building can be changed. Boards can be used in the interior and exterior. Authentic façade can be covered and finished with new render layer. | A All authentic valuable parts should be preserved and cannot be covered. Original building style, determined by monument service, should be preserved. Boards can be used in the interior if there are no protected parts. |
|              | I Removal and replacement of original material is possible, anchoring is allowed. | I Removal and replacement of original material and necessary anchoring points should be minimised.* The Sto Avero boards can be used without anchors, but glued by glue. |
|              | R Reversibility of the application is not required. | R Reversibility of the application is required. Possible addition to existing façade. Visible difference to original material is positive. |
|              | C The physical compatibility of used materials is relevant for durability. For that the practical experience of a stuccoworker is enough. | C Physical compatibility with historical materials and techniques (vapour open, durable) is required. Vapour openness can be influenced by exterior render. Scientific proof of compatibility should be given.* |
| render       | A Visual appearance of building can be changed, if its architectural cultural value is not high enough. | A The original style of the building and all authentic valuable parts should be preserved. On uneven surfaces, mouldable render can be used for artistic and architectural details.* |
|              | I Removal and replacement of original material is possible | I Removal and replacement of original material and necessary anchoring points should be minimised. The aerogel render can be an addition to the existing render. |
|              | R Reversibility of the application is not required. | R Reversibility of the application is required. The aerogel render is considered reversible and can be removed down to original layers with a trowel and residues by hard brush. Its softness is considered a positive property in this context. |
|              | C The physical compatibility of used materials is relevant for durability. Dustiness of final application is an issue. | C Physical compatibility with historical materials and techniques (vapour open, durable) required. Proof should be given scientifically.* |
| granular form | A Visual appearance of building can be changed, if its architectural cultural value is not high enough. | A Authenticity not affected by filling of a cavity with granules if it is not exposed. |
|              | I Removal and replacement of original material is possible. | I Addition of granules do not affect the integrity of building. |
|              | R Reversibility of the application is not required. | R Reversible to previous status.** |
|              | C The physical compatibility of used materials is relevant for durability. Dustiness of final application is an issue. | C Material can cause decrease of adhesion of other materials. If dust escapes, it can lead to skin and eye irritation. Increased hydrophobicity. |
| translucent panel | A Translucent and transparent panels can be used where necessary. | A Daylighting of interior with diffusive effect can be achieved by translucent aerogel boards. Translucent elements are recognisable from original glazing.* Better noise protection is achieved.*** |
|              | I Old glazing/translucent panels can be replaced without change of integrity. | I Replacement of old glazing/translucent panels possible without change of integrity, depending on original frame. Additional structural frame might be required. |
|              | R Reversibility of the application is not required. | R Reversible to previous state. |
|              | C Compatibility can be achieved. | C Compatibility is comparable with original forms of glazing. Panels might fit into original frames. Panels made out of glass and polycarbonate used for outer part of layered panel are considered as compatible. |

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* Research challenge
** Because of this reversibility, aerogel was awarded a cradle-to-cradle award for sustainability
*** Noise protection property is declared for products.

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Fig. 2. Different requirements on four important criteria (authenticity, integrity, reversibility, compatibility) shown in the comparison between ordinary refurbishment and heritage building.
at less than half the thermal conductivity of conventional insulating renders. Different approaches have been presented by several authors [31–34]. The aerogel renders are an interesting material especially for historic uneven surfaces – interior and exterior – and for applications where varying insulation thickness is advantageous, as in the vicinity of window jambs or of beams in timber framing constructions (e.g. quarry stone masonry).

### 3.2.4. Aerogel granules

In some applications, cavities, for example those in double walls, are filled with loose aerogel granulate with thermal conductivity 19 mW/(m K) (Table 1). This application is convenient, as an existing space, namely the cavity between the interior and the exterior brick wall, is used for insulation purposes. It also allows – in principle – for a renovation without any disruption of the building use. Unfortunately, the filling of aerogel granulate into the cavity produces dust, which can escape through small cracks in the walls so that it can enter the building. Hence, better filling methods are necessary in order to allow for a wider use of this method. As an alternative, blow-in of small aerogel blanket pieces has been reported [35], resulting in a somewhat higher thermal conductivity of the filling compared to granules. To our knowledge, presently this approach is not commercially available.

### 3.2.5. Translucent panels

Translucent panels sandwich an aerogel granulate filling between two transparent or translucent panes made from glass or plastic. The panels are completely sealed, so that dust can only occur in the case of breakage of the panel. These panels reach relatively low U-values, as the granular bed inside the panel has a thermal conductivity of around 19 mW/(m K). Their advantage is that they combine good insulation properties with the transmission of diffuse light, but without allowing too high a solar gain [36].

### 3.2.6. Other aerogel materials

Monolithic aerogel has not found any commercial application in buildings so far, as it is rather brittle and cannot be efficiently produced in sizes exceeding a few centimetres. Another type of aerogel material is aerogel windows. In this building element, a monolithic pane of aerogel is sandwiched between two glass panes, resulting in a transparent, thin, highly insulating window [37]. These are not further discussed here, as currently no products are widely commercially available.

#### 3.3. Technical properties & performance

The technical properties of the different available aerogel materials are summarised for specific products in Table 1, also showing the thickness needed to reach a U-value of 0.25 W/(m²·K). Furthermore, indications of current market prices for aerogel materials are given, showing that the cost of aerogel materials is considerably higher than other insulation materials for the same insulation requirement. New technological advances in the production of aerogels, though, are likely to lead to considerably lower prices in the future [20,25]. With that, refurbishments using aerogel materials will become feasible for more building owners than at present, leading to an improvement of the energy consumption in the building stock.

For comparability, Table 1 also lists the two most common building insulation materials, namely expanded polystyrene (EPS) and stone wool. The table shows that aerogel blankets and boards offer the best performance in terms of thermal conductivity, with the thinnest layers for a given U-value. Fire ratings of the products differ, with good ratings being reached for products with a mineral component (render) or glass fibres. Aerogel granulate and the aerogel render are the most economic aerogel materials, with the lowest price for a given U-value.

### 4. Aerogel application in heritage buildings

Their physical properties, foremost their low thermal conductivity and their vapour diffusion openness, make aerogel materials well suited for application in historic buildings. In order to evaluate their suitability in more detail, the potential benefits and harms of their application were examined with respect to the four criteria of authenticity, integrity, reversibility and compatibility. These universal principles say that, new additions should not change the authentic appearance of the original structure and they should not harm the integrity of authentic building structures. Furthermore, new additions should be reversible to the previous state, e.g. new benefits should be added only, and new materials and parts should

### Table 1

| Product Type                        | Thermal conductivity λ [mW/(m K)] | Density [kg/m³] | Water vapour resistance factor Mu µ [-] | Reaction to fire [class] | Thickness for U=0.5 W/(m²·K) [mm] | Price for U=0.5 W/(m²·K) [€/m²] |
|-------------------------------------|----------------------------------|-----------------|----------------------------------------|--------------------------|-----------------------------------|---------------------------------|
| Blanket Spaceloft                   | 15                               | 150             | 5                                      | C-s1-d0                  | 28                                | 180                             |
| Board Heck AERO                     | 19                               | 230             | 3                                      | A2-s1-d0                 | 31                                | 190                             |
| Board Sto Aevero                    | 16                               | >150            | 10                                     | D-s1-d0                  | 29                                | 250                             |
| Render Fixit 222                   | 28                               | 220 (dry)       | 4–5                                    | A2-s1-d0                 | 51                                | 100–190                         |
| Granulate Cabot P300               | 19                               | 65–85 (bulk)    | 2–3                                    | B                        | 35                                | 120                             |
| Translucent panel, OKAGEL, 60 mm fill | 19 (fill)                        | n.a.            | –                                      | Not rated                | Ca. 59*                           | Variable*                       |
| Stone wool (low thermal conductivity) | 34                               | 48              | ca. 1                                  | A1                      | 62                                | 10                              |
| EPS Polystyrene (low thermal conductivity) | 30                               | 19              | 30                                    | E                       | 55                                | 5                               |

Certificates for aerogel blankets (ETA and CE) can be found here [38,39].

- Reference materials for comparison.
- Thermal conductivity as provided by manufacturer.
- A1, A2, B, C, D, E, F (class F without requirements, e.g. not tested) + additional classification in terms of generation smoke (s1, s2, s3) and in terms of generating flaming droplets and particles (d0, d1, d2), (EN13501).
- Prices are based on either list prices or quotes from the manufacturers for amounts of 1 m³ or more. Of course, prices are strongly dependent on the amount of material bought. The values given above should hence only serve as a very rough orientation.
- For a panel with two 2 × 6 mm laminated safety glass panes (i.e. 24 mm glass in total), calculated from the thermal conductivity of the fill.
- The price of the panels depends strongly on the model and the size of the panel.
| Envelope use position | Product type | + Potential benefit | − Potential risk/harm* | Comments & suggestion |
|-----------------------|--------------|---------------------|------------------------|----------------------|
| Perimeter wall         | render boards blanket | Ultrathin thermal insulation solutions: maximisation of internal space, unrivalled U-value improvement Solution for building physics problems (thermal bridges, moisture) Vapour open Reduction of moisture transport to inner wall, non-wicking Biological growth in this environment is low Compatible with historic plaster finish Compatible with heritage restoration techniques Render soft, hence easy to remove | ETICS require anchoring, which may be in conflict with authentic structure of heritage building What will be the final coating and finishing? ETICS should be assessed with final render treatment and anchoring technology Can visually affect appearance of building by loss of patina. | If there are not tangible values, and the authentic façade is not holder of cultural values, these insulation materials can be used. No problem in buildings, where plaster is not considered as a holder of value. Requires assessment of visual impact according to cultural values from interior or exterior side and consultation with local monument preservation service (Monument Board). For listed buildings, the addition and not the replacement of the authentic plaster is suggested. |
| Floors and ground floor | boards blanket | Ultrathin thermal insulation solutions: no change in thickness & floor levels Space saving, e.g. for pipings Hydrophobic Insulation of basement flooring may not influence height of doorstep, door openings and heating equipment (radiators) Ceiling of underground level can be insulated and thermally separated from the rest of the building | Penetration of insulation layers by anchors can cause local thermal bridges | Possible if ground floor does not contain cultural values (mosaic, terrazzo, stone tiles). Often in floor structures of historical buildings there is enough space for conventional materials, so that the same U-value can be achieved for a lower price. Additional insulation of foundations can be a research challenge. |
| Roof                  | boards blanket | Ultrathin thermal insulation solutions: maximisation of internal space, unrivalled U-value improvement No change in proportions of roof structure No special loadbearing structure needed for extra weight | Penetration of insulation layers by anchors can cause local thermal bridges | Test of influence on appearance is required. |
| Windows, doors and openings | blanket | Thin effective insulation of doors or panels | Penetration of insulation layers by anchors can cause local thermal bridges | |
|                      | translucent panels | Translucent thermal insulation solutions for daylight in skylights and large glass areas | White effect of glazed windows, skylights, openings | |
|                      | board blanket | Thermal bridge treatments Mould growth prevention | According to case, what will be final coating and finishing? ETICS should be assessed with final render treatment and anchoring technology | |

* Building physics have to be considered on a case-to-case basis.
be long-term compatible (chemically and physically) with the original building structure. Furthermore, their suitability and potential benefits and risks of application of the materials in different use positions on the building envelope were assessed, namely for the perimeter wall, foundations, floors, roof, windows and openings as well as for details solutions.

Fig. 2 shows the requirements for the different materials, in case of the refurbishment of ordinary, not-listed buildings and in case of heritage building preservation. The requirements are discussed qualitatively with respect to the four criteria of authenticity, integrity, reversibility and compatibility for the two cases of non-listed building (left column) and preservation of heritage (right column). The impact of the new materials is marked with the respective initials of the criteria (A, I, R and C for authenticity, integrity, reversibility and compatibility).

The comparison in Fig. 2 indicates that the aerogel materials in the traditional forms of render, boards and blankets as ETICS appear appropriate for the use in heritage preservation and ordinary refurbishment. The render is the most appropriate material, as it does not need additional fixing equipment and thus, has less impact on the integrity of the heritage building. It can be applied to uneven surfaces and in different thickness as required. Furthermore, it can be removed from original, thus facilitating reversibility. The final properties of a render application in refurbishment are influenced by the use of finishing layers and hence these should be assessed together with the render. Blankets and boards provide better thermal quality than renders and are hence very interesting solutions as well. Translucent panels filled with aerogel granulate may require an additional anchored mounting frame. There is great potential for application in industrial heritage buildings, such as historic factory buildings, where old windows and skylights can be replaced with translucent panels. Filling of cavity walls with aerogel granulate appears to be inappropriate due to the possible release of fine aerogel particles and hydrophobisation of the surrounding structures. Because of this effect, although the material is fulfilling heritage requirements, aerogel particles are hardly used as an insulation for existing cavity walls.

Additionally, the different product types were organised according to application position on the building envelope of existing historical buildings as shown in Table 2. Thus, the product types were linked to specific locations on the building. The potential benefits and harms according to the ICOMOS Charter [14] are described qualitatively. Further comments on the materials are given in the right-hand column of the table. For perimeter walls, blankets, boards and renders are suitable products where the finishing layer of the existing façade is not protected integrally and by appearance. It has to be taken into account that exterior aerogel boards with a thickness of more than 10 mm are made by gluing 10 mm layers. Hence, they need anchoring with plastic dowels that do not constitute strong thermal bridges.

In floors, blankets and boards can be used in most cases, if there is not enough space for conventional materials. For roofs, the influence of fixation and potential change of appearance needs to be evaluated for blankets and boards. Doors and openings can be refurbished with blankets, while for windows, translucent panels can provide a good combination of thermal protection and lighting.

Blankets and boards are often appropriate materials for architectural details, if they are compatible with protection requirement for the façade.

There are several main challenges for using aerogel in heritage buildings. First, the currently still quite high cost of aerogel – about 10 to 15 times higher compared to conventional materials considered per same U-value – can prevent the use of aerogel altogether. The high cost is mainly a result of expensive production process and expensive raw materials, but there are different approaches aimed at reducing it in the near future:

- e.g. by improved synthesis methods [21];
- the heritage principles must allow the use of the material in the considered building element, e.g. for blankets the fixation with dowels must be possible. This is a challenge faced by any retrofit, though, regardless of material;
- compared to conventional insulation materials thermal bridging becomes more critical, as the insulation thicknesses are smaller.

Hence, thermal bridges such as window reveals or penetrations through the insulation layer have to be considered more thoroughly, both in terms of heat loss and with respect to potential damage to the building structure.

On the other hand, aerogel materials provide strong opportunities compared to conventional building materials, especially for heritage buildings. First, aerogel materials are high-performance insulation materials. Hence, they can provide much thinner solutions than conventional materials, which is often times a necessary to make an energetic retrofit feasible at all. Second, they come in different product types, that cover a wide variety of application types and that have favourable working properties. I.e. boards can be cut with usual tools, renders can be applied with spraying machines etc. Third, aerogels are very favourable in terms of building physics, as they are water vapour diffusion open, hydrophobic and can reach good fire ratings. Fourth, the risks associated with the use of a novel product type due to lack of available knowledge have largely been eliminated by a sufficient amount of building examples. Nevertheless, it is important to have the planning and installation performed by building professionals, who have experience with these types of materials, as aerogels are still a niche product and its use requires specific procedures (e.g. gluing, fixing with dowels, etc.).

In summary, while aerogel materials are still costly and thermal bridging is more critical compared to conventional materials, they are often the only material that allows for a reasonable compromise between conservation and energetic retrofitting. Usually, the very thin layers of insulation that can be realised while still satisfying the heritage requirements, with conventional materials often would not have a significant enough effect on energy performance and comfort, in order to justify a retrofit in the first place. With aerogel materials, the increase in thermal resistance is roughly twice as big as for conventional materials. Hence, good comfort levels and acceptable to good energy performance can be reached with only a few centimetres of material.

Examples of applications of aerogel materials in actual buildings, mostly in Switzerland, are presented in the following section.

5. Examples of applications with aerogel materials

In Switzerland, aerogel insulation materials have been introduced in 2008 and applied in many buildings, mostly for refurbishments of existing buildings. Aerogel materials have been used for a full façade renovation with boards or blankets in around 30 cases, for solutions of details in more than 1000 cases (including new buildings) and about 200 objects were equipped with an aerogel render. Switzerland can be considered a leading market for aerogel materials, as more buildings were realised with aerogel than in neighbouring countries due to the high prices in Switzerland – making aerogel relatively cheaper compared to other countries in Europe, like Germany or France.

In order to highlight the potential and particularities of aerogel applications for heritage buildings, reference objects refurbished with aerogel blankets, boards and render are described in the
| Object                      | Year of construction | Year of refurbishment | Use position     | Construction before refurbishment (from inside to outside)                                                                 | Construction after refurbishment (from inside to outside)                                                                 | U-value before [W/(m² · K)] | U-value after [W/(m² · K)] |
|-----------------------------|----------------------|-----------------------|------------------|--------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------|-----------------------------|-----------------------------|
| "Mühl Oberhallau"           | 1608–1609            | 2007–2008             | Wall, ext.       | Quarry, ca. 900 mm exterior render [24]                                                                                  | Quarry, ca. 900 mm exterior render, 30 mm insulating render, 20 mm exterior render [24]                                 | ca. 1.7 (own calculation) | 0.48 [24]                   |
| MFH Fichtenstrasse          | 1877                 | 2010                  | Wall, ext. & int.| Interior render quarry/solid bricks exterior render [41]                                                                   | Interior render plaster board quarry/solid bricks exterior render, 20 mm conventional insulating render, 20 mm exterior render [41] | 1.9 [41]                   | 0.40 [6]                    |
| Duncarrum Centre            | 1860–1862            | 2014                  | Roof             | Roof timbers pitch pine panels air space & slate batten slate (pers. com. B. Cahill, Aspen Aerogels)                    | Existing roof timbers pitch pine panels variable diffusion membrane Spaceloft, 10 mm Spaceloft between battens, 10 mm roofing membrane air space & slate batten existing historic slate (pers. com. B. Cahill, Aspen Aerogels) | ca. 1.0 (own calculation) | ca. 0.56 (own calculation) |
| Mühle Sissach               | 14th – 17th century  | 2012–2014             | Wall, ext.       | Lime quarry, ca. 600–700 mm exterior render [42]                                                                         | Lime quarry, ca. 600–700 mm Fixit 222 aerogel render, ca. 50 mm [42]                                                  | 1.1 (pers. com. E. Franov, Carbotech AG) | 0.4 [42]                    |
| Manoir de Commondreche      | 1554                 | 2014                  | Wall, ext.       | Interior render quarry wall exterior render [43]                                                                          | Interior render quarry wall mortar Heck AERO, 20 mm exterior render [43]                                               | 1.4 [44]                   | 0.4 [44]                    |
| Detached house Biel (not listed) | 1926                 | 2011                  | Cavity wall      | Interior brick wall air gap, ca. 90 mm exterior brick wall exterior render                                                  | Interior brick wall aerogel granules, ca. 90 mm exterior brick wall exterior render                                     | 1.1 (pers. com. AGITEC AG) | 0.17 (pers. com. AGITEC AG) |
following. An overview of the different application examples is given in Table 3.

5.1. Aerogel blankets

5.1.1. "Müli Oberhallau", Oberhallau (Switzerland)

The old mill, built between 1608 and 1609, was refurbished extensively between 2007 and 2008. Until 1890, the mill near the village of Oberhallau in the canton of Schaffhausen had been operated with water and until 1995 the building was still used as a mill [40]. Apart from many other renovations, Spaceloft blankets were used in this first façade refurbishment with aerogel in Switzerland. The goal was to increase the interior surface temperature in order to avoid condensation on a cold wall and in order to improve the comfort in the rooms. Apart from the façade, new roofs, windows, plumbing, electricity and heating with an air heat pump were installed [40].

The walls of the building consist of 90 cm limestone quarry and had a U-value of about 1.7 W/(m² K) before the refurbishment (own calculation). The addition of two layers of 10 mm Spaceloft boards and of 30 mm of insulating render reduced the U-value down to about 0.48 W/(m² K) [24]. For this, a layer of render was first applied to the quarry construction. While this layer was still wet, the aerogel boards were installed and additionally fixed with plastic dowels. Embedded in a mesh, subsequently the insulating render and a finishing layer of render were applied (Fig. 4, bottom). The detail of the insulated wall is shown in Fig. 5.

This object is a good example of how the high insulation performance of aerogel allowed the refurbishment of a historic building while preserving its original character. This can be seen from the images before and after the renovation (Fig. 4 a, b). The comfort inside the building was brought to an appropriate standard while avoiding damage due to humidity. As alternative to the façade renovation with aerogel, an interior insulation was considered. This approach was risky though, with such a building, as it would have led to an inward shift of the dew point, potentially exposing the wooden ceiling beams to condensation.

The old mill now houses a museum and apartments.

5.1.2. MFH Fichtenstrasse, Zürich (Switzerland)

The multi-family house (MFH), built in 1877 in Zürich with solid stone and brick walls, is situated in a settlement that was erected between 1873 and 1889 and which is considered valuable in terms of the urban layout and in terms of cultural heritage [6,41]. Goal of the refurbishment in 2010 was a reduction of the energy use of the building and its CO₂-neutral operation, while maintaining its appearance. This was not possible with a conventional façade insulation. The scientific supervision of the project was supported by the Swiss Federal Office of Energy.

While the roof and the cellar ceiling were insulated conventionally with mineral wool, the walls were insulated from inside with 20 mm of expanded polystyrene and from outside with two layers of Spaceloft blankets of 10 mm each onto which a 20 mm layer of insulating render was applied (Fig. 6, c). The blankets were glued and additionally fixed with dowels that also hold the mesh for the render [41]. With these measures the U-value dropped from ca. 1.9 W/(m² K) (calculated) to 0.40 W/(m² K) (measured [6]). With this value it complies with the technical standard SIA380/1 for renovations of the Swiss Society of Engineers and Architects.
Fig. 4. The mill in Hallau, Switzerland, (a) before and (b) after the renovation. The works on the façade are shown in the bottom images (c–e). First, a base layer of render was applied (c), onto which the Spaceloft aerogel blankets were installed (d). The blankets were fixed with plastic dowels and covered with a mesh, onto which an insulating render and a render finish was applied (e).

Images: Max Schweizer AG Bülach.

5.1.3. Duncairn Centre for Culture and Arts, Belfast (Northern Ireland)

The disused Duncairn church in Antrim Road in Belfast, built between 1860 and 1862, was converted into a Centre for Culture and Arts which opened in 2014.

The former church is listed grade B+ by the NIEA, constituting an example of decorated Gothic style. For its conversion by Doherty Architects in Belfast, the goal for the roof was to maximise the energy efficiency without compromising the existing fabric, i.e. without risking dry or wet rot. After a dynamic hygrothermal...
simulation by Joseph Little of Building Life Consultancy Dublin, Envirolution Solutions installed a 20 mm Spaceloft insulation on the roof with certain intelligent vapour barriers (Fig. 7 a, b and Fig. 8). Through this, the U-value of the roof could be reduced from the uninsulated state with ca. 1.0 W/(m²·K) to ca. 0.56 W/(m²·K) (personal communication Doherty Architects Belfast), while keeping the original appearance of the building (Fig. 7 c, d). The conversion of the Duncairn church was awarded the “RICS NI Awards 2015: Winner in the Conservation Category” and the “RSUA Awards 2014: Commendation Conservation Category”.

5.2. Aerogel render

5.2.1. Mühle Sissach, Sissach (Switzerland)

Between 2012 and 2014, the former mill in Sissach, close to Basel, was renovated using aerogel render (Fig. 9). The first part of the mill was erected in the 14th century with several additions to follow, the last of which was constructed in the 17th century. The building is listed by the heritage protection of the canton Basel-Landschaft. Hence, the renovation – which was one of the first applications of the Fixit 222 aerogel render on a historic building – was conducted under close supervision of the heritage office.

This included tests of the render on small areas on the building. Additionally, it was required that the insulation would not lead to an increase in thickness with respect to the existing render [42].

The existing wall consisted of 600 to 700 mm of lime quarry, with an approximate U-value of 1.1 W/(m²·K). The existing render was neither of historic origin nor of compatible composition – it was based on Portland cement which has led to damage in other historic buildings. Hence, the existing render could be removed and could be substituted by the aerogel render, with a mean thickness of 50 mm, covering an area of roughly 440 m² (Fig. 10). The U-value after the renovation was calculated to be between 0.35–0.40 W/(m²·K) [45]. Additionally, the existing windows were replaced and the ceiling and the ceiling towards the attic were insulated with cellulose material. Through these measures, the energy consumption of the building was decreased by roughly 60% [42] and personal communication E. Franov, Carbotech AG.

The mill is divided into several flats currently housing 12 people. Temperature and humidity between the existing wall and the newly applied render was monitored by [45]. Using the gathered data combined with hygrothermal simulations, the authors found that there was no accumulation of humidity in the render, due to its vapour openness. Hence, also no deterioration or detachment of the render has occurred.

5.3. Aerogel boards

5.3.1. Manoir de Cormondrèche, Cormondrèche (Switzerland)

Built in 1554, the Manoir de Cormondrèche close to Neuchâtel was a grand house with 27 rooms. Inside, it features beautiful wall paintings from the time of its erection. With no change in the building since 1902, the building was in dire need for renovation. It is also under the heritage protection of the canton Neuchâtel. In 2014, extensive renovations were executed, with important works on the roof, the façade and the interior organisation [44]. The roof
Duncairn Centre for Culture and Arts in Belfast, Northern Ireland. The roof was insulated under strong space restrictions with Spaceloft aerogel blankets, keeping the original appearance of the building. (a) Aerogel blankets are visible under and between roof battens. (b) The roof is clad after insulation with the existing, historic slate. (c) View from outside and (d) inside after completion of the refurbishment. The thin insulation made it possible to maintain the subtle details and to keep the wooden soffit visible.

Images: (a, b): Aspen Aerogels, (c, d): Felix O’Hare & Co LTD.

was insulated, the interior was organised into five apartments and the façade was insulated with 20 mm of Heck AERO aerogel boards [43] (Fig. 11, a–d and Fig. 12). The heritage protection required a mineral render on the outside. Due to the wall paintings on the inside, an interior insulation was not possible (Fig. 11, e, f).

With the thermal insulation of the façade, the temperature of the walls could be increased, resulting in an increase of comfort inside the rooms as well as preventing condensation on the interior walls. This is important for the conservation of the wall paintings, which were also restored (Fig. 11).
5.4. Aerogel granulate for cavity walls

5.4.1. Multifamily house Biel (Switzerland) (not listed)

In this detached house in Biel in the canton of Bern built in the year 1926 (Fig. 13), the insulation of the perimeter walls was improved strongly in 2011 using aerogel granulate that was blown into the cavity of the double wall construction by the AGITEC AG. An air gap of 90 mm between the interior and the exterior brick wall was filled with Cabot aerogel granules, reducing the U-value of the wall (without thermal bridges) from 1.1 W/(m²·K) to 0.18 W/(m²·K) (personal communication AGITEC AG and [46]). With no other material such a strong improvement in thermal performance could have been achieved. For the filling, several holes were drilled into the outer façade, through which the cavity wall was filled with granulate with a dedicated blow-in machine.

5.5. Translucent panels

5.5.1. Alte Börse, Zürich (Switzerland)

The old stock exchange in Bleicherweg 5 in Zürich, built between 1928 and 1930, has been under heritage protection since 1992. The building was refurbished extensively in 2012. Some aspects of the refurbishment have received strong criticism, namely the interior refurbishment and some aspects of the design of the façade [47]. An interesting new solution, though, was found for the roof. The existing roof covering (Fig. 14a) was substituted with translucent aerogel elements, namely OKAGEL elements of OKALUX with a U-value of 0.6 W/(m²·K) (Fig. 12). Strong winds close to the lake of Zürich meant no exterior shading could be used on this roof, posing the challenge of overheating of the top floor in the summer with a standard glass roof. The translucent aerogel elements on the other hand provide a good thermal insulation for the cold season and let through enough visible light, providing glare-free illumination. But the overall solar gain is only 12%, the summer overheating is not an issue (Fig. 4).

6. Discussion & conclusion

The different, currently available aerogel materials of blankets, boards, renders, granules and translucent elements were presented and their physical properties have been discussed: low thermal conductivity, vapour diffusion openness, hydrophobicity and...
good fire ratings. From a theoretical standpoint, these properties make them appropriate materials for the application in historical buildings—in those cases where heritage protection allows the use of modern building materials and techniques at all. This has been vindicated in practice by the use in many building projects, examples of which were presented for each material type. These are impressive demonstrations of the improvement in thermal properties of the respective building envelopes with aerogel materials, as can be seen from the U-values before and after refurbishment (cf. Table 3, last two columns). It should be noted though that, unfortunately, these U-values were calculated and not measured. Hence, it would be desirable to see more refurbishment projects with monitoring in the future. In any case, aerogel materials could turn out to be a key for the reduction of energy consumption of old buildings.

Additionally, the presented projects demonstrate that contemporary comfort requirements can be achieved in historical buildings, allowing regular use as apartments or as public or commercial rooms. Because of the drastically improved thermal envelope, moisture problems due to condensation on cold building elements, which can give rise to mould and bacteria growth, can be avoided. This is especially important for historical buildings as the goal is to protect the historical building substance as well as possible. Furthermore, the thermal properties of a dry wall are better compared to a humid one. On the other hand, additional insulation can create moisture problems if it hinders vapour transmission through the building element. Internal thermal insulation can create risks for historic building substance, so use of this has to be considered carefully. Again, aerogel materials are favourable in this respect as they are vapour diffusion open, like many of the traditional building materials (brick, wood, lime plaster, lime mortar etc.). Of course, in the case of inside insulation, special attention has to be given to potential humidity issues.

Additionally, it should be noted that some of the presented refurbishments were realised already several years ago, in particular the old mill in Oberhallau and the multi-family house in Zürich’s Fichtenstrasse. To date, no problems with the aerogel solutions have been reported in these buildings. This is a positive indication for the durability of aerogel applications in historical buildings.

The potential of aerogel has also been confirmed in a study by Walker & Pavía, noting that “aerogel shows good potential for insulating historic structures as its thickness is almost half the other insulation materials, which should minimise the adverse visual impact of insulating historic structures.” [48].

A clear disadvantage of aerogels compared to other insulation materials is their high price, as can be seen in Table 1. Hence, if there are other technical solutions for a certain building requirement, as of now, these alternatives are preferable from an economic point of view. But in many cases, there are no other materials that can be used under the constraints of heritage protection, i.e. materials that allow for a thin, high performance thermal insulation, which is vapour diffusion open and can thus in many cases be applied without the risk of damages to the building structure. Additionally, it is to be expected that aerogel prices will drop significantly within the next few years due to improved production methods and the economy of scales with larger production volumes [20, 21, 25].

Cultural heritage buildings represent a wide spectrum of a historic/traditional material base – stones, bricks, wood, lime, mortar and other materials transformed into artistic and architectural details. Therefore is not possible to generalise advice for preservation. While decreasing energy demands using new material additions, heritage requirements should be met according to general heritage criteria and to the local heritage preservation policy.

New aerogel product types need to be assessed with respect to their possible benefits and downsides in heritage buildings. The appropriateness of the material needs to be assured according the material base of the heritage building and the existing historical values, reflecting local material differences, weather conditions and protection rules.

As the buildings presented in this article show, in many cases the heritage requirements can be met by aerogel materials. Thus, aerogel-based insulation represents an exciting new option to increase sustainability in the building stock by decreasing the
Fig. 11. The Manoir de Cormondrèche (a) before and (b) after the renovation in 2014. Both the façade and the roof were renovated. 20 mm of Heck AERO aerogel boards were used as exterior insulation in combination with a mineral render. (c) application of the aerogel boards and (d) the finished façade. (e, f) Interior of the Manoir de Cormondrèche after refurbishment. The original wall paintings made an interior insulation impossible.

Images: (a, c, d) AGITEC AG, (b, e, f) Jacqueline Mingard (http://www.jacquelinemingard.ch).
Fig. 12. Detail of a wall in the Manoir de Cormondrèche. The aerogel layer is marked in blue in the legend, the existing structure in grey font.

Fig. 13. House in Biel with a cavity wall that was filled with aerogel granulate. (a) blowing in of aerogel granulate and (b) house after refurbishment. Images: AGITEC AG. (c) Detail of cavity wall insulation with aerogel granules as implemented in the house in Biel.
energy demand of heritage buildings where the protection of appearance is required.

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