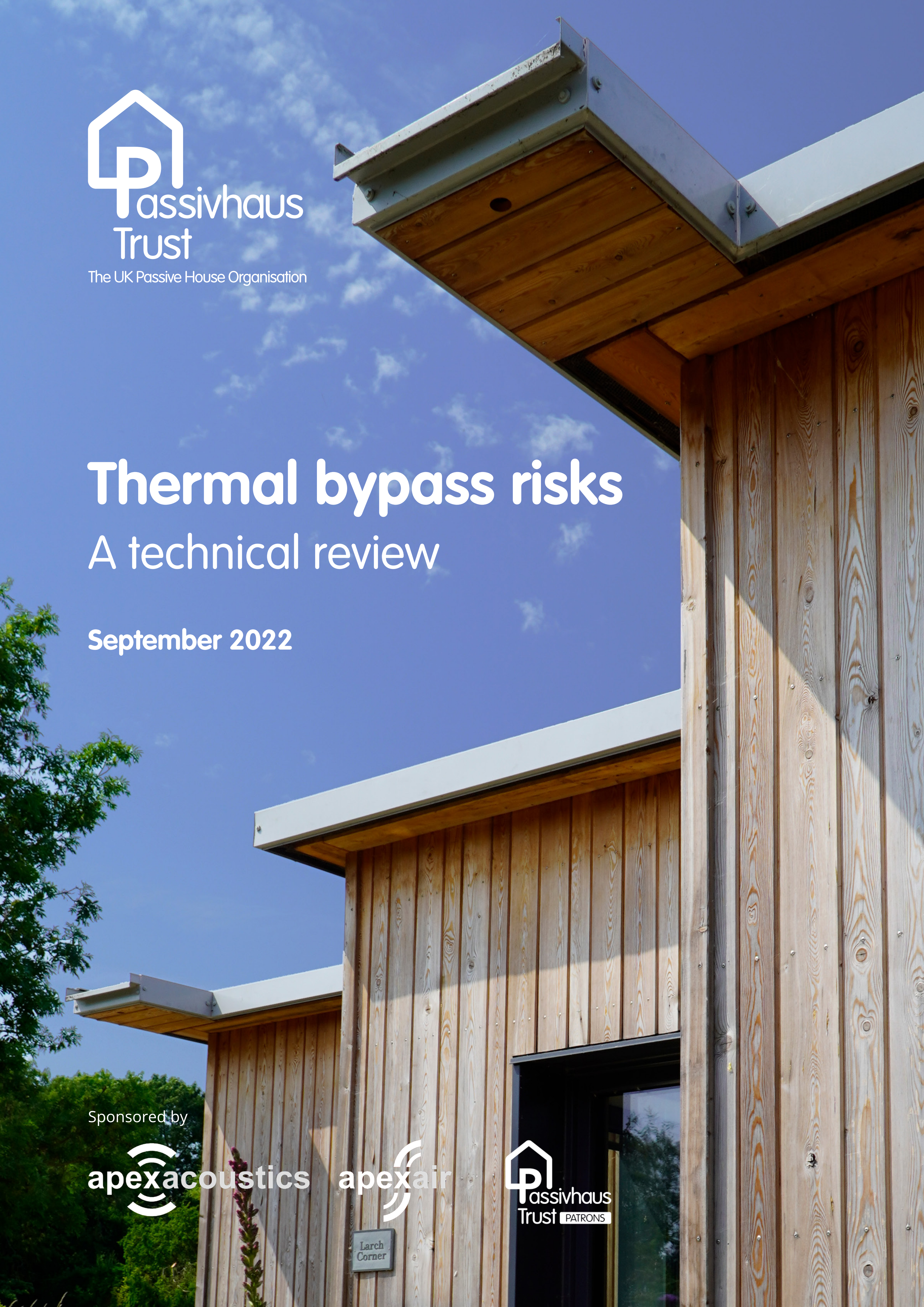
Passivhaus Trust
The UK Passive House Organisation

Thermal bypass risks

A technical review

September 2022



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HOW TO USE THIS GUIDE

This technical guide has a number of uses:

1. It avoids duplication and fragmentation of thermal bypass related considerations that may otherwise arise when developing other technical documents.

2. It provides a single point of reference for technical working groups and therefore allows supplementary guidance to be developed which conforms to the performance criteria identified in this document.

3. It provides a sound evidence base and a common point of reference for designers and certifiers alike, thereby allowing building design and certification to be implemented in a fair and consistent manner.

To fulfil these uses this guide makes extensive reference to peer-reviewed papers and then, at the end of each section, identifies the practical implications and consequences which arise. It is the practical implications which are most useful for busy practitioners - look out for the outlined boxes throughout.

HELP THIS TECHNICAL GUIDE BECOME EVEN MORE USEFUL

Whilst every effort has been made to make this technical guide as robust as possible it should only be considered a snapshot of current knowledge. If you are aware of evidence-based literature which could expand, improve, or refine this guide, your support would be appreciated.

To help this technical guide become even more useful, please confirm the Author(s), Publication date, Title of paper, Title of publication, and (ideally) provide a copy of the paper. If the paper is available online, please include a link to where the paper can be found and the date it was last accessed.

Help this guide improve - email evidence-based literature on thermal bypass to **info@passivhaustrust.org.uk**

SECTION 1:

An introduction to thermal bypass

INTRODUCTION

The need to reduce carbon emissions in order to reduce the impact of climate breakdown is well understood (IPCC, 2018). Furthermore, Parliament has declared a climate emergency and, relative to 1990 carbon emissions, the UK Government is committed to reducing emissions by 100% by 2050 (Gov, 2008). Any failure to deliver a meaningful reduction in carbon emissions is therefore a failure to address the needs of future generations.

> *"[The IPCC] report is a code red for humanity. The alarm bells are deafening, and the evidence is irrefutable: greenhouse-gas emissions from fossil-fuel burning and deforestation are choking our planet and putting billions of people at immediate risk."*
>
> **António Guterres,**
> UN Secretary-General

Founded upon sound physics, buildings built to the Passivhaus standard (PHI, 2022) have been demonstrated to perform reliably. For instance, following a robust and comprehensive review of published coheating test data, thermography results and in-situ U-value measurements, Johnston et al. (2020) found that, unlike dwellings designed and constructed to industry norms, new UK dwellings which reached Passivhaus standard consistently demonstrated higher congruity between the design and as-built performance. Furthermore, when remarking upon international data considering the space heating energy demand of more than 2000 new Passivhaus dwellings and nearly 300 retrofitted dwellings which feature Passivhaus components, Johnston et al. observed that “there is no noteworthy ‘performance gap’ for this sample.”

However, what is described above is far from the norm. There is increasing recognition of the energy performance gap (Doran, 2000; Doran, 2005; Doran, 2008; ZCH, 2014; Johnston, Farmer, Brooke-Peat, Miles-Shenton, 2014; Johnston, Miles-Shenton and Farmer, 2015; Gupta and Kotopouleas, 2018).

One of the major contributors to the energy performance gap is faulty, ill-considered design and construction that can result in a thermal bypass. A thermal bypass has been defined as heat loss that bypasses the thermal insulation layer between two areas of the construction. This is caused by a combination of conductive and radiative heat loss mechanisms which result in uncontrolled air movement (Beyea et al. 1978; Socolow 1978; Socolow et al. 1979, Harrje et al. 1979a; Harrje et al. 1979b; Harrje et al. 1985).

In 2012 the British Board of Agrément (BBA), one of the UK’s leading certification bodies, published a report on the detrimental impact of air movement in pitched roofs. It showed that thermal bypasses detrimentally increased U-values by up to 80%. Interestingly Roels and Langmans (2016) observe that “most striking in this study are not the obtained results as such – similar results have been reported in previous studies, but the fact that the pitched roof constructions tested are considered as standard building practice.” This observation, made by internationally respected researchers and building physicists, clearly suggests there is something wrong with current UK construction methods.

The family of mechanisms which circumvent conductive and radiant heat transfer are collectively known as thermal bypasses. In a practical sense all types of thermal bypasses involve the convection of a fluid, and because a fluid is any substance that flows, in this case it means air. As such, by addressing thermal bypasses, heat loss can be reduced, thermal comfort can be improved, the building fabric can be protected, performance gaps can be mitigated against or avoided, carbon emissions and fuel poverty can be reduced, and health, well-being and energy security can be improved.

Whilst recognising the importance of these multifaceted aspects of thermal bypasses, and with a focus upon delivering successful high performance, low energy and Passivhaus buildings, the aims of this guide are to:

1. Introduce terminology, create shared contextualised understanding, and establish common points of reference.

2. Use an evidence-based approach to identify appropriate performance thresholds and criteria.

3. Provide practical guidance which can be implemented by designers and constructors.

In order to fulfil our professional duties to clients and to ensure the building's optimal performance, unacceptable performance gaps must be avoided. For this to be achieved, it is important that designers and certifiers share a common understanding, have common expectations and work to the same performance standards.

This review is focused on matters relating to the thermal performance of buildings and does not remove the need for designers and constructors to consider buildings as a system. This means matters such as ventilation, all forms of moisture transfer, heating and cooling etc. also require consideration.

Types of thermal bypass

In principle there are two types of thermal bypasses: closed loop and open loop (Harrje, 1985).

Conceptually, a closed loop thermal bypass takes place within a closed cavity. In such cases heat is transferred from warm regions to colder regions via the convection caused by warm air rising and cold air falling. The purest example would be the cavity in a double-glazed unit, but in this paper we are using the example of air movement around insulation (Figure 1a).

The other concept that needs to be considered is an open loop thermal bypass, which occurs when air moves through, in or out of a structure, say a wall. A typical example of this would be wind (forced convection) which is driven through the wind barrier and then across, into and behind the insulation, but not through the air barrier – a phenomenon known as wind washing (Figure 1b).

Another, perhaps more familiar, example of open loop bypass occurs when that same body of air continues on its journey, passes deeper into the wall, and finally through the air barrier – bringing cold air into the heated space. This is described as infiltration. The process where warm air exits the building envelope (the process of exfiltration) is also a form of open loop bypass (Figure 1c).

In practice all these phenomena act upon a building and influence its thermal performance (Figure 1d).

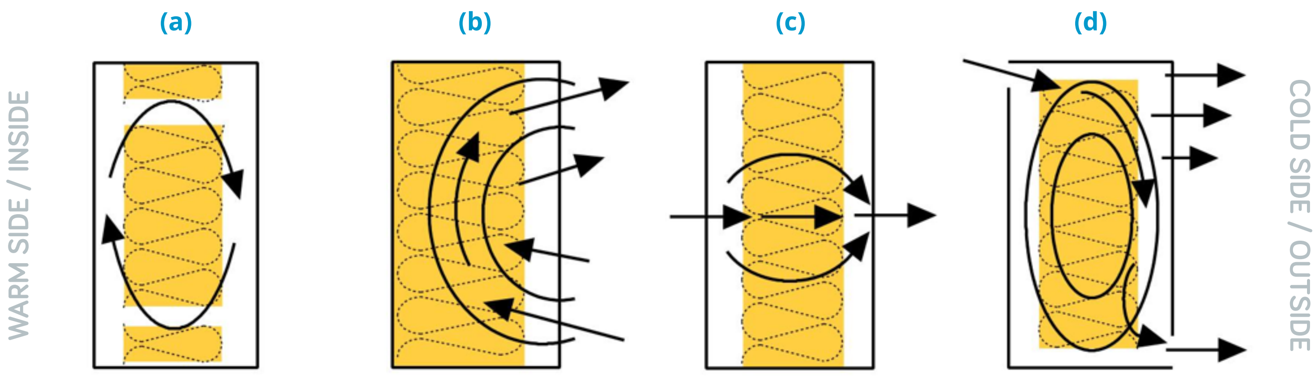


Figure 1: *Types of thermal bypass:*
(a) *closed loop*
(b) *open loop: wind washing*
(c) *open loop: air leakage (infiltration or exfiltration)*
(d) *reality*

Some terms of reference

AIR GAPS

Air gaps can exist in any number of locations. Some are intentional, others are not. In this context it is valuable to define different types of air gap. For the purposes of this document the following definitions apply, and are illustrated in Figure 2:

AIR GAP
An air gap located on the warm side of the insulation

JOINT
An interface/abutment between two pieces of insulation

CAVITY
Located on the cold side of the insulation, a cavity inhibits rainwater penetration into the building envelope by providing a capillary break, enabling pressure equalisation and allowing drainage

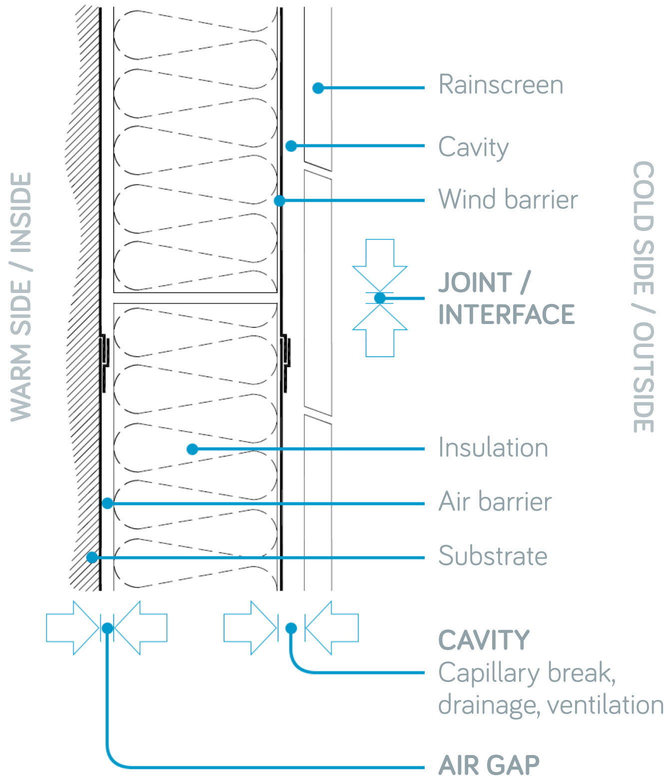


Figure 2: *Partial section through wall construction*

VAPOUR RETARDER

Diffusion is a process by which water vapour migrates through a material. The principal function of a vapour retarder is to inhibit the passage of moisture as it diffuses through the assembly of materials in a wall (Quirouette, 1985). By definition diffusion is only one mechanism by which water vapour can be transported into a wall or roof, therefore, a vapour retarder only addresses one moisture transfer mechanism. Quirouette observes, contrary to popular belief, that unsealed laps, joints, pin holes etc. do not lead to an appreciable increase in the rate of diffusion.

AIR BARRIER SYSTEM

Air leakage, as a means for transporting water vapour, is considered a more significant mechanism than diffusion (Quirouette, 1985). In this context unsealed laps, joints, holes etc. do lead to an appreciable increase in the rate of heat and moisture transfer. Air movement is driven by pressure difference. This difference may be caused by natural convection (stack effect) or forced convection (wind or mechanical systems). The principal function of an air barrier system is to inhibit the passage of moisture.

An air barrier system and a vapour retarder can be combined to create an air barrier/vapour retarder system. A functional air barrier/vapour retarder is particularly important in high humidity buildings such as data centres, museums, archives, hospitals, and swimming pools. A successful air barrier/vapour retarder system is placed on, or at an interstitial location near, the warm side of the insulation - which is normally the side with the highest vapour pressure.

Within this document the generic term for an air barrier system is “air barrier”.

WIND BARRIER SYSTEM

The purpose of a wind barrier system is to inhibit pressure differences which drive air movement across, through or behind thermal insulation. Stack effect, the wind and mechanical systems drive this air movement. Unsealed joints in the wind barrier lead to an appreciable increase in the rate of heat transfer and can change the internal surface temperature causing discomfort and mould. To reduce the risk of interstitial condensation the wind barrier system must allow sufficient diffusion. This means the vapour permeability of the wind barrier is interrelated to the air permeability and the vapour permeability of the air barrier/vapour retarder system. A wind barrier system may also assist with preventing the ingress rainwater.

Within this document the generic term for a wind barrier system is "wind barrier."

AIR LEAKAGE

Air leakage is typically expressed in one of two ways:

1. **As air changes per hour (ACH)** i.e. the number of times an hour that all of the air inside the building is replaced with external air, *or*

2. **As a permeability ($m^3/h.m^2$)** i.e. meters cubed per hour, per meter square of surface area (as adopted by Building Regulations in England and Wales, and Building Standards in Scotland).

It is also standard practice for air leakage to be stated at a reference pressure difference of 50 Pascals (50 Pa). These reference pressures may be stated as a positive, a negative pressure or as an average. Whilst the average is a more representative reflection of a building's condition, it is common for pressure differences to be stated as a positive pressure. Therefore, unless otherwise stated, this document refers to air changes per hour (ACH @ 50 Pa) and permeability ($m^3/h.m^2$ @ 50 Pa). Where air changes per hour or permeability is stated but not suffixed with '@ 50 Pa', it is the air leakage which occurs under natural conditions.

Performance criteria

On the understanding that thermal bypasses cannot be prevented in absolute terms, it becomes necessary to introduce a justifiable range of tolerance. When considering the impact of convection, and accounting for measurement uncertainty, Dyrbøl, Svendsen & Elmroth (2002) consider an increase in the total heat flow of more than 3% to be significant. This guidance follows the intent of research by Uvsløkk (1996a) and Ojanen (1993) that led Norway to adopt a standard which limits the effect of air movement to 5% of the reference U-value.

The methodology adopted for this paper reflects this approach and draws upon an evidence base to establish practical tolerances and appropriate criteria.

A note for the global audience

The papers presented in this review are dominated by research undertaken in latitudes north of 50 degrees (notably Brussels, Canada, Norway, Sweden, United Kingdom etc.) As such this document is ideally suited to heating climates. Whilst all concepts relating to heat transfer and thermal performance remain true for all regions, the reader should also consider cultural and climate specific matters, particularly concerning or affected by moisture, and especially when implementing aspects of this report on their own building project.

SECTION 2:

Convective loops in wall constructions

Air gaps on the warm side of insulation

Research examining various construction technologies allows us to draw certain generalised conclusions about the impact of thermal bypasses on building performance.

Using the example of deficient workmanship, which leads to a continuous air gap between the insulation and the substrate and an open joint leading to the outside at the top and bottom, Hens and Carmeliet (2002) demonstrated that the heat loss from a wind washed wall, with a 4 Pa pressure difference between top and bottom[1] and a design U-value of 0.21 W/m².K, will be increased by an order of magnitude. The size of the air gap behind the insulation has a decisive and dramatic impact upon the thermal performance:

- 2 mm gap = 12% increase in heat loss
- 7.5 mm gap = 203% increase in heat loss
- 15 mm gap = 520% increase in heat loss

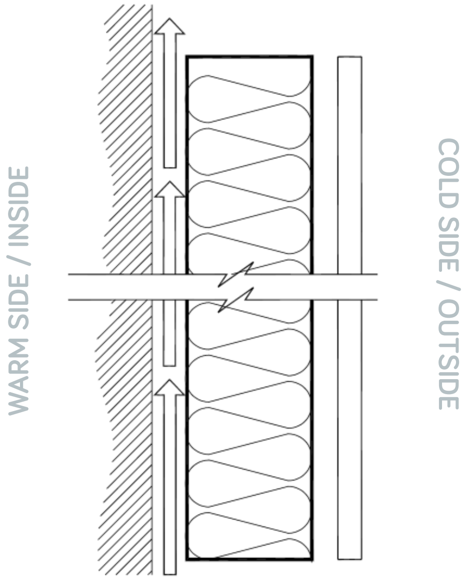


Figure 3: *An air gap behind the insulation has a decisive and dramatic impact upon the thermal performance*

But what happens when the U-value is reduced? Though this is pending further research[2], Table 1 below demonstrates how, as notional U-values diminish and air gaps increase, the proportion of heat loss attributable to thermal bypass increases dramatically:

Width of air gap	Notional U-value (W/m².K)	Thermal bypass (W/m².K)	Effective U-value (W/m².K)	Proportional increase
2mm	*0.210**	0.025	0.235	***12%****
	0.150	0.025	0.175	**17%**
	0.100	0.025	0.125	**25%**
7.5mm	*0.210**	0.216	0.426	***203%****
	0.150	0.216	0.366	**244%**
	0.100	0.216	0.316	**316%**
15mm	*0.210**	0.882	1.092	***520%****
	0.150	0.882	1.032	**688%**
	0.100	0.882	0.982	**982%**

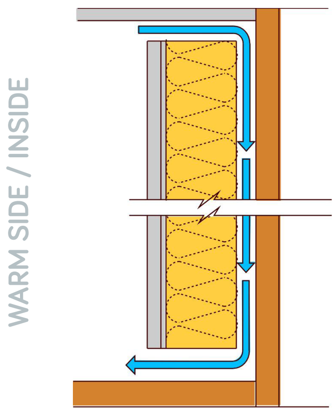
Table 1: *Extrapolated heat losses for various U-values, based on Hens and Carmeliet (2001) (*original data shown in italics)*

1 A pressure of 4 Pa is generally accepted as the reference value which characterises the driving pressure of wind-induced infiltration (Modera et al., 1992). 1 Pa of pressure is roughly equal to 100 g/m². (Good quality printer paper weighs 100 g/m².)

2 The author's calculations presented in Table 1 are based on simplified calculations extrapolated from available data. However, it is noted that as the insulation becomes thicker, the depth of a joint (from front to back of the insulation) also becomes longer. Therefore, for a given joint width, as the joint depth increases, friction will also increase, which will in turn lead to a pressure drop. The significance of this pressure drop and its impact on thermal bypass remains to be understood. For this reason, the figures should be considered illustrative rather than factual.

A similar trend has also been observed for internal insulation (Figure 4) where heat flow caused by natural convection, driven by density differences between cold and warm air, was dominated by forced convection (wind-induced losses) and was, in the worst case, 2.5 times higher than the 0.5 W/m².K U-value suggested by one-dimensional predictions (Hens, 1998). A 2 mm wide joint leads to a sharp rise in air flow and consequently heat loss.

Complementary observations are made in other research such as Bankvall (1978a), Berlad et al.(1979), Yarbrough & Toor (1983), Harrje (1985), Dutt (1985), Lecompte (1990), Uvsløkk et al. (1996b), Hens (1998), Hens (2002) and Hens et al. (2007). Figures 5a, 5b and 5c illustrate some of the mechanisms that have been found.



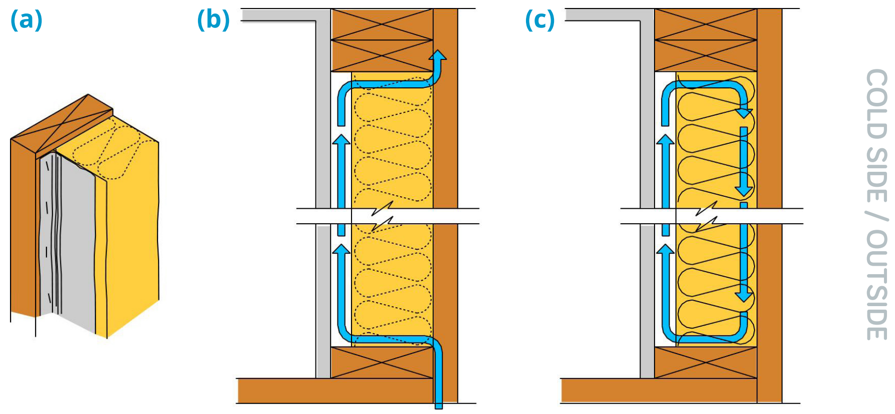


Figure 4: *Internal wall insulation*

Figure 5a-c: *Air gaps on the warm side support wind washing & closed loop bypass (after Harrje, Dutt, Gadsby, 1985a; Dutt & Nisson, 1985; & reflecting Uvsløkk, 1996a)*

Cavity wall masonry

Visual inspection of partial-fill cavities during construction found that some materials, such as mineral wool, can accommodate rough, uneven surfaces to some extent, whereas semi-rigid materials (such as foam insulation) are frequently poorly fitted against such surfaces (Doran & Carr, 2008). Doran & Carr also found that the difference between the measured U-value and predicted U-value of partially filled cavity walls was approximately 0.10 W/m².K.

Five wall constructions were simultaneously tested by Hens et al. (2006). Three were partial-fill cavity walls and two full-fill cavity walls. Although both partial-fill walls and one full-fill wall failed to deliver the intended thermal resistance, the performance gap for the full-fill wall was much less i.e. a mean of 3% rather than 19%.

Miles-Shenton, Gorse and Thomas (2015) provide a literature review and discuss their own research involving partial-fill cavity walls and observe that "the vast majority of site observations made by the Leeds Beckett research team show problems with partial fill, some of which are so common they could be described as typical installation, others are less common but may have more severe consequences than just unplanned additional heat loss."

Partial-fill cavity walls, classified as hard-to-treat by Iwaszkiewicz (2010), may benefit from top-up insulation. However, it is not without risk as newly-installed insulation could lead to increased damp penetration. Following the addition of 'top-up' blown fibre insulation within the residual cavity Wingfield & Miles-Shenton (2011) report that the measured U-value fell from 0.46 W/m².K to 0.28 W/m².K. More recently, when commenting upon this research, Miles-Shenton, Gorse and Thomas (2015) observe that the benefits of retrofitting blown fibre 'top-up' insulation to walls with partial fill insulated cavities was 10 and 20 times more effective than calculations suggested because the blown-fibre also prevented thermal bypass around the partial fill insulation board. This highlights the importance of addressing thermal bypass before it becomes an expensive problem requiring remediation.

Owing to outstanding moisture tolerance, the reduced risk of wind washing and good sound insulation, Hens et al. (2007) recommend fully-filled unvented cavity wall construction. They also note that "the correct built-up sequence is first the inside leaf, including all trays, then fixing the fill and finally brick-laying or glueing the brick or block veneer. Such a sequence demands the use of outside scaffolding."

PRACTICAL IMPLICATIONS

Evidently, with respect to limiting the effect of air movement to less than 5% of the reference U-value, the lower (better) the design U-value, the greater the need to design, specify and install insulation systems in a manner that eliminates air gaps on the warm side of the insulation. Continuous air gaps adjacent to the warm side of the insulation should not be tolerated.

With regard to retrofit, initial research by Wingfield & Miles-Shenton (2011) suggests that it is both possible and beneficial to install blown-in insulation into partial-fill cavity walls. However, available literature does not yet appear to have considered the moisture risks associated with such work.

Buildability: Design, specification, the installation process and sequencing

Workmanship is often cited as the most determining factor affecting thermal performance — two examples being Timusk, Seskus and Ary (1991), and Hens, Janssens and Depraetere (2001). Lecompte (1990) stresses that problematic thermal performance was not a result of the insulation materials themselves but the workmanship. Hens et al. (2007) go on to state an understanding that “bad workmanship refers to open joints left between the insulation boards in combination with an air layer behind the fill, while good workmanship refers to care in mounting, leaving no open joints and no air layer behind.”

Schuyler & Solvason (1983) recognise that “convective air flow within the wall cavity, however, does not receive sufficient attention at the design stage.” This is a conclusion the author and reviewers of this report fully support. As such we recognise that poorly designed construction details, poorly considered materials and products specifications and a failure to consider buildability all strongly contribute to instances of ‘poor workmanship’.

Because compressible insulation can accommodate irregular and uneven surfaces more readily than rigid (foam) insulation boards, fibrous materials (and fibrous backed materials) such as glass wool and mineral wool are strongly preferable (Hens et al., 2007). Exposed mineral wool insulation can be more susceptible to wind washing, a subject that is discussed further in Section 3: Wind washing and the permeance of surfaces.

When undertaking research into wind barriers, Uvsløkk (1996a) used mineral wool (31.9 kg/m³) and glass wool (21 kg/m³). The research highlighted the impact of wind induced air movement through joints, around and behind the insulation (as Figure 4 above).

Uvsløkk observed that when insulation is mounted toward the wind barrier, there can be a gap between the insulation layer and the air barrier/substrate. Air in this gap will be heated and any convection which arises will result in higher heat loss compared to the gap being packed with insulation. When insulation is mounted from the exterior side toward the air barrier/substrate this gap can be avoided, and the risk of air movement can be significantly reduced (Figure 6). Though it did not prevent wind washing, Uvsløkk’s measurements suggested that installing insulation toward the air barrier reduced heat loss by two thirds (i.e. by a factor of 3.5).

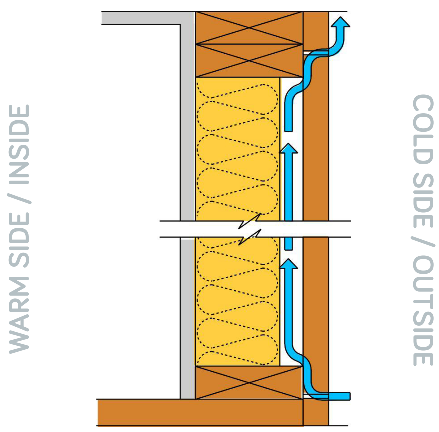


Figure 6: *Insulation installed toward air barrier reduces extent of thermal bypass*

Within a sample of 29 timber-frame dwellings, Doran (2000) observed a close agreement between measured and calculated U-values and theorised that it was because the insulation that was placed between the studs was thicker than the studs themselves, which caused the insulation to become lightly compressed. Through the understanding developed in this paper, it would appear that this over-stuffing between studs inhibits the potential for convection and subsequently inhibits thermal bypasses. Furthermore, given the success of slightly over-stuffing the void between the air barrier and wind barrier, it should not be entirely surprising to find that a Passivhaus project at Kronsberg employed a method requiring 10-15 mm over-stuff for a 300 mm thickness (i.e. approximately 3 to 5% over-stuff) which helped to ensure a lightly compressed insulation quilt (Feist, 2005).

Figure 7 below describes a range of conditions and the nature of their impact upon thermal performance.

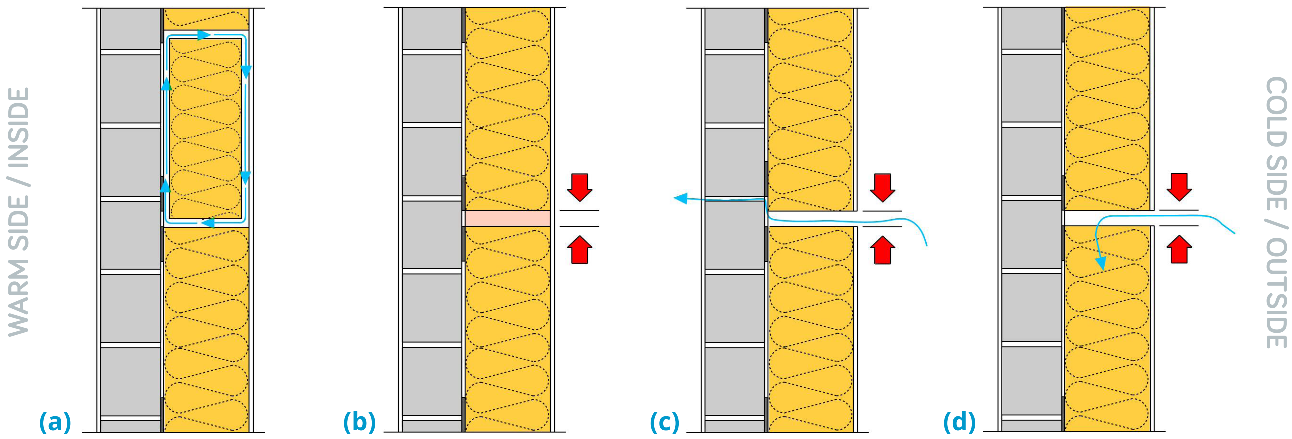


Figure 7: *Impact on thermal performance of a range of conditions:*
(a) *Communicating cavities considerably increase convection thus rendering the insulation ineffective*
(b) *Cavities are windtight and airtight but insulation is missing*
(c) *A joint is open on both sides of the wall permitting airflow through the wall*
(d) *Insulation gaps are open on one side only*

Lecompte (1990) suggests a number of concepts that would inhibit thermal bypass (Figure 8). However, the practical consequences of these options warrant further commentary. It is therefore worth noting that:

- Elimination is an absolute term i.e. no air gap (0 mm).
- Option (c) requires a seal around the full perimeter of the insulation and does not address the risk of air permeability (Figure 7c above) or wind washing (Figure 7d). Option (d) requires the air gap to be unvented i.e. the top, bottom and sides of the air gap to be closed.
- Option (d) is considered high risk and prone to failure. Therefore in light of other evidence provided in this paper, whilst the diagram infers open joints, this is considered to be for illustrative purposes only.

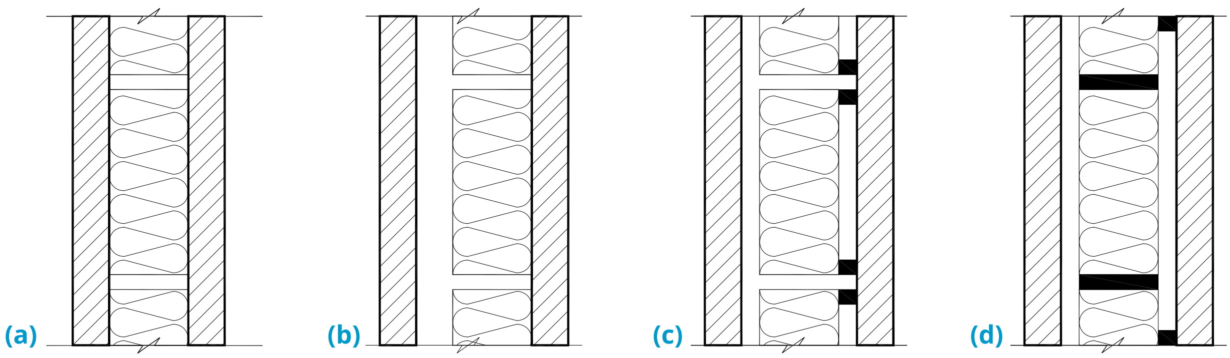


Figure 8: *Conception options for avoiding thermal bypass behind the insulation:*
(a) *Eliminate both cavities*
(b) *Eliminate one cavity*
(c) *Seal a cavity*
(d) *Seal all joints (adapted from Lecompte, 1990)*

PRACTICAL IMPLICATIONS

It should not be assumed that insulation will adapt to the shape of protrusions and obstructions. To prevent air flow, insulation should be placed in contact with a substrate that supports or forms the air barrier and where possible insulation should be encapsulated between the air barrier and the wind barrier (Figure 9). To achieve this:

1. Where practical an installation method requiring 10-15 mm over-stuff for a 300 mm thickness (i.e. approximately 3 to 5% over-stuff) provides a lightly compressed insulation quilt which serves to reduce the risk of thermal bypass
2. Special attention should be paid to protrusions (such as mortar “snots” and debris), ties, hangers, etc.
3. It is highly preferable that insulation is either blown into the cavity or, where this is not possible, it is installed toward the air barrier/warm side and provides a 10-15 mm over-stuff so that the insulation remains firmly in contact with the air barrier.

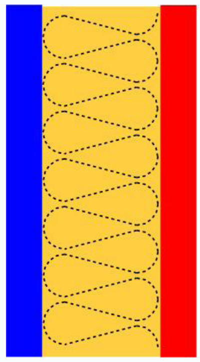


Figure 9:
Encapsulation -
blue = wind barrier
red = air barrier
yellow = insulation

Experience shows that as the insulation thickness increases relative to its length, flexibility reduces. Where short lengths of insulation or thick insulation is to be used, to avoid air gaps arising on the warm side, it becomes increasingly important to consider the flatness and regularity of the substrate. This subject is discussed in greater detail below.

Workmanship: Blown fibre insulation

Discussing cellulose insulation, Bomberg & Solvason (1980a) note that the thermal resistance is basically a function of its thickness and density. The same is true for other types of blown fibre insulation. Bomberg & Solvason identify many variables which influence the density of blown insulation (more than are appropriate to discuss here).

This means specifying the thickness of the insulation alone does not ensure that the thermal resistance will be achieved. Similarly, installing blown fibre at a higher density than specified will mean the thickness of the insulation is reduced. In both cases Bomberg & Solvason (1980a, 1980b) observe that the thermal performance will be inhibited. When specifying blown fibre insulation it is therefore imperative to specify the thickness, the density and workmanship clauses which will ensure suitable quality standards are achieved.

Concerns about slump arise when considering the installation of blown fibre insulation within walls. For cellulose insulation, Rasmussen (2003) demonstrated that the density required to prevent settlement is determined by changes in relative humidity, and therefore the actual climate which the insulation will be exposed to. With this acknowledged, for a thickness of up to 300 mm, it would appear that practically no settlement occurs within blown cellulose insulation once the density is in the range of 71 to 73 kg/m^3 (Bomberg & Solvason, 1980b; Rasmussen, 2003).

PRACTICAL IMPLICATIONS

For quality assurance purposes proof/certification is to be provided demonstrating that the installer is accredited to install the specified blown fibre insulation. Furthermore, to confirm that the required thermal performance has been installed, the contractor shall confirm the average installed thickness of the insulation and the number of bags of insulation that have been installed and the weight of the bags supplied by the manufacturer.

The installed thickness shall not be less than that required by the specification, and the number of bags installed shall not be less than the minimum number calculated prior to the order being placed. However, if the as-installed density is less than was specified, the installed insulation thickness will need to be greater than that specified in order to achieve the same level of thermal performance. For lofts and attics, thickness indicators should be installed prior to installation.

Workmanship: Flatness and surface regularity

Uneven and irregular surfaces can cause air gaps on the warm side (mortar “snots” and debris being one striking example). Furthermore, planar surfaces, such as walls, are rarely absolutely flat which means the convex and concave surfaces which result cause joints to fan open or closed respectively. The result is sometimes referred to as ‘birds mouthing’ and occurs with increased frequency at abutting joints and interfaces when installing insulation that is more than 50 to 75 mm thick. These continuous open joints support thermal bypass mechanisms and should be avoided. Joints should therefore be pointed with a complimentary material. For example, joints in foam insulation should be pointed with expanding foam, and joints in mineral wool insulation should be packed with mineral wool. To avoid birds mouthing it is necessary to address the flatness and regularity of the substrate.

Flatness

The surface regularity and conformity that is necessary to avoid air gaps, and consequently thermal bypass, will be informed by the flexibility and compressibility of the insulation and the pressure that can be exerted by the fixings upon that insulation. In this case a suitable insulation will be able to accommodate irregular surfaces which are not flat (Figure 10).

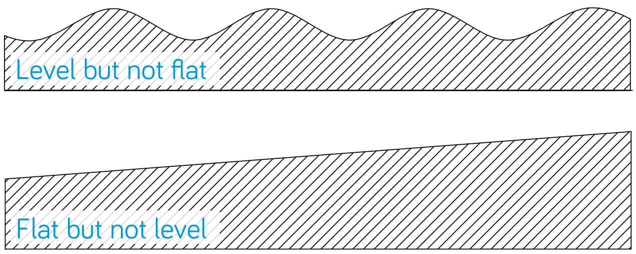


Figure 10: *The difference between flatness and levelness*

Surface regularity

Where insulation is not able to accommodate minor surface irregularities, perhaps due to a lack of flexibility, insufficient fixing pressure or the surface being insufficiently flat, there are essentially two options:

1. Adhesive can be applied to the warm side of the insulation (refer to option (c) in Figure 8 above). This should be done as a continuous band around the perimeter. Additionally a mesh of adhesive could be applied within the central area (creating small, unvented, air pockets). This type of technique is commonly used when installing external wall insulation.
2. In circumstances where insulation is inflexible and adhesive can not be applied, it would be appropriate to specify the flatness of the substrate in order to limit the bumpiness. This conceptual approach required here has been used to ensure the conformity of walls and floors for many years. In essence flatness relates to variations over short distances, whereas verticality, straightness and level refer to larger distances. By defining appropriate tolerances and then undertaking measures that will ensure conformity, it is possible to provide surface regularity (Figure 10).

PRACTICAL IMPLICATIONS

When considering the installation of insulation, specifications should consider the flexibility of the insulation, the pressure imposed by the fixings, the flatness and regularity of the substrate and the as-built conformity of the construction.

Where a rigid insulation of the requisite thickness has been shown to flex, say, 3 mm over a 2 m length, a specification seeking sufficiently uniform surface would read:

- **Surface regularity:** The maximum permissible departure from a 2 m straight-edge resting in contact with the substrate shall be +/- 1.5mm.

- **Conformity:** The straight edge is used to check in two directions with each check having minimum overlap of 1 m. For more information about accuracy and tolerance in design and construction refer to BS 5606:2022.

It would appear that further research is required to understand the relationship between the material properties of insulation (as relating to flexibility, compressibility and thickness), the fixings used to support/restrain them (compression), the flatness and regularity of various substrates (particularly at joints) and the impact of thermal bypass mechanisms.

Workmanship: Joints and interfaces (tuck ends)

When installing friction fit insulation, tuck-ends, arising from poor workmanship, can occur at the interface between the insulation and the stud (Figures 11 and 12). These defects have been shown to increase heat loss. Brown et al. (1993) found that for a U-value of ~0.3 W/m².K at -5°C (25°C delta-T), mineral wool insulation with a density of 35.1 kg/m³ performed as expected when there were no defects but suffered a 2% increase in heat loss when tuck-ends constituted a 3% defect (for reference, when the frame spacing is 500 mm, a gap of 3% would mean a full depth gap with a total width of 15 mm i.e. 7.5 mm each side). Under the same conditions, mineral wool insulation with a density of 13.7 kg/m³ demonstrated a 2% increase in heat loss. Heat loss increased by 5% with lower density mineral wool (9.0 kg/m³).

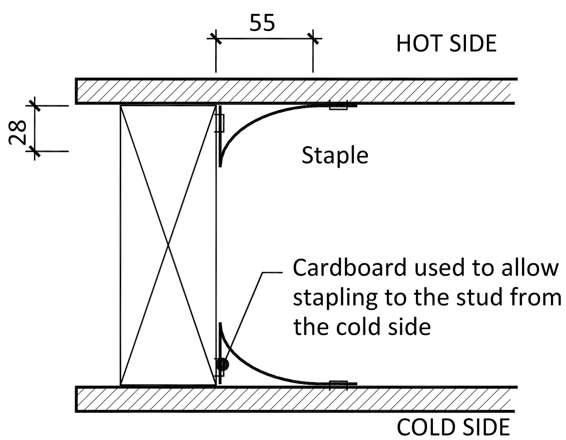


Figure 11: *6% tuck-end installation defect, (after Brown et al. 1993)*

Figure 12: *Sample panel showing a real tuck-end*

Though this is pending further research[3], Tables 2a and 2b below illustrate that as U-values are reduced, the order of magnitude of the heat loss can be expected to increase.

Insulation with a density of 13.7 or 35.1 kg/m³				
Tuck-end defect	Notional U-value (W/m².K)	Thermal bypass (W/m².K)	Effective U-value (W/m².K)	Proportional increase
3%	*0.300**	0.006	0.306	***2%****
	0.150	0.006	0.156	**4%**
	0.100	0.006	0.106	**6%**

Table 2a: *Extrapolated heat losses for various U-values, based on Brown, Bomberg, Ullett, Rasmussen (1993) (*original data shown in italics)*

Insulation with a density of 9.0 kg/m³				
Tuck-end defect	Notional U-value (W/m².K)	Thermal bypass (W/m².K)	Effective U-value (W/m².K)	Proportional increase
3%	*0.300**	0.015	0.315	***5%****
	0.150	0.015	0.165	**10%**
	0.100	0.015	0.115	**15%**

Table 2b: *Extrapolated heat losses for various U-values, based on Brown, Bomberg, Ullett, Rasmussen (1993) (*original data shown in italics)*

PRACTICAL IMPLICATIONS

The lower the design U-value the greater the impact that thermal bypasses can have on the as-built U-value, therefore with better (lower) design U-values, better installation is required to meet the 5% tolerance. So that the impact of air movement is limited to 5% of the reference U-value, mineral wool insulation should have a density greater than 13.7 kg/m³ and good workmanship should limit defects to less than 3%. Refer to Section 8: Site inspections and visual assessment for further information.

3 The author's calculations presented in Tables 2a and 2b are based on simplified calculations extrapolated from available data. However, it is noted that as the insulation becomes thicker, the depth of a joint (from front to back of the insulation) also becomes longer. Therefore, for a given joint width, as the joint depth increases friction will also increase, which will in turn lead to a pressure drop. The significance of this pressure drop and its impact on thermal bypass remains to be understood. For this reason, the figures should be considered illustrative rather than factual.

Workmanship: Joints and interfaces (general)

Roofs with horizontal insulation

Threthowen (1991) examined the impact of vertical air gaps (such as those between joints/abutments) at ceiling level. Threthowen established that, when rigid ceiling insulation was placed over a 47 mm batten and the width of the vertical joint was varied, joints which were less than 3 mm had a marginal impact upon the measured resistance. However, the resistance was significantly reduced when air gaps were 4mm or greater.

Walls with vertical insulation

Deconstruction analysis by Wingfield & Miles-Shenton (2011) examined a masonry cavity wall insulated with foam board and found as-built joint widths ranging from 3 mm to 4 mm. Discrepancies between predicted and measured U-values led the researchers to suggest that air movement gave rise to open and closed loop thermal bypass.

In Belgium 21 site visits were conducted and width of the air gap on the warm side of the insulation was inspected (Langmans et al. 2017). The average vertical air gap was 2.5 mm whilst the horizontal air gap was 2.2 mm. In a further 11 site visits the air gap width was found to range between 0 and 6 mm. Overall the typical air gap ranged 1.5 to 3.5 mm while the joints ranged 0 to 10 mm. Across 90% of the sites inspected the joints were taped, thereby impeding the opportunity for convection. For air gaps ranging 2.5 mm to 4 mm, simulation then showed that taping joints had limited effect upon preventing thermal bypasses. For the 80 mm thick insulation boards[4] that were examined the predicted increase in heat loss was 10%. It was concluded that for cases where joints are taped or tongue and groove joints are limited to 0 to 2 mm, it is important to close joints at the top and the bottom of the insulation panels (top and bottom of walls) and around openings such as doors, windows and service penetrations. This can be achieved by adding compression tape or by applying PUR foam.

Building upon work by Kronvall (1982) and Schuyler & Solvason (1983), Lecompte (1990) investigated close loop natural convection in a 2 metre high masonry cavity wall with a theoretical U-value of 0.34 W/m².K and included wall constructions using mineral fibre and polystyrene insulation. A 40 mm wide cavity was formed on the cold side and, to simulate the impact of mortar "snots" or debris, a 10 mm wide air gap was formed on the warm side. Lecompte then investigated the impact of joints that were 10 mm, 3 mm and 0 mm wide. Measurements established that a 10 mm joint resulted in a 193% increase in heat transfer and a 3 mm joint resulted in a 158% increase in heat transfer, whilst a 0 mm gap only resulted in a 101% increase in heat transfer. It is clear from Lecompte's numerical simulation that any joint greater than a 1 mm wide has a significant impact upon thermal performance.

The validity of the simulation is supported by Threthowen (1991) who studied a wall with a 15 mm air gap to both sides of the insulant, and measured a sharp reduction in thermal resistance when the horizontal air gap (i.e. joint) at the top and bottom of the wall was 1 mm or greater. After corroborating his results by comparing his work with other similar studies he concludes that there is no tolerance for imperfect workmanship, as convection around the insulant causes major loss of performance.

These conclusions echo those of Hens (1998) and Hens and Carmeliet (2001), discussed earlier, whilst also permitting us to understand the impact of joint widths when there is also a cavity on the warm side of the insulant.

The width of the joint at the interface between abutting insulation boards also has a significant impact upon the resulting heat loss. For a wall with a notional U-value of 0.5 W/m².K, Hens (1998) demonstrated that for buoyancy-induced air intrusion (no wind), joints of 2 mm and greater have a significant impact upon thermal performance.

4 At a notional U-value circa 0.256 W/m²K (calculated by the author of this paper) this suggests convection increases heat loss by roughly 0.026 W/m²K. For a U-value of 0.15 W/m²K this would suggest a 17% increase in heat loss.

At the 2008 AECB National Conference, Berthold Kaufmann from the Passivhaus Institute observed that foam insulation materials have a tendency to shrink by a substantial margin during the first six weeks post-manufacture. Shrinkage can be up to 0.2-0.5%, thus a 1 m board could shrink by 2-5 mm. If new boards are installed before they have matured, then there is a risk that a 4-10 mm joint could open up after installation. To ensure performance, this joint would need to be filled with a low expansion foam, which could add considerable time and cost penalties. Kaufmann recommends that a maturation period of six weeks be given to foam insulation boards prior to installation.

PRACTICAL IMPLICATIONS

Horizontal insulation: Joints should be less than 3 mm.

Internal vertical insulation: Where internal wall insulation is installed, abutting joints should be no greater than 2 mm (Hens, 1998).

Natural convection within fibrous insulation

Natural convection arises within insulation when the temperature difference between the cold and warm faces causes air to change density and generate sufficient force as to enable air movement to take place. The warmer air layer rises and consequently the colder, denser air descends. The net effect of convection upon energy demand is a function of the area affected, the temperature difference, and the duration of the cold weather conditions (Whalgren, 2007). Compared to free air, insulation increases the resistance to airflow (Bankvall, 1978b).

The extent of air movement within an insulation material is influenced by various factors including the density of the insulation, its permeance (air permeability), height, inclination and thickness, the temperature difference, the presence of ventilation and the aspect ratio (geometry) of the space (Bankvall, 1978b; Shankar & Hagentoft, 2000; Whalgren, 2007; Saha & Khan, 2011; Roels & Langmans, 2016). For insulation held in a horizontal plane, as with a cold roof, the height is restricted to the thickness of the insulation itself. It is worth noting that convection also assists with the redistribution of moisture, consequently increasing the moisture load on the cold, upper, face of the construction and leading to the temporary risk of mould growth (Uvsløkk et al., 1996b; Uvsløkk et al., 2010; Langmans, 2013).

Structure of fibrous insulation

The orientation of fibres within fibrous insulation has a substantial impact upon the permeability of the insulation and consequently impacts upon convection and heat flow. The distribution of these fibres and their orientation is affected by the manufacturing and installation process used for a given product (Gullbrekken, 2017a; Kivioja & Vinha; 2020). For rolls and batts, fibres tend to run parallel to the surface though this is not necessarily consistent throughout. By contrast loose-fill is less ordered and larger pockets of air can occur, particularly adjacent to surfaces and intrusions. These air pockets decrease the resistance to air flow, and so can increase heat loss.

Loose-fill blown-fibre insulation

As loose-fill blown fibre insulation can fill the narrow spaces around roof trusses, pipes and other obstructions with little waste, and because relative to insulation boards it is low cost and quick to install, this type of insulation material is widely used in Nordic countries. However, investigation shows it is permeable to air so has increased potential for natural convection, which in turn leads to the possibility of increased heat transfer, greater condensation risks, and mould, particularly when the upper surface of the loft insulation is exposed and unprotected (Wahlgren, 2002a; Gullbrekken 2017a; Kivioja & Vinha, 2020).

Modified Rayleigh number (RA*)

The onset of natural convection within a permeable material is described using the modified Rayleigh number. The larger the number the greater the forces which drive natural convection (Wahlgren, 2007). When the modified Rayleigh number exceeds a certain critical value convection is said to occur. However, because the onset of convection is a gradual process it is difficult to estimate the precise point when natural convection begins. The modified Rayleigh number increases with changes in geometry, such as at the eaves, or by increasing the insulation thickness (Wahlgren, 2005).

Considering that different calculation methods provide slightly different results, Wahlgren (2004) suggests that a single critical modified Rayleigh number cannot be determined. Therefore, it is wise to consider a range of possible values.

According to EN ISO 10456 (2007), for horizontal heat transfer (walls) natural convection can be neglected when calculating U-values if the critical modified Rayleigh number is < 2.5. For roofs with horizontal insulation where the upper surface is unprotected, natural convection can be neglected if the critical modified Rayleigh number is < 15. When a porous material is placed between two impermeable plates, the bottom plate being warmer than the upper, natural convection occurs when the modified Rayleigh number exceeds 40 (Nield & Bejan, 1992).

Nusselt number (Nu)

The increase in heat flow arising from natural convection can be described by the ratio between the heat flow through the insulation with convection and the heat flow without convection for the same situation. This ratio is known as the Nusselt number. A value of one represents transfer by conduction, and any value greater indicates that convection is contributing to heat loss.

Insulation density

Taken in combination a review of Powell et al. (1989), Anderlind (1992), Ciucasu et al. (2005), and Wahlgren (2007) would appear to suggest that insulation with a thickness of up to 500 mm and a density > 20 kg/m^3 (glass wool) and > 30 kg/m^3 (mineral wool) is acceptable when seeking to inhibit natural convection, as long as the internal/external temperature difference is less than 30K. A wide-ranging literature review by Roels & Langmans (2016) also identifies papers which suggest the density of insulation should be > 20 kg/m^3. However, when considering the discussion presented below, these conclusions should be treated with a degree of caution.

Insulation materials

Measurements undertaken by Kivioja & Vinha (2020) suggest that there is less risk of natural convection when using wood fibre insulation than glass fibre insulation. Measurements by Gullbrekken et al (2019) established that wood fibre insulation (~48 - 56 kg/m^3) is at less risk of natural convection than mineral wool (~17 – 17.4 kg/m^3). In the context of these observations, it is perhaps surprising that calculations by Ciucasu et al. (2005) suggest 'stone wool' insulation (30 kg/m^3) (rock wool?) was more prone to convection than glass wool (15 kg/m^3 and 18 kg/m^3).

Horizontal insulation

Considering horizontal insulation for cold roofs, Powell et al. (1989) observed that natural convection can occur within insulation that has a density less than 13 kg/m^3. This effect was reported to disappear as the density increased toward 30kg/m^3.

Wilkes (1991) tested low density (6 kg/m^3 to 8 kg/m^3), loose fill (permeable) horizontal insulation products and demonstrated that convection could be responsible for a 50% decrease of thermal resistance in very cold outdoor air temperatures (-28 oC) and with a large internal/external temperature difference (49K).When considering horizontal loose-fill blown-fibre insulation Wahlgren observed the following:

- A reduction in density (from 15 kg/m^3 and 9.4 kg/m^3) only has a modest impact upon the modified Rayleigh number. However, a reduction in density affects other characteristics, such as thermal conductivity and air permeability, and these properties have greater influence upon the modified Rayleigh number (Wahlgren, 2005).
- A increase in insulation thickness from 400 mm to 600 mm, resulting in a change in geometry, increases the modified Rayleigh number from 16 to 23 (Wahlgren, 2005).
- From the measurement of an unventilated roof structure insulated with 439 mm of loose-fill fiberglass[5] (9.4 kg/m^3) Wahlgren (2001a, 2002a, 2002b) found that at a Δt of 20K convection commenced at a modified Rayleigh number of 22, whereas calculation suggested a value of 27. Above the modified Rayleigh number of 22 there was a measured reduction in thermal resistance

5 Fibreglass insulation is widely used in the USA, though rarely used in Europe.

with the maximum increase in heat loss arising from natural convection being 25% at a Δt of 30K and a modified Rayleigh number of 34.

- Wahlgren (2002b) concludes that fibreglass is not suitable for cold climates.
- In contrast, according to Wahlgren (2001a, 2002a, 2002b), the thermal resistance of an attic floor insulation with loose-fill rock wool (33.6 kg/m³) and an unventilated roof structure was unaffected and showed no sign of convection even when thermal bridges (the joists) were present. The modified Rayleigh number of the rock wool was 10. For rock wool a 4% discrepancy between measurement and calculations based on standard measured thermal conductivities was within the margin of error (Wahlgren, 2001b).

This paper has not sought to replicate Table 1 of Wahlgren (2007) which summarises the modified Rayleigh numbers arising from various research up until that date. What is clear however is that there is great variation within the reported values (from 10 to 30). Therefore, no critical modified Rayleigh number can be assumed for attic insulation.

According to Wahlgren (2002a; 2005) the onset of natural convection occurs at a modified Rayleigh number between 22 to 27. Similar values are stated in Serkitjis (1995) and Silberstein (1991). However, other research has shown convection can occur before the (assumed) critical modified Rayleigh number is reached (Delmas & Wilkes, 1992; Langlais, Arquis, & McCaa, 1990 and Kivioja & Vinha, 2020).

Using a calibrated hot-box to examine horizontal insulation subjected to varying airflow velocities (0.0-0.1 m/s and 0.5-0.7 m/s), at set temperature differences (20K and 35K), Kivioja & Vinha (2020) report an average increase in heat loss of 0-10% for wood fibre insulation (36 kg/m³ at 300 mm thickness and 40 kg/m³ at 600 mm). For glass wool (25 kg/m³ for both 300 mm and 600 mm thickness), they report an average increase of between 30-40%. They also observe that internal natural convection can increase heat loss by up to 60%. Low density insulation was most susceptible to internal convection when exposed to airflow across the exposed upper surface, whereas temperature difference was found to have the greatest impact upon internal convection within higher density insulation.

For cases where the modified Rayleigh numbers were between 2.6 and 3.4, Kivioja & Vinha (2020) did not observe internal convection. For wood fibre insulation, when the Nusselt number exceeded 1.00 (i.e. convection increased heat loss), they found the modified Rayleigh number exceeded 5.

At a modified Rayleigh number of 3.4 and a 20K Δt, none of the wood fibre studies were subject to convection. However, 600 mm thick glass fibre insulation was subject to convection. When the Δt was 30K, both the wood fibre and the glass fibre exceeded the modified Rayleigh number of 3.4 and are therefore understood have experienced convection.

Table 3 shows that the Nusselt numbers ranged between 0 and 16% for blown-in wood fibre insulation, whereas for blown-in glass wool insulation with trusses it ranged from 10–53%.

		Temperature difference 20K		Temperature difference 35K	
Insulation / thickness	**Inclination**	**300 mm**	**600 mm**	**300 mm**	**600 mm**
Wood fibre (36 kg/m³ at 300 mm, 40 kg/m³ at 600 mm)	**0°**	**1.05**	**1.0**	**1.16**	**1.02* to 1.08**
Glass wool (25 kg/m³)	**0°**	**1.1**	**1.10 to 1.35***	**1.15**	**1.10 to 1.53***

** indicates velocity of air 0.6 m/s*

Table 3: *Nusselt numbers for horizontal insulation after Kivioja & Vinha (2020)*

In contrast to Kivioja & Vinha's findings, the critical modified Rayleigh number suggested by EN ISO 10456 (2007) would suggest no internal convection would have occurred. It is therefore understandable why, referencing their own measurements and the work of Gullbrekken et al. (2017a) and Shankar & Hagentoft (2000), the researchers call into question international standards including EN ISO 6946 (2017) and EN ISO 10456 (2007), as they appear to not consider natural convection adequately.

The influence of joists upon natural convection

According to numerical analysis by Delmas and Arquis (1992) the size of the joists and the distance between the joists influence convection. At a modified Rayleigh number of 46, thermal bridges, such as joists, increased the risk of natural convection, with the simulated thermal resistance reducing by 50% when the attic air temperature is -17ºC (Wahlgren, 2002a). Despite these observations, experimental and numerical studies by Delmas and Wilkes (1992), Delmas and Arquis (1995) and Wahlgren et al (2002a) conclude that the introduction of joists into the insulation has no significant impact upon performance.

When considering measurement uncertainty, Kivioja & Vinha (2020) found trusses had negligible impact upon blown-in wood fibre insulation. In contrast, trusses within blown-in glass wool insulation reduced internal convection by 11–36%.

Pitched insulation

Convection in highly insulated pitched wooden roof constructions was thoroughly reviewed by Roels and Langmans (2016), who highlight the benefit of using high-density insulation (>20 kg/m^3) with a continuous wind barrier system. For a warm roof the height is informed by the pitch of the insulation (Roels & Langmans, 2016).

Vertical and pitched insulation

Uvsløkk et al. (1996b) studied two timber frame structures (2.40 m high, 3.04 m wide). Using members positioned at 600 mm centres, one structure was formed using 198 mm x 35 mm studs, the other using 298 mm deep I-beams (formed from 45 mm x 45 mm flanges and a 10 mm web of wood particle board). Each structure was insulated with two different types of insulation (glass wool and rock wool insulation). With good workmanship, at a temperature difference of 20K, natural convection occurred within both rock wool scenarios. Uvsløkk et al. observe that convection within the rock wool may have arisen because the insulation is not perfectly homogeneous. Furthermore, it was theorised that greater measurement uncertainty could have arisen within the rock wool variants due to challenges which arose when placing thermocouples. Glass wool was less prone to convection. With good workmanship, for the 198 mm studs insulated with glass wool, convection occurred when the temperature difference was greater than 30K, and for the 298 mm I-beam variant, when it was greater than 30K. Later Uvsløkk et al. (2010) report results which showed natural convection occurring at a modified Rayleigh number less than 2.5. Whilst recognising practical boundaries for workmanship, such results throw into question guidance within EN-ISO 10456 (2007).

Dyrbøl, Svendsen & Elmroth (2002) identified convection in 200 mm insulation at a temperature difference of 20K and observed that convection was related to the permeability of the insulation. Gullbrekken et al (2017a), citing Janssen (1997), observe that 200 mm glass wool insulation showed a Nusslet number between 1.07 and 1.12, which means the U-value of the wall increased by 7 to 12% compared to a wall without convection. For a wall with 300 mm of insulation the Nusselt number was 1.04 and 1.14.

After examining 500 mm wide cavities filled with glass wool insulation (16 to 19 kg/m^3) Gullbrekken et al (2017a) show the RA* is > 4 and the Nusselt number is > 1 for all but downward heat transfer when the temperature difference is > 20K. The analysis showed that even at a modified Rayleigh number of 4 there was significant convection for all inclinations except for the floor configuration. The modified Rayleigh number was observed to be lower than previous studies have indicated, and the researchers observe that the likely cause was due to imperfections in the insulation layer.

For the inclinations of 30º and 60º, the angles with the highest recorded U-values, the Nusselt number increased significantly when the temperature difference increased from 20K to 40K (from roughly 1.08 to 1.30) indicating an 8% to 30% increase in the U-value. For the wall configuration the Nusselt number ranged from 1.08 (Δt 20K) and 1.15 (Δt 40K).

It is the temperature difference across the insulation which drives natural convection. Therefore, subdividing the total insulation thickness into layers means the magnitude of the driving force can be reduced. Building upon research presented by Uvsløkk et al. (2010), where the total insulation thickness exceeds 200 mm and the inside/outside temperature difference is between 20 to 40K, Gullbrekken et al. (2017a) recommend installing a convection barrier[6] in both wall and pitched roof structures. Showing insulation without subdivisions, the results from Gullbrekken et al. (2017a) and Janssen (1997) are summarised below:

		Temperature difference 20K			Temperature difference 40K		
Element / thickness	**Inclination**	**200 mm**	**300 mm**	**500 mm**	**200 mm**	**300 mm**	**500 mm**
Upward heat transfer (warm roof)	30º			1.06			1.29
Upward heat transfer (warm roof)	60º			1.09			1.30
Upward heat transfer (horiz. ins., cold roof)	0º			1.08			1.09
Horizontal heat transfer (wall)	90º	1.07*	1.04*	1.08	1.12 *	1.14 *	1.15
Downward heat transfer (floor)	180º			1.0			1.0

** results from Janssen (1997) referenced in Gullbrekken et al. (2017a)*

Table 4: *Nusselt numbers for glass wool rolls (16 to 19 kg/m³)*

Gullbrekken at al. (2019) undertook further research examining mineral wool (~17 – 17.4 kg/m³) and wood fibre (~48 - 56 kg/m³) insulation. Walls resulted in the highest Nusselt number, though a systematic correlation with orientation could not be established. Those cases where the Nusselt number is less than one (wood fibre roofs) is associated with measurement uncertainty (in practical terms this means the Nusselt number should be considered 1.0). For the various inclinations the modified Rayleigh number of mineral wool ranged from 1.34 to 2.68 at 250 mm thickness, and from 1.68 to 3.35 at 400 mm thickness.

Similarly for wood fibre the modified Rayleigh number ranged from 1.68 to 3.35 at 250 mm thickness, and from 2.66 to 5.3 at 400 mm thickness. At 250 mm thickness, the design U-value for mineral wool was 0.133 W/m²K and for wood fibre 0.143 W/m²K. At 400 mm thickness, the design U-value for mineral wool was 0.087 W/m²K and for wood fibre 0.093 W/m²K. The thermal performance of the insulation materials was unaffected by moisture within the hygroscopic range. Table 5 presents the results of the research:

		Temperature difference 20K		Temperature difference 40K	
Insulation / thickness	**Inclination**	**250 mm**	**400 mm**	**250 mm**	**400 mm**
Mineral wool	90º	1.015	1.074	1.038	1.068
	30º	0.998	1.083	1.014	1.022
	180º	1	1	1	1
Wood fibre	90º	0.953	1.011	1.001	1.014
	30º	1.001	0.995	0.974	1.014
	180º	1	1	1	1

Table 5: *Nusselt number for mineral wool and wood fibre (Gullbrekken at al, 2019)*

6 A convection barrier divides an insulated cavity into layers. It can be formed by a membrane which runs parallel with, but between, the air and wind barrier. Uvsløkk et al. (2010) show a convection barrier formed from building paper which is bonded to the face of the insulation.

The Nusselt numbers presented in Table 5 suggest mineral wool, at an inclination of 90º and 30º, is more susceptible to convective heat loss than wood fibre.

PRACTICAL IMPLICATIONS

In all cases good detailing and careful workmanship are required to prevent the formation of interlinking cavities, air gaps and joints which contribute to the risk of natural convection. This may be achieved by using staggered joints and subdividing building elements at discrete points e.g. closing cavities at intervals and at the junction between walls, roofs and floors etc.

Amongst other factors, temperature difference and the angle of inclination influence convection and consequently affect heat transfer, the Nusselt number and the U-value. If the impact of air movement is to be limited to less than 5% of the reference U-value, the results presented above suggest internal convection should be considered when designing structures, particularly in cold climates.

The research undertaken in recent years calls into question current standards and, where insulation exceeds a thickness of 200 mm, suggests designers adopt one of two strategies:

- a convection barrier should be included to limit the uninterrupted insulation thickness to < 250 mm, *or*
- a correction factor should be applied to the U-value calculation by multiplying the U-value by an appropriate Nusselt number. Where a correction factor is to be applied using the Nusselt number it should be ≥ 1.

With regard to the second point, whilst the magnitude of the correction factors will be influenced by a range of considerations and remains to be agreed by international standards, this review suggests it would be reasonable to apply a Nusselt number to any U-value calculation where the insulation thickness exceeds 200 mm. To this end, where a given temperature difference is likely to be exceeded for a given fraction of the year, say 10%, it appears appropriate that the Nusselt numbers from Tables 2.4, 2.5 and 2.6 are applied to heat loss calculations for equal or broadly comparable insulation types.

Density
To reduce the risk of convection occurring in cold roof construction, high permeability insulation materials should be avoided, therefore very low-density insulation should not be used. At the very least, glass wool insulation should have a density > 20 kg/m³ (preferably > 30 kg/m³) and for mineral wool a density > 30kg/m³. Wood fibre insulation should have a density of ~36 kg/m³ or greater for 300 mm thickness, and ~40 kg/m³ or greater for a thickness of 600 mm.

Vertical and pitched insulation
Where insulation is exposed to a cavity, also refer to Section 3: Wind washing and the permeance of surfaces.

Further research

This section has identified the opportunity for further research which would examine the behaviour of various thicknesses and types of insulation material (including wood fibre, cellulose, rock wool, glass wool, straw etc.) at a range of inclinations (say 0º, 30º, 60º, 90º, 180º) when exposed to a temperature difference which is representative of various climate zones (which would include 20K and 40K). This body of research should be conceived in such a manner that it will present sufficient information as to inform the revision of EN ISO 6946 (2017) and EN-ISO 10456 (2007).

Party walls

According to Harrje (1986), the earliest reference to (non-occupied) warm lofts, which is associated with the party wall thermal bypass, dates back to 1941. However, it was not until almost 40 years later that Beyea et al. (1978) observed that attics at Twin Rivers, New Jersey were warmer than conventional conduction models had predicted. The high attic temperatures that were measured implied that heat loss was five times greater than anticipated. The two major causes of ineffective attic insulation were found to be (a) air flow into the attic from other parts of the house (b) heat transfer into the attic via party walls. Subsequent research illustrates many of the common and surprising heat loss mechanisms that were identified and confirmed significant heat losses could be attributed to party walls and thermal bypass in general – see Harrje et al. (1979a, 1979b, 1985a, 1986), Socolow (1978 and 1979), Siviour (1994), Wingfield et al. (2007), Lowe (2007), Palmer et al. (2019).

Common forms of thermal bypass can be associated with air movement. For framed construction, frequently identified leaks fall into four categories:

1. Joints between sheets or boards of the air barrier
2. Interfaces with other envelope systems, such as the wall-roof and wall window interface
3. Junctions around structural penetrations (columns, joists, trusses, etc.)
4. Electrical and plumbing penetrations

In the UK, Siviour reported in 1994 that a terraced house with unfilled party-wall cavity had a measured U-value of 0.85 W/m².K and that an unfilled party-wall cavity in a semi-detached home had a measured U-value 0.44 W/m².K. The suggested reason for the heat loss through the party wall was the movement of cold air in their cavities; the greater the U-value the greater the air movement. Significant air movement between the loft and the cavity of one of the party walls was through incomplete vertical mortar joints, that were detected using a small hand-held smoke generator of the type used in airtightness testing. Siviour suggested that fire stopping at such walls would be expected to reduce airflow considerably in such cavities, although it would not be expected to make them completely airtight.

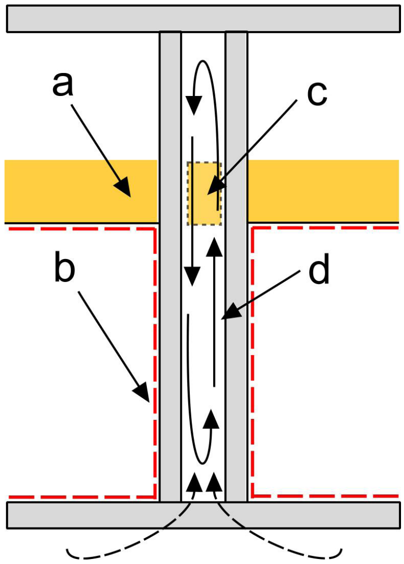


Figure 13:
Party wall bypass mechanism: Close loop convection coupled with wind washing and air leakage.
(a) *insulation*
(b) *airtight barrier*
(c) *cavity sock*
(d) *cavity*

In the UK, research undertaken at Stamford Brook found that the whole house heat loss coefficients exceeded the predicted values by between 75% and 103% (Wingfield, 2007a). Warm attics were once again one of the first signs of thermal bypass (Figure 13). Theoretical analysis suggested that thermal stack driven bypass (i.e. natural convection) in the party wall cavity gave rise to a significant source of heat loss, with a magnitude equivalent to an effective single sided party wall U-value in the order of 0.6 W/m².K.

Using blown mineral wool insulation, Wingfield et al. (2009a, 2009b) demonstrated via measurement that fully filling the party wall with insulation reduced the risk of a thermal bypass occuring to almost zero. Such an approach has also been undertaken elsewhere. For instance, in Kronsberg, Hanover Feist et al. (2005) mitigated the risk of party wall bypass by filling the party wall cavity with insulation and by providing a continuous air barrier across the cavity.

More recently, observing that wet finishes block air paths, Palmer and Terry (2022) theorise that 'dry' party wall construction (without wet plaster) is likely to suffer from greater heat loss into the party wall cavity. Drawing on a wider data set than has previously been available (284 measurements), they suggest the mean uninsulated cavity party walls may have a U-value in the order of 0.21 W/m².K (highest U-value 0.81 W/m².K, lowest U-value 0.05 W/m².K).

PRACTICAL IMPLICATIONS

New party walls should be fully filled, preferably with blown insulation and the insulation should be encapsulated between the air barrier of each respective building. This is particularly the case when the U-value of the external wall has a U-value below 0.21 W/m².K. Furthermore, measurements suggest retrofitting existing cavity-party walls with insulation may only be beneficial in those circumstances where the party wall U-value has been proven to exceed 0.21 W/m².K.

Moisture risks and roofs

A warmer air temperature means air has a greater moisture-carrying capacity. Consequently, when this body of air cools, there is greater potential for condensation and subsequent moisture damage.

Moisture risks and roofs

Gullbrekken et al. (2016) examined roof defects in Norwegian construction. The roof type with a cold loft, horizontal insulation and a vapour barrier at ceiling level was found to be twice as vulnerable to defects as warm roof construction (which has either separate or combined wind barrier and roofing underlay). Of the two types of cold lofts considered, one ventilated and the other with a continuous exterior wind barrier, the ventilated typology was found to be more prone to air leakage at ceiling level. Interestingly Gullbrekken et al. specifically highlight that a significant number of these defects (19%) come from other sources, many of which are associated with loft storage.

Attic trusses used to form a room in the roof, the final typology studied by Gullbrekken et al., were also found to be prone to moisture damage, with 41% of damage caused by air leakage of indoor moisture. This type of cold, ventilated roof construction (rather than a thermally insulated, non-ventilated attic) was found to increase the risk of moisture damage. It is interesting to note that the non-ventilated attic has a profile which encapsulates the insulation between the air barrier and the vapour open underlay (which acts as the wind barrier), thereby simplifying the design and construction of the thermal envelope.

Basements and bypass

The basements of the dwellings at Twin Rivers were outside the thermal envelope, yet, due to the presence of the boiler and heat distribution networks, they were adventitiously heated to temperature similar to that of the indoor conditions (Beyea et al., 1978). As a result of the party wall thermal bypass, heat and moisture were transferred to the attic and subsequently lost through ventilation. Measures to reduce heat loss were retrofitted and successfully demonstrated that it could be reduced. The researchers recognised that the nature of defects meant they were likely to be common throughout the USA. More importantly, the combination of warm basements and high humidity introduces an elevated risk of moisture damage within the attic space.

PRACTICAL IMPLICATIONS

It appears some roof types are less prone to moisture risks than others. All constraints permitting (climate, cost etc), warm roofs may be considered preferable to cold roofs.

Heating equipment located outside the thermal envelope can result in significant heat loss. Where it is located outside the envelope, care should be taken to prevent heat and moisture transfer between the plant room and the attic.

SECTION 3:

Wind washing and the permeance of surfaces

Wind washing

Wind-driven air movement across, through or behind the thermal insulation is known as wind washing. A review of the available literature has identified a range of variables which influence the impact of wind washing upon a building. They include:

Wall system vulnerability

- Cladding system permeance
- Air velocity within cavity
- Wind barrier system
  - permeance
  - joints
- Insulation system
  - permeance
- air gaps and joints
- Air barrier system
  - permeance
  - joints

Wind exposure

- Geographical location
- Local sheltering
- Elevation of site above sea level
- Height above ground level
- Building geometry

Wind pressure

Wind pressure along a ventilated cavity wall causes air to flow inside the cavity, as it moves from a region of positive pressure to one of negative pressure (figure 14). This, in turn, influences the thermal performance of the wall under adverse weather conditions.

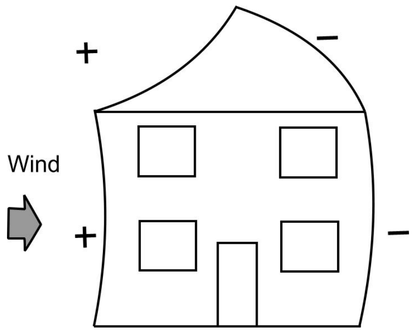
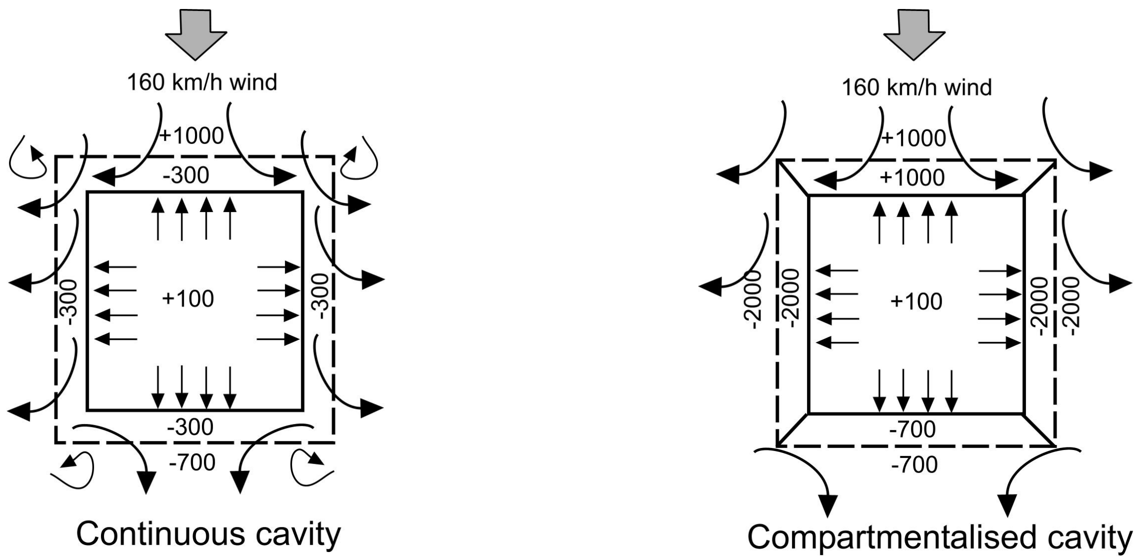


Figure 14: *Wind moves from a region of positive to negative pressure*

Ganguli (1986) studied the influence of wind pressure upon a multi-storey building. Figure 15a shows the notional plan. The outside walls are outlined by a double line: the dashed outer line represents the vented cladding; the solid inner line represents the wall's wind barrier. The 100 Pa internal pressure may be accounted for by fan pressurisation and/or stack effect, while the 1000 Pa positive pressure on the windward side is a result of the 160 km/h wind. The -300 Pa pressure in the cavity is based on the interior pressure coefficients and assumes a continuous cavity all around the building, with openings uniformly distributed in all four walls. The drawing shows that where the wind is relatively free to circulate within a wall cavity, much of the wind pressure is resisted by the cladding and not by the air barrier; the cladding must be designed to carry the load.



Figures 15a and 15b: *Wind pressures upon facades (after Ganguli,1986)*

The flow of air can also cause rainwater and snow to enter the cavity, where it can stain the façade or cause the deterioration of some of the materials within the wall. Such air flow can also have a detrimental effect on the performance of the insulation in the wall, thus adding to the heating and cooling loads of the building.

Ganguli notes that dividing the cavity into compartments both horizontally and vertically, as shown in Figures 15a and 15b, can prevent the flow of air within the cavity. With the flow of air in the cavity stopped, the air pressure acting on the cladding is the same as that acting on the air barrier, thus eliminating the pressure difference across the cladding. This compartmentation can result in a more economical cladding design and means snow and rain cannot enter the cavity. It also means that air movement within the cavity is reduced thus decreasing wind induced heat losses. Pertinent conclusions drawn by Ganguli are:

1. A wall system has to be capable to supporting high peak pressures (800 Pa); within one second the pressure can increase from 225 Pa to 800 Pa and decrease to 500 Pa.
2. During a building's life, gusts of wind lasting 3 to 5 seconds can exert forces in excess of 2500 Pa. When subjected to such loads unsupported membranes could tear and insulation could be dislodged.
3. Under gusty conditions a brick veneer can support approximately 70% of the wind pressure (thus the wind barrier needs to be able to withstand a high load of 300 pa and up to 750 pa at peak wind load).

The details that tend to be most susceptible to wind washing are vertical corners and the tops of walls (eaves, verge and ridge), horizontal and pitched assemblies (such as raised insulated floors that separate an unheated garage from a living space above, cantilevered or suspended living spaces, and compact/ cathedral roofs).

In the UK pressurised rainscreens should be designed in accordance with the Centre for Window and Cladding Technology (CWCT) standard for systemised building envelopes (CWCT, 2006). The CWCT states that the air gap should be at least 25 mm and that open joints should be a minimum 6 mm, but "joints that are required to remain unblocked shall have a minimum opening of 10 mm".

PRACTICAL IMPLICATIONS

The key to reducing the likelihood of wind washing is to increase resistance to external airflow within the cavity; as noted above this may be achieved by windtight construction and the compartmentation of the cavity (which can be achieved with continuous, vertical baffles at each corner). Whilst it is beyond the scope of this paper to discuss these relationships further, Van Straaten (2016) explores this subject in more detail.

Building height

Wingfield & Miles-Shenton (2011) measured U-values through the entire height of a 3-storey partial-fill masonry cavity wall town house throughout the course of a coheating test which showed the mean U-values varied with altitude. The cause of these deviations was not established, warranting further research, though theory would suggest a combination of effects are at play, including exfiltration and conduction, which raise the temperature within an air gap on the warm side of the insulation, and consequently result in thermal bypass.

PRACTICAL IMPLICATIONS

The risk of convective loops in multi-storey buildings should be considered during the design process and measures should be undertaken to reduce the risk of convection. This may necessitate subdividing tall walls with a horizontal barrier.

Building geometry

Under suitable conditions, Timusk, Seskus and Ary (1991) recognise that mould and mildew on interior surfaces, and increased heat loss, occur as a result of wind washing. They note a wind cooling effect that occurs at exterior corners (including eaves) when deficiencies (arising from careless workmanship, permeability of insulation, permeability of sheathing, spaces caused by shrinkage, and unfilled corners reducing wind resistance) permit wind to blow through the exterior sheathing of the wall assembly (Figures 16 and 17). Under suitable conditions, they also recognise that mould and mildew can occur on interior surfaces and increased heat loss can also occur as a result of wind washing.

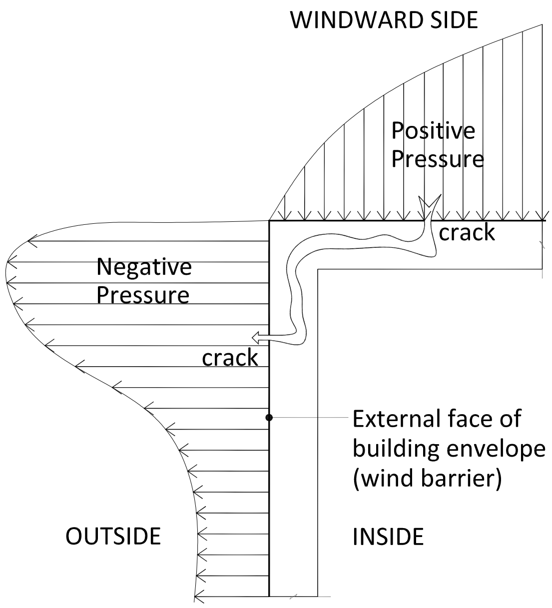


Figure 16: *Wind pressure exerted upon the corner of building - based upon Timusk, Seskus and Ary (1991)*

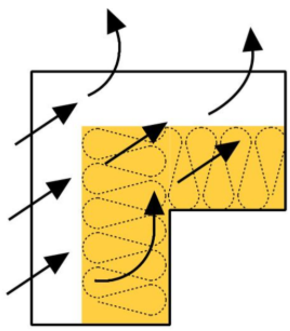


Figure 17: *Wind washing*

Warm roofs

In-situ measurements by Deseyve and Bednar (2005) identified bulk air movement through an existing roof (Figure 18 overleaf). Thermography showed that when the wind speed rose to between 7 and 9 m/s, surface temperatures were significantly reduced relative to when the wind speed was 0 m/s. Tracer gas analysis showed that air entered at the eaves and exited at the ridge. The measured U-value in windy conditions was 2.5 W/m².K. It was calculated that wind washing during such conditions resulted in a 660% increase in heat flux. The extreme degradation through wind washing was due to bulk air movement occurring as a result of cold external air entering at eaves level and being drawn up through the insulation into a small attic space at high level that was ventilated to the outside. Figure 18 indicates bulk air movement through the roof insulation and out through a ridge vent.

Later Deseyve and Bednar (2008) constructed test elements to investigate the effects of wind-induced airflow and air patterns. The study examined pitched roofs with low density glass wool insulation (14.5 kg/m³) and 20 mm air layers either side of the insulation. The authors claim this construction accords with permitted building practice in Austria. In higher wind speeds, greater heat flux occurs in the region surrounding the eaves, where, compared to the static conditions, heat flux increased by 900% when the velocity of the air was 5 m/s. Recommendations to avoid these air flows were not made.

Janssens and Hens (2004, 2006) undertook a 2 year study of duo-pitched insulated warm roofs (Figure 19). The test roofs had a good theoretical U-value of 0.2 W/m².K and the final design U-value was 0.18 W/m².K. For an external wind speed of 4 m/s , the U-value of an unventilated compact roof increased by 0.02 W/m².K, whilst the U-value of a ventilated compact roof rose by 0.07 W/m².K. Thus, the unventilated roof was degraded by 11% compared to the theoretical U-value whereas the ventilated roof was degraded by 39%. Their 2006 paper concluded “In order to minimise the thermal effects of wind washing in cavity insulated sloped roofs, it is recommended to use an underlay material with sufficiently low air permeance in accordance with upper limits reported in literature, and to pay attention to the continuity of the layer at joints and at eaves and ridge details.”

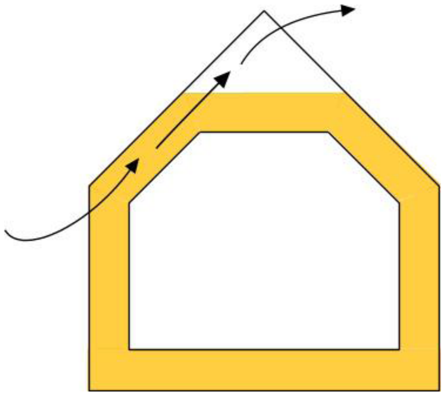


Figure 18: *Ridge vented warm roof (after Deseyve and Bednar, 2005)*

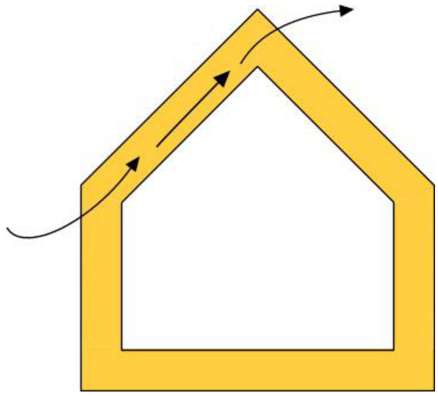


Figure 19: *Warm roof (after Janssens and Hens, 2004, 2006)*

These considerations serve to support the need for wind barrier systems to have a performance requirement (as will be discussed later).

Vented cold roofs

In Canada Walker and Forest (1995) performed field measurements and demonstrated that, for a roof with eaves vents, attic ventilation is mainly wind-driven and increases with wind speed (ranging between 1 and 10 ACH.)

In the UK, Gale (1980) reported natural ventilation rates between 1.5 and 5.5 ACH in a low energy house in a sheltered location (wind speed between 0.3 to 5.2 m/s), and 6 and 22 ACH in an old 4-bedroom detached house (wind speed between 0.5 to 4.9 m/s). Because of the reduced number of air changes within the loft of the low energy home the proportion of air observed leaving the house through the loft was much greater than for the older house. In the older property it was generally observed that increased wind speed meant a lower proportion of the air leaving the house exited through the loft space. In order to conserve energy the authors conclude, air flow from a dwelling to the loft space should be restricted.

The attics studied by Hansen (2021) had highly variable air change rates, with an average air change rate of 6.7 ACH during the winter, and 5.5 ACH in the summer. During cold weather the lowest air change rate was 0.9 ACH, and during warm weather it was 0.5 ACH. The highest ventilation rates were 20.2 ACH and 28.2 ACH respectively.

Unvented cold roofs

A large (370 m²) attic space was insulated with 400 mm of loose-fill mineral wool insulation which was designed and subsequently constructed following recommendations by Strand & Hansén (2009)[7]. The attic features a minimal ventilation rate and 20 mm of insulation which was laid externally over the sheathing. The findings of this case study were presented in Kurkinen and Hagentoft (2011) and subsequently Kurkinen (2014). The research serves to demonstrate that:

1. The climate of such roofs can be more robust and less likely to fluctuate than a ventilated roof without an insulated sheathing layer.
2. Radiant heat losses, which arise as a consequence of a clear night sky, can be reduced through the application of 20 mm of insulated sheathing on the outer side of the roof construction.

7 The bachelor thesis is in Swedish and has not been translated by the author of this paper.

3. The application of insulated sheathing means the internal surface temperature adjacent to the sheathing can remain higher than the uninsulated the case, therefore the risk of high surface humidity and subsequent condensation can be reduced, and subsequently

4. The mould growth potential of the minimally ventilated roof void can be lower than that of external conditions, however, to avoid moisture damage and mould growth a high standard of airtightness must be achieved for the life of the building.

Siddall et al. (2021) monitored the unvented loft of a single dwelling with a humidity variable underlay (0.1 MNs/g; Sd-value 0.02 m). Upon completion of the construction the dwelling had a measured airtightness of 0.31 ACH @ 50 Pa (q50 = 0.31 m³/h.m² @ 50 Pa) and at the end of the monitoring period, the dwelling had a measured airtightness of 0.49 ACH @ 50 Pa (q50 = 0.50 m³/h.m² @ 50 Pa)[8]. CO_2 decay tests suggested the loft space had a background ventilation rate of 0.27 ACH (0.17 m³/h.m² @ 50 Pa). A blower door test of the loft reported 8.12 ACH @ 50 Pa (q50 = 5.0 m³/h.m² @ 50 Pa). The attic floor interface was estimated to have a permeability of 0.21 m³/h.m² @ 50 Pa (Effective Leakage Area 698 mm²). Largely owing to solar gains the Mould Risk Index values show the risk of mould formation in the loft is lower than those occurring in external conditions.

Cold roofs with horizontal insulation

Timusk, Seskus and Ary (1991) report that air pressure under the windward eaves soffit can result in (1) snow being blown into attic spaces, (2) wind penetrating through the attic insulation, and (3) wind penetration that can scour away loose cellulose insulation.

Recently Elwell et al. (2017) observed that the experimental wind speeds used in studies by Anderson (1981) and Simpson et al. (1988) were likely to be higher than those experienced in typical loft spaces. This led Elwell et al. to conclude that the in situ effect of wind speed on the performance of cold pitched insulated roofs is likely to be small. However, this assumption appears to neglect the risk of bulk air movement through insulation at the eaves. Other literature examined during the course of this review has not addressed this specific area of concern; however, differing strategies are evident, some of which appear to be more considered.

For instance, when one commonly used UK eaves detail[9], such as that in Figure 20, is compared to Nordic eaves details (Figures 21 and 22) there is a notable lack of wind protection. Anderlind (1992), Blom P. (2000), Ciucasu et al. (2005), and Wahlgren (2007) all show wind deflectors (*vindavledare*, Figure 21) extending beyond the plane of the insulation. This protection prevents insulation material being dislodged by the wind and avoids the insulation being subject to wind washing.

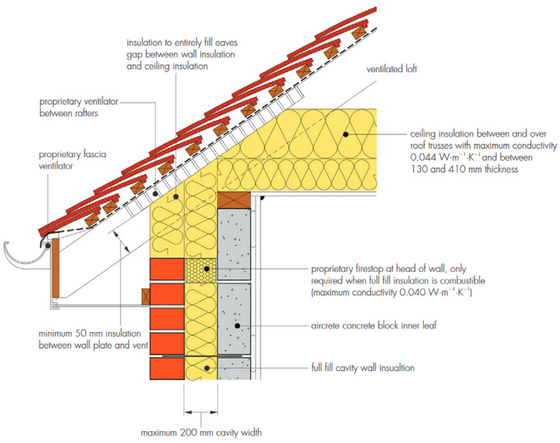


Figure 20: *A standard UK construction detail which is prone to wind washing (BBA and RDL, 2013)*

Figure 21: *A wind deflector / vindavledare (https://www.bygma.se)*

8 Increased dwelling air leakage arose from a worn/damaged door seal, measurement uncertainty and possible boiler panel leakage.

9 Other examples of UK eaves details have been produced by BBA and RDL (2012); LABC (2014); NHBC (2019); ZCH (2015 and 2016); Gov. Scot (2010).

Ciucasu et al. (2005) show dimensions (Figure 22) whereby the width of the ventilation slot is 25 mm, the thickness of the wind protection board (high density mineral wool) is 20 mm and the extended leg of the wind protection, following the rake of the roof, projects 300 mm into the roof space. Alternatively, measured perpendicular to the upper plane of the insulation, Blom shows the eaves wind deflector extending at least 100 mm into the roof space. Carlsson, Elmroth and Engvall (1980) show similar details and note that the external face of the high-density mineral wool insulation should be protected by building paper. Though not discussed in literature, given the position of eaves wind protection, it is notable that both high density mineral wool and building paper are vapour permeable. Unfortunately, wind deflector products are not currently available on the UK market, therefore it is up to designers and trades to form them from suitable wind proof, low permeance materials.

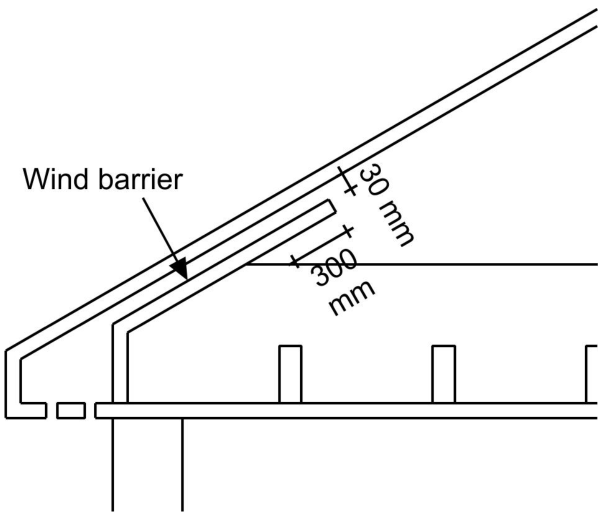


Figure 22: *Eaves detail (after Ciucasu et al., 2005)*

PRACTICAL IMPLICATIONS

The exposure of insulation to wind washing at corner and edge locations should be considered. Wherever possible, a continuous wind barrier should be provided, and where this is not possible (say at the eaves of cold roofs) appropriate wind deflectors should be put in place.

Air movement in vertical cavities

A form of wind washing occurs when air moves across a surface (Figure 23). Just like when you blow on a spoon of soup to cool it down, wind washing increases heat loss from a building. When wind is not present, or where buoyancy-induced airflow suppresses wind-induced airflow, thermal buoyancy becomes the primary driver of air movement (Falk and Sandin, 2013).

The extent to which wind washing can impact upon performance is influenced by the velocity of the air and the permeance of the surface that is exposed to the air movement. These subjects are explored in greater detail below.

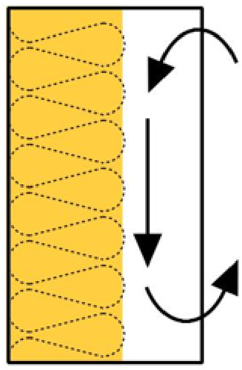


Figure 23: *Surface wind washing*

Air movement within vertical cavities (between ventilated cladding and the wind barrier)

The impact of air movement within cavities has been studied in order to understand the impact upon moisture transport. In this regard, Falk (2014) notes that cavities <10 mm wide are much less efficient than cavities with a depth of 25 mm and that the drying time is only reduced by increasing the cavity to 40 mm. Cavities greater than 25 mm permit greater air movement and may therefore be understood to increase the risk of wind washing, though they do not improve the performance of the capillary break formed by the cavity.

In this context, it is notable that the minimum cavity width permitted by the NHBC (2020), for cavity walls and panels with open joints, is a surprising 50 mm. Where baffled or labyrinth (rebated) joints are used the cavity can be reduced to 38 mm.

Poorly ventilated cavities

Often, due to the reduction in airflow, the air velocity within cavities with discrete vent holes (3 to 25 mm diameter and spaced 0.3 to 0.9 m apart) at both the top and bottom of an air gap cannot be measured (Sandin, 1991). Consequently, air exchange is measured instead (Sandin 1991, Hens 2007, Langmans and Roels 2015). Under these conditions it may be considered that the risk of wind washing is low. Langmans and Roels (2015) also observed that various measurement techniques do not provide consistent/comparable results. They report the measured air change rate behind masonry was in the range of 2-3 ACH. In summarising many years of field measurements which examined vented brick cavity walls, Hens et al. (2007) concluded no wind washing effect could be discerned in these poorly ventilated walls.

Ventilated cavities

Clearly, regarding thermal performance, ventilated cavities pose a more significant risk. Bortoloni et al. (2016) determined that solar-driven buoyancy becomes dominant at a wind speed <1.5 m/s, whilst Falk and Sandin (2012) observed that a wind speed of approximately 6 m/s was required to counteract buoyancy-driven air flow. Gullbrekken (2017a) established the air velocity in a 50 mm cavity ranged between 0–1.2 m/s when correlated with the air speed 10 m above the ground. Langmans & Roels (2015) note that air movement within the cavity took place in various directions and was related to wind pressure and direction, i.e. it could move up, down or sideways. Behind a vertical rainscreen they measured 100-1000 ACH.

Other observations

Pending further evidence, for buildings less than 10 m above the ground, it is inferred that buoyancy is the primary cause of air movement within a cavity. For buildings more than 10 m above the ground there is likely to be greater risk of wind-driven thermal bypass.

In a cavity with vertical timber battens, the mean velocity was 0.195 m/s (ranging 0.127 m/s to 0.253 m/s). Two cavities were formed by perforated horizontal battens, one with small holes and one with big holes. For small holes (5 mm dia, 6 rows @ 13 mm x 7.5 mm staggered cts.), the mean velocity was 0.080 m/s (ranging 0.061 m/s to 0.099 m/s). For big holes (18 mm dia., 1 row, @ 36 mm cts.), the mean velocity was 0.064 m/s ranging 0.040 m/s to 0.085 m/s (Falk and Sandin, 2012).

Wingfield & Miles-Shenton (2011) measured the velocity of air within the cavity of two masonry gable walls using hot bead anemometers with sensor cowls orientated to give flow velocity in either the vertical or horizontal direction. On days when there was measurable air flow, higher velocities were observed in the horizontal direction, which would appear to infer wind induced air movement.

Table 6 overleaf summarises the findings from a range of research studies. As the table presents measured cavity velocities, based upon Sandin (1991), it is inferred that the effective orifice area of each cavity is greater than “3 to 25 mm diameter and spaced 0.3 to 0.9 m apart.”

Reference	Cladding and exposure	Wind speed (m/s)	Cavity velocity (m/s)	Air changes (h^{-1})
Schwartz (1973)	**40 mm** residual cavity, smooth cladding, **18 storey** building	0 - 8	0.2 - 0.6	
Gudum (2003)	**25 mm** residual cavity, **1 storey** test building	0.7 - 2.1	0.12 - 0.22	260 - 480
Falk and Sandin (2012)	**25 mm** residual cavity, vertical battens behind smooth panels in **1 storey** test building	0 - 5	mean 0.195 (0.13 - 0.25)	
Silberstein, Arquis, McCaa (1991), Silberstein & Hens (1996)	**3 m high** masonry clad façade, residual cavity width unknown	7.5	0.02 - 0.18 0.06 ave.	
Wingfield & Miles-Shenton (2011) Leeds A	Partial fill insulated masonry cavity wall, **50 mm** residual air cavity (+/- 10 mm), **2 storey** gable, dwelling		(daily mean) 0.04 - 0.15	
Wingfield & Miles-Shenton (2011) Wakefield	Partial fill insulated masonry cavity wall, **50 mm** residual air cavity (+/- 10 mm), **2 storey** gable, dwelling		(daily mean) 0.05 to 0.1	

Table 6: *Summary of field measured velocities in vertical cavities*

PRACTICAL IMPLICATIONS

Vertical cavities (between ventilated cladding and the wind barrier)
The velocity of air within a cavity is strongly dependent upon wind exposure, stack effect, cavity width and the size of the orifices located at the top and bottom. Whilst it is beyond the scope of this paper to discuss these relationships further, Van Straaten (2016) explores this subject in more detail. For the purposes of this paper, an awareness of the measured cavity velocity (Tables 3 and 4) can be used to inform the performance criteria of the wind barrier, most notably those characteristics that influence the permeance of the wind barrier's surface.

Large orifices and cavities should be avoided to reduce risks such as rainwater penetration, spread of fire, insect infestation, excessive ventilation and poor thermal performance. Whilst acknowledging that some standards may require wider cavities, evidence suggests 25 mm should be sufficient in many instances.

Air movement in roofs (loft spaces and batten spaces)

Natural convection within roof voids (lofts and attics)

The influence of natural convection upon the thermal performance of loose-fill attic insulation was investigated by Wahlgren (2002). Following assessment using a large-scale attic test model, which included scenarios with and without attic ventilation, and on loose-fill rock wool (33.6 kg/m³) and fiberglass insulation

(9.4 kg/m³), it was concluded "Measurements of the attic floor insulation with rock wool loose-fill and without attic ventilation showed no sign of air movement that affects the thermal resistance of the insulation." However, it was also concluded that the highly permeable fiberglass loose-fill insulation was not suitable for attic insulation in cold climates.

Using simulation and measurement to study cold roofs with insulation thicknesses of up to 500 mm, Serkitjis and Hagentoft (1998) observed that the occurrence of natural convection in the air space over the surface of insulation (in this case polystyrene beads) has only a marginal effect on heat transfer in the underlying insulation. Serkitjis (2003) observed that both calculations and measurements show that the thermal performance of the loose fill insulation may deteriorate considerably due to external factors such as the wind.

Forced (wind-driven) convection within roof voids (lofts and attics)

In discussions, Powel (1983) suggested that unless the air velocity is high (1 m/s was considered unrealistically high), the thermal performance of exposed insulation would not be significantly affected. At the 1983 ASTM conference, Powel (1983) also noted, with reference to a paper by Scanlan et al. (1983), that 23 out of 24 field measurements found the actual thermal performance correlated with that predicted using the ASHRAE Handbook.

For a roof with horizontal insulation and a continuous 20 mm opening at the soffit of the eaves, Anderson and Ward (1981) studied air speeds within a loft space and concluded that, with external wind speeds ranging up to 10.4 m/s, the corresponding air speed within the loft was 0 – 0.3 m/s (98% of measurements were within the range 0 – 0.1 m/s). The majority of these measurements were located away from the eaves; however, a maximum air speed of 0.3 m/s was found 50 mm above horizontal attic insulation close to the eaves. This suggests, where a cold roof space is ventilated, the frequency and magnitude of detrimental air speeds within the loft is limited to those areas adjacent to the eaves.

Air movement within roof cavities (batten spaces of warm roofs/cathedral roofs)

Table 7 presents the cavity velocities for batten space roof cavities. Within an insulated compact/cathedral roof pitched at 22° where the external wind speed was no higher than 7 m/s, Silberstein and Hens (1996) reported a cavity velocity of up to 1.5 m/s.

Reference	Cladding and exposure	Wind speed (m/s)	Cavity velocity (m/s)	Air changes (h^{-1})
Silberstein, Arquis, McCaa (1991), Silberstein & Hens (1996)	Roof pitch 22°. Roof length 3 m.	0 - 6.75	0 - 1.4	0.4 ave.
Gullbrekken, 2017c	Wind speed measured 10 m above the ground.		0 - 1.2	260 - 480

Table 7: *Summary of field measured velocities in batten space roof cavities*

Silberstein (1991) examined the impact of force convection effects in fibrous thermal insulation by conducting a laboratory hot box study and field study to understand the impact of air movement across the surface of insulation located within roof and wall cavities. Silberstein concluded: "..air penetration into the insulating material is not sensitive for commonly encountered flow velocities of about 0.5 m/s and less" and went on to note "velocities in the cavities remain very low, and have little dependence on external wind speed. On average one can consider that velocities remain around 0.5 m/s with peaks around 1.5 m/s for high wind speeds." For these velocities, with a fairly windtight construction and good workmanship, a marked decrease in thermal performance was not expected.

Across various seasons/periods, Gullbrekken (2017c) reports the air velocity inside the batten space as a function of wind speed at 10 m above ground level. The air velocity inside the air cavity was reported to range between 0 - 1.2 m/s.

PRACTICAL IMPLICATIONS

Pitched cavities
The limited data that has been found suggests that the cavity velocity within a pitched compact roof is higher than other roof types. Taken at face value, this suggests windtightness is more important for compact/cathedral roofs.

Roof void with horizontal insulation
With suitably dense insulation the low air velocities identified suggest the risk of wind washing is limited, though care should be taken to protect insulation located at the eaves. No research has been identified that proves or disproves whether loose fill is preferable to rolls, however, experience suggests blown fibre is preferable because it fits around trusses more readily, avoids joints and does not involve the time-consuming task of scribing insulation around roof trusses and other obstructions.

Permeance: Forming an effective wind barrier without using a membrane

As far back as 1967, Wolf, Solvason and Wilson presented an analysis which showed that the thermal resistance of 50 mm thick mineral wool insulation can be significantly reduced when both sides of insulation were exposed to air spaces. Furthermore, it was observed that the influence of air flow increased as the overall temperature difference increased. When compared to cases where a convection barrier was installed on either one or both sides of the insulation, at -12°C (10°F), heat loss increased by approximately 216% to 240%. Later, Berlad et al. (1979) experimentally observed that air movement has a detrimental impact upon a permeable insulation system, including instances where the insulator was sealed on all sides but one. Furthermore, perfectly sealed permeable insulators can have their effective resistance degraded by natural convective processes.

Whilst it is acknowledged that wind barrier membranes are often preferred because they offer low air permeance and high vapour permeability, it is important to realise that they may not be suited to all types of building construction. Therefore, in the absence of a membrane insulation surface remains exposed to potential wind washing effects. Though the impact of surface wind washing upon the surface of insulation has received limited research, it would appear that the permeance of a material is influenced by its density. The following paragraphs summarise the literature which has been found to date.

Bankvall (1978a) reports upon experiments which were undertaken on a windtight wall with “no” defects. The wall, subject to an air velocity of 2.5 m/s (corresponding to a pressure gradient of 0.7 Pa/m) parallel to the insulation (density 16.3 kg/m^3), suffered less than 10% degradation in thermal performance. For context, it is noted that a degradation of more than 5% exceeds the performance requirement underpinning the standards developed by Uvsløkk (1996a). It is also noted that the velocity reported by Bankvall is greater than that observed in (low rise/domestic height) cavities both within Straube (2018) and other papers that have been consulted (see Table 3).

In contrast, laboratory hotbox tests on attic insulation undertaken by Taylor & Phillips (1983) found that an air velocity of 1.0 m/s parallel to the insulation resulted in a 40% reduction in thermal resistance (insulation density 10 to 12 kg/m^3). When ill-fitting insulation was subject to 5% gaps lengthwise and widthwise, the results indicated a 60% reduction in the thermal resistance.

Straube (2018) reports that Tanner and Ghazi (1996) studied glass fibre (20 kg/m^3) and mineral wool (62 kg/m^3) which was exposed to cavity air velocities of 0.3 and 1.0 m/s. Quoting Tanner and Ghazi Straube states there “was ‘practically no influence’ on the measured thermal performance” on the measured thermal performance.

In considering mineral wool insulation, Van Straaten et al. (2016) and Straube (2018) presented results from a number of experimental measurements which considered the impact of air movement along a cavity at a range of velocities. After noting that their samples were installed with greater care and against a flatter, more consistent substrate than is typically found in the field, they confirmed the importance of good workmanship and the need to avoid joints and air gaps that permit air movement through and behind the insulation. The observations made by Van Straaten et al. (2016) support the need for designers to specify the flatness and surface regularity of the substrates.

Based upon 25 and 50 mm thick samples of mineral wool which were exposed to velocities ranging between 0 and 1 m/s, Van Straaten et al. (2016) confirmed that in order to experience negligible wind washing, mineral wool with a density of 70 kg/m³ is required, while Straube (2018) suggests a density of more than 64 kg/m³ should be sufficient.

PRACTICAL IMPLICATIONS

Where cladding is vented and where a wind barrier membrane is not present, high air permeance insulation products should be avoided. In light of the literature presented in Table 3, which suggests cavities in buildings up to 18 storeys high are unlikely to experience an air velocity greater than 1 m/s for a significant period of time, based upon the work undertaken by Van Straaten et al. (2016) and Straube (2018), it is concluded that exposed mineral wool should have a density of 64 kg/m³ or greater to mitigate against surface wind washing. Whilst other types of insulation can, no doubt, resist surface wind washing, this review has not succeeded in identifying any empirical evidence which supports this.

It is important to recognise that the studies above tend to consider surface wind washing in isolation. In addition, they also assume that the materials form an infinite uninterrupted surface. In practice, whether they are sheets, batts or rolls, these products will have limited dimensions. For this reason, the impact of joints, interfaces, air gaps, flexibility and the flatness of the substrate upon the thermal performance of the material must also be considered. Consideration of this matter is given below when discussing the wind barrier system and in Section 2: Convective loops in wall constructions above.

Vertical and pitched insulation

The papers reviewed in Section 2 suggest that joints within insulation systems should be protected from both forced convection (wind washing) and natural convection (stack effect). This can be achieved by encapsulating the insulation on all six sides. Wind washing effects can be reduced by providing an appropriate standard of windtightness detailing at the joints (the standard of workmanship required for which is discussed in Section 4: The wind barrier system below).

Whilst further research is required, the theoretical risk of wind washing could be reduced by mounting insulation on a flat, regular surface and using a low permeance insulation system which consists of either:

1. multiple layers (say 2 or more), where the joints of each layer are staggered relative to each subsequent layer i.e. no joints should align, or,
2. tongue-and-groove, suitable lap-joints, or joints with a continuous sealant which bond to the substrate (this may include certain tapes, paints, parging treatment or renders). Where tapes, paints, parging treatment or renders are used they should be capable of withstanding the highest expected air pressure load, accommodating structural movement and not creep.

SECTION 4:

The wind barrier system

Performance criteria

In Norway, based upon research examining glass wool (21.0 kg/m³) and mineral wool (31.9 kg/m³), Uvsløkk (1996a) developed a windtightness standard. This limited heat loss caused by air movement (namely wind washing) to less than 5% of the notional U-value. The standard was based upon a notional U-value of 0.27 W/m².K and a windtightness of 0.05 m³/m² h Pa (1.4E-5 m³/m² s Pa), which is equivalent to an air permeability of 2.5 m³/h.m² @ 50 Pa.

To date, no comparable windtightness guidance has been identified for Building Regulations in the United Kingdom, Germany, Austria, or Passivhaus buildings. Therefore, if building performance issues are to be addressed, an appropriate windtightness target would be beneficial.

Based upon Uvsløkk (1996a), where the permeability of the windtightness layer is 2.5 m³/h.m² @ 50 Pa and as-built performance is to be within 5% of the design U-value (0.27 W/m².K), it is possible to suggest the requisite windtightness for a given U-value by assuming a linear relationship and extrapolating the results. Table 8, right, shows the resulting targets.

At a similar point in time, Ojanen's (1993) research focussed on corners, eaves and verge type locations as these are at the greatest risk of wind washing. Using numerical simulation and based upon glass wool thermal insulation (density of 17 - 20 kg/m³), threshold values were established for the thermal performance of wind barrier systems.

U-value	Windtightness target	
W/m².K	m³/m² h Pa	m³/h.m² @ 50 Pa
0.27*	*0.05**	2.5
0.2		1.9
0.15		1.4
0.1		0.9
0.05		0.5

** indicated by Uvsløkk (1996a)*

Table 8: *Leakage criteria (inc. joints) after Uvsløkk (1996a), where heat loss is limited to 5% of the notional U-value. (*original data shown in italics, remaining data based on an extrapolation assuming a linear flow pressure relation)*

Citing measurements undertaken by Kohonen et al. (1986), Ojanen limited any increase in heat loss to less than 10% of the design value. The research recommended three air permeance values, each relating to specific conditions (standard, corner and sheltered). The standard exposure value was for a wall for which a lower and upper range of permeability were provided (low/high in Table 9). However, this value was adjusted for corners because convection in these locations significantly increases heat losses. It is therefore recommended that the wind barrier in this location has a significantly lower air permeability. Where, due to sheltering, winds do not result in a pressure gradient, the air permeance of the wind barrier could be reduced.

Although the construction and thickness of the insulation for walls and roof was given by Ojanen (1993), the thermal conductivity of insulation is not stated. Therefore, assuming a thermal conductivity of 0.04 W/mK, the notional U-value has been calculated to be 0.2 W/m².K. Applying the same methodology used with the Uvsløkk (1996a) example (where, assuming a linear relationship, the windtightness target is determined by extrapolation) it is possible to suggest the requisite windtightness based upon the work undertaken by Ojanen (1993). The extrapolated windtightness targets are presented in Table 9:

U-value W/m².K	Windtightness target m³/h.m² @ 50 Pa			
	Standard (low)	Standard (high)	Corner	Sheltered
*0.20**	*4.5**	*5.4**	*1.8**	*18.0**
0.15	3.4	4.1	1.4	13.5
0.10	2.3	2.7	0.9	9.0
0.05	1.1	1.4	0.5	4.5

Table 9: *Leakage criteria after Ojanen (1993), where heat loss is limited to 10% of the notional U-value. (* original data shown in italics, remaining data based on extrapolation)*

It is notable that Uvsløkk's performance requirements broadly align with Ojanen's windtightness target for the corner condition. Thus, in terms of a practical, deliverable quality assurance standard, it is not unreasonable to expect wind barriers to conform with extrapolations based upon Uvsløkk's performance parameters. Furthermore, it is recognised that even in the most challenging of circumstances, these performance targets are no more onerous than the airtightness requirements for Passivhaus buildings.

PRACTICAL IMPLICATIONS

If we are to limit the effect of air movement to 5% of the reference U-value, then the performance specifications given above clearly demonstrate the need to avoid joints that could permit open loop bypass behind the insulation.

Whether or not the proposals in Tables 5 and 6 accurately reflect the scientific reality remains uncertain. However, in the absence of more specific research papers (that would specifically consider the impact of windtightness and convection upon super insulation), when seeking to maintain heat losses incurred by wind washing to 5%, the above tables currently offer the most reasonable estimates for performance targets that are currently available.

Whilst it is difficult to measure windtightness (due to construction sequencing), the reference values given in Tables 5 and 6 infer that prevention of avoidable thermal bypasses requires a good standard of workmanship and that all joints and interfaces along the plane of the wind barrier should be sealed. Depending upon the nature of the substrate, joints may be mechanically closed (pressure batten), wind barrier taped or parged.

SECTION 5:

The air barrier system

Performance criteria

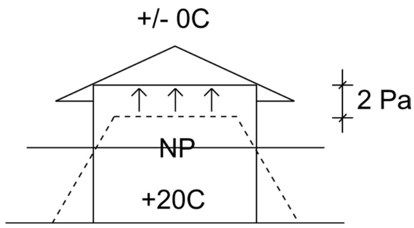


Figure 24: Neutral pressure plane of a dwelling

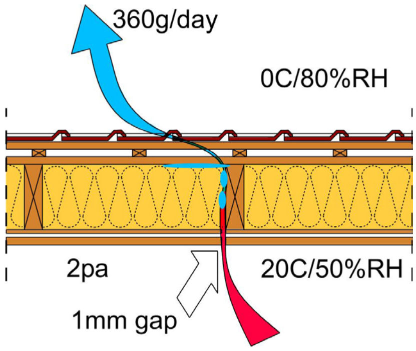


Figure 25: After Kaufmann et al (2002)

Airtightness is an umbrella term that can be used to establish performance criteria that impact upon thermal performance, moisture tolerance, sound insulation, draught discomfort and energy consumption.

It can be observed from Ganguli (1986) that above the neutral plane, at a temperature difference of 20°C, the stack effect exerts a pressure roughly equivalent to 1 Pa/m, and that at a temperature difference of 40°C this rises to approximately 2.2 Pa/m. Consequently, a pressure of roughly 2 Pa is normally exerted upon the upper ceiling of a two-storey building (Figure 24). This pressure difference is capable of transporting warm, moist air into the building envelope which can in turn lead to the rot and decay of timber.

With mature contributions appearing during the 1960s, it has long been established that airtightness is required to prevent interstitial condensation (Hutcheon, 1954; Hutcheon; 1960; Wilson 1961; Garden 1965; Wilson and Garden 1965 to name a few). By the late 1970s Canadian research had moved from understanding the effects of air leakage to recognising the need to control air leakage.

On the heels of this work, between 1981 and 1984, Eyre and Jennings published various editions of 'Air-Vapour Barriers' with clearly described diagrams and construction details showing how air-vapour barriers could be successfully implemented. The functional distinction between an air barrier and a vapour barrier was clearly articulated by 1985 (Quirouette, 1985) and the Canadian R2000 Home Program - which required dwellings to pass a depressurisation test, with an air leakage rate of less than 1.5 ACH @ 50 Pa (CHBA, 1987) - began in 1982.

'Airtightness and Thermal Insulation' (Carlsson, Elmroth and Engvall, 1980) reports on over 20 Swedish dwellings, built in accordance with SBN 1975, that achieved levels of airtightness ranging between 0.5 and 1.4 ACH @ 50 Pa, whilst recognising Swedish construction standards required buildings to achieve 3 ACH @ 50 Pa. Within this same kind of time frame, in the USA, Nisson and Dutt (1985) recommend an airtightness target of between 1 and 3 ACH @ 50 Pa.

By the mid 1980s, measurements undertaken by Harrje et al. (1986) confirmed that, because of the stack effect, air transfer between the attic and living space was negligible. These findings have been confirmed in more recent tracer gas measurements, reported by Roppel et al. (2013, 2014). However, what has been less well understood is the level of airtightness required to avoid these risks. More recently, Hansen (2021) documented measurements from 30 Danish dwellings and observed that air exchange did take place in both directions (from attic to living space and vice versa) during both the summer and the winter. Across the 30 dwellings measured, the average downward air exchange was approximately 22 m^3/h. The differences in these findings (Harrje et al., Roppel et al. and Hansen) may relate to the standard of airtightness achieved across the attic/loft floor.

As the positive pressure caused by the stack effect cannot be easily controlled in dwellings with balanced ventilation, Kalamees and Kurnitski (2010) concluded that it was essential to employ a good standard of airtightness to limit the exfiltration of moist air (4 g/m^3) into roof spaces located in cold climates. For two storey dwellings with roof spaces which include a roof sheathing with a high thermal resistance and water vapour permeability (such as mineral wool), they recommend an airtightness of 0.33 L/(s.m) @ 50 Pa (no condensation) to 0.63 L/(s.m) @ 50 Pa (condensation < 0.5 g/m^2), which respectively equates to a permeability of 1.19 to 2.27 $m^3/h.m^2$ @ 50 Pa. The research determined that the high vapour permeability and good thermal resistance give mineral wool-board sheathing, covered with SBPO film, better drying potential compared to the 12 mm wood fibreboard where condensation was identified. Consequently, mineral wool sheathing was found to be much more tolerant to exfiltration, especially at low moisture excess values. Dynamic simulation determined that following cold conditions (-10°C), a relatively short 1.5 month drying out period was required (Kalamees and Kurnitski, 2010). By not stating an airtightness standard for wood fibreboard, it is inferred that the authors do not endorse this approach as they believe the airtightness requirements are likely to be beyond practical limits.

Introduced in 1996, the Passivhaus standard requires buildings to achieve an air leakage rate of less than 0.6 ACH @ 50 Pa under pressurisation and depressurisation (Johnston et al., 2020). At a similar point in time, in Canada, Di Lenardo et al. (1995) prescribed a target value for the air permeability of air barrier systems, including anticipated joints and perforations (according to Jansenns (1998) 2.7 10^{-6} $m^3/s.m^2/Pa$, which equates to 0.00972 $m^3/h.m^2/Pa$, or 0.486 $m^3/h.m^2$ @ 50 Pa). This value is based on numerical simulations using the Canadian climate which considered, as a function of the water permeance of the materials on the cold side of the thermal insulation, limiting values for moisture accumulation and the increase in heat transfer due to air leakage, which was capped at 15%. However, it is not clear which U-value provided the datum for the 15% reference value. It is considered to be likely that the U-value was greater than 0.2 $W/m^2.K$, therefore, with regard to thermal bypass, the performance target should be considered with care.

In 2000, Di Lenardo updated the work. Table 7 shows revised air leakage rates, derived from calculations, where the maximum permissible air leakage rate was determined using a vapour barrier (3.33 Sd-value) on the warm side and interior conditions of 21°C and 35% RH (at 20°C RH = 37%).

It is understood from Roels and Langmans (2016), that Straube (2011) proposed tightening Di Lenardo's 1995 limit from 0.00972 $m^3/h.m^2/Pa$ (0.486 $m^3/h.m^2$ @ 50 Pa) to 0.0047 $m^3/h.m^2/Pa$ (0.235 $m^3/h.m^2$ @ 50 Pa). In recognition of vapour permeability, Straube's assessment is consistent with the later work undertaken by Di Lenardo (2000), which is given in Table 10.

Sd-value of outermost uninsulated (non-vented) layer of the wall assembly (metres)	**Maximum permissible air leakage rates** ($m^3/h.m^2$ @ 50 Pa)
13.3 to <3.33	**0.12**
3.33 to <1.18	**0.24**
1.18 to <0.25	**0.36**
>0.25	**0.48**

Table 10: *Permissible air leakage rates, based on Di Lenardo (2000). NOTE: For the purposes of this paper ng/(Pa•s•m²) has been converted to Sd-value and air leakage rates, assuming a linear flow coefficient, have been converted from 75 Pa to 50 Pa.*

In other work, Feist et al. (2005) present the results of calculations developed to prevent moisture accumulation and moisture damage in roof spaces. Feist et al. recommend an air permeability of 2 $m^3/h.m^2$ @ 50 Pa, where the fabric is diffusion-open, and an air permeability of 0.5 $m^3/h.m^2$ @ 50 Pa where it is diffusion-closed construction.

In addition to improving thermal comfort by avoiding draughts, reducing heat loss, reducing energy bills and avoiding unnecessary carbon emissions, Van Den Bossche (2013) observed that airtightness is necessary for reducing the risk of wind-driven rain, which can cause moisture damage at the window-wall interface.

As there is not a linear relationship between n50 (required by the Passivhaus standard) and q50, which is used for regulatory purposes in the UK, the air permeability of large buildings or buildings with a low surface area to volume ratio (such as terraced dwellings) could exceed 0.6 $m^3/h.m^2$ @ 50 Pa whilst obtaining an n50 of < 0.6 ACH @ 50Pa. The Passive House Institute defines large buildings as those buildings with an air volume Vn50 ≥ 1500m^3. Such buildings must achieve an air permeability < 0.6 $m^3/h.m^2$ @ 50 Pa and an n50 <0.6 ACH @ 50 Pa.

The Passivhaus Database (passivehouse-database.org), a voluntary index of Passivhaus buildings, contains over 3014 projects where the air leakage of each newbuild is < 0.6 ACH @ 50 Pa. A growing number of projects achieve < 0.1 ACH @ 50 Pa with the lowest air leakage result on the database being 0.01 ACH @ 50 Pa (project ID: 4848). In the UK, a non-domestic building (project ID: 6550) has achieved an air leakage rate of 0.033 ACH @ 50 Pa and an air permeability of 0.06 $m^3/h.m^2$ @ 50 Pa. The UK's most airtight house, with a permeability of 0.041 $m^3/h.m^2$ @ 50 Pa, achieved an air leakage rate of 0.047 ACH @ 50 Pa (project ID: 6029) i.e. some 195 times more airtight than required by the Building Regulations/Standards in England, Wales and Scotland (Gov, 2022; Gov. Wales, 2022) and 171 times more airtight than required by Scottish Building Regulations (Gov. Scot, 2022).

PRACTICAL IMPLICATIONS

When considering moisture risks, air permeability is a useful metric. Pending further UK based research, an air permeability of 0.5 $m^3/h.m^2$ @ 50 Pa or lower is appropriate and a growing body of evidence demonstrates that it is both possible and practical to achieve this level of air permeability in UK buildings.

Buildings designed to achieve Passivhaus, EnerPHit and PHI Low Energy Building standards should be tested in accordance with the criteria set out in PHI (2022). For more guidance about how to plan for and deliver a high standard of airtightness, refer to the Passivhaus Trust's 'Demystifying airtightness: Good practice guide' (PHT, 2020).

Longevity of air barriers

Research by Elmroth and Logdberg (1980) and Warren and Webb (1980) suggests air leakage increases over time as the building fabric settles and shrinks. Furthermore, wear-and-tear and changes by the occupants can influence the longevity of a building's airtightness.

Airtightness tests on homes built to the R2000 standard, established that the homes "demonstrated possible, albeit slight, evidence of airtightness degradation over monitoring periods which ranged up to thirty-six months" (Proskiw & Eng, 1997).

Investigating the long-term performance of Passivhaus buildings in North East England, Siddall et al. (2016) returned to dwellings 5 years after construction and undertook blower door tests to determine whether airtightness had degraded. Allowing for uncertainty arising from an unavoidable variation in the test procedure, the results suggested that the air leakage remained unchanged since the original completion tests were undertaken in 2011. This conclusion is backed up with further studies presented in Hasper et al. (2021).

Orr et al. (2012) examined the airtightness of six older generation energy efficient houses in Saskatoon, Canada. After 20–30 years, the air leakage ranged from 0.78 to 2.55 ACH @ 50 Pa with four houses below 1.50 ACH @ 50 Pa. One house built in 1992 had an original air leakage of 0.47 ACH @ 50 Pa, and 20 years later, this had increased to 0.78 ACH @ 50 Pa.

The durability of building fabric components in Passivhaus buildings was explored by Feist (2019) where over 25 years, there was a negligible increase in air leakage from n50 = 0.21 ACH @ 50 Pa to n50 0.26 ACH @ 50 Pa.

PRACTICAL IMPLICATIONS

With good airtightness design and execution, excellent long-term performance can be achieved. Further longitudinal research is warranted in order to evidence long-term trends.

SECTION 6:

Air and wind barrier strategies

The air and wind barrier can be placed in a range of positions within a given build-up. Each position has strengths and weaknesses which should be considered on a project-by-project basis. A range of options are shown in Table 8 overleaf. However, as external air barriers warrant specific consideration, there is greater discussion of that subject below.

External air barrier

At first glance, external air barriers are an attractive proposition as they could be easier to construct and have lower cost of installation. However, they are not without risks.

In an attempt to avoid wind washing, Timusk, Seskus and Ary (1991) investigated using an external air barrier system formed from a diffusion-open, spun bonded polyolephin, both in laboratory conditions and on a prototype dwelling which achieved an air leakage rate of 1.33 ACH @ 50 Pa. Whilst the concept was successful at reducing wind washing, hygrothermal risks do not appear to have been explored in any great detail.

Hens (2002) observed that a combined external wind/air barrier could permit wind washing as it could act like a diaphragm whereby warm internal air is drawn into the depth of the wall element, assisting heat loss and thus increasing the U-value.

More recently, the application of external air barriers to walls insulated with blown cellulose (60 kg/m^3) and mineral wool (30 kg/m^3) has been considered for European climates (Langmans, Klein & Roles 2010, 2012, 2013a, 2013b, 2013c; Langmans 2013; and Langmans & Roels, 2015b). A range of external air barriers were considered by the study, including OSB, fibre cement board (FCB), 18 mm bituminous impregnated fibreboard (BIFB) and spun bonded foils.

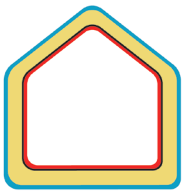
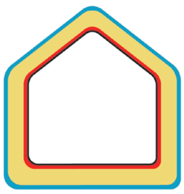
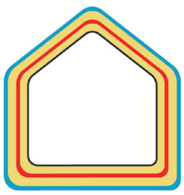
Analysis determined that Northern and Western Europe (including Ireland and the United Kingdom) are most vulnerable to moisture problems. Drier, more continental climates (such as Berlin and Vienna) were considered sufficiently dry to be suitable for external air barrier solutions. Moisture problems were limited to walls insulated with mineral wool, as they were found to suffer from excessive mould risk on the upper parts of the exterior air barrier. Furthermore, with a 3 mm air gap on both sides of the mineral wool insulation, simulations showed a 10% increase of the yearly heat loss.

PRACTICAL IMPLICATIONS

Wall systems with an external air barrier and mineral wool cannot be recommended. However, the combination of higher density insulation and close contact between blown fibre insulation and the adjacent layers means natural convention, and subsequent moisture loads, become negligible. Therefore, a well-executed wall with blown cellulose insulation (>60 kg/m^3) and a hygroscopic external air barrier can be considered, but only once supported by climate specific moisture analysis, undertaken in accordance with BS EN 15026 (BSI, 2007). In light of the above, appropriately formed internal air barriers successfully contribute to reducing the risk of interstitial condensation.

Air barrier strategies

The following Table 11 has been informed by the papers discussed in this technical review and has been developed with specific reference to Carlsson (1980), Elmroth (1983), Timusk (1991), Proskiw (1997), Langmans (2013c).

Construction principle	Advantages	Disadvantages
 **Internal airtightness e.g. plaster or parge**	• Uses common material properties • Can be checked relatively easily and rectified where necessary • Ease of access for repair and maintenance	• The barrier lies unprotected • Risk of puncturing during construction and building life • The joints must be sealed carefully particularly at floors and roofs e.g. locations sensitive to movement and subsequent crack formation NOTE: Plasterboard is not a suitable long term air barrier.
 **Internal sealing layer e.g. membrane, OSB**	• Vapour barrier can naturally be used for air sealing as well • Large membranes can be used, reducing the number of taped joints • Without a service void it is difficult to provide electrical distribution whilst avoiding penetrations through the air barrier	• Certain difficult construction problems • Accuracy required at joints • Risk of puncturing during construction and building life • Services installation penetrations cause problems • Ease of access for repair is impaired
 **Drawn under sealing layer e.g. service void, or air barrier place outside of the structure (but on the warm side of the insulation)**	• Vapour barrier can naturally be used for air sealing as well • Large membranes can be used, reducing the number of taped joints • Air sealing layer is protected against damage • A service void accommodates electrical installation, DIY projects, and future rewiring etc (during the operational life) without the air barrier being damaged • Good prospects of achieving high level of airtightness • Reduced risk of puncturing during construction and building life	• Moisture damage risks not known (temperate climates: membrane max 1/3rd depth of insulation from warm side) • The effects of supplementary insulation and carpentry and furnishing, e.g. on moisture conditions in the sealing strip, in particular, are unknown • Requires double wooden frame or EWI strategy • Ease of access for repair is impaired

continues over...

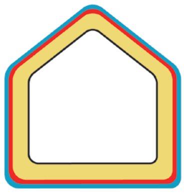
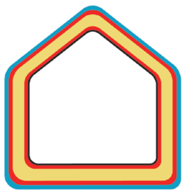
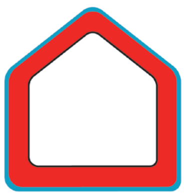
Construction principle	Advantages	Disadvantages
 **External air sealing and wind protection**	• The wind protection system's air sealing properties can be used • It can form a part of a pressurised rainscreen • Allows early installation, inspection, testing and remediation without disruption to programme and before substantial completion • Allows for conventional scheduling of sub-trades • Barrier not penetrated by floors, partitions, or electrical services • Avoids the requirement for cable seals/ polypan or strapping to accommodate services • Can be repaired externally before being covered • Allows ease of site access and has fewer complicated junctions • Ease of access for repair (does not cause disruption to occupant) • Electrical installations, DIY projects, future rewiring etc (during the operational life) is possible without sealing strip being damaged	WARNING: TO BE READ WITH DISCUSSION IN PARAGRAPHS ABOVE. • Moisture can condense inside the construction (ensure suitably vapour permeable wind barrier) • Provided that a reliable and effective vapour barrier system is employed on the warm side of the building fabric, moisture diffusion can be attenuated. • The layer is affected by the external climate; consequently materials and joints are exposed to more extreme moisture and temperature conditions. In order to ensure long term integrity, suitable methods for sealing the envelope should be considered. • Stringent requirements on internal vapour barrier
 **Combination of internal and external air sealing**	• Double safety for air sealing	• Use of double sealing layers is impractical and uneconomic (there can be only one successful air barrier)
 **Homogenous construction**	• Simple design • Electrical cables can be included without jeopardising airtightness	• Limited choice of materials which are both insulating and airtight • Connection details to other materials have to be solved separately • All building sections should be able to be carried out applying the same system, which limits the method and choice of material.

Table 11: *Wind and air barrier concepts*
(Red = Air barrier, Blue = Wind barrier, Yellow = Insulation)

SECTION 7:

Designing out thermal bypass risks

Understandably, the selection of construction technologies is dependent upon the brief for any specific building, However, the strategies that allow successful implementation require consideration from an early stage. The Passivhaus Trust technical guide 'Demystifying airtightness: Good practice guide' (PHT, 2020) provides a sound basis for much informed decision-making and includes an overlay for the RIBA Plan of Work. In addition, this guide - the one you are reading - adds further nuance. For strategic decision-making, the following guidance notes are relevant:

Air and wind barrier design

The principal recommendations are to eliminate air gaps within and either side of the insulation layer, to preserve airtight construction, and to protect the insulation layer against wind induced air movement. However, to achieve this there are several simple guides that can assist with the design and construction of insulation, air and wind barriers:

Encapsulation

1. Encapsulate the insulation between the wind and air barrier. To achieve this, voids should be designed out i.e. the insulation must completely fill the cavity. This may be achieved by ensuring that insulation is 10 mm to 15 mm thicker than is technically required by U-value calculations. This will help ensure that the insulation is lightly compressed across the entire surface area by the encapsulating material. **NOTE:** Compression should not be to the extent that deformations occur.

   It may also be considered wise to consider the insulation installation methodology: e.g. for timber frame installation from the outside towards the air barrier. This would help to be doubly certain that voids are not formed on the warm side of the insulation.
2. Avoid the possibility of forming interlinking cavities by designing the building elements as discrete components i.e. close cavities at wall-to-wall junctions (including corners), between walls and roofs and walls and floors. To avoid thermal bridging, the cavity may be closed with a membrane or, where cavity barriers are required, insulation wrapped in a polythene sheath.
3. Junction rule for insulation: No gaps, misalignment or interruptions. Workmanship: ensure that all insulation is square cut with a sharp knife. Stagger joints where insulation is more than one layer deep.

Planning an air or wind barrier

1. Mark up the plans, sections and details so that they clearly delineate continuous insulation and barrier systems, for example using a red line for airtightness, a blue line for windtightness and an orange for the insulation (Elmroth, 1983; Webb and Barton, 2002).
2. If you can't draw it (or haven't drawn it) it can't be built. All details need to be planned well in advance. Furthermore, no 'site fixes' should be permitted. Where alterations are required, a proper change control procedure should be implemented. Where necessary, they should be resolved in three dimensions, with supporting axonometric drawings.
3. Keep it simple, keep it safe: to avoid errors and complexity ensure that the air barrier is in the same plane throughout the structure (Elmroth and Levin, 1983). In essence, avoid complicated solutions that create kinks and bends and require skills in origami.
4. Ensure that the respective barrier remains unbroken. Pay particular attention to continuity at structural openings and services penetrations. If you identify any gaps, find a simple solution that allows the barrier to be continuous (Elmroth and Levin, 1983).
5. Do it once, do it right: Determine the principal air barrier and ensure that this is tested and where necessary easily accessed and repaired. Do not rely upon the secondary sealing of non-air barrier systems to achieve airtightness (this is costly, time consuming and very likely to result in poor longevity of the air barrier) (Wingfield et al., 2007).

The planar barriers

Airtightness and windtightness is not about making sure that materials “tightly abutt” using tapes, foams or adhesives. This is a common error. A masonry wall without the parge coat will not achieve adequate standards of airtightness. It is, therefore, key to identify a continuous surface that will function as the air barrier i.e. not the wall but the plaster.

1. Identify the airtight plane of each element.
2. Ensure that this plane can be connected to the next. For example, extend the plaster into the reveals so as to allow easy connection to the frames.
3. All joints in the barrier should be supported by a rigid element.
4. Minimise and seal of joints: when using membranes use wide rolls or when using masonry specify continuous wet plaster/parge finishes.
5. Choose suitably airtight materials that are capable of withstanding wind pressures and stack effect (Webb and Barton, 2002; Elmroth and Levin, 1983).
6. Ensure that materials are durable and that maintenance access can be achieved (Webb and Barton, 2002).
7. Ensure that the air barrier extends into unseen areas including behind kitchen units, baths, floor voids, dropped soffits and staircases.

Linear barriers and nodal junctions

Conceptually there are two types of joint:

- 2D (linear, abutment corners) and
- 3D (nodes, which are formed by the connection of three or more construction components, such as a corner interface where the wall/wall/ceiling intersect).

Experience from Passivhaus projects suggests that it is the junctions that remain the problematic connection, so with regard to airtightness and windtightness, the following should be considered:

1. All sealed planar elements will have to lead to a 3D nodal connection point.
2. It is almost impossible to make offset/complex 3D connections airtight, therefore i) they should be avoided wherever possible ii) Individual 3D nodal connections should be separated sufficiently to allow practical installation.
3. Consider building movement and settlement appropriately i.e. a door frame and plaster can move due to drying, expansion and contraction, movement (opening closing doors etc). The joint has to be able to cope with movement in the order of ~2 mm. Tapes and membranes can withstand this degree of movement. Alternatively, a plaster stop-bead can be used to form a joint >8 mm wide, this can then be filled with silicone or acrylic mastic Pokorny (2007). Any designed gap should be of sufficient size for the sealing process to be effective, and a gap of around 15±5 mm is suggested as appropriate for most situations (Elmroth, 1983).

Penetrations and perforations

1. Designed penetrations in the sealing layer should be avoided or at least minimised (Elmroth, 1983).
2. Before air testing, and certainly before covering, seal all perforations. Small holes may be taped or caulked, large holes of tears should be repaired using a membrane patch that is caulked and mechanically fixed in place (Eyre, 1984).

Construction

1. Be familiar with the airtightness requirements, including the items above.
2. Where barriers could be subject to damage, provide temporary protection (ply sheet or some other panel material). Typical examples might include, wall/ floor junctions, and doors openings require particular attention. During some preparatory work, membranes may be tucked safely away from damage by temporary stapling.

Longevity

According to Quirouette (1985), to function successfully over time, the design and assembly of both wind and air barriers should

1. withstand the highest expected air pressure load, whether it is inward or outward, without risk of rupture of detachment from the supporting substrate.
2. withstand structural movement including deflection and settlement, without displacing other materials such as insulation.
3. Not creep away from the substrate when exposed to pressure differences or under self-load.

SECTION 8:

Site inspections and visual assessment

In the USA, RESNET (2013) has documented a practical example of describing the quality of workmanship that is expected on site and offers a practical means of assessment. The standard developed three classifications of assessment. Based upon the evidence presented above, Grade A would appear to be the most relevant.

PRACTICAL IMPLICATIONS

In addition to relevant aspects of the guidance set out above, the following guidelines should be included:

Joints and gaps (Figure 26):

1. Insulation should be installed according to the manufacturer's instructions and the contract documents i.e. construction details and specifications.
2. Insulation should completely fill the cavity and be encapsulated on all six sides (very small and minor gaps (up to 3 mm wide and 600 mm long) are acceptable i.e. the substrate should never be visible).
3. Where cables and pipes exist within the insulation (within service voids), it should be cut around electrical junction boxes, and where appropriate split around wires and pipes.
4. Occasional very small irregularities are acceptable (see Figures 25 and 26).

Compression and incomplete fill (Figure 27):

1. Insulation should not be compressed, have tuck ends or spots which are incompletely filled and exceed 2% of the total area. If a spot is incompletely filled, any localised compression should be no more than 10% of the total depth or 10 mm, whichever is smaller. The total compressed area should not be clustered into one zone.

Where the conditions above are not met, then the insulation should be removed and replaced.

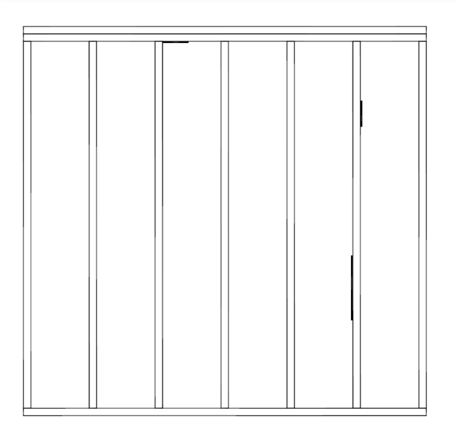


Figure 26: *Occasional very small irregularities are acceptable*

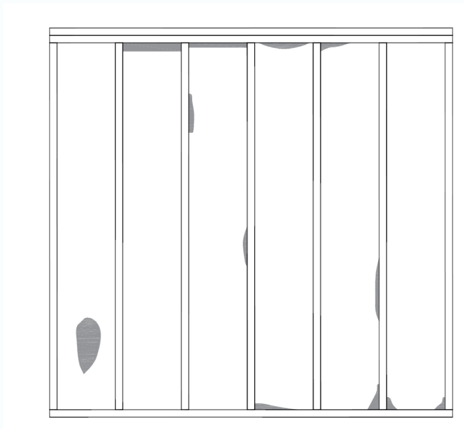


Figure 27: *Light compression or incomplete fill amounting to 2% or less, if the empty spaces are less than 10% of the intended fill thickness, or 10 mm, whichever is smaller*

To create a sound foundation of understanding, include suitable workmanship clauses which will enable the contractor to appreciate and understand expectations prior to commencing.

SECTION 9:

Building performance evaluation

The term 'building performance evaluation' is used to describe the process of gathering of quantitative and qualitative data and interpreting that information in order to draw conclusions about the performance of one or more of a building's attributes.

BS:40101 (BSI, 2022) establishes a framework for undertaking building performance evaluation and can be used to support analysis which identifies the presence/absence, magnitude and impact of thermal bypass mechanisms upon energy use and thermal comfort. Techniques include but are not limited to:

1. Thermographic surveys
2. Smoke tests
3. Tracer gas decay tests
4. Air velocity measurements
5. Temperature measurements
6. Heat flux measurements

Heat flux density measurements should be undertaken in accordance with ISO 9869-1:2014 (BSI, 2014). The total measurement uncertainty of these measurements lies between the quadrature sum and arithmetic sum of the errors, namely ±14% to 28% (BSI, 2014). Therefore, when all measurements are undertaken in accordance with ISO 9869-1:2014 (BSI, 2014), it can be assumed that the total uncertainty associated with the measurements is at most ±28%.

These spot measurements, which are taken with flux plates, are not necessarily representative of the performance of the element as a whole because building elements exhibit heterogeneous heat flow across their surfaces (BRE, 2014 & Pelsmakers, 2017). This means that, in order for measurements to be representative of one dimensional heat flow, the siting of flux plates needs to be carefully considered.

For well-insulated construction, when comparing the design intent with in-situ measurements, the appropriate value to scrutinise is the absolute difference in values, rather than the percentage difference in values. It is also important to consider the margin of error which, for well insulated construction (such as Passivhaus dwellings), can be comparatively high. According to Johnston et al. (2020) this can range from ±0.03 to ±0.08 W/K.

PRACTICAL IMPLICATIONS

To avoid conjecture during the interpretation of heat flux measurement results, secondary measurements aid understanding and can be used to support a theory. For instance, where a thermal bypass is suspected, in situ measurements showing the velocity and direction of air movement allow comparative analysis to be undertaken between the air movement and in situ heat flux measurements. Where there is a strong correlation between the two, a theory can be supported much more strongly.

SECTION 10:

Conclusion

CONCLUSION

Policy-makers, developers, designers and constructors need to be confident the buildings they are responsible for will perform as predicted. The evidence base considered in this paper clearly demonstrates that failures in design and construction do not have to be the norm and that they can, with the right knowledge, intent and skill, be addressed in practice and on the building site. As has been demonstrated in the literature, Passivhaus buildings clearly demonstrate how performance gaps can be closed reliably (Johnston et al., 2020).

This literature review, and the supplementary analysis undertaken to create a contextualised understanding of thermal bypass, supports the construction of contemporary high performance, low energy and Passivhaus buildings and clearly demonstrates that, if thermal performance gaps are to remain within an acceptable tolerance, then continuous insulation should be encapsulated on all sides by uninterrupted, unbroken air and wind barriers. Only once this is achieved will buildings deliver the energy savings, carbon emissions, comfort, health and well-being that owners, investors, occupants and future generations rightly expect.

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NOTE ON METHODOLOGY

Objective

Cost optimisation, durability (extended service life over the lifecycle), and high standards of energy efficiency are well established performance goals. The purpose of this literature review has been to summarise and disseminate the impact of thermal bypass mechanisms, develop an understanding of how they impact upon building performance and, where possible, present evidence documenting how these mechanisms can be managed and addressed so as to support policy makers, practitioners and consumers who might otherwise lack time or resources to undertake similar work.

Data sources

Peer-reviewed literature and related documentation such as guidance was accessed for this research. Relevant information was identified by inspecting citations and bibliographies presented within peer-reviewed literature, well-referenced reports and UK-based guidance, and then obtaining and reviewing copies of these documents in order to determine their relevance and usefulness. Though not exhaustive, this wide-ranging, branched gathering of evidence revealed 170 relevant documents covering a range of related sub-topics.

Study selection

Articles, textbook chapters and guidance dealing with the general subject area were reviewed and relevant laboratory and site measurements were identified, and calculations presented within the literature.

Data extraction

One author read the material, synthesised the data and recorded pertinent results; the collated evidence was then reviewed by a technical panel and disagreements were resolved by conference.

Data synthesis

Comparative analysis and a summary of the results was undertaken, with recommendations and implications of the research made by various experts. Where appropriate, supplementary calculations were undertaken to help contextualise the available evidence and infer the likely consequences.

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Mark is Director of Architecture and Research at LEAP. A multi award-winning architect with over 35 years' experience in the construction industry, Mark is one of the pioneers that brought Passivhaus to the UK. As a leading Passivhaus Designer he has contributed to peer-reviewed journals and the training of over 1000 Passivhaus Designers, and presented at conferences around the world. He is a technical advisor for both the Passivhaus Trust and the AECB. He is also a trustee of the AECB and co-chair of the RIBA North East Sustainable Futures Forum. Notable experience includes:

- The Racecourse Estate, the North East's largest Passivhaus development
- Shepherds Barn, the North East's first EnerPHit Plus, winner of 3 RIBA North East 2022 Awards
- Larch Corner, the UK's most airtight house and winner of a 2021 Passivhaus Trust Award
- Steel Farm, winner of a 2015 Passivhaus Trust Award
- Preston Springs Passivhaus
- St. Mary's Way Passivhaus (Passivhaus Consultant)