HSE

Health and Safety
Executive

Spray foam insulation applied to timber sloped roofs in dwellings

Modelling of moisture risk for retrofitted spray foam insulation in existing dwellings

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February 2024

Acknowledgments

This project was initiated by the Department for Levelling-Up, Housing and Communities and then completed and published by Health and Safety Executive as the Building Safety Regulator. Its contents, including any opinions and/or conclusions expressed, are those of the authors alone and do not necessarily reflect DLUHC or HSE policy.

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Executive summary

A modelling assessment has been made which investigates the level of moisture and timber degradation risk which may be encountered when a sprayed foam insulant is applied to typical domestic timber roofs.

The modelling indicates that risks are low when an open cell (moisture permeable) insulant is applied in accordance with the prescriptive roof constructions and guidance described in British Standard BS 5250:2021. These constructions include the provision of an air and vapour control layer (AVCL) on the warm side of the insulation and a space left between the insulation and the roof underlay (which needs to be specifically ventilated from the eaves in the case of high resistance underlays). For sprayed foam insulation such spaces can be created by the use of card spacers inserted between rafters or other similar techniques.

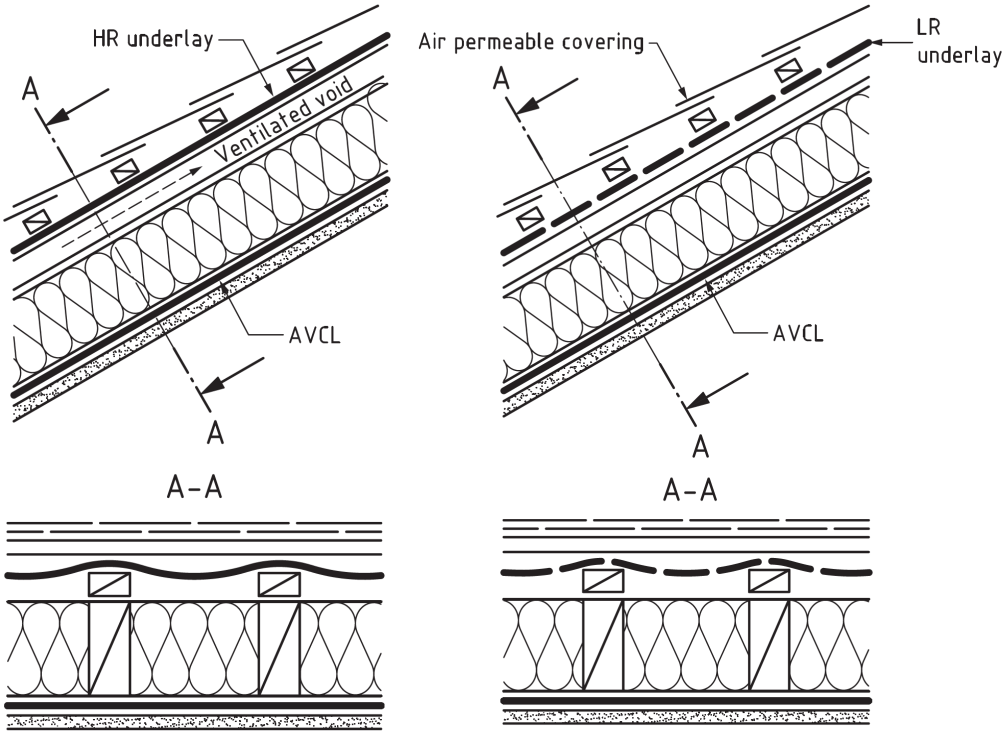

Figure 1: Prescriptive guidance diagrams from BS 5250:2021 for warm pitched roofs with High Resistance (left) and Low Resistance (right) underlays. Modelling indicates that these constructions provide a moisture safe design.

Other methods of application of sprayed foam insulants, not in alignment with BS 5250:2021 have also been modelled as being applied in typical climates of London and a more severe climate of Newcastle. These assessments considered both open-cell and closed-cell types of insulation, high and low-resistance underlays, application of the insulation directly to underlays and/or roof tiles, and the presence and absence of an air and vapour control layer (AVCL) on the warm side of the insulation.

Levels of theoretical risk vary with the temperature conditions when the insulant is applied directly to a low resistance underlay, i.e. without an air gap maintained between the underlay and insulant. Low levels of risk were found in a climate considered typical for London for all scenarios. Medium levels of risk were found in a climate considered typical for Newcastle for all scenarios, except for the use of closed cell insulation together with an AVCL where the risk was found to be low.

Table 1 summarises the risks predicted by the simulations modelled for these scenarios. The table categorises the risk according to the severity of timber decay in the outer region (i.e. the layer of timber nearest to the external climate) over a five-year period:

- Red: High risk (>25% predicted timber decay)
- Amber: Medium risk (between 1% and 25% predicted timber decay)
- Green: Low risk (<1% predicted timber decay)

Table 1: Summary of risk: insulation applied to a low resistance underlay

		London	**Newcastle**
No AVCL	Open Cell	Low risk	Medium risk
	Closed Cell	Low risk	Medium risk
Foil-backed plasterboard AVCL	Open Cell	Low risk	Medium risk
	Closed Cell	Low risk	Low risk

The modelling identified higher levels of risk were when a sprayed foam is applied to high resistance underlay (**Table 2**). In particular, high risks were determined in London when open cell insulation is applied with no AVCL present, reducing to low risks when a closed cell insulant and/or an AVCL is used. High levels of risk were also identified in Newcastle, which were reduced to a medium or low risk by the presence of an AVCL.

Table 2: Summary of risk: insulation applied to a high resistance underlay

		London	**Newcastle**
No AVCL	Open Cell	High risk	High risk
	Closed Cell	Low risk	High risk
Foil-backed plasterboard	Open Cell	Low risk	Medium risk
	Closed Cell	Low risk	Low risk

The highest risk assessed is when spray foam insulation is applied directly onto tiles or slates (**Table 3**). This leads to high risks under all modelled scenarios.

Table 3: Summary of risk: insulation applied directly to roof tiles

		London	**Newcastle**
No AVCL	Open Cell	High risk	High risk
	Closed Cell	High risk	High risk
Foil-backed plasterboard	Open Cell	High risk	High risk
	Closed Cell	High risk	High risk

Additional modelling work considered the effect of alternative conditions within the loft void and associated moisture conditions. Generally, these scenarios did not affect the risk from timber degradation but did lead to other problems with surface condensation and mould growth.

- A high rate of ventilation within the loft void would reduce mould and condensation risks but would almost entirely undermine the thermal benefit of the installation such that the original purpose of insulating would be lost.
- Increased levels of leakage through the ceiling, perhaps due to cracks or higher than typical levels of unvented moisture production from a bathroom, would increase the risk of condensation problems within the loft void.
- A colder loft void, which would be created, e.g. if the original loft floor insulation were retained, leads to increased levels of mould growth risk (although the risk of timber degradation remains broadly aligned with the modelling results under standard conditions).

Further work considered the effects of imperfect roof coverings (leading to water ingress through the roof covering) and small gaps being present between the sprayed insulation and the rafters. Both of these scenarios further increased the risks of condensation gathering on the cold side of the insulation. These risks are likely to be highest if closed cell spray foam insulation is used.

Introduction and background

Concerns exist that spray foam insulation (SFI), when applied at rafter level to timber sloped roof in homes may create and/or conceal moisture problems. Such problems in this region could potentially lead to decay of the roof timbers and surrounding fabric elements. A related concern is that the insulation could conceal rain ingress directly into the roof structure and prevent it from drying.

The aim of this research report is to assess and identify the extent of moisture risk associated with the application of SFI when installed in timber, pitched roofs and when applied to a range of substrates:

- Low-resistance (LR) underlay (e.g. breathable/vapour open membrane)
- High resistance (HR) underlay (e.g. bitumen felt)
- Directly to roof tiles

Through consultation with industry representatives, it was established that application of SFI to both low and high resistance membranes is common practice and that creation of an air-gap between the membrane and applied insulation, for example using card spacers, is less frequent. The application directly to tiles is now less common although this practice was more prevalent in the past and may still occur. It was also established that open cell SFI is currently the most common insulant applied.

This research assesses moisture risks associated with SFI in roofs via numerical hygrothermal simulations, which include:

- Dynamic one-dimensional models to assess the level of moisture risk within the SFI insulated roof make-up
- Dynamic two-dimensional models to specifically assess the level of moisture risk to timber rafters within the SFI insulated roof make-up
- Specific analysis of both the risk and rate of timber decay
- Risk of mould and condensation formation

This research report identifies the moisture risks for the scenarios modelled. It is not intended as prescriptive guidance for the installation of SFI. The report assesses the moisture risks in timber pitched roofs in dwellings only. It does not evaluate risks in other roof types, such as flat roofs or metal profile roofs.

Assessment methods

Moisture may not necessarily be a problem in buildings, as it is present in construction materials, albeit normally at low concentrations. However, it can be an agent of deterioration, particularly if it is able to accumulate within the construction build-up. This is often referred to as interstitial condensation, although problems such as mould and timber decay can occur in the absence of liquid condensation, i.e. at a relative humidity less than 100%. Elevated relative humidity on internally exposed surfaces within a loft space can also lead to mould growth, which may be an indicator of excess moisture. This could lead to the potential decay of timbers elements.

Moisture risks can be assessed using a range of methods. Those that have been used in this study are outlined in this section.

Hygrothermal Risk Assessment

Hygrothermal risk in buildings is a complicated topic that requires careful assessment by an experienced assessor. Guidance for this is given in a number of documents and standards, with the most notable being:

- BS EN ISO 15026:2007[1] Hygrothermal performance of building components and building elements – Assessment of Moisture Transfer by Numerical Simulation
- BS EN ISO 13788:2012 Hygrothermal performance of building components and building elements – Internal surface temperature to avoid critical surface humidity and interstitial condensation – Calculation methods
- BS 5250:2021 Management of Moisture in Buildings
- BS EN ISO 6946:2007 Building components and building elements – thermal resistance and thermal transmittance

One-dimensional models using Wufi Pro

Wufi Pro is a one-dimensional hygrothermal simulation tool based on principles outlined in BS EN 15026:2007. These simulations are a simplification of the physical processes occurring in the model. In this study, one-dimensional models consider the effect of the spray foam insulation within the roof make-up, between the timber rafters. However, the one-dimensional model does not explicitly include the rafter.

Two-dimensional models using Delphin

To explicitly include the moisture risk of the timber rafter associated with spray foam insulation, a selection of roof build-ups have been modelled in a two-dimensional hygrothermal simulation environment using Delphin software. Delphin simulates the same physical process as Wufi (i.e. vapour and liquid transport and storage). The precise details

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[1] n.b. this study was undertaken prior to the release of the latest version of BS EN 15026 in July 2023.

of the mathematical representation of the physics are slightly different but both tools have been validated according to BS EN 15026:2007.

Risk Assessments for timber decay and mould growth

The one- and two-dimensional simulations provide an assessment of the predicted conditions of temperature, humidity and moisture content at any given point. In some cases, this information is sufficient to reach a judgement regarding the moisture risk and the likely conditions that could lead to timber decay. However, further assessment using specific techniques and risk thresholds is often needed to specifically investigate the risk of timber decay and mould growth. Further details of the timber decay and mould growth models are given in Appendices 1 and 2.

Timber decay

Elements within a structure that consist of either solid timber or timber-based products (e.g. plywood, wood fibre, OSB) can be at risk of decay when their water content exceeds certain risk thresholds: 20M-% (percent by mass) for solid timber materials and 18M-% for timber-based materials (DIN 68800-2:2022[2]).

The moisture content of the timbers in the roof structure is not directly assessed in the one-dimensional hygrothermal models. To evaluate the level of moisture, the relative humidity (RH) conditions of the materials in which timber is embedded is used to infer the moisture content. A generic moisture storage function for a spruce timber material is used, where a 20M-% water content corresponds to a RH of approximately 85%. Hence, this RH value can be used to assess the initial risk threshold to determine whether specific wood decay analysis is necessary.

The risk of timber decay is dependent upon the temperature and duration of excess RH conditions, which is not accounted for by using a uniform 85% RH method. The methods used in this research to assess the extent and rate of timber decay, which takes account of both temperature and RH excess duration, is outlined in WTA 6-8[3] and assessed using the VTT timber degradation model[4].

The VTT timber degradation model estimates wood decay based on the results of laboratory tests using a pine sapwood, which is a widely used, but relatively vulnerable material. Hence, more resilient types of timber may be at a lower risk than the model predicts. The model is based on time-stepping and proposes the development of decay as two processes: the initial activation process and the eventual mass loss process. Once the timber is ‘activated’ then irreversible mass loss can occur when the temperature is greater than 0°C and the RH is above 95%.

Mould growth

Mould growth can occur either on a surface or within a structure. At certain levels, mould can lead to negative health impacts for occupants. In general, mould growth can occur when the relative humidity on an exposed surface remains above 80% for an extended period of time. However, spore germination and mycelium growth are heavily dependent upon the temperature and the nature of the substrate.

Mould growth risks have mainly been assessed for scenarios when the loft conditions have been varied, based upon different levels of loft space ventilation, airtightness, and when original (loft floor) insulation is retained. This is covered in the ‘Impact of varying loft conditions’ section and in Appendix 3. The mould growth risk has been carried out using a mould growth post processing tool based on the VTT mould model (Viitanen et al 2010). The VTT mould model is a mathematical model that can be used to evaluate the level of mould growth on a range of materials under different temperature and relative humidity

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[2] DIN 68800-2:2022-02 Wood preservation - Part 2: Preventive constructional measures in buildings

[3] WTA Merkblatt 6-8:2016-08 Assessment of humidity in timber constructions - Simplified verifications and simulation. This specification outlines the conditions for degradation by wood-destroying fungi. This states that the relative pore air humidity in the solid wood product must not exceed 95% at 0 °C and 86% at 30 °C on a daily average.

[4] H.Viitanen et al (2010. Towards modelling of decay risk of wooden structures')

conditions. The model was developed by the Technical Research Centre of Finland (VTT) and was derived empirically with reference to the scale shown in Table 4 below.

Table 4. Mould Growth Index (definition used in VTT model)

Mould Index	**Description of the growth rate**
0	No growth
1	Small amounts of mould on surface (microscope), initial stages of local growth
2	Several local mould growth colonies on surface (microscope)
3	Visual findings of mould on surface, < 10% coverage, or, < 50% coverage of mould (microscope)1
4	Visual findings of mould on surface, 10 – 50% coverage, or, > 50% coverage of mould (microscope)
5	Plenty of growth on surface, > 50% coverage (visual)
6	Heavy and tight growth, coverage about 100 %

A study by Viitanen[5] et al. determined that the acceptable limit for locations **within a build-up without direct contact to the indoor air** is for a Mould Growth Index (MGI) of up to 3 (i.e. no visible mould present), although a MGI lower than this would be preferable. The MGI in the VTT model considers spore germination and mycelium growth is unlikely during warmer times of the year. This allows for a higher MGI than assumed in other mould models.

In this research, the area of interest is the **internal surfaces** of timer rafters and the spray foam insulation when the loft conditions are varied as described above. For internal surfaces, the recommendation by Viitanen is for the MGI to be no higher than 1.

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[5] H. Viitanen et al (2015. Mold Risk Classification Based on Comparative Evaluation of Two Established Growth Models)

Model set up for SFI applications

Climate

External

Two separate external climate files were selected for the simulations: London and Newcastle. These were chosen based on their annual solar radiation levels along with their respective relative humidity and temperature throughout the year so as to represent a typical/less severe climate (London) and a more severe climate (Newcastle) within England. Newcastle also has the highest average vapour pressure differential for climate files in England.

External climate files were generated using the Meteonorm software. Together with the simulation software (Wufi or Delphin), the effects of solar gain, wind driven rain, wind direction, external temperature and relative humidity are accounted for in the models.

Internal

Unless otherwise stated, the results from the simulations assume a “medium +5%” internal moisture load, which had a relative humidity between 35% and 65% RH (for both climates). The internal climate file was simulated using an algorithm linked to the external climate as defined in BS EN 15026:2007. This algorithm means that the internal climate will vary depending upon the external climate file used. Since Newcastle is generally more humid than London this is reflected in the resulting internal relative humidity.

For the purpose of this research (with exception to the section “impact of varying loft conditions”), the temperature and relative humidity conditions within the loft area have been taken to be the same as the occupied zones of dwelling. This may underestimate some risk (for example of mould growth) if the loft zone remained unheated. This is because the temperature may be slightly lower in the loft (assuming separated from occupied zone by, e.g. a plasterboard ceiling), which would increase the relative humidity in the loft area.

Starting conditions

The initial temperature and moisture content conditions within the build-up will have a bearing on the initial stages of the simulation. These may not be representative of long-term performance but give an indication of moisture safety depending upon the rate of drying (or becoming wetter) at the beginning of the simulation. In practice, the starting conditions will depend on the recent history of moisture conditions and, for example, whether a water-based foam is used.

To allow direct comparison, all models were simulated with an initial starting relative humidity throughout the build-up of 80%. This is a standard assumption used for hygrothermal risk assessments when the starting conditions are unknown. This value is a conservative (slightly moist) condition, and an initial reduction in total moisture content from this initial level may indicate robust construction. The impact of insulation applied onto an existing wet/damp roof structure has not been included in this study, as it would be poor practice to do so.

Assessing the condensation risk on underside of high resistance underlay or tiles

To achieve numerical stability and assess the risk of condensation forming on the underside of situations where spray foam insulation is applied to a high resistance (HR) underlay or directly to the tiles, a notional 1mm layer of material with a lower porosity than the insulation is included within the model directly beneath the underlay/tiles[6]. This notional layer aids numerical stability and allows for assessment of moisture content at this location.

Materials

For this research study, two types of SFI material were modelled with properties selected to broadly reflect properties of SFI products used within the UK market. It has been assumed that there is negligible liquid transport in the SFI modelled, which significantly reduces the risk of unstable or unrepresentative behaviour in simulation.

Table 5 lists the properties of the materials modelled. Spray foam insulation characteristic properties used within the simulations were based on published performance data from BBA or KIWA where this was available. Generic construction materials, such as plasterboard, concrete tiles and timber rafters were chosen from available material files within the relevant software and based on design values from Table 3 in BS EN ISO 10456:2007. The underlay materials were generic and selected based on S_d values in line with definitions for HR and LR underlays in BS 5250:2021.

Table 5. Key hygrothermal properties for the materials used

Material	Density (kg/m^3)	Thermal Conductivity (W/m.K)	Water Vapour Resistance Diffusion Factor (µ-value, (dimensionless) unless stated	Porosity (m^3/m^3)	Spec. Heat Capacity (J/kgK)
Plasterboard	850^{C,E}	0.200^{C,E}	8.3^{C,E}	0.65^{E}	850^{E}
Foil backing	-	-	Sd=20m	-	-
Open cell spray foam	7^{A,B}	0.039^{A,B}	3.3^{A,B}	0.99^{E}	1470^{E}
Closed cell spray foam	42^{A,B}	0.026^{A,B}	61.12^{A,B}	0.99^{E}	1470^{E}

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[6] Hygrothermal simulation models do not specifically evaluate the formation of intensive condensation on surfaces. In scenarios where the spray foam insulation is near saturation and where moisture is unable to diffuse at a greater rate at which it is generated (zero liquid transport is assumed for these materials), convergence errors can occur. To account for this, a thin, 1mm notional porous material layer is included in the model to provide additional moisture capacity for excess moisture to accumulate. This both stabilises the model and allows for the condensation risk to be evaluated.

Low resistance underlay (breather membrane)	-	-	S_d =0.04m[D]	-	-
High resistance underlay (felt)	-	-	S_d=5m[D]	-	-
Notional Layer	65[E]	2.300[E]	1.1[E]	0.95[E]	850[E]
Concrete (tiles)	2104[C,E]	1.373[C,E]	76[C,E]	0.22[E]	776[E]
Timber (rafters)	554[C,E]	0.186[C,E]	348[C,E]	-	2673[E]

[A]BBA, [B]KIWA, [C]BS EN ISO 10456, [D]BS 5250: 2012, [E]modelling software

Simulation Duration

All hygrothermal models were simulated for either a 5-year duration (one-dimensional simulations) or 3-year duration (two-dimensional simulations). In all cases the modelled build-ups are lightweight and a dynamic equilibrium is reached during the simulated period. Once dynamic equilibrium is reached, a time period in the final year of the simulation has been presented within the graphs in this report to aid clarity and comparison between cases.

Build-ups

Figure 2 shows the build-ups that were modelled in the one-dimensional Wufi Pro interface for the insulation applied directly to the roof membrane or tiles, with the external layer on the left and internal layer on the right-hand side for each build-up shown.

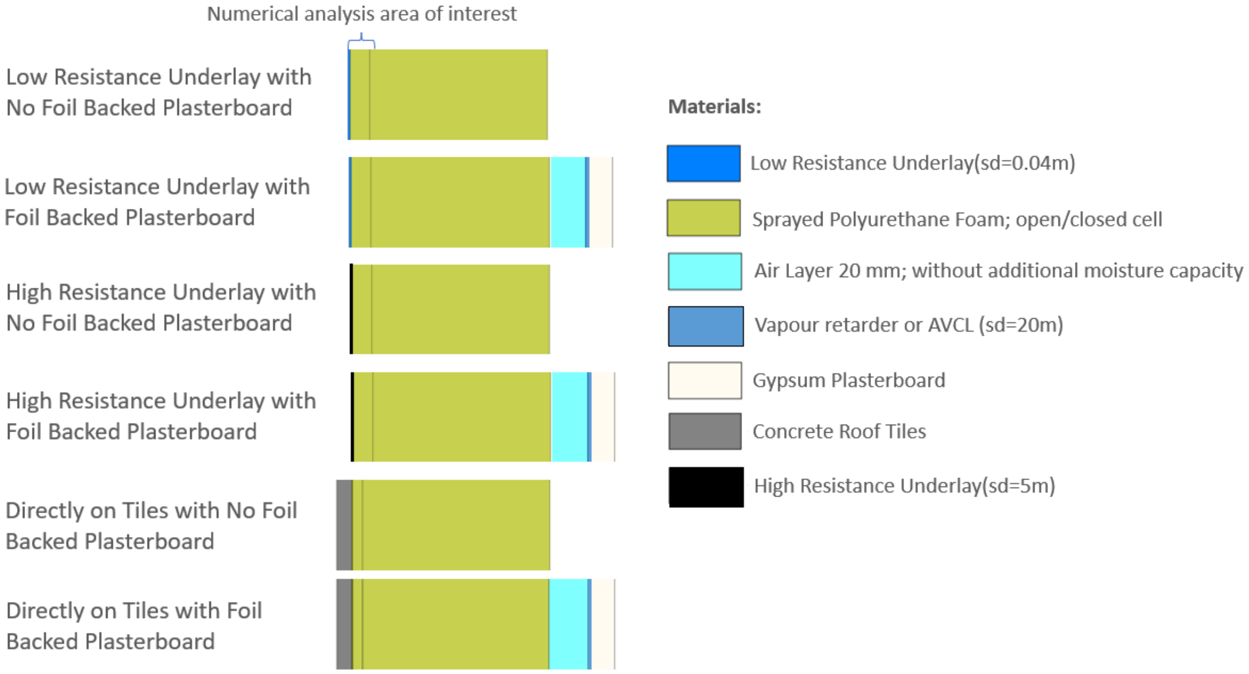

Figure 2. Wufi Pro interface – range of build-ups modelled

The numerical analysis area of interest is indicated toward the outer edge of the spray foam insulation.

Figure 3 below shows the one-dimensional (Wufi Pro) modelled build-up for open cell insulation, applied in accordance with the prescriptive BS 5250: 2021 guidance. A nominal 30mm air layer is included between the cold side of the insulation and the underlay. Two types of underlay have been assessed: both HR and LR, and an AVCL has been included for both underlay types. Two weather climate files have been assessed as used for the main modelling results in this report: Newcastle (representing a severe climate) and London (representing a less severe climate). The batten space and tiles are not represented explicitly. Instead, the surface emissivity and absorption values have been adjusted using the modelling methodology proposed by Kölsch (2017) whereby the external short wave radiation absorptivity is altered by a factor to account for the reduced solar radiation on the underlay (due to the presence of the tiles and air space).

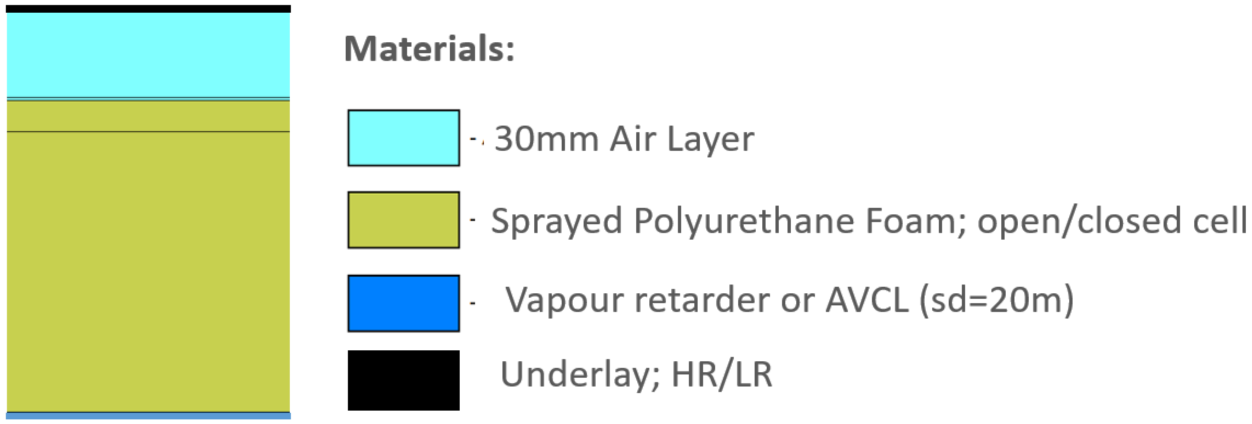

Figure 3. The model build-up for the BS 5250: 2021 prescriptive guidance.

Figure 4 shows the build-up that was modelled in the two-dimensional Delphin interface, with the external layer at the top and the internal layer at the bottom. The timber rafter is shown in the central section of the build-up with spray foam insulation applied to both sides of the rafter.

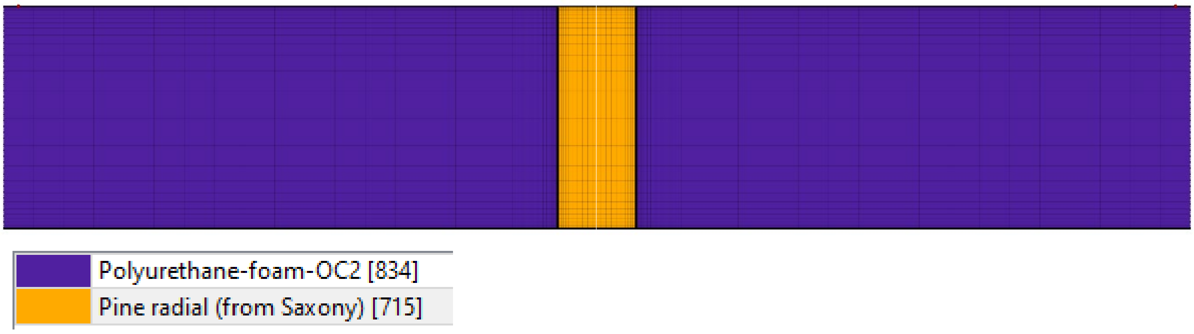

Figure 4. Delphin interface typical build-up modelled

For the two-dimensional (Delphin) scenarios modelled with a Low Resistance (LR) or High Resistance (HR) underlay, it has been assumed that the batten and counter batten spaces are well-ventilated such that the conditions in this zone are similar to the external climate, generally in line with the prescriptive guidance in BS 5250:2021. As with the one-dimensional modelling work, the methodology proposed by Kölsch (2017) has been implemented.

For all modelling where an air and vapour control layer (AVCL) was included, foil-backed plasterboard was selected as an internal finish. In principle, this type of AVCL is representative of membranes or other products that provide a comparable vapour resistance and airtightness.

Assumptions

To constrain the scope of the main modelling in this study, a number of assumptions have been made in the models:

- The waterproof covering of the roof (e.g. tiles) is in good condition such that no external rainwater leakage can enter into the roof structure (unless otherwise stated).
- There is a standard occupancy and ventilation such that the internal moisture load (i.e. internal relative humidity) falls within the ranges described, unless otherwise stated.
- The external tiles have a short-wave radiation absorptivity of 0.82 and a long wave radiation emissivity of 0.9. This is representative of a dark concrete tile.
- There is a well-ventilated batten space for all cases modelled with an underlay (either with counter-battens or an appropriate ‘drape’ between rafters).
- There is no insulation present at ceiling level within the roof space, unless otherwise stated.
- The insulation is installed such that there are no gaps or cracks within the insulation or between the insulation and the timber roof structure (unless otherwise stated) at the point of installation or subsequently due to e.g. differential movement.
- The insulation is installed to a thickness of 100mm or 200mm, which have been selected to be representative of the nominal range of thicknesses applied (once the insulation is fully expanded).
- The rafter depth is 100mm or 200mm, although this has not been explicitly represented in the one-dimensional simulations.
- The timber rafters are either 100mm deep x 50mm wide or 200mm deep x 50mm wide at 400mm centres.
- The roof pitch is 35°.

Model limitations

The one-dimensional hygrothermal models consider the effect on and condition of the spray foam insulation directly but do not specifically include the timber elements within the roof structure – this being the subject for the risk of deterioration. Hence, when assessing timber conditions, the conditions in surrounding insulation elements have been used to infer the possible degradation risks to the timber elements. To validate this approach and evaluate the risk in further detail, a selection of the one-dimensional models has been re-analysed using more complex two-dimensional hygrothermal models, where the timber elements are able to be explicitly assessed. Due to the additional complexity of this type of modelling, this selection has been limited to a sub-set of open cell insulation products and application which are considered to be most typical. The results section includes the analyses from both one-dimensional and two-dimensional models, with the two-dimensional results taking precedence for those scenarios modelled in that environment.

The simulations are limited to the roof assumptions previously stated, and within two locations in England. The results will provide useful guide for the general risk, although it is important to acknowledge that every household is unique and any variables to these assumptions cannot be accounted for.

The climate files used have been selected from Meteonorm 7.3 (2021) (according to guidance from Fraunhofer IBP and BS EN 15026 (2007)) and reflect weather data for the London and Newcastle regions. These climate files are considered appropriate for present-day simulations. However, the simulation results may not reflect the impact and effect of climate change in these regions.

BS 5250: 2021 prescriptive guidance

BS 5250: 2021[7] is an important standard for designers as it provides guidance on preventing moisture risk in buildings, including pitched roofs, which recommends either:

- Prescriptive guidance be followed, or
- The risk is assessed using:
    - Modelling in accordance with BS EN ISO 13788: 2012
    - Modelling in accordance with BS EN 15026:2007
    - Non-standardised, complex two- or three-dimensional models where air movement is dominant.

Discussion around the latest revision to BS 5250: 2021 and the merits of the various modelling approaches is provided later in the report (see ‘Review of relevant standards, specifications, and guidance’ section below).

Adopting prescriptive guidance

BS 5250: 2021 states that in many cases the recommendations contained in the prescriptive guidance, which are based on practical experience, and which are sufficient to provide robust designs to minimise moisture problems, should be followed without the need for any further analysis.

For warm pitched roofs, the prescriptive guidance recommends:

- For a high resistance (HR) underlay, such as bitumen felt:
    - An AVCL should be provided on the warm side of the insulation
    - Ventilated voids should be formed between the underside of the underlay and the insulation. Each void should be at least 25mm deep and ventilated at both high and low level and should take account of the underlay drape. A drape of 15mm is suggested for design purposes. Hence, the ventilation void should be 25mm + 15mm = 40mm.
- For a low resistance (LR) underlay, such as a breathable membrane, there are two options.
    - Option 1:
        - An AVCL should be provided on the warm side of the insulation
        - For air permeable roof coverings (e.g. tiles in traditional roofs), an air gap is needed in the counter batten space. This does not need to be specifically ventilated as vapour will diffuse outward into the outer tile batten space, which is ventilated.
    - Option 2 is for situations where it is impracticable to provide an AVCL:

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[7] BS 5250:2021 – Management of moisture in buildings. Code of practice. BSI Standards Publication

- Ventilated voids should be formed following the guidance for HR underlay.

This guidance is illustrated in **Figure 5**, which is taken from BS 5250: 2021.

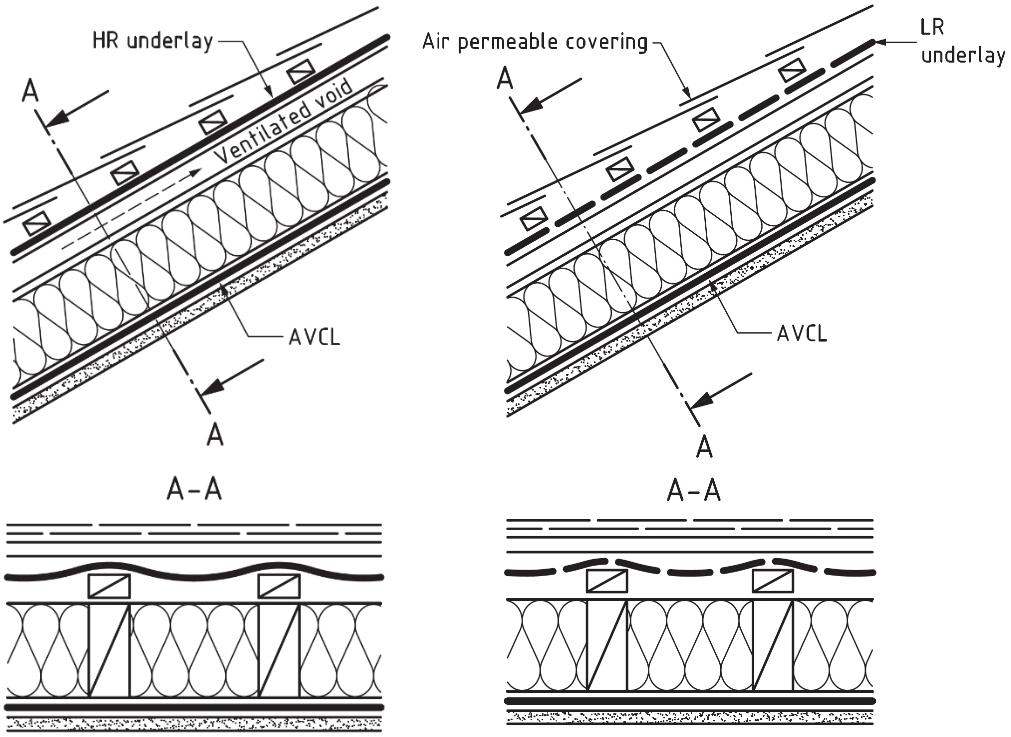

Figure 5: Prescriptive guidance diagrams from BS 5250: 2021 for warm pitched roofs with High Resistance underlay (left) and Low Resistance underlay (right) underlays

Official government guidance on moisture risk is provided in Approved Document C, although it is worth noting that Approved Document C[8] was last fully revised almost twenty years ago in 2004 (with minor amendments in 2010 and 2013). This Approved Document references the 2002 edition of BS 5250[9], and the text of the guidance between this earlier version of BS 5250 and the latest revision differs slightly. Much of the difference revolves around the details of practicalities of installing an airtight, joint-lapped AVCL for the design life of the roof, and the 2002 edition of BS 5250 did not provide an option not to include an AVCL. Later editions of BS 5250 provide greater clarity and have evolved to provide prescriptive guidance: the principles of which (as described above) remain unchanged between the revisions.

The 2002 edition of BS 5250 recommends that “condensation analysis” be undertaken for situations with LR underlay where ventilation in the batten space is to be omitted from the design. However, the calculation method referenced in this revision was limited to BS EN ISO 13788: 2012, and not BS EN 15026: 2007 or other non-standardised modelling

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[8] Approve Document C – Site preparation and resistance to contaminants and moisture. 2004 edition incorporating 2010 and 2013 amendments. HM Government

[9] BS 5250:2002 Code of practice for the control of condensation in buildings. BSI Standards Publication

techniques (introduced in later editions). The method described by BS EN ISO 13788: 2012 (also known as the Glaser method) may be useful for estimating liquid condensation risks under specified environmental conditions. However, unlike the method for BS EN 15026: 2007, the Glaser method is unable to simulate the effects of heat and liquid transport and storage. Also, care must be taken to represent the influence of solar gain and clear-sky cooling. As such, risks that can occur in the absence of liquid (i.e. less than 100% RH conditions which can nonetheless result in mould and timber decay) need to be taken into consideration. As such, the Glaser method may underestimate the risks as it is only able to deal with liquid moisture (condensation conditions).

Assessing the moisture risk for the prescriptive guidance

The assumption is that the BS 5250: 2021 prescriptive guidance provides a robust, moisture-safe approach for the roof. To evaluate this assumption, a set of hygrothermal models have been assessed that follow the principles set out in the prescriptive guidance. The modelling method used for this assessment is based upon the BS EN 15026: 2007 method using one-dimensional hygrothermal modelling environment. This is the same approach which will be used in the modelling of SFI directly to the membrane (see 'Model set up for SFI applications' above).

Figure 6 and **Figure 7** presents the predicted relative humidity profile in the outer region of the insulation layer for the two underlay types and the two climate files for London and Newcastle. These charts illustrate the profiles during a typical winter week (**Figure 6**) and a typical summer week (**Figure 7**) during the last 12-months of a 5-year simulation.

The charts illustrate that, by following prescriptive guidance, the relative humidity in the outer region of insulation remains below the timber decay risk threshold of 85% for the majority the time. At times where the threshold is exceeded, there is sufficient diurnal drying in both the winter and summer months, down to ~30% in Newcastle and ~20% in London during the summer. **Hence, this assessment indicates that following the predictive guidance in BS 5250: 2021 is likely to result in a moisture-safe design**.

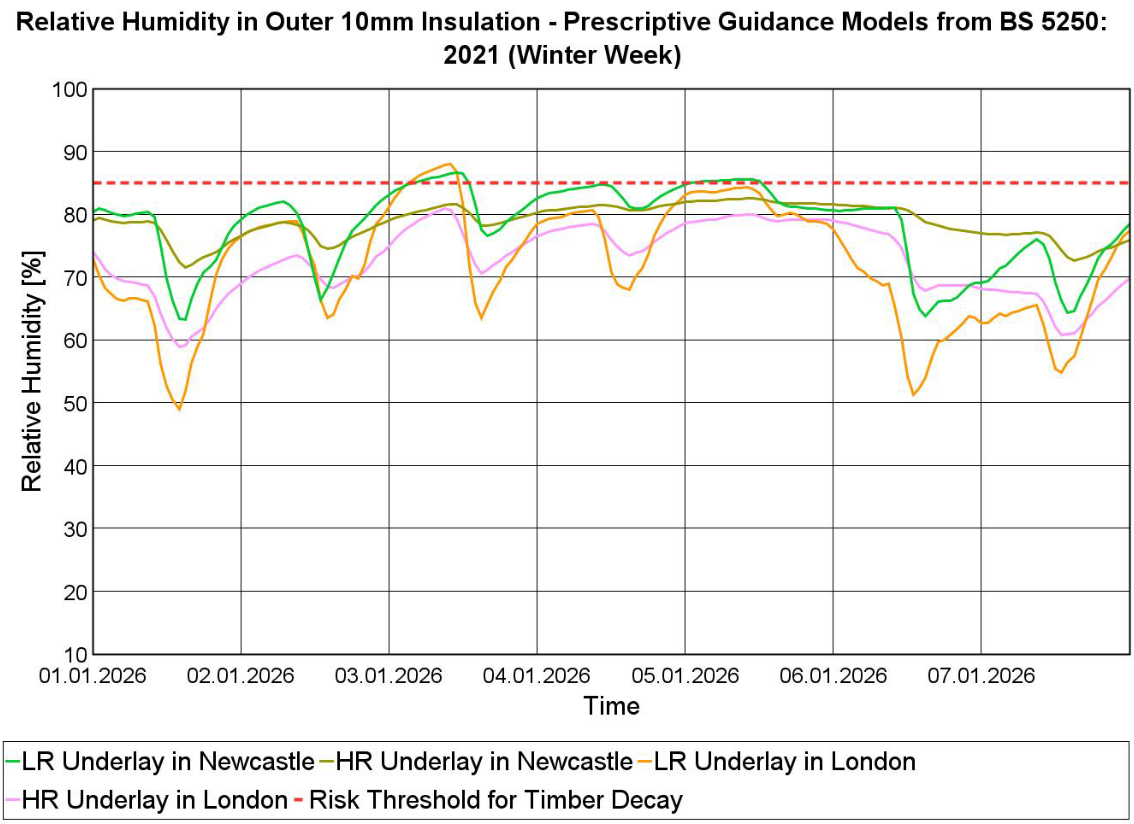

Figure 6. RH in the outer region of open cell insulation for one week in the winter for insulation applied in line with the prescriptive guidance

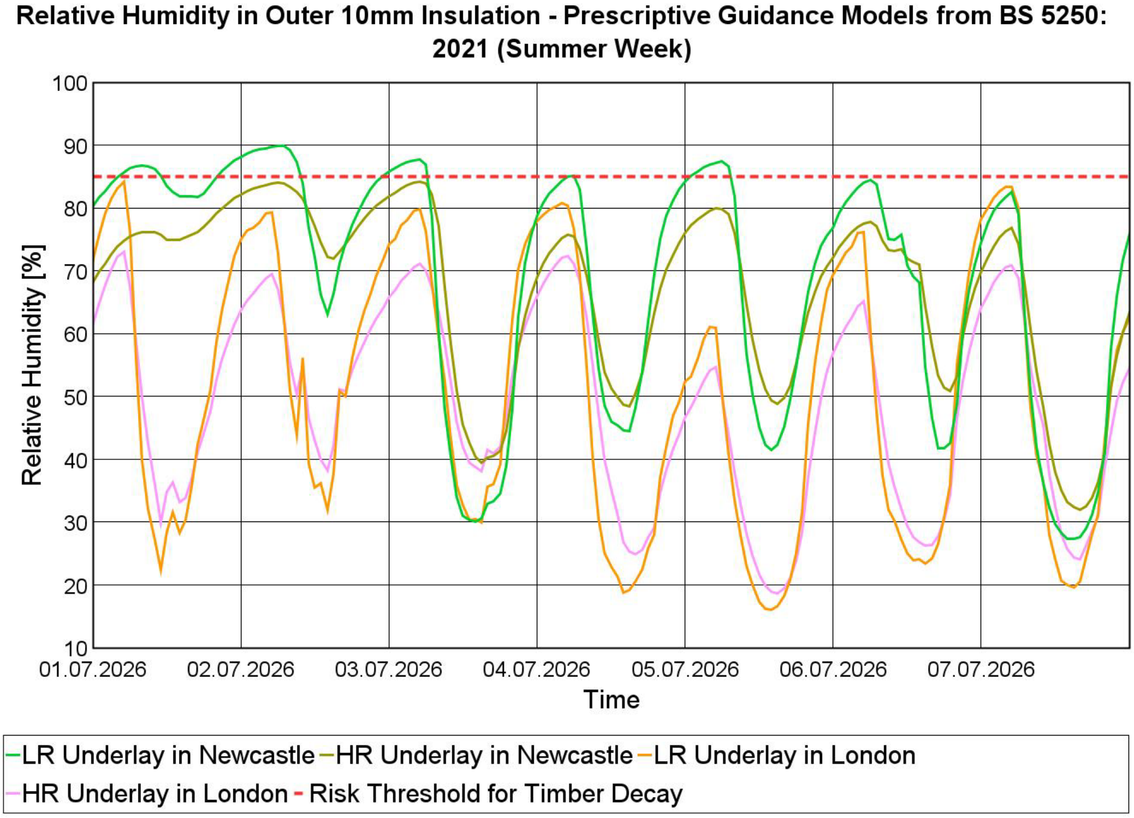

Figure 7. RH in the outer region of open cell insulation for one week in the summer for insulation applied in line with the prescriptive guidance

Results –application of SFI directly to roof membranes and roof tiles

This section presents the results from the hygrothermal simulations for a range of scenarios where spray foam insulation is applied to low and high resistance membranes, and directly to roof tiles (i.e. for situations where no membrane is present or not installed as part of the insulation process). In most cases, simulation results include for scenarios both with and without an AVCL.

The hygrothermal model simulations predict the relative humidity (RH) and temperature conditions in the outer region of insulation (i.e. the region of insulation beneath the underlay or tile), spanning a 5-year period. Only the final year of simulation is referenced in the results, to ensure the results assessed are under conditions of dynamic equilibrium.

Insulation applied to low resistance membranes – standard conditions

All of the cases modelled in this section assume the conditions in the loft zone are identical to the occupied space, based on a medium +5% internal moisture load (BS EN ISO 15026) – see p.14 for further information, and also assume that there is no insulation or vapour resistance installed at loft ceiling level. These models also are based on a uniform application of insulation to the thicknesses specified (either 100 or 200mm), and that no gaps are present, e.g. there is no shrinkage or movement. These conditions are referred to as “standard conditions”.

Open Cell applied to low resistance (LR) underlay – severe climate

Without foil-backed plasterboard

The simulations created for this scenario assume that open cell insulation is applied between rafters, directly to the low resistance membrane. The underside of the insulation is exposed to the roof space, i.e. no air and vapour control layer (AVCL).

A summary of the predicted temperature and relative humidity (RH) conditions from the one-dimensional simulations can be found in **Figure 8** (typical winter week condition) and **Figure 9** (typical summer week condition). These weeks are taken from the final year of the 5-year simulations as this is representative of longer-term equilibrium conditions.

In **Figure 8**, the RH for both insulation thicknesses remains above the risk threshold for most of the period during winter and presents a risk of timber decay. Whereas in summer, **Figure 9**, shows the RH peaks above the risk threshold (e.g. during the cold night), but for only part of each day. The RH cycles below the risk threshold to below ~40%, every day which indicates significant drying during this period. This rapid drying would suggest a lower risk because biological agents of decay take some time to initiate.

The RH at the approximate location of the internal rafter surface (assumed to be 100mm in from the underlay) and the internal surface were found to be below the 85% risk threshold for timber decay. This would suggest that it is only the outermost region of timber would be at risk of decay.

Note that the risk threshold of 85% RH is based on the hygroscopic sorption curve of a typical timber at 20%-M, which is a generic, slightly conservative threshold for timber decay. This level is considered to be the threshold for further investigations; in situations where this threshold is exceeded for significant periods of time, further analysis has been made of the risk to the timber rafter decay using the WTA 6-8:2016 and the VTT wood destruction model.

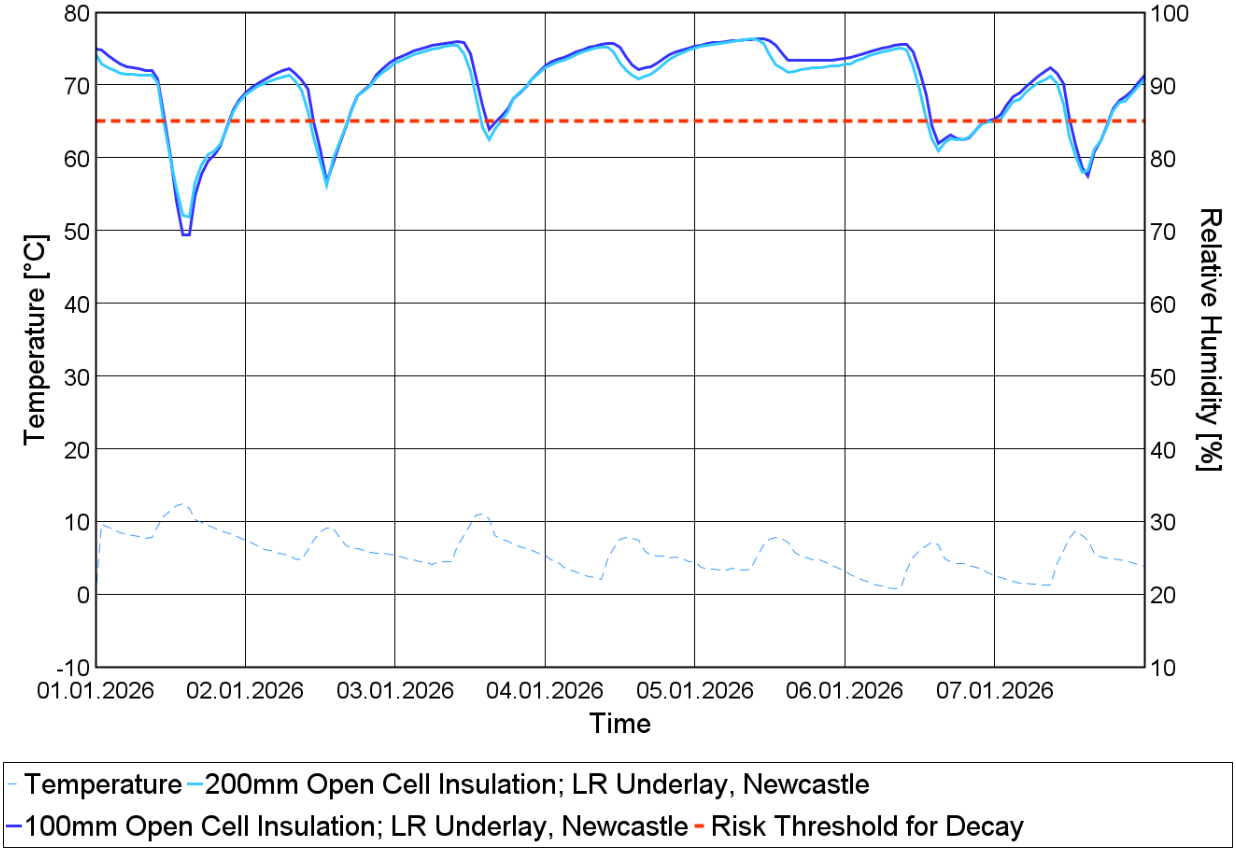

Figure 8. RH in the outer region of open cell insulation for one week in the winter in Newcastle for insulation applied to a LR underlay

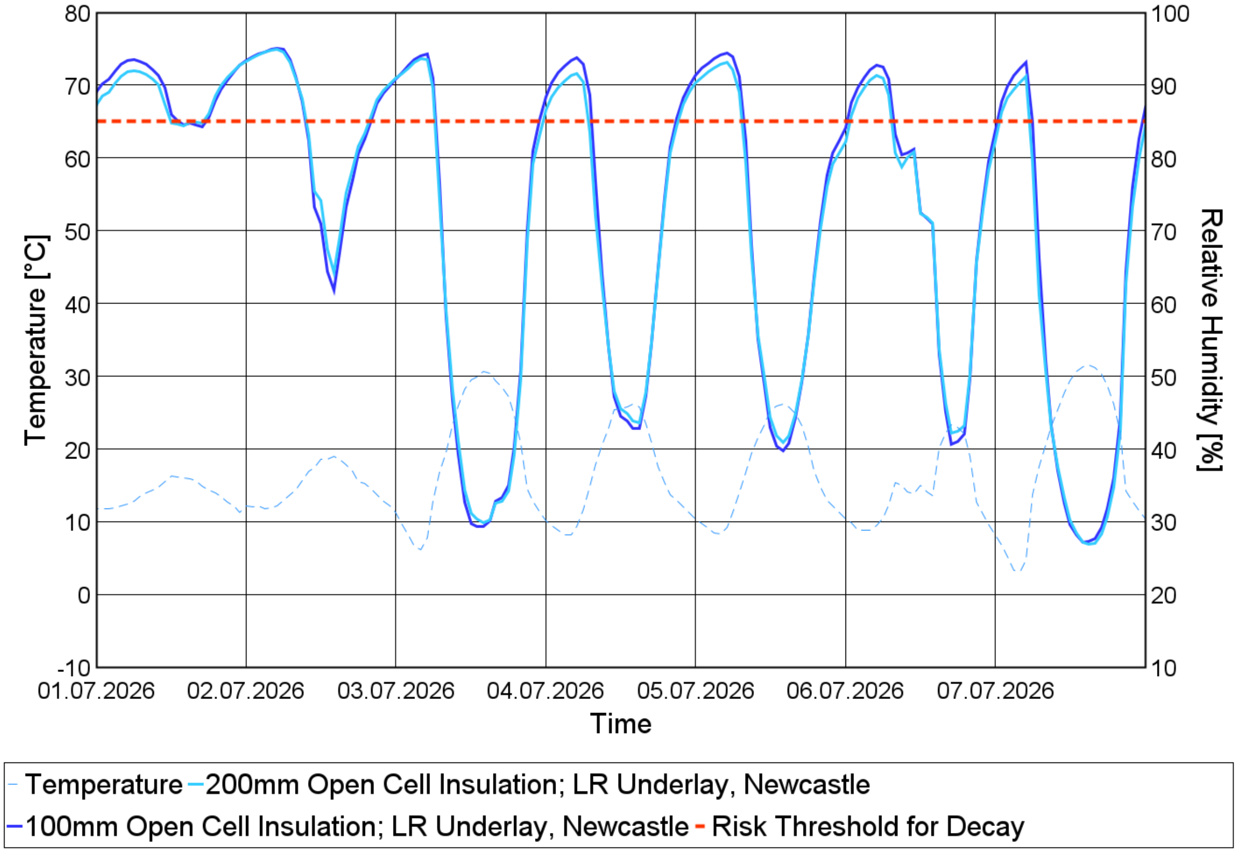

Figure 9. RH in the outer region of open cell insulation for one week in summer in Newcastle for insulation applied to a LR underlay

The simulations were repeated using two-dimensional modelling to assess the RH conditions in the outer region of both the insulation and the timber rafter. The results for the RH in the outer layer of insulation are in close agreement with the one-dimensional models. **Figure 10** presents the predicted RH profile for the whole of the last year from the 5-year simulation specifically for the timber rafter. This shows that the RH conditions here also exceed 85% risk threshold for timber decay, but to a lesser degree than within the insulation itself. The conditions in the warmer periods fall below the risk threshold, and this is likely to reflect the hygroscopic characteristics of timber, and the ability to dry toward the inside.

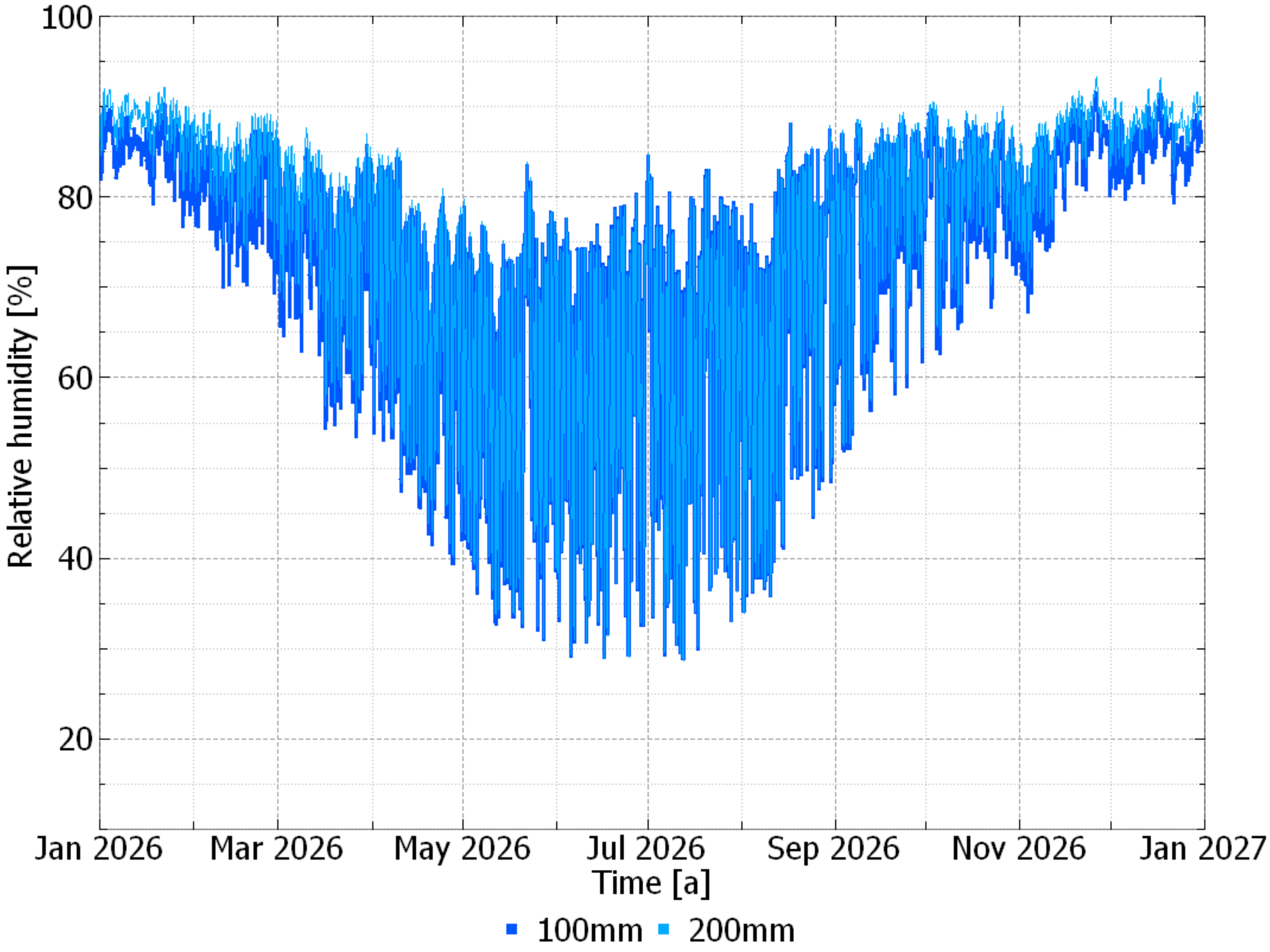

Figure 10. RH in the outer region of timber rafter for a 1-year period in Newcastle for open cell insulation applied to a LR underlay

The predicted conditions suggest a risk of decay when open cell insulation is applied to a low resistance membrane without any vapour control. Despite the lower predicted RH in the warmer periods, the wood destruction model (see Appendix 1) indicates that there may be a risk of deterioration of the rafters. The predicted rate of loss of timber mass is slow but steady, resulting in a total loss of mass of the outer layer of 3% after 5 years. More resilient timbers may not be at risk, and less resilient timbers may be at higher risk.

With foil-backed plasterboard

The addition of foil-backed plasterboard serving as an AVCL and a 25mm service void to the inside of the insulation/rafter in this modelling scenario also included an amount of air infiltration to represent air movement through joints and around edges in the plasterboard.

In this case, the typical winter (**Figure 11**) and summer (**Figure 12**) week charts show similar RH profiles to those predicted in the exposed insulation (no AVCL) simulations in **Figure 8** and **Figure 9**. For comparison, the charts in **Figure 11** and **Figure 12** overlay both with and without AVCL scenarios, which indicate a small decrease in the RH in the outer region of insulation when foil-backed plasterboard is installed. This identifies that there is a benefit of including a AVCL of this type, as the peak RH in the cases with a AVCL are always lower than those without. However, this may not always be sufficient to mitigate risks during the colder periods.

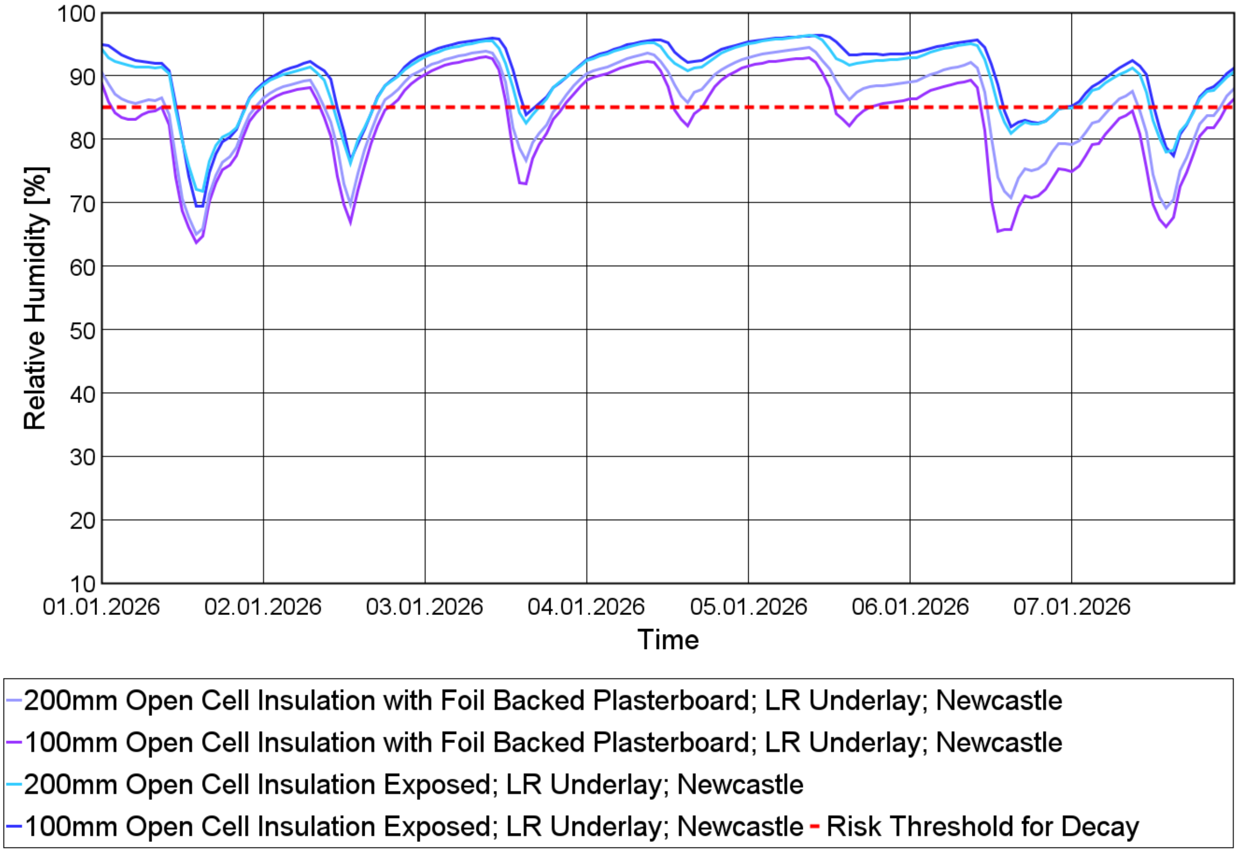

Figure 11. RH in the outer region of open cell insulation for one week in the winter in Newcastle for insulation applied to a LR underlay with foil-backed plasterboard as an AVCL.

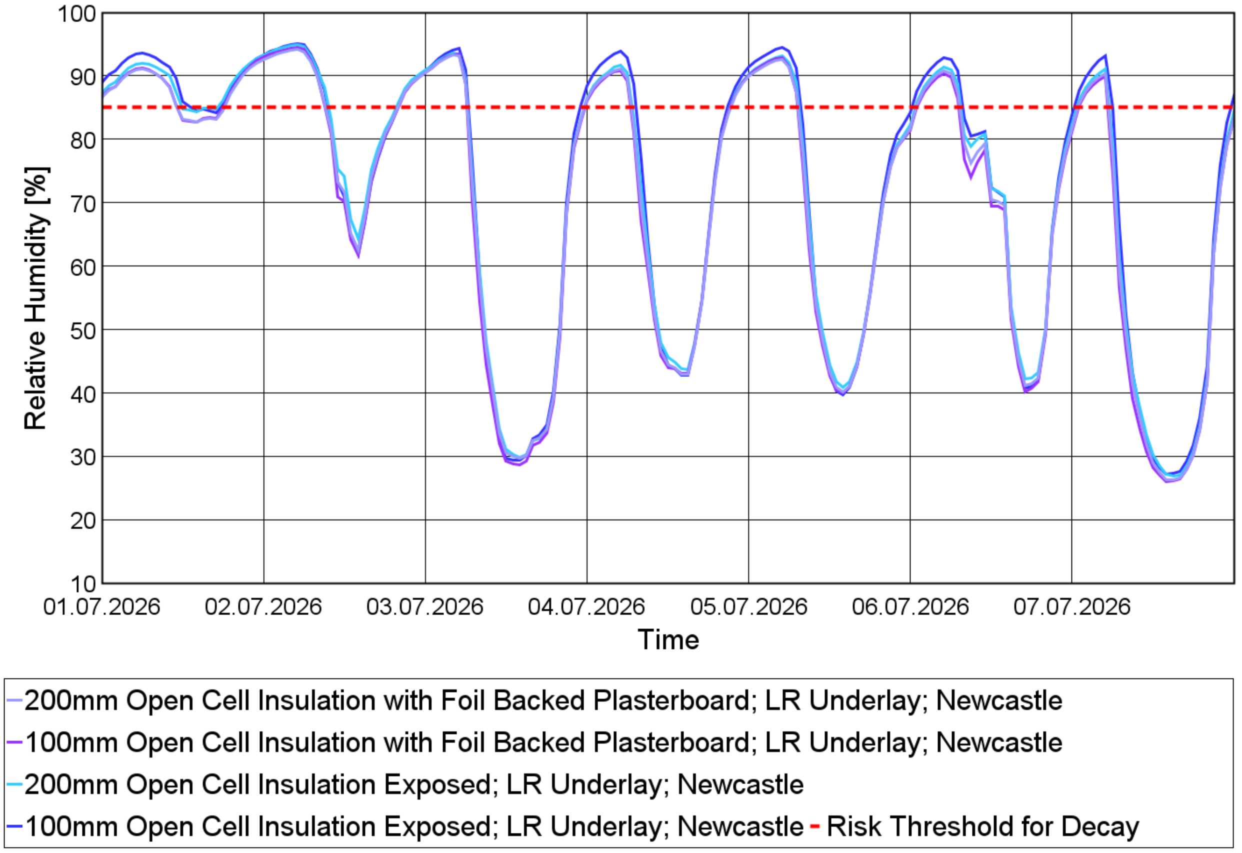

Figure 12. RH in the outer region of open cell insulation for one week in the summer in Newcastle for insulation applied to a LR underlay with foil-backed plasterboard as an AVCL

To investigate the risk to the timbers, the wood destruction models include the RH predicted in the one-dimensional models (i.e. implied timber conditions). We can infer from the previous analysis presented, that the timber destruction model for this scenario may be based upon a slightly higher RH in the outer timber layer (the two-dimensional model for open cell without an AVCL showed lower RH in this region). Nonetheless, the model for this particular scenario predicts a medium risk of timber decay over the 5-year simulation period. This is because variations in hygrothermal properties and resilience of the affected timber may result in a positive feedback loop and result in runaway decay. Hence, the predicted conditions suggest a medium risk of decay when open cell insulation is applied to a low resistance membrane with a vapour control layer to the warm side.

Closed Cell applied to low resistance (LR) underlay – severe climate

Without foil-backed plasterboard

The simulations created for this scenario assume that closed cell insulation is applied between rafters, directly to low resistance membrane with no vapour control layer (AVCL).

With closed cell insulation, there is a greater variation to the predicted RH throughout the year, compared to the equivalent open cell insulation simulation and a single week is less able to reflect equilibrium conditions. Therefore, **Figure 13** presents the predicted conditions during the whole final year of the 5-year simulation rather than the typical winter/summer weeks.

The results suggest the thickness of closed cell insulation has a minor impact on the RH conditions in the outer region of insulation. For both 100mm and 200mm thicknesses, the risk threshold for timber decay of 85% is exceeded for some periods, mainly during the colder season. The high RH periods coincide with periods of low temperature, which would aid in mitigating the risk of timber decay. It is notable that the peak RH during warmer months is much lower compared with the open cell insulation (as shown in **Figure 9**).

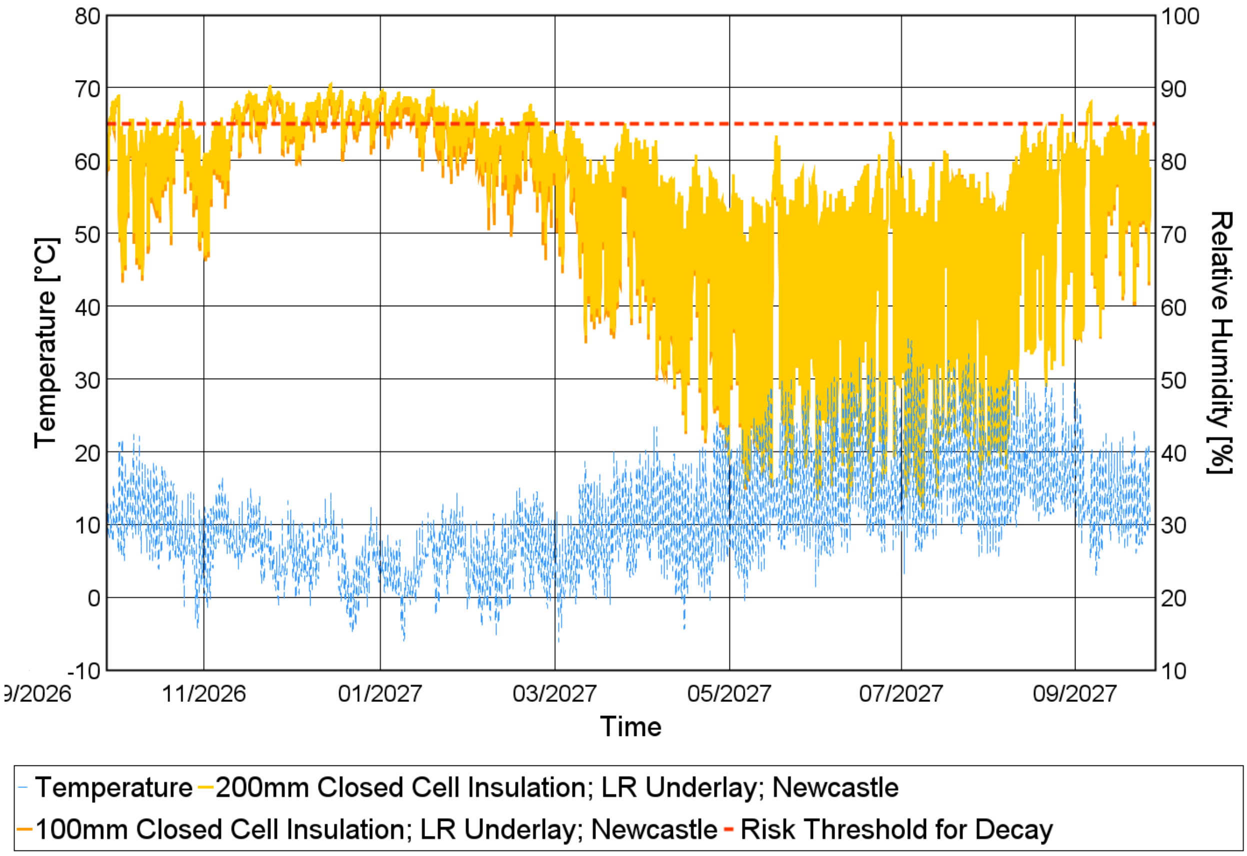

Figure 13. RH in the outer region of closed cell insulation for a 1-year period in Newcastle for insulation applied to a LR underlay

The wood destruction models for this scenario suggest a lower overall risk of the outer region of timber rafters decaying compared to the equivalent open cell insulation analysis. In the case of closed cell insulation (without foil-backed plasterboard), the predicted a marginal medium risk of timber decay over the 5-year simulation period. This marginal risk may result in a degree of acceptable decay, but it is important to note that marginal results could be quite variable. This is due to uncertainties around specific timber characteristics versus those used in the destruction model, and the varying internal RH conditions. Hence, the use of closed cell insulation applied to a LR underlay may still presents some degree of risk in some climate regions. Additional risks, associated with moisture ingress through the roof covering are covered later in this report.

With foil-backed plasterboard

The addition of foil-backed plasterboard and a 25mm service void onto the inside of the closed cell insulation/rafter in this modelling scenario included an amount of air infiltration represent air movement through joints in the plasterboard (assuming that these have not been sealed or taped).

For comparison, **Figure 14** overlays the closed cell scenarios, both with and without foil-backed plasterboard, for both 100mm and 200mm thicknesses. Both sets of profiles are near identical, which suggests that the presence of foil-backed plasterboard only has a small effect. Thus, the use of an AVCL in this scenario may have marginal benefit owing to the vapour resistance of the foam insulation itself.

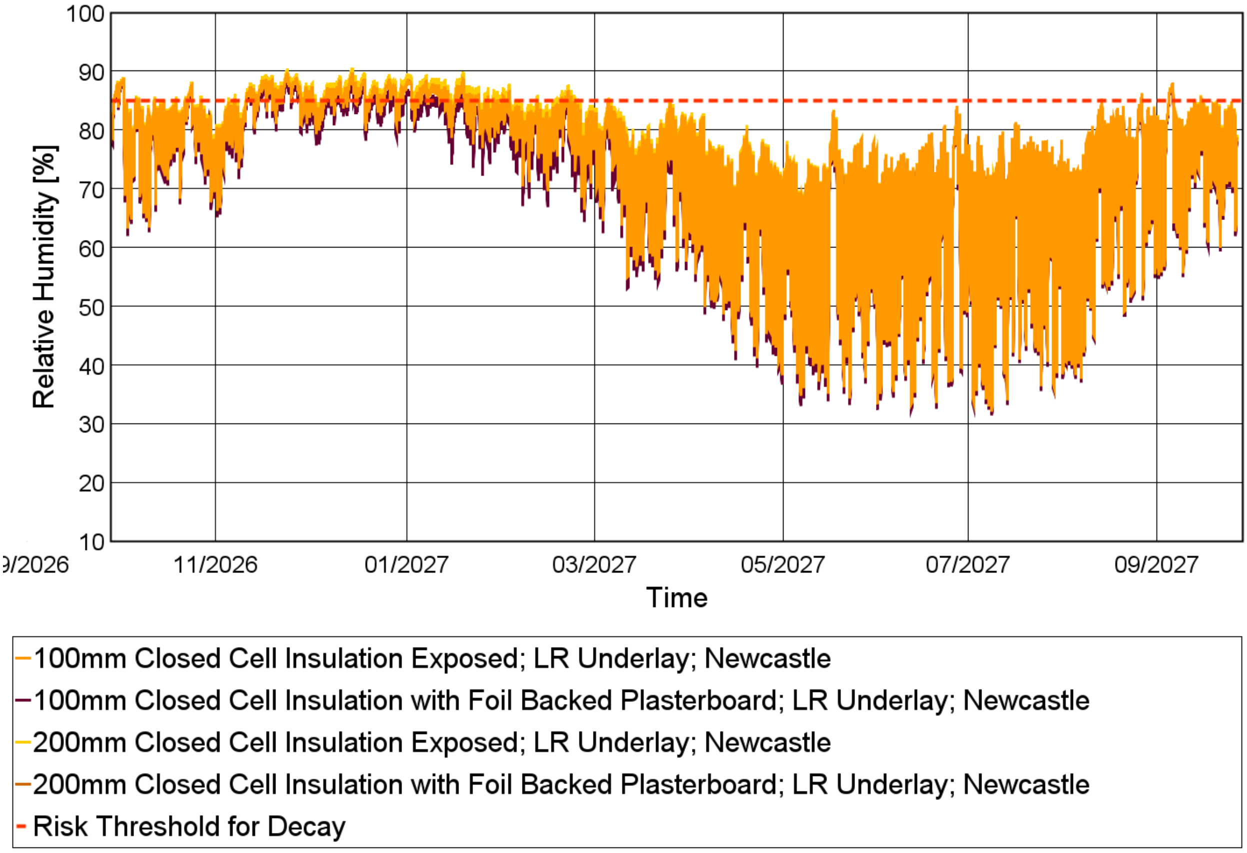

Figure 14. RH in the outer region of closed cell insulation for a 1-year period in Newcastle for insulation applied to a LR underlay with foil-backed plasterboard as an AVCL

The wood destruction models for this scenario suggests a low risk (<1% mass loss) to the timber rafters, meaning that the inclusion of the AVCL reduces the risk category from medium to low. This assumes the SFI can be applied in a consistent and uniform manner without any discontinuity, and an AVCL applied continuously to the warm side.

Open and closed cell applied to low Resistance (LR) underlay – less severe climate

Simulations for both open cell and closed cell insulants (applied to a low resistance membrane) were repeated to assess the risks for a less severe (London) climate. **Figure 15** provides a comparison of results for Newcastle and London. Only scenarios without AVCL are presented. For open cell insulation, the results for London show a lower RH throughout the year compared to Newcastle. However, the RH within the outer region of insulation still exceeds the 85% risk threshold for most periods of the year. Hence, there is still a potential risk of timber decay for the application of this type of insulation in this region.

For closed cell insulation, the risk in London is predicted to be lower than the severe climate of Newcastle. The 85% risk threshold is exceeded only for limited periods in London during the colder months. By comparison, Newcastle exceeds the threshold for more significant periods during these months.

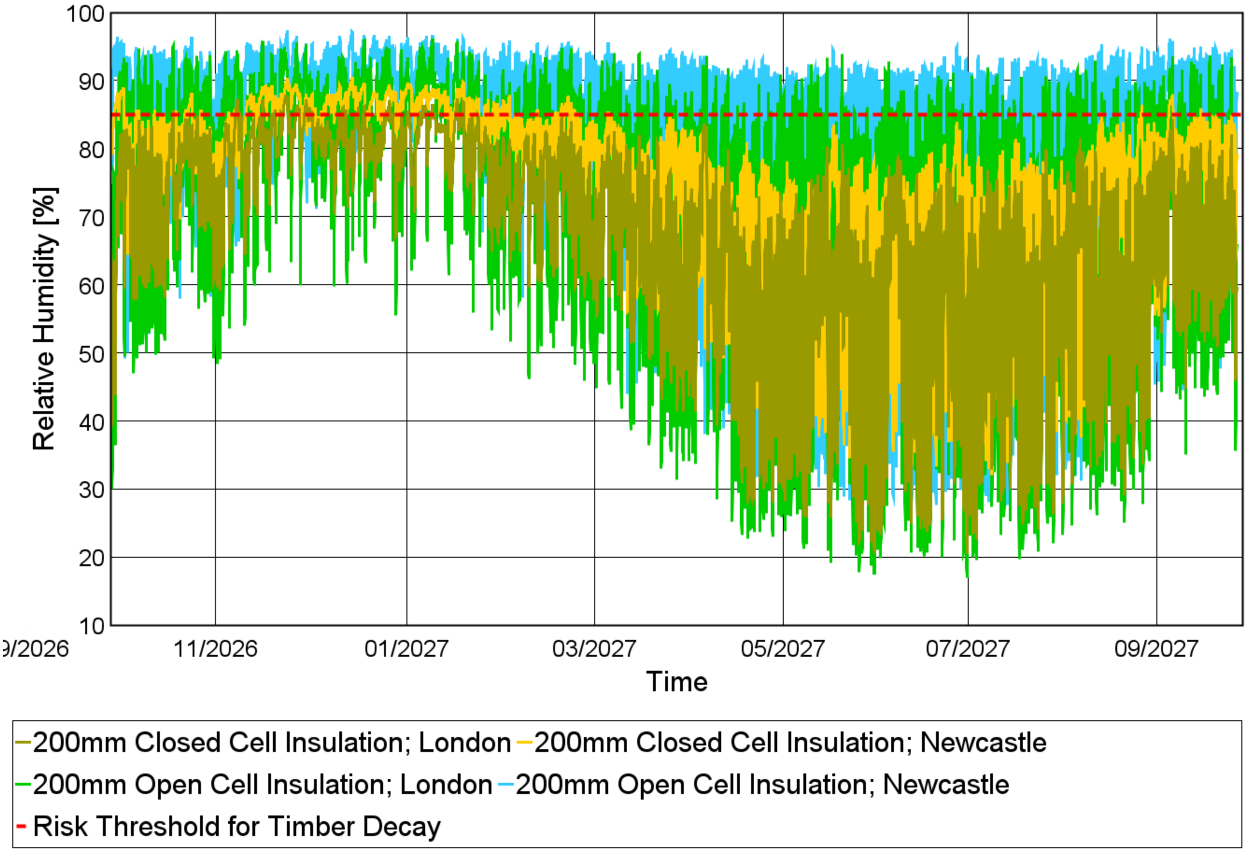

Figure 15. RH in the outer region of open and closed cell insulation for a 1-year period for insulation applied to a LR underlay. Comparison of Newcastle and London climates

As with previous models where the 85% RH risk threshold is exceeded, further analysis of the likely timber decay has been carried out using wood destruction model. However, for both open and closed cell insulation types (with and without foil-backed plasterboard) in the London climate, the analysis indicates a low risk of decay (<1% mass loss) in the outer region of the timber. This lower risk may be due to the RH fluctuations facilitating a greater degree of drying in this region.

Summary: spray foam insulation applied to a low resistance underlay

Table 6 below summarises the risks predicted by the simulations in this section. The table categorises the risk according to the severity of timber decay in the outer region over a five-year period:

- Red: High risk (>25% predicted timber decay)
- Amber: Medium risk (between 1% and 25% predicted timber decay)
- Green: Low risk (<1% predicted timber decay)

Table 6: Summary of risk: insulation applied to a low resistance underlay

		London	**Newcastle**
No AVCL	Open Cell	Low risk	Medium risk
	Closed Cell	Low risk	Medium risk
Foil-backed plasterboard	Open Cell	Low risk	Medium risk
	Closed Cell	Low risk	Low risk

The application SFI to a LR underlay results in a medium moisture risk when applied in a severe climate, such as Newcastle. The higher RH levels within the severe climate will be likely to cause greater moisture accumulation and this accounts for the higher risk. The exception for the severe climate is when closed cell insulation applied in conjunction with an AVCL. Note, that the timber decay risk summarised in the table is based upon one-dimensional hygrothermal model results. This risk may differ if modelled in a two-dimensional environment.

The simulations for low resistance membranes indicate that the LR underlay will facilitate an amount of outward diffusion and eventual evaporation, but there is a benefit, albeit small in the case of closed cell, of limiting the amount of moisture diffusion, e.g. through the use of an AVCL to the warm side.

Insulation applied to high resistance membranes – standard conditions

All of the cases modelled in this section assume the conditions in the roof zone, are identical to the occupied space, based on a medium +5% internal moisture load (BS EN ISO 15026: 2007), and also assume that there is no insulation or vapour resistance installed at loft ceiling level. These models also are based on a uniform application of insulation to the thicknesses specified (either 100 or 200mm), and that no gaps are present, e.g. there is no shrinkage or movement.

Open cell applied to high resistance (HR) underlay – severe climate

Without foil-backed plasterboard

The simulations created for this scenario assume that open cell insulation is applied between rafters, directly to a high resistance underlay, such as bitumen felt with no vapour control layer.

A summary of the predicted RH conditions from the simulations can be found in **Figure 16** (typical winter week condition) and **Figure 17** (typical summer week condition). These weeks are taken from the final year of the 5-year simulations as this is representative of longer-term conditions.

Figure 16 indicates that RH conditions remain at very high levels (close to 100%) during a week in the winter. This condition would be likely to result in a high risk of decay of any timber elements in this outer region of insulation. **Figure 17** indicates that during a typical summer week, the daytime RH falls significantly below the threshold. This shows that some drying occurs during this period, although this may be insufficient to prevent decay.

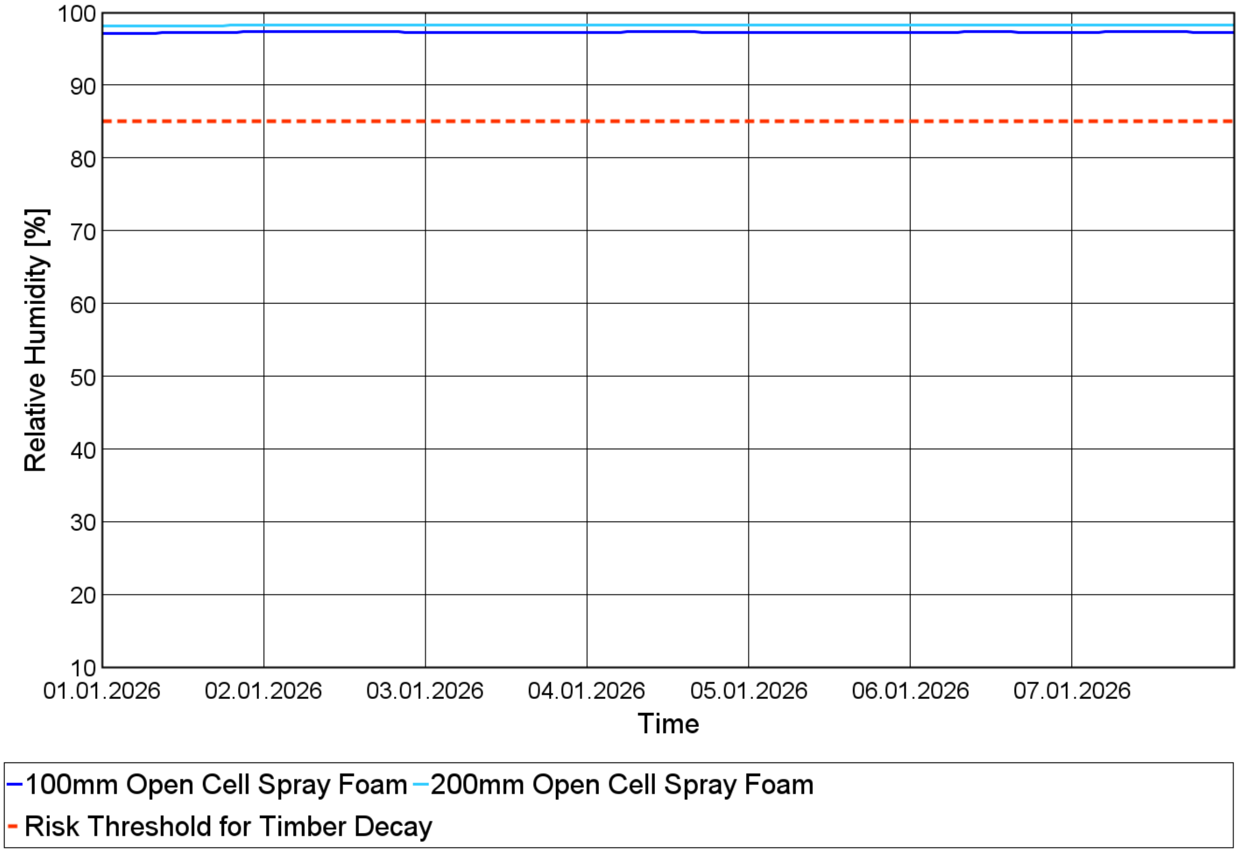

Figure 16. RH in the outer region of open cell insulation for one week in the winter in Newcastle for insulation applied to a HR underlay

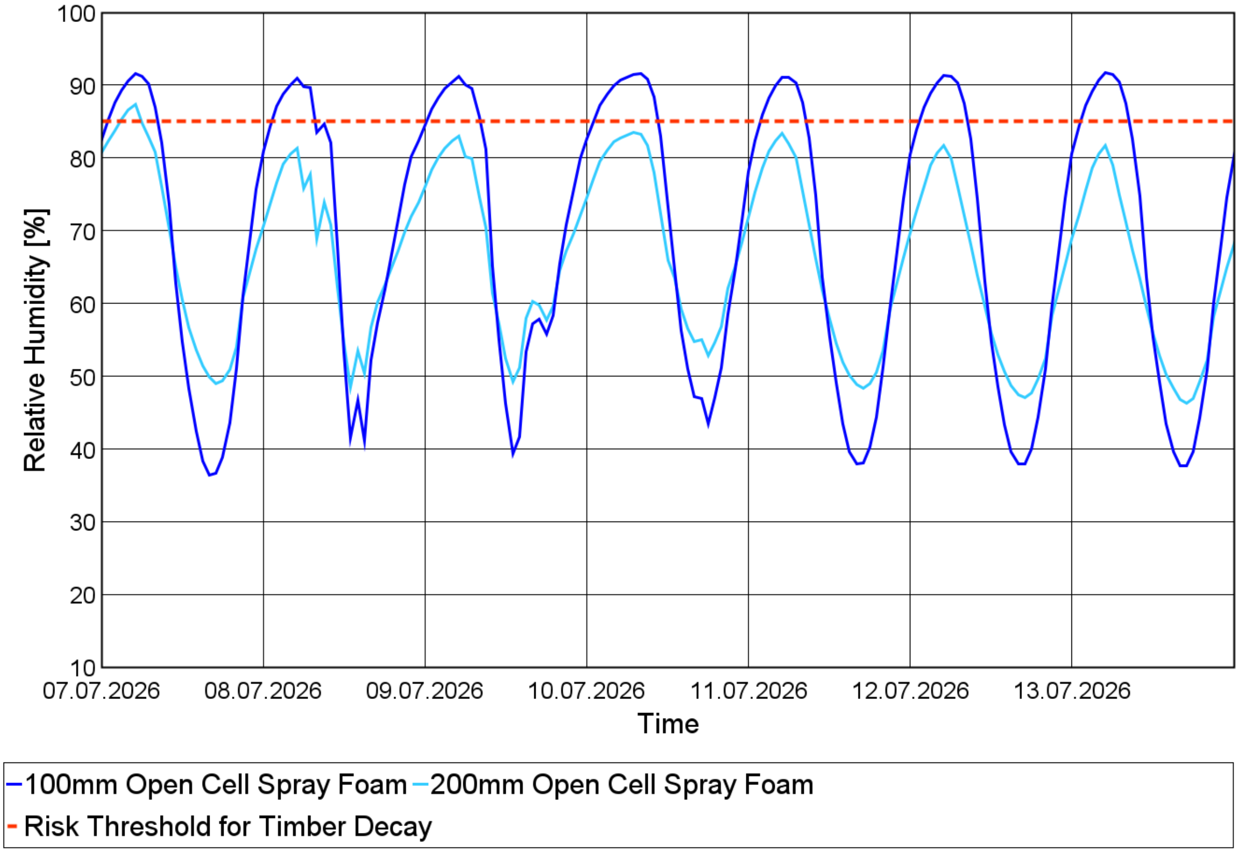

Figure 17. RH in the outer region of open cell insulation for one week in summer in Newcastle for insulation applied to a HR underlay

Further analysis of the risk to timbers indicates that the continuously high RH in winter, leads to a high risk of decay to the outer region of the timber rafters. Hence, the predicted temperature and humidity suggest a high risk of decay when open cell insulation is applied to a high resistance membrane without a vapour control layer. This risk is most likely due to the diffusion of moisture vapour through the open cell insulation during periods of higher internal vapour pressure. Outward diffusion is limited by the high vapour resistance of the HR underlay, resulting in high RH conditions in this outer region.

With foil-backed plasterboard

The addition of foil-backed plasterboard (with a 25mm service void) to the inside of the insulation/rafter in this modelling scenario included an amount of air infiltration to represent air movement around the edges of the plasterboard and through unsealed joints.

Figure 18 and **Figure 19** overlays the data for 100mm insulation provided in **Figure 16** and **Figure 17** above with data showing the effect of installing a plasterboard outer layer on an installation of this type[10]. Note that **Figure 18** includes the entire winter period (rather than a single week shown in **Figure 16)** to show how the addition of an AVCL reduces the RH throughout the winter, particularly during the milder winter months. The RH profile is

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[10] The analysis of the effect of adding foil backed plasterboard has only been undertaken for 100mm thickness of insulation as this thickness of insulation indicated increased levels of risk without plasterboard as indicated in **Figure 11** and **Figure 12**.

always lower compared to the non-AVCL scenario but is still above the 85% risk threshold for timber decay.

The chart for the summer (**Figure 19**) is also expanded from a single week in **Figure 17** to show the two months of July and August. This indicates a significant decrease in the peak RH in the outer region of insulation when foil-backed plasterboard is used as an AVCL during this period (a summer week), and the 85% timber decay threshold is not breached. This suggests there a benefit of including an AVCL, although this is insufficient to prevent all risks of timber decay in the winter.

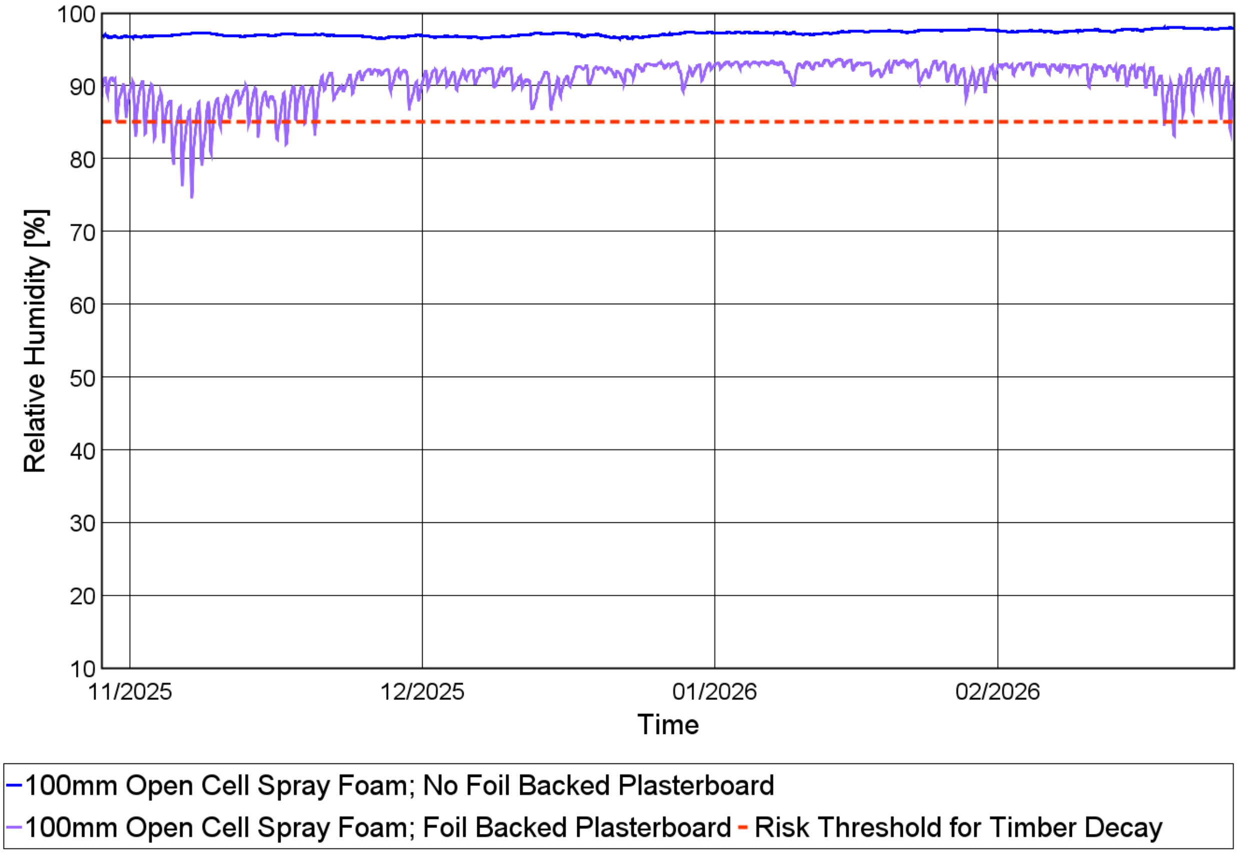

Figure 18. RH in the outer region of open cell insulation for the winter period in Newcastle for insulation applied onto HR underlay with foil-backed plasterboard as an AVCL

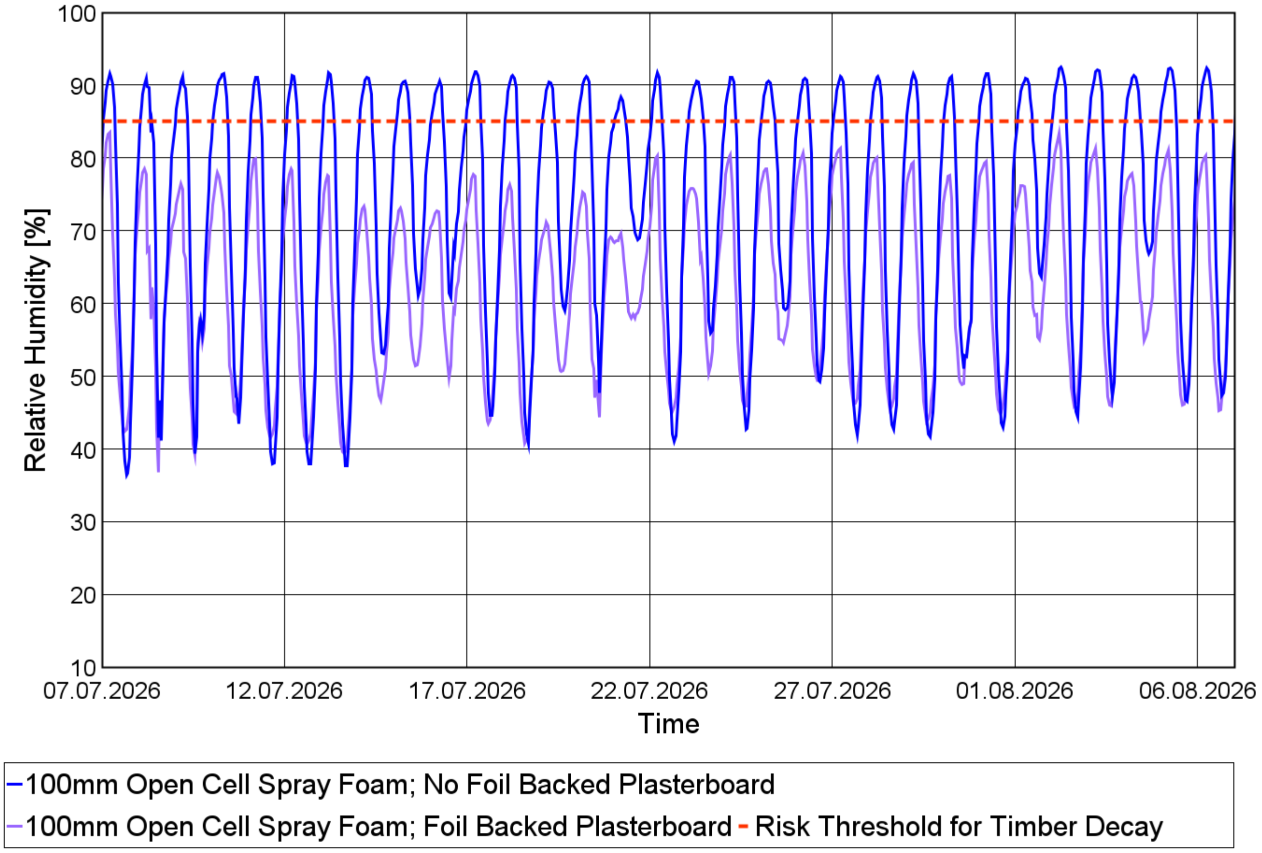

Figure 19. RH in the outer region of open cell insulation for one month in the summer in Newcastle for insulation applied onto HR underlay with foil-backed plasterboard as an AVCL

In this case, the wood destruction model identified a medium risk of timber decay after the 5-year simulation. Despite the RH being above the 85% risk threshold during the coldest parts of the winter, the RH through the milder, shoulder periods indicate an amount of drying out, with the RH being both above and below the risk threshold during this time. This drying out continues through the summer periods and, along with the increased temperatures during this period, means that the rate of decay is significantly reduced. The RH cycles for the AVCL scenarios are significantly different to the non-AVCL scenario, and this has a significant bearing on the differences between the risk level assessed between high decay (no AVCL) and a medium risk of some loss of mass (with AVCL). Hence, this indicates that the inclusion of some form of AVCL while significantly reducing the risk, is unlikely to remove any risk entirely.

Closed cell applied to high resistance (HR) Underlay – severe climate

Without foil-backed plasterboard

The simulations created for this scenario assume that closed cell insulation is applied between rafters, directly to the high resistance membrane with no vapour control layer.

Figure 20 shows that the 200mm insulation results in a lower RH in the outer region of insulation, compared to the 100mm layer. This is contrary to the results of the previous

simulations, i.e. when closed cell insulation is applied to a low resistance membrane. This is likely to be due to the higher vapour resistance of the foam.
Insulation material, such as closed cell SFI that has a high vapour resistivity provide a degree of inherent vapour control. In this scenario, the use of closed cell insulation reduces the risk of moisture accumulation behind the underlay, where a thicker layer provides a greater overall vapour resistance.

For both insulation thicknesses, the higher vapour resistance of the insulation results in significantly less diurnal variation compared to the equivalent simulation for low resistance membrane (see **Figure 13**). However, the risk threshold is exceeded by a greater magnitude and for an extended period during the winter and spring periods.

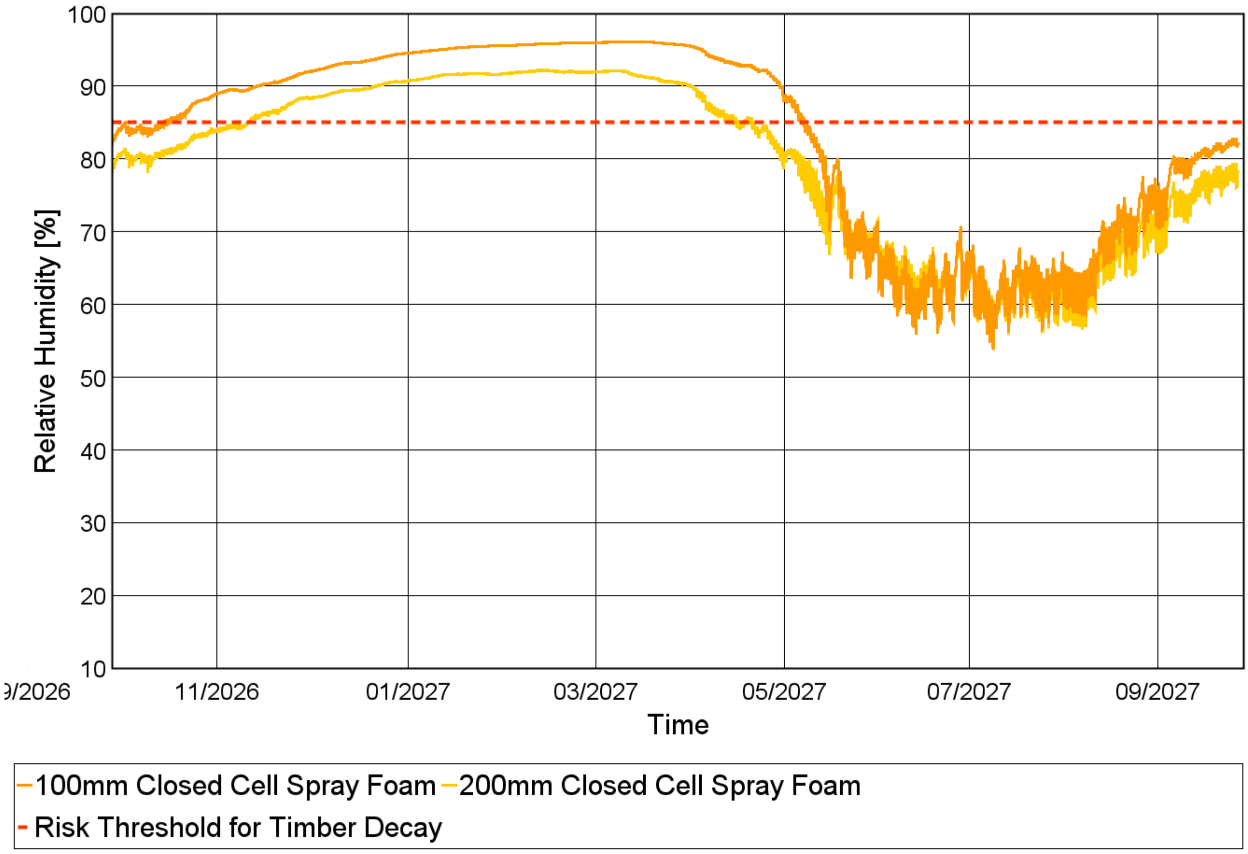

Figure 20. RH in the outer region of closed cell insulation for a 1-year period in Newcastle for insulation applied to a HR underlay

For this scenario, the wood destruction model analysis predicts that, after 5 years, there is a high timber decay. These predicted conditions suggest a significant risk of decay when closed cell insulation is applied to a high resistance membrane without a vapour control layer.

With foil-backed plasterboard
As with the scenarios for open cell insulation, shown in **Figure 18** and **Figure 19** the 100mm build-up simulations were reassessed, but in this scenario included a foil-backed plaster board as an AVCL and service void.

To allow comparison, **Figure 21** overlays the 100mm closed cell results with and without AVCL. This suggests that the presence of an AVCL can result in a lower RH in the outer region of insulation. In this instance, the 85% risk threshold is exceeded for shorter periods of time each year and then dries during the warmer summer months. This indicates that there would be a low-medium risk to the timbers in this region if a AVCL is provided. The risk is likely to be lower compared to the scenario without an AVCL because the AVCL material will be continuous across the roof, whereas the SFI is assumed only to be applied between rafters (i.e. leaving the underside of the timber rafter exposed).

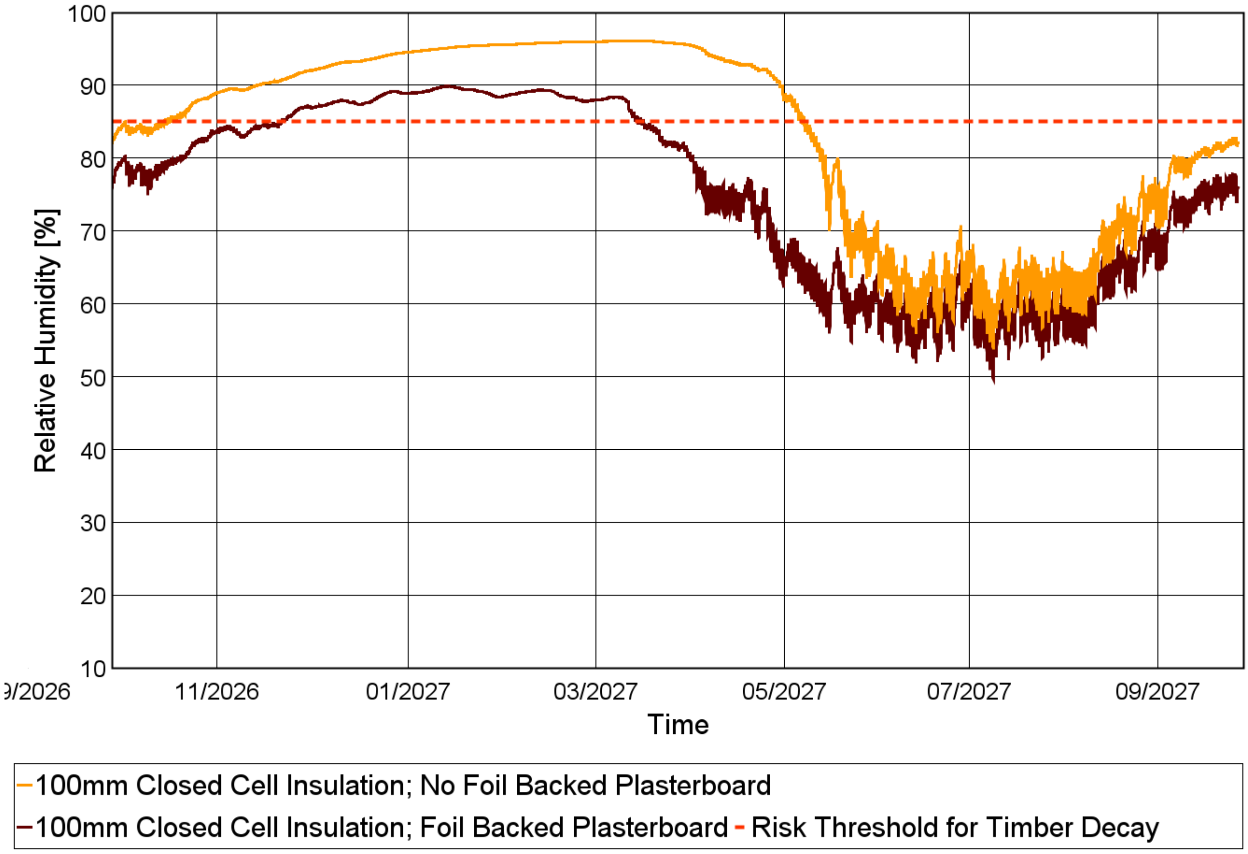

Figure 21. RH in the outer region of closed cell insulation for a 1-year period in Newcastle for insulation applied to a HR underlay. Comparison of with and without foil-backed plasterboard as an AVCL

The wood destruction model for this scenario predicted that, after 5 years, there is a low risk that the outer region of the timber rafters would decay. This is an improvement when compared to closed cell model (without foil-backed plasterboard), which predicts a high risk of timber decay over the same period. The timber decay model has been applied assuming a relatively vulnerable material, so there may be a lower risk for more resilient types of timber.

Open and closed cell applied to high resistance (HR) underlay – less severe climate

Simulations for both open cell and closed cell insulants applied to a high resistance membrane were repeated for a less severe climate in London.

For open cell insulation (without an AVCL), the results shown in **Figure 22** for London show a similar RH profile throughout the year compared to Newcastle. For both climates, the RH within the outer region of insulation exceeds the 85% risk threshold for most periods of the year, albeit for a 5–6-week shorter period in London. Hence, there is still a high risk of timber decay for the application of open cell insulation applied to a high resistance underlay in this region. Note, when the RH levels are consistently above 95% there is a much greater risk of timber decay. The open cell profiles show the predicted RH to be between 98 and 99% for 8-9 months of the year.

For closed cell insulation (without an AVCL), the RH profile in London is also predicted to be similar to the severe climate of Newcastle, but for somewhat shorter periods, and with more pronounced drying cycles during the shoulder periods. The risk to the timbers is further assessed in the timber destruction model analysis for the closed cell (London) scenario.

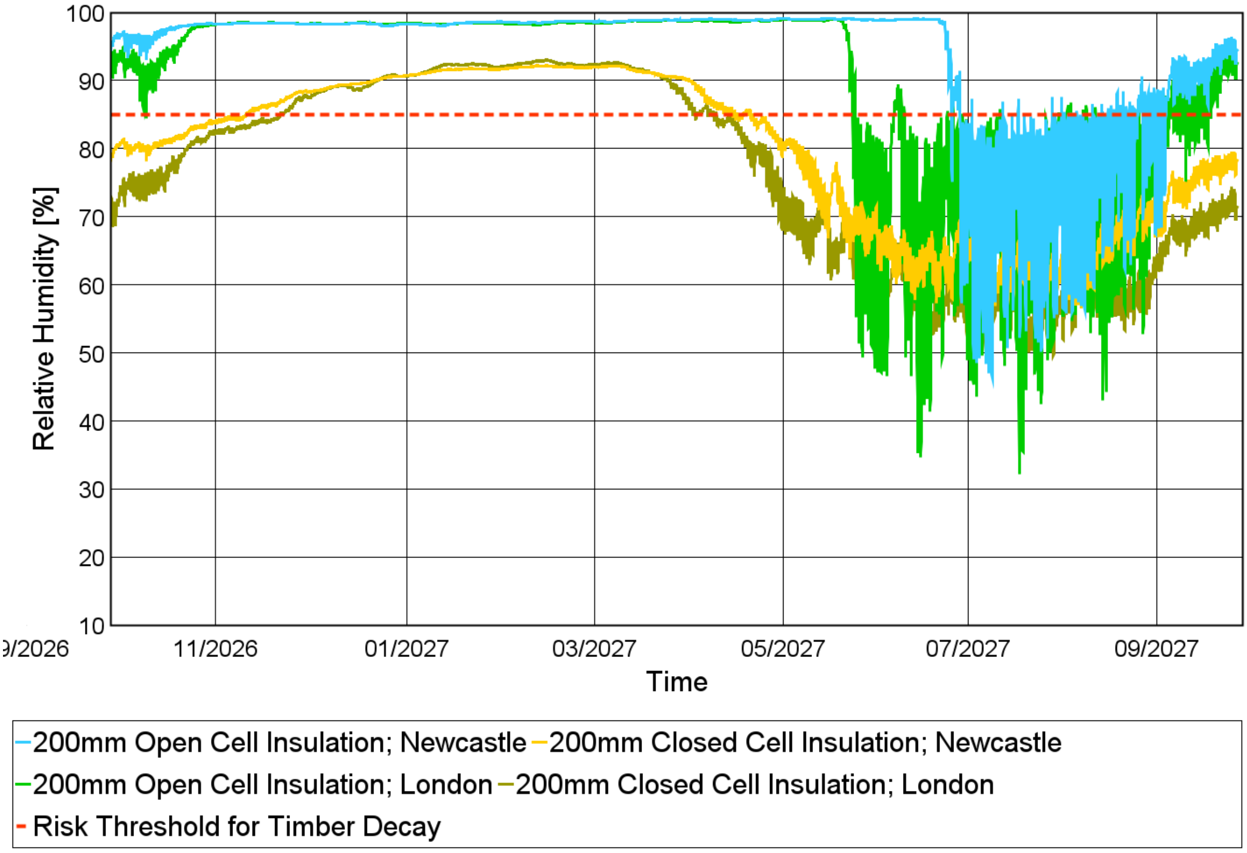

Figure 22. RH in the outer region of open and closed cell insulation over a 1-year period for insulation applied to a HR underlay. Comparison of Newcastle and London climates

The previous analysis for the severe climate identified a low timber decay risk over a 5-year period. For the same reasons identified for the severe climate (e.g. an ability for the drying to occur in the shoulder and summer months), despite the significant periods of RH exceedance above the risk threshold, the wood degradation model predicts that there would be a significantly reduced risk when compared to the open cell equivalent. For the London climate, the risk timber decay remains low.

Summary: spray foam insulation applied to a high resistance underlay

Table 7 summarises the risks predicted by the simulations in this section. The table categorises the risk according to the severity of timber decay in the outer region:

- Red: High risk (>25% predicted timber decay)
- Amber: Medium risk (between 1% and 25% predicted timber decay)
- Green: Low risk (<1% predicted timber decay)

Table 7: Summary of risk: insulation applied to a high resistance underlay

		London	**Newcastle**
No AVCL	Open Cell	High risk	High risk
	Closed Cell	Low risk	High risk
Foil-backed plasterboard	Open Cell	Low risk	Medium risk
	Closed Cell	Low risk	Low risk

The application SFI to a HR underlay results in a higher moisture risk (compared to LR underlay), particularly for open cell SFI, as vapour diffuses through the insulation to the colder side. The higher resistance underlay causes a localised increase in vapour pressure resulting in high relative humidity and, potentially, condensation. The risk reduces when an AVCL, such as foil-backed plasterboard, is included for open cell insulation, particularly for the less severe (London) climate. Note, that the timber decay risk summarised in the table is based upon one-dimensional hygrothermal model results. This risk may differ if modelled in a two-dimensional environment.

Insulation applied directly to tiles – standard conditions

This section of the report investigates the application of Spray Foam Insulation directly to roof tiles. All of the cases modelled in this section assume a ‘standard conditions’ in the roof zone, based on a medium +5% internal moisture load (BS EN ISO 15026), and also assume that there is no insulation or vapour resistance installed at loft ceiling level. These models also are based on a uniform application of insulation to the thicknesses specified (either 100 or 200mm), and that no gaps are present, e.g. there is no shrinkage or movement.

Open cell applied directly to tiles – severe climate

The simulations created for this scenario assume that open cell insulation is applied between rafters, directly to the roof tiles. For this scenario, both simulations (with and without foil-backed plasterboard) are assessed together.

A summary of the predicted RH conditions from the simulations during the final year of the 5-year simulation can be found in **Figure 23**. The chart presents the profiles for 100mm of open cell insulation both with and without foil-backed plasterboard. Both cases result in high RH in the outer region of the insulation, which exceeds the 85% risk threshold for the majority of each year. The scenario without foil-backed plasterboard shows that the insulation begins to dry to below 85% during the warmer months of each year. However, the scenario with an AVCL remains above 90% for the whole year. This is in contrast to the results previously shown (with both LR and HR underlays) which indicated that risks were generally lower when foil backed plasterboard was present.

This indicates a process of inward drying is likely to be particularly important for this type of build-up, and the presence of an AVCL may hinder this process. Nonetheless, these simulations indicate that there would be a high risk of decay of timber elements (rafters, battens and other pieces of structure) both with and without an AVCL.

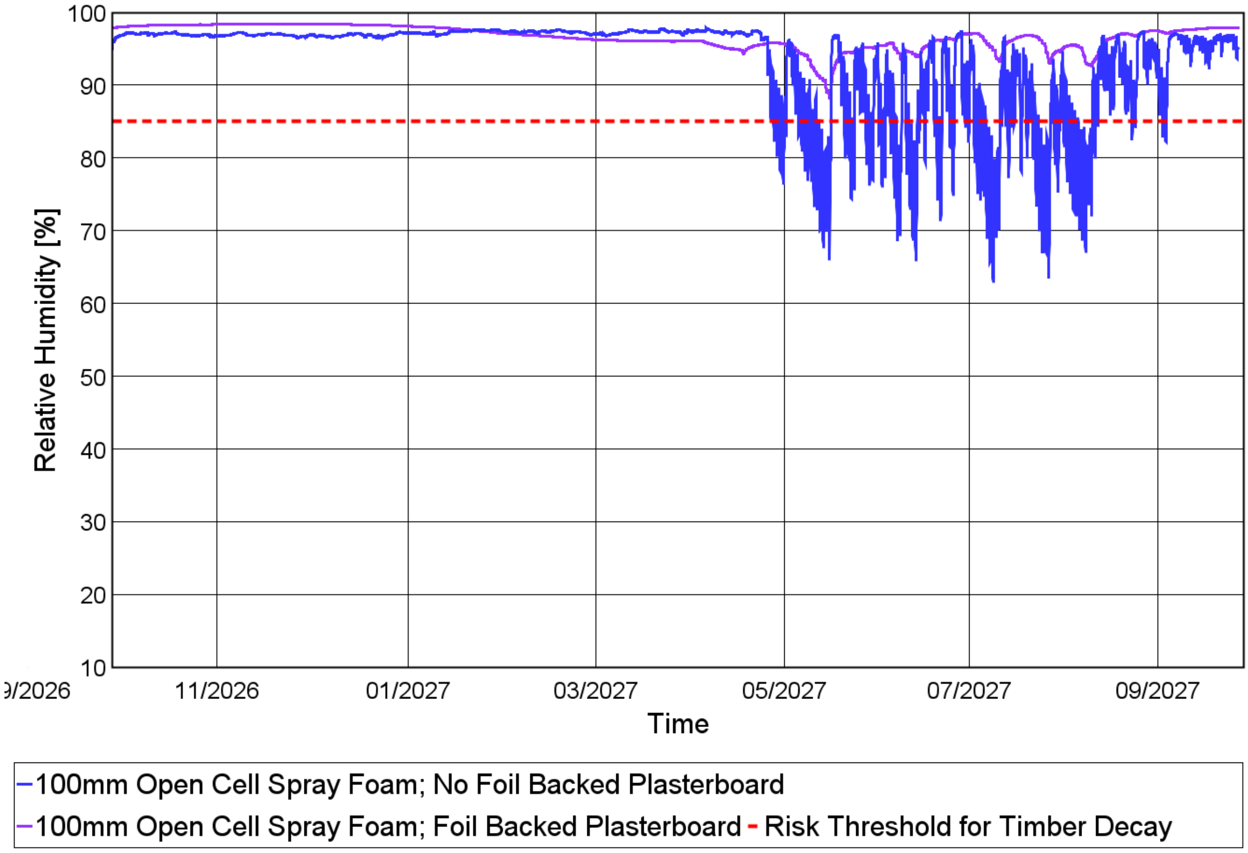

Figure 23. RH in the outer region of open cell insulation for a 1-year period in Newcastle for insulation applied directly to tiles. Comparison of with and without foil-backed plasterboard as an AVCL

As for all other scenarios when the RH exceedance is routinely above the risk threshold, further analysis of the specific risk to timbers is assessed using the wood destruction model. For both scenarios (with and without foil-backed plasterboard) this identified that, after 5 years, there is a risk that the outer region of the timber rafters would decay. Hence, the predicted conditions suggest a high risk of decay when open cell insulation is directly to the tiles, irrespective of the presence of an AVCL.

Closed cell applied to directly to tiles – severe climate

The simulations created for this scenario assume that closed cell insulation is applied between rafters, directly to the roof tiles. For this scenario, both simulations (with and without foil-backed plasterboard) are assessed together.

A summary of the predicted RH conditions from the simulations during the final year of the 5-year simulation can be found in **Figure 24**. The chart presents the profiles for 100mm of closed cell insulation both with and without an AVCL. Both cases result in high RH which exceeds the 85% risk threshold for the entire year; indeed, both scenarios predict RH to be >95% for most of the year. This corresponds to a high risk of decay of timber elements in this outer region of insulation.

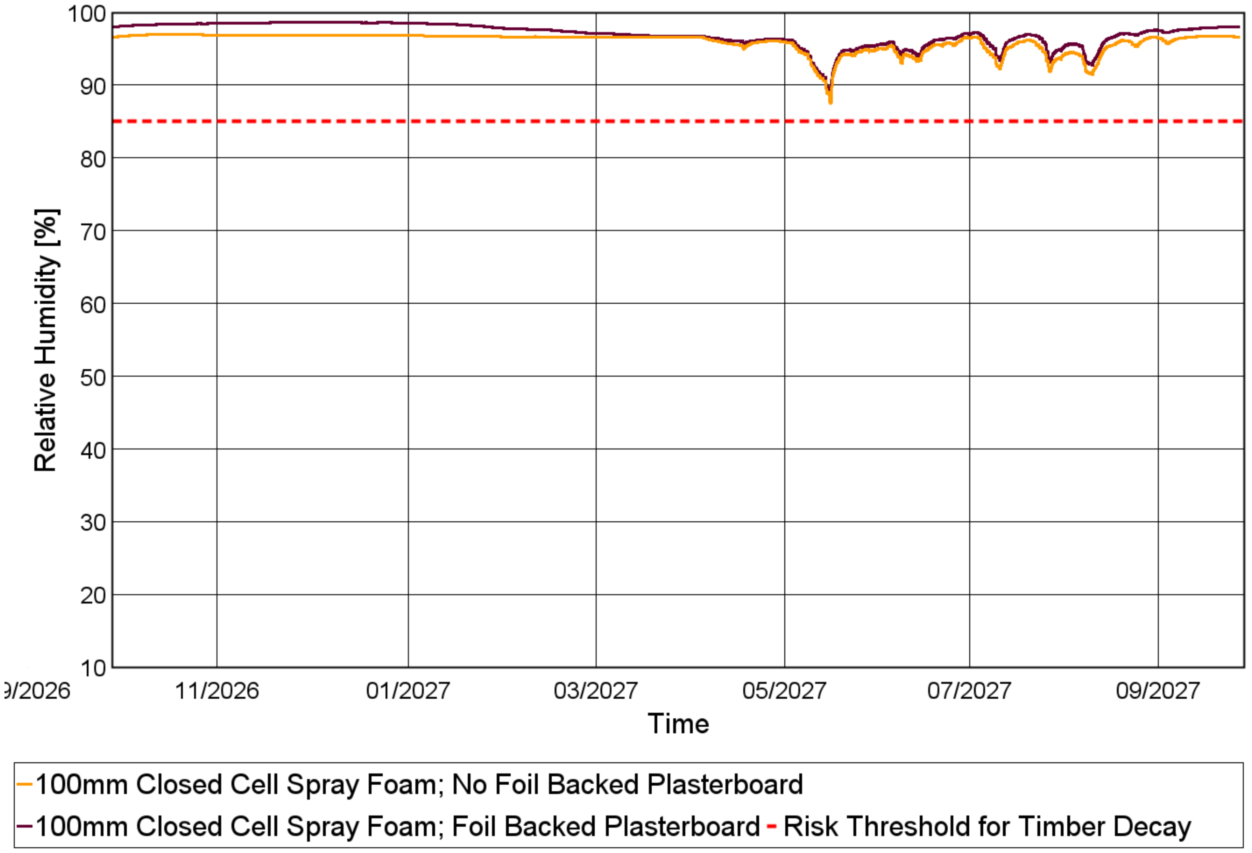

Figure 24. RH in the outer region of closed cell insulation for a 1-year period in Newcastle for insulation applied directly to tiles. Comparison of with and without foil-backed plasterboard as an AVCL

The wood destruction model for both closed cell scenarios (with and without foil-backed plasterboard) this identified that, after 5 years, there is a high risk that the outer region of the timber rafters would decay. The predicted conditions suggest a high risk of decay when closed cell insulation is directly to the tiles, irrespective of the presence of an AVCL.

Open and closed cell applied direct to tiles – less severe climate

Simulations for both open cell and closed cell insulants (applied directly to tiles) were repeated for a less severe climate in London.

The simulations for both open and closed cell insulation are represented in **Figure 25** which shows the final year of the 5-year simulation. This shows that the differences between the Newcastle and London climates are minimal, and the risk identified previously for the severe climate also applies to London. This means that there is a high risk of timber decay in the outer region of the timber rafters when applying open cell or closed cell insulation (with or without an AVCL) directly to the roof tiles, irrespective of region.

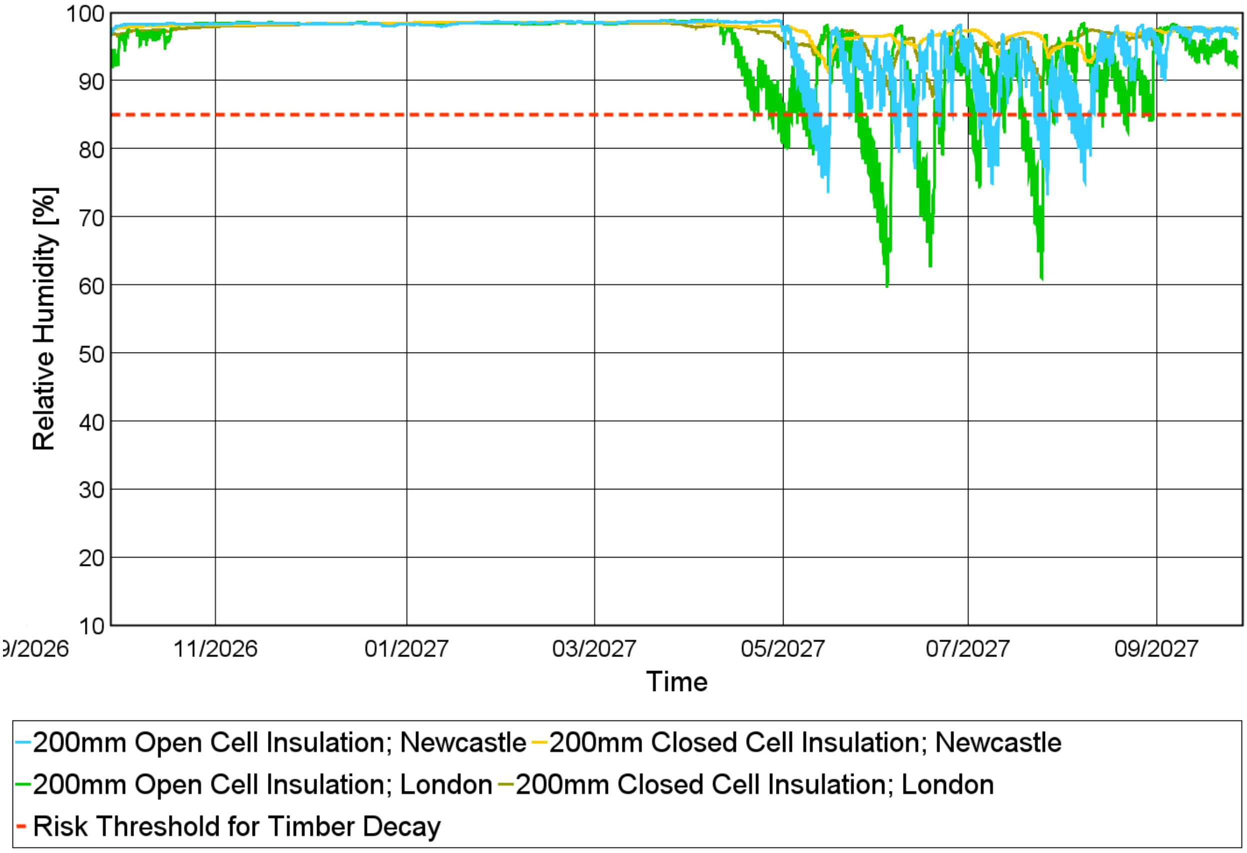

Figure 25. RH in the outer region of open and closed cell insulation for a 1-year period for insulation applied directly onto tiles. Comparison of Newcastle and London climates

Summary: spray foam insulation applied directly to tiles

Table 8 summarises the risks predicted by the simulations in this section. The table categorises the risk according to the severity of timber decay in the outer region:

- Red: High risk (>25% predicted timber decay)
- Amber: Medium risk (between 1% and 25% predicted timber decay)
- Green: Low risk (<1% predicted timber decay)

Table 8: Summary of risk: insulation applied directly to roof tile

		London	**Newcastle**
No AVCL	Open Cell	High risk	High risk
	Closed Cell	High risk	High risk
Foil-backed plasterboard	Open Cell	High risk	High risk
	Closed Cell	High risk	High risk

The application of spray foam insulation directly onto the tiles results in the highest risk for both insulation options. There is a high risk of timber decay, irrespective of climate or the presence of an AVCL. The increase in risk is due, in part, to the exposure to the external environment and the cooling effects of night-time radiation. Hence, any warm, moist air from the internal environment that reaches this outer layer (either by diffusion through the insulation or via gaps and cracks) will result in a high relative humidity as the temperature of the air decreases.

There may also be potentially wider risks to the roof covering (i.e. not limited to timber rafters) when the insulation is applied directly to the tiles. This may include decay of the timber battens and tile fixings, and also to the tiles or slates themselves. High moisture levels in this region could lead to absorption of the moisture into the tile, which may lead to freeze-thaw spalling of the tile.

Impact of discontinuous insulation

The risk assessment models carried out so far have assumed that the spray foam insulation has been uniformly applied. In practice, there may be areas where imperfections to the continuity of insulation may exist. The analysis in this section considers the effects of gaps in the insulation layer, which may arise from, for example, the use of materials that either shrink or do not move with the timber structure or imperfect application of the material.

To account for the impact of discontinuity in the insulation layer, a 1mm air gap has been included in the modelled scenarios between either side of the timber rafter and the spray foam insulation. Hence, to include this gap, the simulations in this section have been performed using a two-dimensional hygrothermal model. All modelling has assumed a 100mm thickness of spray foam insulation.

Discontinuous insulation: Open Cell applied to low resistance (LR) underlay – severe climate

Figure 26 presents the RH profile for the final 12 months from the 5-year simulation when open cell insulation is applied to a LR underlay. This chart provides the predicted conditions in the outer region of the timber rafter. The ‘standard condition’ (no air gap) scenario is overlaid with the air gap scenario for comparison. This shows that when an air gap is introduced, the RH in the outer region of the rafter increases slightly throughout the year, and the drying out is less efficient during summer months (compared to the equivalent scenarios modelled earlier that did not include an air gap).

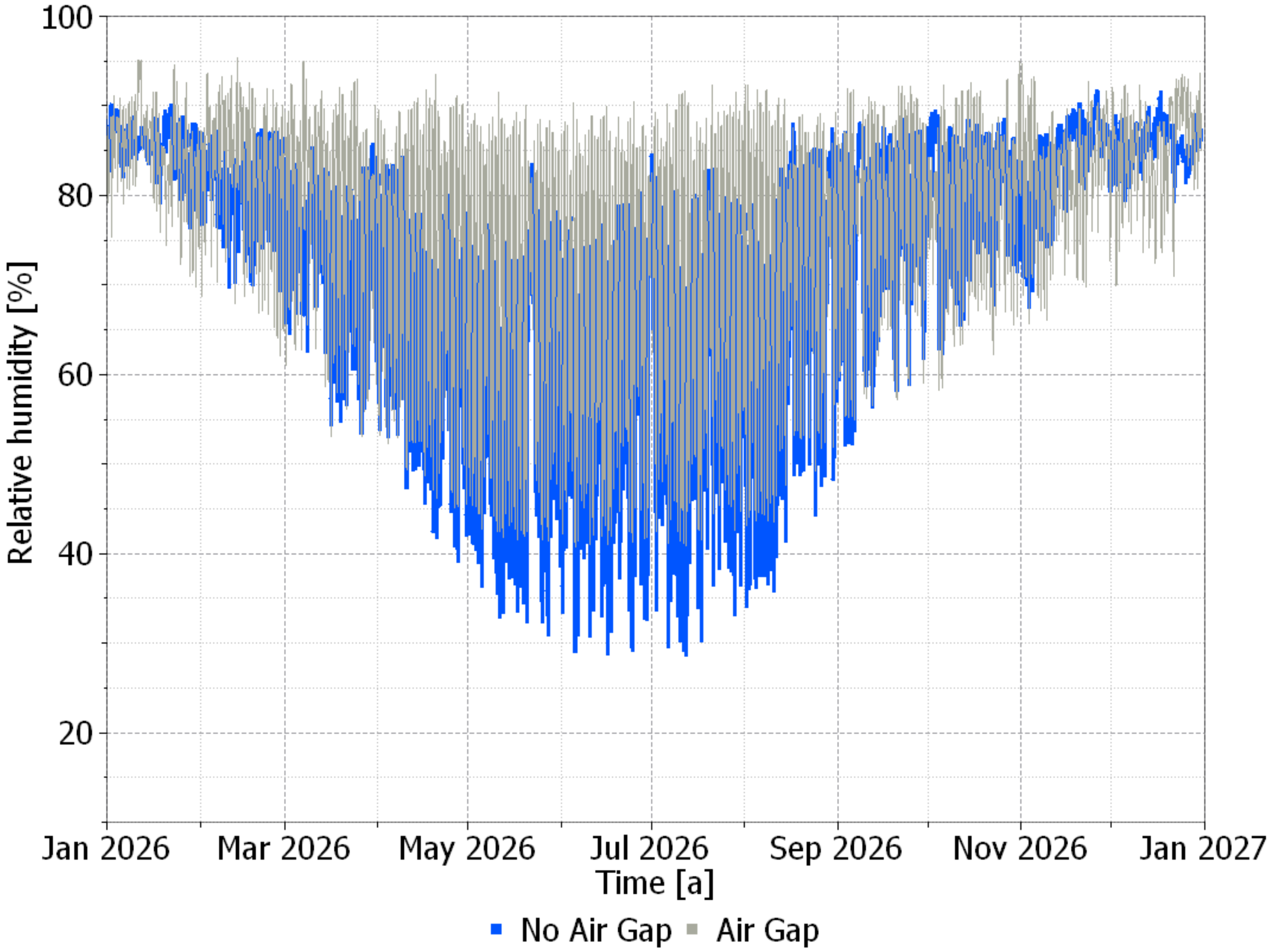

Figure 26. The impact of an air gap between the insulation and the rafter on the relative humidity in the outer region of the timber rafter over a 1-year period in Newcastle for 100mm of insulation applied to a LR underlay

Figure 27 presents the predicted RH for the same simulation as **Figure 26**, but in this case the profile represents the conditions in the outer region of the insulation layer. This also shows that, when there is an air gap present, the average RH is higher. The RH conditions remain above 95% for an extended period of time during the winter and summer months. This provides a potential situation where multilayer adsorption occurs and liquid transport begins to dominate. Thus, there is a high risk of moisture accumulation, undermining the performance of the insulation.

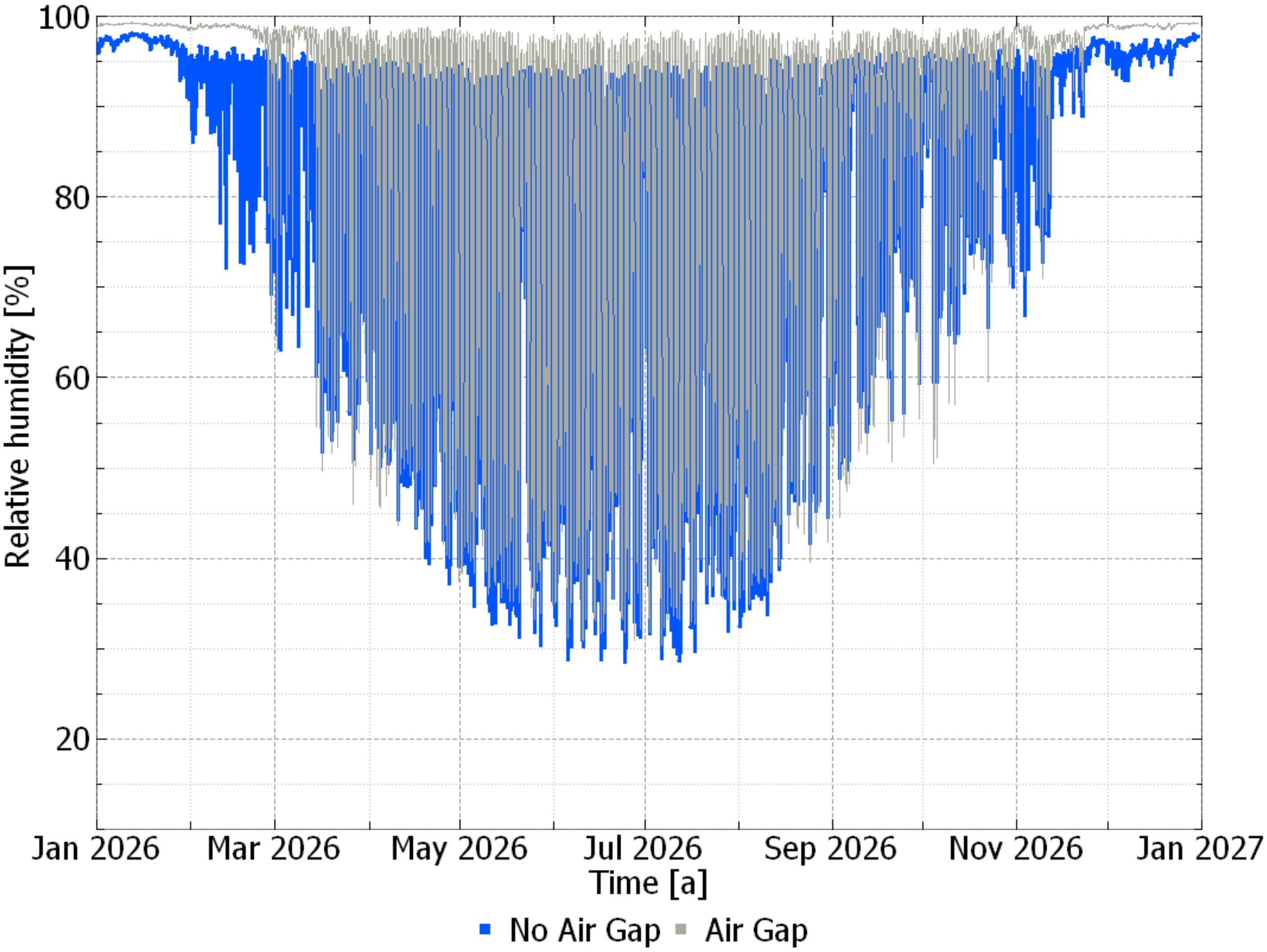

Figure 27. The impact of an air gap between the insulation and the rafter on the relative humidity in the outer region of the spray foam insulation over a 1-year period in Newcastle for 100mm of insulation applied to a LR underlay

Discontinuous insulation: Open Cell applied to high resistance (HR) underlay – severe climate

Figure 28 presents the RH profile for the final 12 months from the 5-year simulation when open cell insulation is applied to a HR underlay. This provides the predicted conditions in the outer region of the timber rafter. The ‘standard condition’ (no air gap) scenario is overlaid with the air gap scenario for comparison. This shows that when an air gap is introduced, the RH in the outer region of the rafter is more heavily influenced by the internal conditions. In which case there is a higher risk of mould growth and decay. In both cases, the 80% and 85% risk threshold for mould growth and timber decay respectively are exceeded for significant periods of time each year, and do not dry out below 60% during the warmer months.

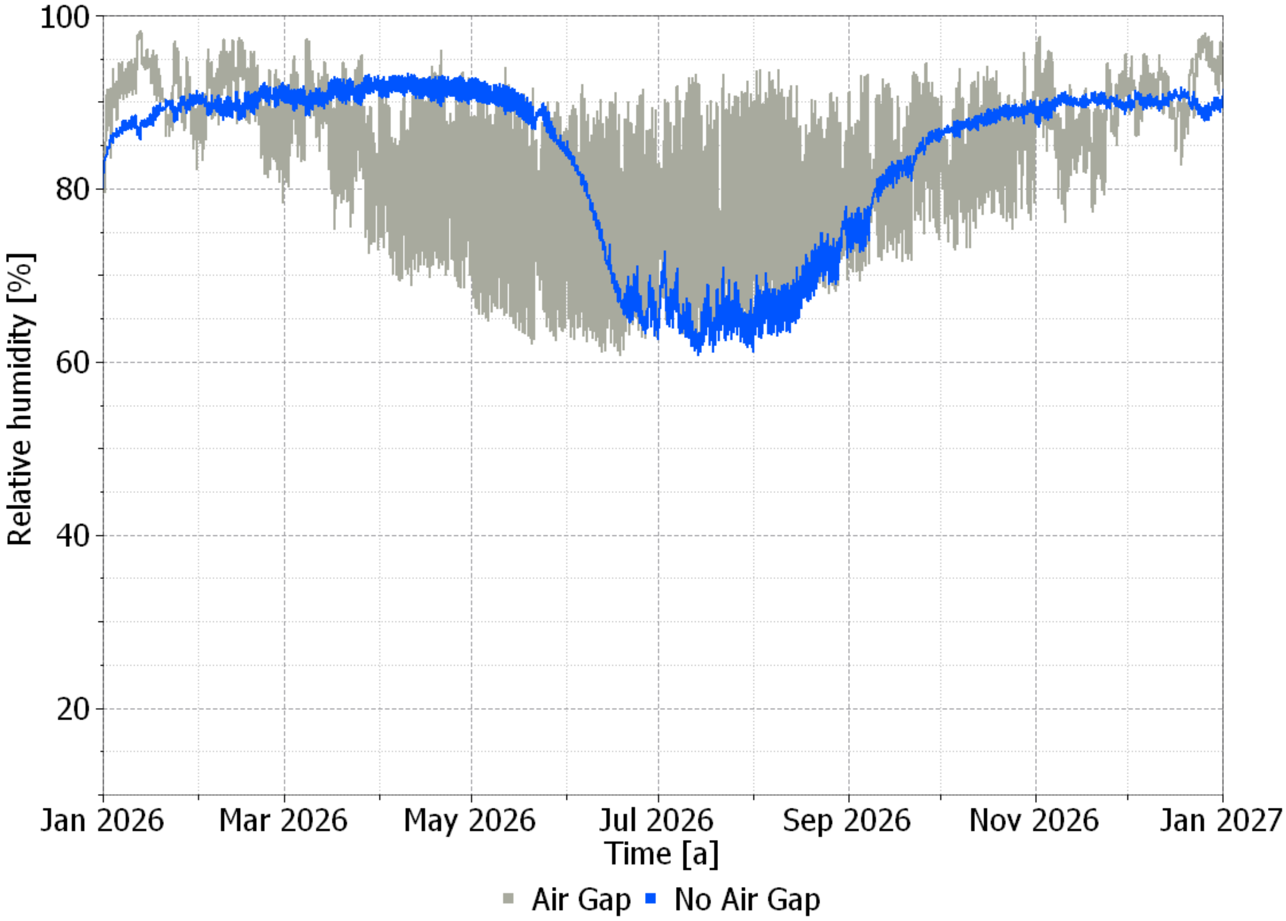

Figure 28. The impact of an air gap between the insulation and the rafter on the relative humidity in the outer region of the timber rafter over a 1-year period in Newcastle for 100mm of insulation applied to a HR underlay

Figure 29 presents the predicted RH for the same simulation as **Figure 28**, but in for the conditions in the outer region of the insulation layer. This also shows that, when there is an air gap present, the average RH is higher than without any air gap. However, the RH conditions in winter reaches 100% with an air gap, which indicates a very high risk of condensation occurring at this location. During the summer period there is effective drying, down to approximately 40% but the RH still reaches over 95% during this period.

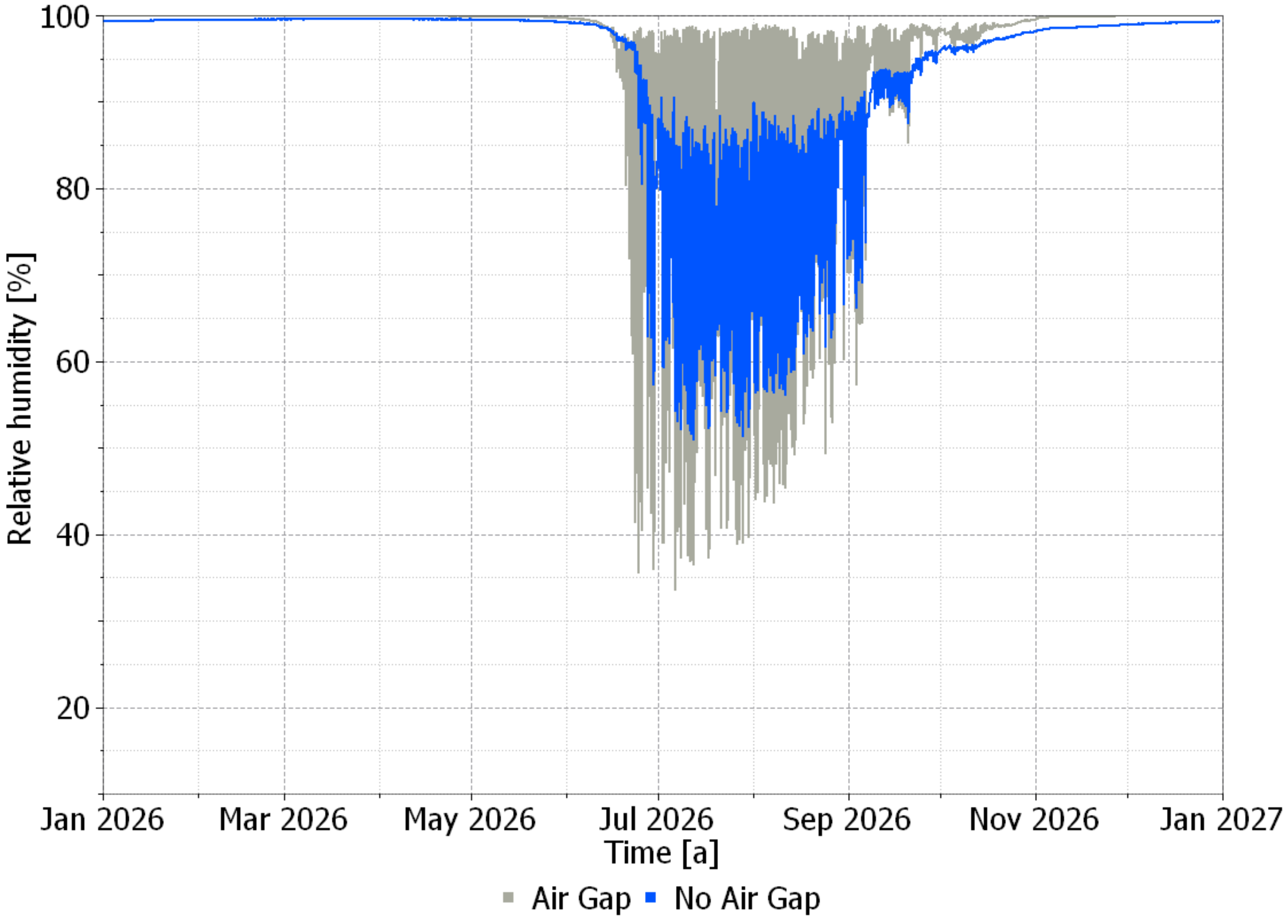

Figure 29. The impact of an air gap between the insulation and the rafter on the relative humidity in the outer region of the spray foam insulation over a 1-year period in Newcastle for 100mm of insulation applied to a HR underlay

Discontinuous insulation: Summary

The assessment of the timber rafter and the insulation layer in these simulations validates the ‘significant risk’ category assigned for the standard condition model (see **Table 7**). The introduction of air gaps increases this risk further, potentially into a ‘high risk’ category.

The presence of air gaps, as small as 1mm, significantly increase the moisture risk, and may lead to a build-up of moisture that could result in premature timber decay. The simulations may be more representative of ‘As Built In Service’ (ABIS) conditions, as discussed in BS 5250: 2021. Hence, the presence of gaps should be taken into account in a risk assessment.

Impact of an imperfect roof covering

The risk assessments in this section represent a scenario where ingress of rainwater occurs as a result of displaced or cracked tiles that are not repaired or replaced prior to the application of the spray foam insulation. Simulations have been performed only for scenarios when the insulation is applied directly to the tiles. This imperfection has been included in the form of a 1% wind driven rain source (i.e. 1% of rain incident on the roof will be deposited in the outer region of insulation).

The analysis presented in this section focuses on condensation risk, rather than predicted RH levels, as it is the effect of liquid moisture that is the primary risk factor in this scenario.

Figure 30 shows the risk of moisture accumulation beneath the tiles when 100mm of open cell spray foam insulation is applied. For comparison, a perfect roof (with open cell spray foam applied) is overlaid alongside. This shows that the moisture content for both a ‘perfect’ and ‘imperfect’ roof is predicted to be above the condensation risk threshold during the winter and early spring periods. However, the condensation risk period for the imperfect roof extends further back into the autumn period, hence, extending the risk further.

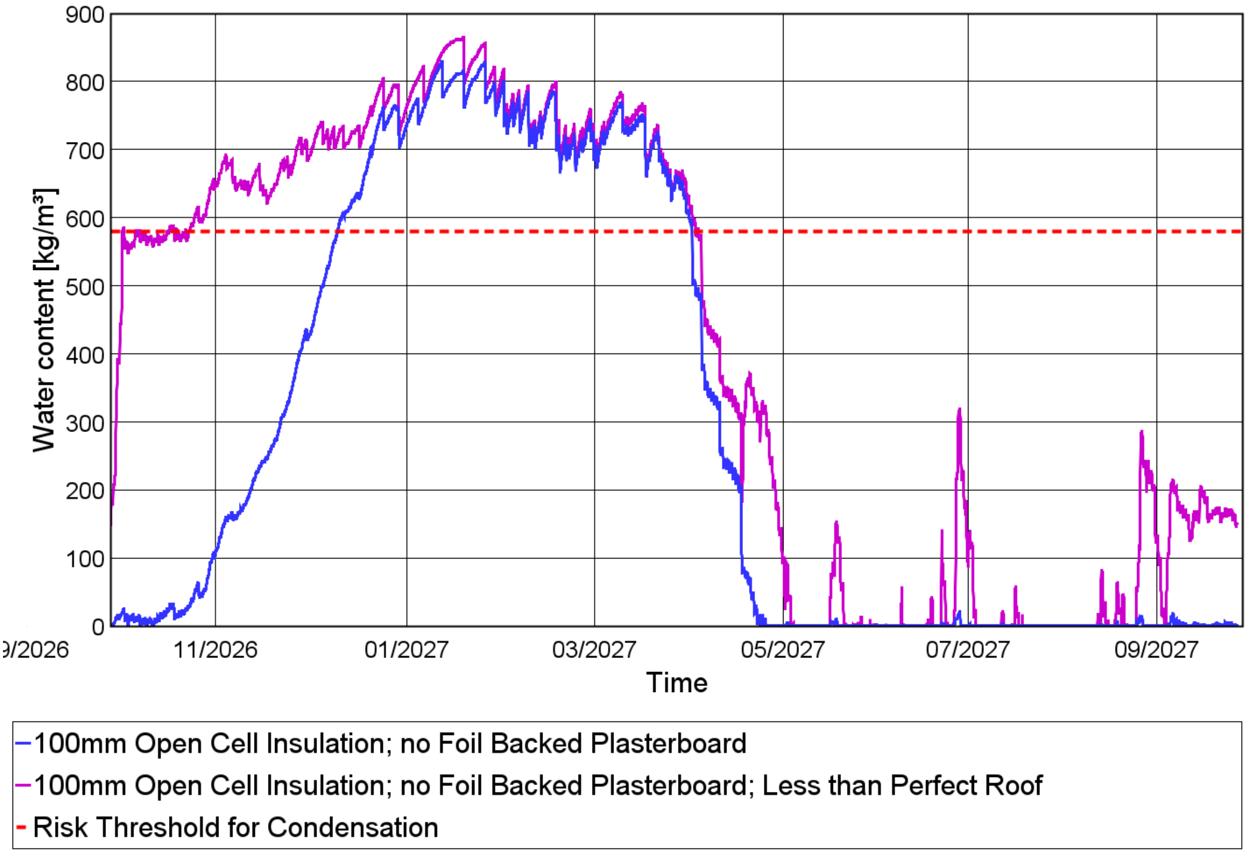

Figure 30. The impact of an imperfect roof on the condensation risk on the underside of the tiles for a 1-year period in Newcastle for 100mm open cell spray foam insulation is installed directly onto tiles

Figure 31 shows the same simulation, but in this case for the scenario when 100mm of closed cell insulation is applied directly to the tiles. This would suggest that there is a risk of condensation occurring on the underside of the tiles with the imperfect roof, with the risk spanning the same period as for the open cell scenario.

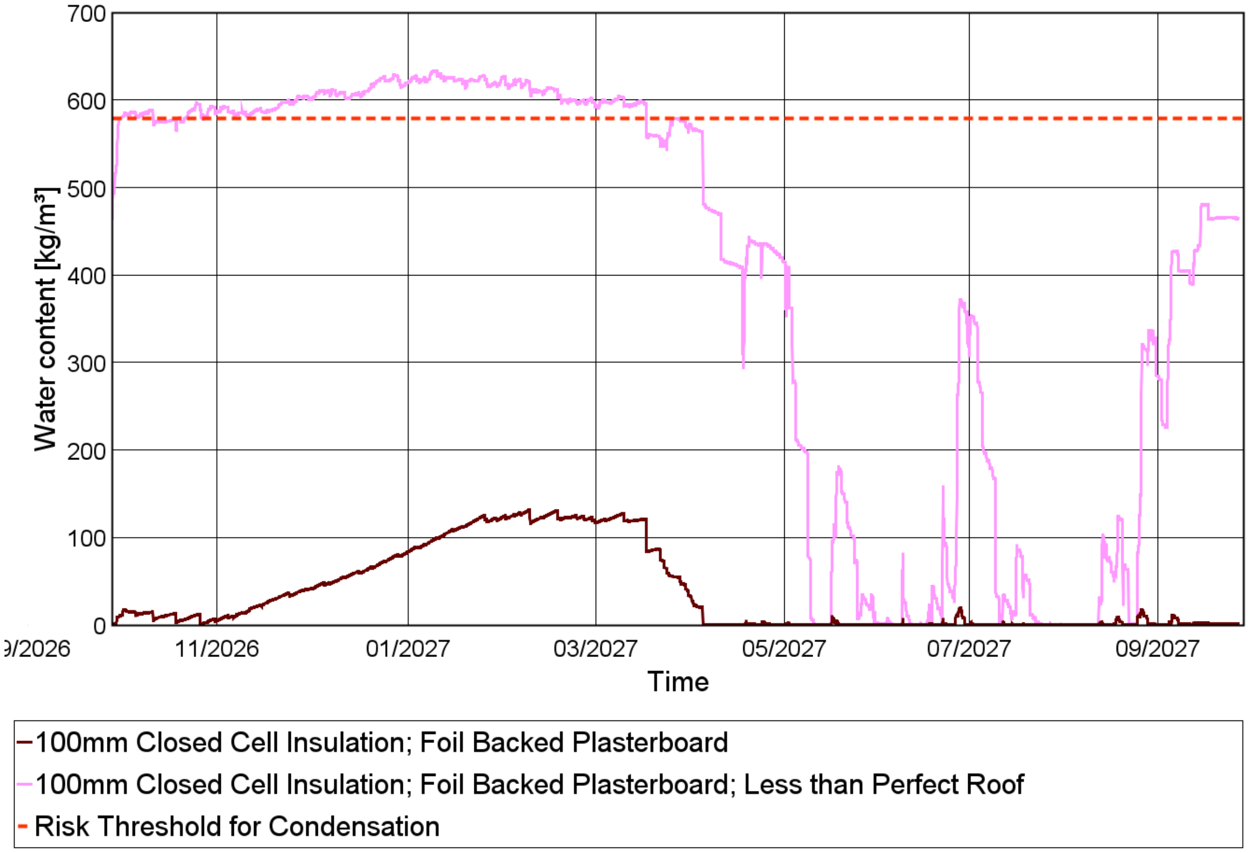

Figure 31. The impact of an imperfect roof on the condensation risk on the underside of the tiles for a 1-year period in Newcastle for 100mm closed cell spray foam insulation is installed directly onto tiles

Summary

The scenarios modelled identify a significant condensation risk when open or closed cell spray foam insulation is applied to an imperfect roof. For open cell insulation, the condensation risk model offers further information to support the risks, identified earlier, when applying insulation directly to tiles.

Whilst it is understood that the practice of applying spray foam insulation to an imperfect roof and directly onto tiles is now uncommon, historic examples of this practice exists, and the analysis in this section identifies that there is a very high risk of condensation occurrence if rainwater was able to penetrate into the insulation layer.

Impact of varying loft conditions

The risk assessments until now assume that the conditions within the loft are identical to those in the occupied space. This may be the case if all of the following are considered true:

- Standard moisture load in the dwelling
- No insulation or vapour resistance is installed at loft ceiling level.
- Original eaves ventilation pathways have been sealed.

This section explores the risk in situations where the loft conditions differ from those in the house. The conditions within the loft investigated in this section include an assessment of the following scenarios:

- Original loft floor/ceiling insulation is retained after the SFI has been applied (two thicknesses of loft roll: 50mm and 300mm)
- Ventilation paths in the loft (e.g. eaves vents) are either sealed over or left unsealed with the loft floor/ceiling insulation retained
- Air leakage and moisture transfer rates vary as a result of either high or low leakage between the conditioned dwelling and the loft space via the ceiling.

Different combinations of these scenarios will alter the temperature, relative humidity and vapour pressure conditions within the loft space which, in turn, may have an impact on the moisture risk in the outer roof layer, and the associated risk of decay to the timber rafters. These different conditions were assessed using a simple heat, air and moisture balance tool, and the resulting conditions were used to simulate the boundary conditions (instead of the medium +5% internal moisture load). All modelling in this section is for 100mm of open cell insulation.

The loft conditions predicted in the model identified that:

- If the ceiling has a typical level of airtightness but the eaves etc. are poorly sealed (assumed 5 air changes per hour), the conditions in the loft are similar to outdoors. This results in low vapour pressure differences which reduce the risk of damage however the loft ventilation almost completely undermines the thermal benefit of any SFI. The effect of the ventilation rate of an unheated loft on the thermal performance of rafter level insulation is outlined in Appendix 4.
- If the roof eaves are well sealed (assumed 0 ach) and there is minimal insulation at ceiling level, the loft conditions are similar to the occupied space and the risk assessment can be expected to be similar to the scenarios modelled previously.
- If the eaves are well sealed (assumed 0 ach), there is significant ceiling level insulation, and the ceiling is not airtight, the loft conditions are cooler, relative to the occupied space, which increases the relative humidity levels on the loft zone.

The results presented here provide a summary of the range of scenarios modelled. A sub-study report that details all of the scenarios modelled is included in the Appendix 3.

Note, the results of the analysis of the various loft conditions in this section identify that there would be **minimal additional impact on the risk of timber degradation to the rafters** compared to when the loft is assumed to have the same conditions as the occupied space (i.e. the risks are similar to those presented in the main results section). Hence, the results for timber degradation are not presented further here but are presented in Appendix 3.

Mould growth risk for alternative loft conditions: Open Cell applied to low resistance (LR) underlay – severe climate

Figure 32 and **Figure 33** present the RH profile for a typical winter and summer week during the final 12 months from the 5-year simulation when 100mm of open cell insulation is applied to a LR underlay. In this case the charts show the predicted conditions at the internal surface for the scenarios when the original ceiling insulation is left in-situ under varying ventilation conditions (N.B. this is the most relevant region for mould growth, rather than the outer surface of the insulation which is of most relevance for timber decay and shown in charts in preceding sections). The standard internal condition (green) is overlaid for comparison. The 80% threshold line is added as the risk threshold for mould growth.

This shows that the existing ceiling level insulation, loft ventilation and ceiling airtightness have a strong influence on the conditions at and near to the internal surface of the modelled build-up. The standard condition scenario is shown to be well below the mould risk threshold. However, in all other cases, both in winter and summer there are significant periods of exceedance above this threshold. The RH conditions appear to be worse with a greater thickness (300mm) of ceiling insulation retained, as this will have the greatest influence for lowering the temperature in the loft space. The RH reduces slightly when the external ventilation rate conditions are increased, although this would be counter-productive to the thermal performance of the insulation, i.e. there would be significant thermal bypass.

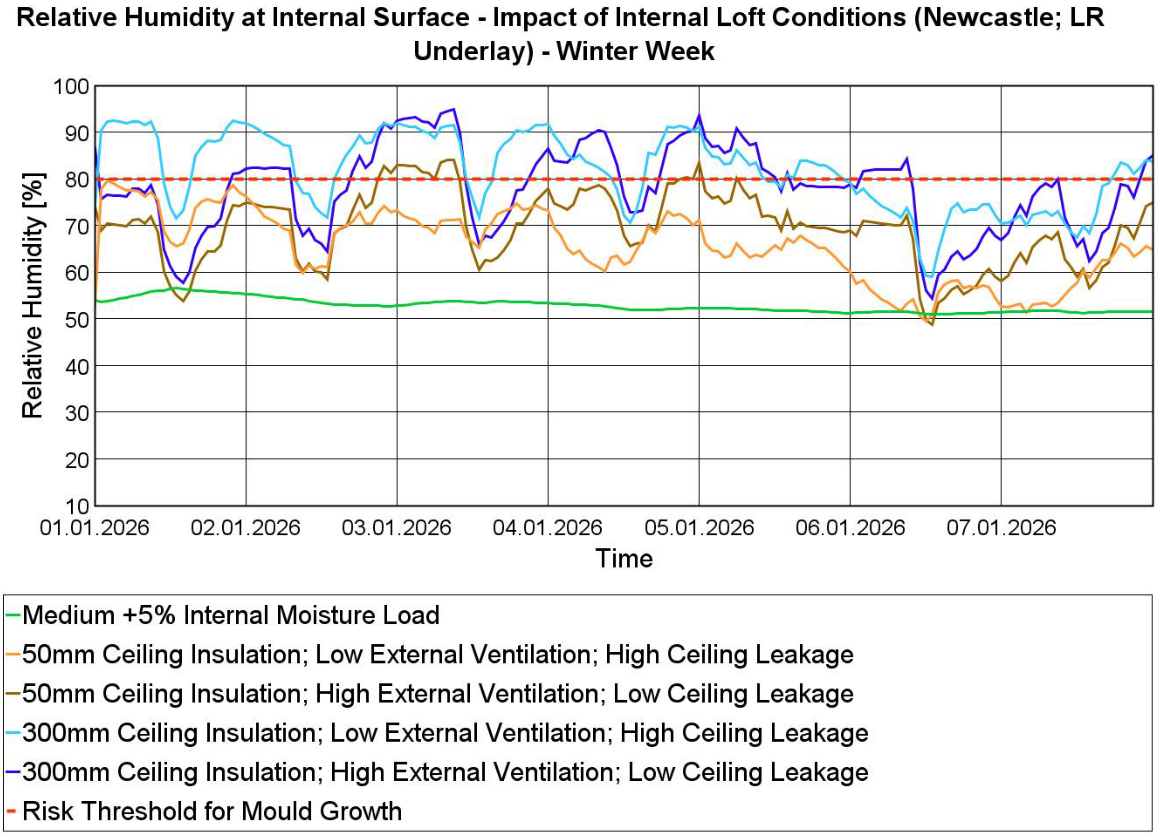

Figure 32. The impact of loft conditions on the relative humidity at the internal surface over a 1-week period in winter in Newcastle when there is 100mm of open cell SFI applied to a LR underlay

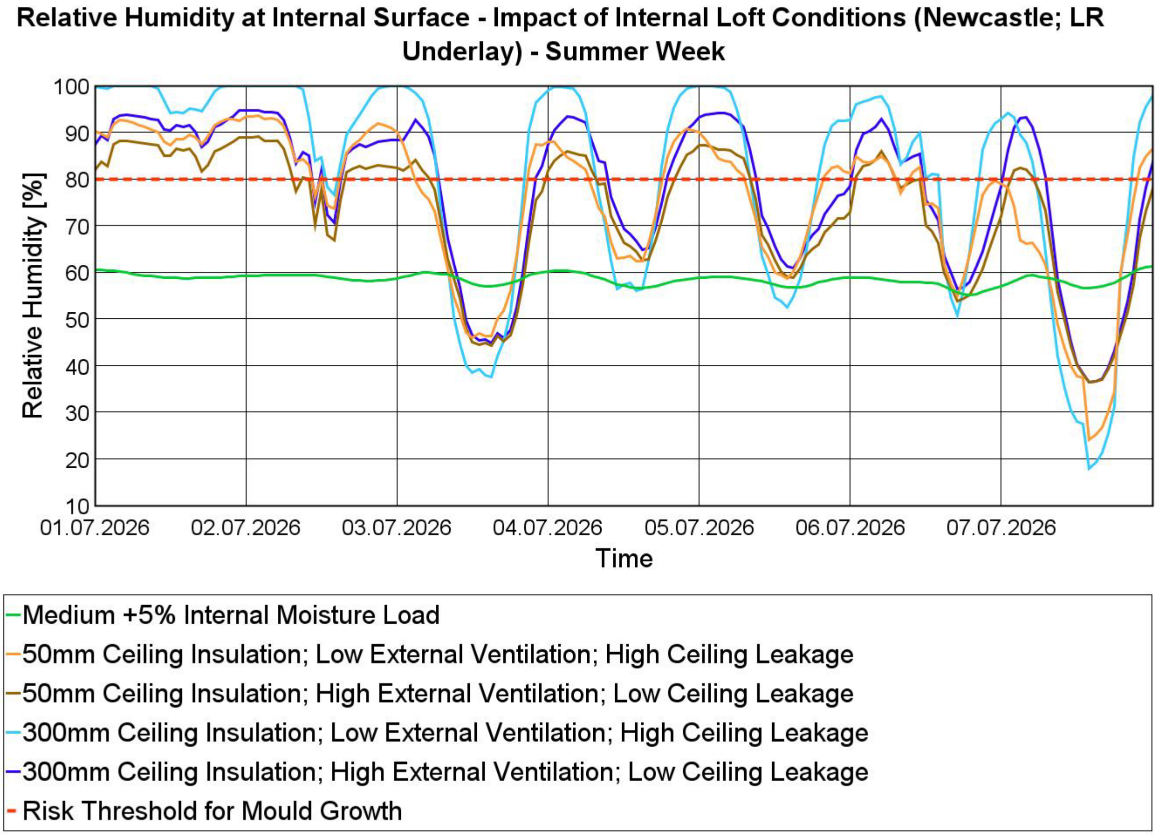

Figure 33. The impact of loft conditions on the relative humidity at the internal surface over a 1-week period in winter in Newcastle when there is 100mm of open cell SFI applied to a LR underlay

The analysis of mould growth risk to the internal surfaces of both the timber rafter and the SFI (both exposed internally), identified a greater risk compared to the standard boundary conditions. **Table 9** summarises these results alongside a summary of the mould risk for the scenarios modelled.

- Red: Significant risk. Mould Growth Index >3
- Amber: Medium risk. Mould Growth Index of between 3 and 1
- Green: Low risk. Mould Growth Index of <1

Table 9: Summary of mould risk: insulation applied to low resistance (LR) underlay – severe climate

	Loft conditions same as previous models	50mm ceiling insulation		300mm ceiling insulation	
		Eaves vents sealed and high ceiling leakage	Eaves vents un-sealed and low ceiling leakage	Eaves vents sealed and high ceiling leakage	Eaves vents un-sealed and low ceiling leakage
Risk of mould growth on internal surfaces	Low risk of mould growth on to timber rafters Low risk to underside of mould growth on SFI	Significant risk of mould growth on timber rafters Medium risk of mould growth on underside of SFI	Low risk of mould growth on to timber rafters Low risk to underside of mould growth on SFI	Significant risk of mould growth on timber rafters Significant risk of mould growth on underside of SFI	Significant risk of mould growth on timber rafters Low risk to underside of mould growth on SFI

Mould growth risk for alternative loft conditions: Open Cell applied to high resistance (HR) underlay – severe climate

Figure 34 and **Figure 35** present the RH profile for a typical winter and summer week during the final 12 months from the 5-year simulation when 100mm of open cell insulation is applied to a HR underlay. As with the LR underlay assessment, the charts show the predicted conditions at the internal surface for the scenarios when the original ceiling insulation is left in-situ with and under varying ventilation conditions. The standard boundary condition scenario (green) is overlaid for comparison. The 80% threshold line is added as the risk threshold for mould growth.

These charts show a similar but more pronounced trend to the LR underlay assessment. Again, the standard boundary condition scenario is shown to be below the mould risk threshold, and all other cases, both in winter and summer, exceed the risk threshold for significant periods. The conditions worsen with a greater thickness (300mm) of ceiling insulation retained and, throughout the year, conditions for surface condensation within the loft space may be met.

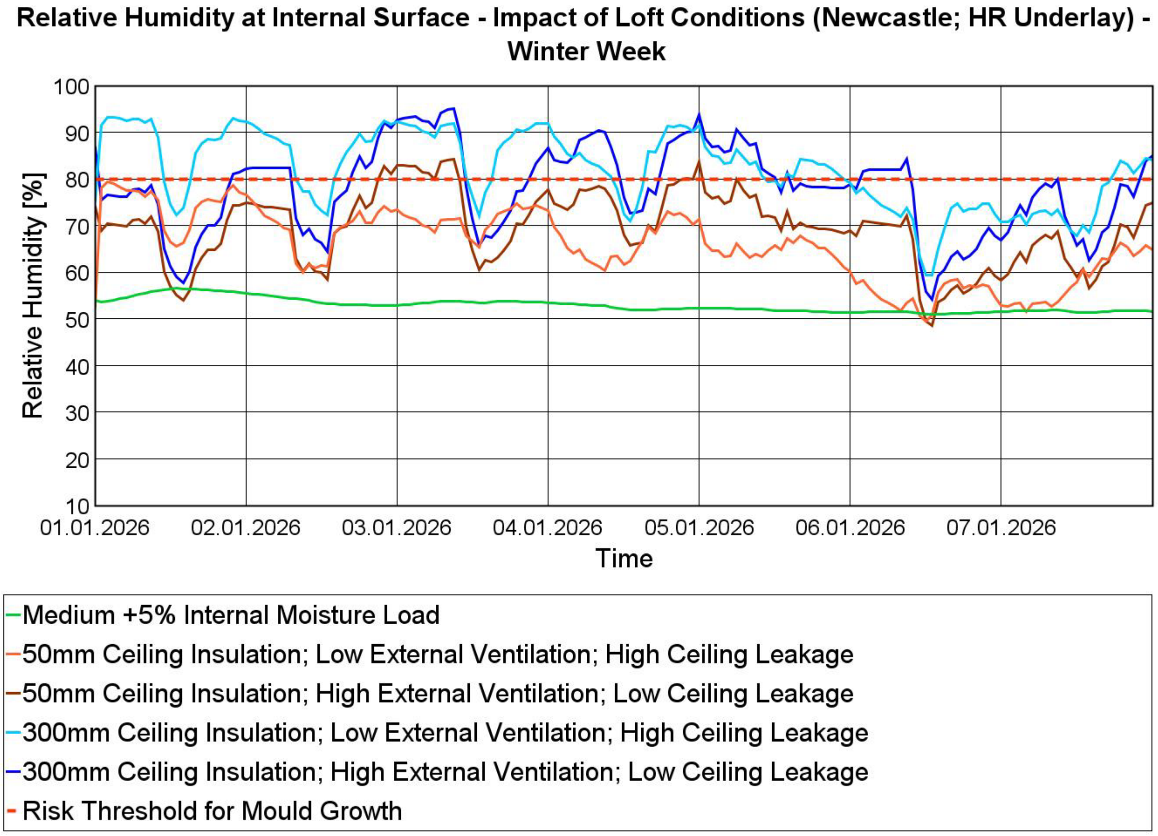

Figure 34. The impact of loft conditions on the relative humidity at the internal surface over a 1-week period in winter in Newcastle when there is 100mm of open cell SFI applied to a HR underlay

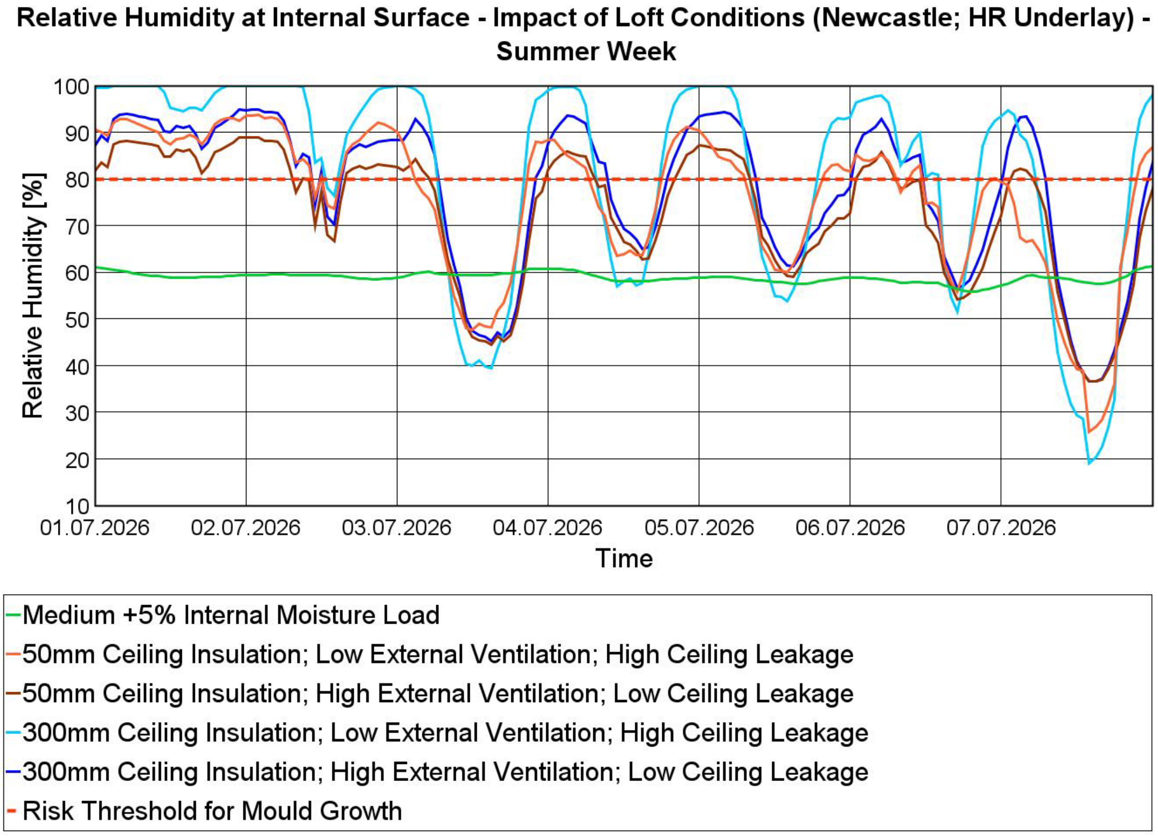

Figure 35. The impact of loft conditions on the relative humidity at the internal surface with HR underlay over a 1-week period in summer when there is 100mm of open cell SFI applied to a HR underlay

Table 10 provides a summary of the mould risk for the scenarios modelled but, irrespective of loft conditions, applying open cell SFI to a HR underlay without an AVCL has been shown to present a high risk of decay to the timber rafters.

Table 10: Summary of mould risk: insulation applied to high resistance (HR) underlay – severe climate

	Loft conditions same as previous models	50mm ceiling insulation		300mm ceiling insulation	
		Eaves vents sealed and high ceiling leakage	Eaves vents un-sealed and low ceiling leakage	Eaves vents sealed and high ceiling leakage	Eaves vents un-sealed and low ceiling leakage
Risk of mould growth on internal surfaces	Low risk of mould growth on timber rafters Low risk of mould growth on underside of SFI	Significant risk of mould growth on timber rafters Significant risk of mould growth on underside of SFI	Medium risk of mould growth on timber rafters Low risk of mould growth on underside of SFI	Significant risk of mould growth on timber rafters Significant risk of mould growth on underside of SFI	Significant risk of mould growth on timber rafters Medium risk of mould growth on underside of SFI

Summary of assessments in different loft conditions

Earlier analyses for open cell spray foam applied to either low or high resistance underlays under standard conditions (i.e. when the loft conditions are identical to the occupied space after SFI is applied) have shown that there is a high risk of timber decay in a severe climate. Hygrothermal assessments for scenarios when the original ceiling-level loft insulation is retained, indicate the risks to timber rafters (i.e. at the outer surface of the insulation) are similar to the risk for the standard boundary condition.

However, modelling indicates that varying loft conditions are likely to affect mould growth on the internal boundary layer, i.e. the timber and SFI layers exposed inside the loft area. The equivalent hygrothermal assessments and associated Mould Growth Index analyses for these areas and presented in this section show an increased risk of mould growth both to the exposed timber rafters and to the SFI exposed surfaces compared to the standard condition loft scenario. In the cases where the loft insulation is retained, with a reasonably well-sealed ceiling, and assuming the application of SFI has sealed over the original eave's vents, there is a significant risk of mould growth on the internal surface of the timber rafters and other exposed surfaces in the loft. In scenarios where it has been assumed that the eaves vents have not been sealed, the additional ventilation in this zone will reduce the mould growth risk. However, if these vents are left unsealed there will be significant thermal bypass to an extent such that the thermal benefit of applying SFI would be significantly diminished.

The same analyses were carried out for the less severe climate (London). In these cases, the level of risk of timber decay was the same as previous analyses. The risk of mould growth to the internal boundary layers were slightly less than identified for the severe climate, but there is still a significant risk of mould growth to the timber rafters. See Appendices document for full details.

These results indicate that the application of open cell spray foam insulation onto both LR and HR underlay may introduce significant risk of mould growth to the internal surface of timber rafters, and, in some cases, to the underside of the SFI if the original loft insulation is left in-situ after the SFI has been installed, and conditions inside the loft zone differ from the occupied zone of the dwelling.

Review of relevant standards, specifications, and guidance

This section provides an overview of some of the relevant standards and other publications that provide calculation assessment methods, risk management processes, or practical guidance for minimising moisture risks in thermal elements, including roofs insulated at rafter level.

- BS 5250: 2021 Management of moisture in buildings. Code of practice
- PAS 2035: 2019- Retrofitting dwellings for improved energy efficiency – specification and guidance
- BR262 Thermal insulation: avoiding risks (now withdrawn)

Where relevant, recommendations are made for future revisions to these documents, based upon the findings of this research.

BS 5250: 2021 Management of moisture in buildings. Code of practice

BS 5250: 2021[11] is a full revision of BS 5250: 2011 given that knowledge of the problems caused by moisture in buildings has advanced rapidly. Up until now, it has been known as a Code of practice for the prevention of condensation in buildings. This latest edition of BS 5250 to include other moisture problems such as excessive humidity, rising damp, rain penetration and roof leaks, and the impacts on both the building fabric and the health of the occupants.

The new edition reflects the growing understanding of moisture risk in buildings, which are increasing due to greater levels of airtightness and insulation, fuel poverty, overcrowding, and changing use of buildings. As a result, it adopts the whole-building approach to moisture safe design as published in the BSI white paper[12] on moisture in buildings. This takes account of the interaction of multiple elements in a joined-up way and is, therefore, more closely related to real-world moisture problems and risks. Importantly, it now considers the approaches to building context, coherence of design and detailing, capacity, and as-built in-service (ABIS) conditions. Hence, rather than assessing individual elements, the interactions between them and the effects on the whole building as a system must be considered.

Guidance relating to roofs:

Major revisions were undertaken in BS 5250: 2021 for the prescriptive guidance for floors and walls in buildings undergoing energy efficient retrofit. There were fewer changes in the section covering design principles for roofs, and where much of the prescriptive guidance

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[11] BS 5250:2021 – Management of moisture in buildings. Code of practice. BSI Standards Publication

[12] May N. Sanders C. Moisture in buildings: an integrated approach to risk assessment and guidance. British Standards Institution 2016. BSI/UK/899/ST/0816/EN/HL

remains unchanged. The prescriptive guidance is covered in the section on Moisture safe design but in summary advises:

- an AVCL be provided in all cases, both for HR and LR underlay
- for HR underlay and for LR underlay in circumstances where it is not practicable to provide an AVCL, a ventilated air gap be provided between the underlay and the insulation.

For existing roofs, the new BS 5250, does now acknowledge that where *investigations are needed in order to establish the nature, implications and extent of moisture in the roof of an existing building*, that the guidance given in Annex C should be followed. Annex C provides methods suitable for the diagnosis of dampness problems, which include historical context, building use (informed by occupants), physical surveys and monitoring.

In addition, BS 5250: 2021 provides guidance on moisture risk assessment methods. Where appropriate, the recommendation is to follow the prescriptive guidance (see Moisture safe design above). As an alternative, modelling can be undertaken using the following approaches:

- Simple steady-state condensation risk using the ‘Glaser method’ described in BS EN ISO 13788: 2012 *Hygrothermal performance of building components and building elements. Internal surface temperature to avoid critical surface humidity and interstitial condensation. Calculation methods.*
- One-dimensional, non-steady state heat and moisture model described in BS EN 15026: 2007 *Hygrothermal performance of building components and building elements. Assessment of moisture transfer by numerical simulation.*
- Non-standardised, complex two- or three-dimensional models to account for the effects of air movement.

BS 5250: 2021 notes some limitations associated with the Glaser method in BS EN ISO 13788: 2012. These being that the method:

- Works only on the basis of monthly averages that may not be representative.
- Does not account for solar gains (which the analysis presented here suggests may be significant).
- Does not account for differences between loft conditions and those within the occupied space.
- Cannot allow for moisture loads other than due to diffusion, i.e. from air leakage and rain ingress.

Furthermore, the typical implementation of the Glaser method used in the UK report the occurrence of liquid condensation only. It is well established that the threshold for mould and timber decay is lower than 100% RH. Therefore, it is possible for conditions that support mould and timber decay to persist without liquid condensation, so the method may underestimate risk in some circumstances. This is particularly so when diffuse open materials are used, such as low resistance (LR) underlay.

An alternative, more complex assessment method is described in BS EN 15026: 2007. This involves dynamic (non-steady state) moisture modelling, which takes account of a range of hygrothermal properties, including liquid transport and moisture storage, and accounts for a wider range of external variables such as wind and solar effects. This method is recommended in BS 5250: 2021 for situations where a greater level of confidence is needed for assessing the moisture risk, and is the method used in this study for the one-dimensional models. However, a limitation of one-dimensional models is the inability to deal with interfaces and junctions (such a timber rafters). Accordingly, some of the models in this report have been evaluated using more sophisticated two-dimensional methods, along with the VTT the post-processing tools to help investigate specific levels of risk. These methods are outside of the scope of BS EN 15026: 2007, which is due to be updated. The more sophisticated methods are acknowledged in BS EN 15026: 2007 as well as BS 5250: 2021.

BS EN 15026: 2007 does not include moisture loading or stressing due to rain ingress or air movement. For these situations, BS 5250: 2021 recommends that the prescriptive guidance be followed (see **Moisture safe design** above) and that this should be backed up by non-standardised, complex two- or three-dimensional modelling methods.

The two-dimensional scenarios assessed in this research specifically include the timber rafter, surrounded by SFI (see **Figure 4**). Hence, both the moisture risk in the roof build-up for both the SFI and the timber rafter can be assessed together. The moisture risks identified in the outer layer of the SFI in the two-dimensional models were found to be very similar to those identified using the one-dimensional, BS EN 15026: 2007-compliant, approach. Hence, this research would suggest that one-dimensional (BS EN 15026: 2007) dynamic hygrothermal simulations are sufficient in most cases.

One particular benefit of using the two-dimensional models, as used in this research, is the ability to assess the implications of introduced imperfections in the model. In this study a 1mm air gap was introduced into some of the modelled scenarios between the rafter edges and the insulation to allow air movement to be simulated (see section: ‘Impact of discontinuous insulation’ above). This air gap might be typical for rigid board insulation, but may also apply to SFI products, if they shrink slightly over time. The inclusion of a modest air gap in the models indicate that there would be an elevated moisture risk above the risk threshold identified for the same models without any gaps. Such gaps would also undermine the thermal performance if present.

Simulations, both one-dimensional and two-dimensional estimate conditions of temperature, humidity and water content, but do not constitute a risk assessment, which requires careful interpretation of the simulated results. This interpretation can be supported using more sophisticated post-processing tools that account for multiple factors (such as temperature, humidity, vulnerability of materials) sometimes including their dynamic interactions. The non-standardised models used in this study also include the VTT timber degradation and mould risk analysis simulations. The results from these tools have provided a valuable insight into the potential deterioration risks over a 5-year period.

Whole-building approach and ABIS conditions

As well as recommending the appropriate use of numerical models or adopting prescriptive guidance, the new BS 5250: 2021 now includes guidance (Annex A – Guidance for designers and builders: whole-building approach), to ensure a moisture-safe design. It is important to note that BS 5250: 2021 does not contain specific clauses around insulant types, whether they be spray applied, or e.g. rigid foam board or mineral fibre batts. Instead, the standard lays down the principles to be applied to ensure the moisture risks in the design and application have been adequately assessed to mitigate the risk to a reasonably safe level.

The key principles of the whole-building approach are:

1. Understand the context of the building and the building project and ensure compatibility of the design with this context.
2. Ensure coherence in approach and detailing.
3. Build in capacity in the design and construction phase for mistakes, uncertainties and future challenges.
4. Ensure that caution is taken in the use, maintenance and after care phase where there are ongoing requirements of care and uncertainty of outcomes.

Context and compatibility

Context of the building includes geographical context, form, materials, construction methods, condition and occupancy. Within the remit of this study, geographical context has been shown to have a significant bearing on the level of risk, with the models from the severe climate generally resulting in a higher degree of risk than the less severe climate. The guidance advises that designers should consider the effects of solar, wind and driving rain in a risk assessment using local weather data. As such, the Annex A recommends that modelling is carried out in accordance with BS EN 15026: 2007 (and not BS EN 13788: 2012, the Glaser method).

This study has also shown the importance of understanding both the material to be used (e.g. open cell or closed cell insulation) and the materials that exist (e.g. LR or HR underlay) where the guide identifies that compatibility checks between these materials is essential. In terms of condition, Annex A recommends that the condition of an existing building forms part of a moisture risk assessment. In the case of roofs, the underlay should be in a good condition prior to thermal treatment. This study has shown that there is a detrimental impact if rainwater was able to penetrate into the insulated roof slope.

Coherence

Management of moisture can be achieved by two fundamentally different approaches: moisture open (e.g. open cell SFI) and moisture closed (e.g. closed cell SFI). A moisture open approach, most commonly used in traditional buildings, should allow moisture to freely move through a build-up and evaporate out. This is why some of the open cell modelled scenarios in this study have shown a higher risk when applied to a high resistance underlay.

A moisture closed approach, which is used in most modern buildings attempts to exclude moisture from the fabric by using impermeable materials. In the case of closed cell SFI, the models have shown a lower risk to timber degradation than with the moisture open material. However, there is still a significant risk if there are any imperfections to the application of closed cell SFI; hence physical coherence of the installation is crucial. Annex A also recommends thermal bridges be minimised by employing approved calculation methods or applying principles such as those published in the, now discontinued, Accredited Construction Details. Although the models in this research have not assessed the interactions between a SFI insulated sloped roof and adjoining wall structures, there may be a significant thermal bridging (or complete thermal bypass) and mould risk associated with the application of SFI as a single measure. For example, if a roof, which was previously a cold roof, is treated with SFI but the adjoining gables were only insulated up to the original, insulated ceiling level, these walls will be much colder than other surfaces, including the newly insulated roof slope. Heat will largely bypass the insulated slope via the uninsulated gable wall, and the cold surfaces will increase the mould risk on this surface.

Capacity
There is a risk that increasing the thermal performance too far can lead to a moisture risk that is beyond the capacity of a building to deal with. In the case of retrofit, Annex A recommends a balance be struck between energy reduction and moisture safety.

In the context of this study, two insulation thicknesses: 100mm and 200mm have been considered to provide a range between potential minimum and maximum. Whilst the assessed risk category did not change between these thicknesses, the predicted RH in the outer layer of the insulation tended to be higher with the thicker insulation. Hence, the amount of SFI applied to achieve a given U-value should account for the potential additional moisture risk.

Summary

The modelled simulations from this study assessed alongside the guidance in BS 5250: 2021, would suggest that adopting its recommendations would result in a moisture-safe design. However, the practice of applying spray foam insulation may not be in alignment with the prescriptive guidance, and therefore it is imperative that the risks of removing prescriptive measures, e.g. omitting an AVCL is adequately modelled to assess and mitigate the moisture risks for the appropriate environment. Furthermore, the practice of single, energy efficiency measures is contrary to the key principles of the whole-house approach laid out in BS 5250: 2021.

PAS 2035: 2019[13] – Retrofitting dwellings for improved energy efficiency – Specification and guidance

PAS 2035 was introduced following the recommendations of the Each Home Counts review[14]. It provides an over-arching framework for retrofit standards to quality assure energy retrofits of existing domestic buildings, alongside best practice guidance for implementing energy efficiency measures.

A key purpose of PAS 2035 (incorporating PAS 2030 - specification for the installation of energy efficiency measures in existing buildings) is to strengthen the protection of homes and occupants against poor quality retrofit and its unintended consequences. PAS 2035, refers to other relevant standards, such as BS 5250 to help avoid key moisture risks.

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[13] PAS 2035: 2019 has since been updated to PAS 2035:2023 Retrofitting dwellings for improved energy efficiency – Specification and guidance.

[14] Each Home Counts: An Independent Review of Consumer Advice, Protection, Standards and Enforcement for Energy Efficiency and Renewable Energy. BEIS and DLUHC (2016)

However, both PAS 2035 and BS 5250 focus on risk management, and do not, therefore, explicitly reference any particular insulation treatments, including spray foam insulation.

PAS 2035 includes a range of specific professional retrofit roles, each with clear responsibilities to ensure that individuals deliver quality retrofit and that they are accountable for their actions. These roles include, among others:

- Retrofit Assessor
- Retrofit Coordinator
- Retrofit Designer

Any professional involved in the delivery of PAS 2035 domestic retrofit projects needs to undergo specific retrofit training and qualifications and be registered with the TrustMark scheme.

By following the processes set out in PAS 2035, a Retrofit Assessor will determine the level of risk that the proposed retrofit will create and provide relevant information for use by the Retrofit Designer. The Retrofit Coordinator will oversee the project from beginning to end to ensure compliance with the PAS and, as part of their role, will produce a medium-term retrofit plan for the property. Each of these professionals will be able to assess the suitability of insulating an element and the associated risks that relate, not only to that measure, but any interactions with other measures proposed in the plan.

The example described previously (under BS 5250: 2021 – coherence), where a roof is insulated at slope level as a single measure, but without consideration to the gable walls, would not be PAS compliant. Furthermore, unless a roof space is being converted for additional accommodation (e.g. room-in-roof) a Retrofit Coordinator will likely query why the roof insulation strategy is being changed from a cold loft to a warm roof, when re-insulating the loft at ceiling level may be more appropriate.

BR 262 Thermal insulation: avoiding risks

In 2002, the Building Research Establishment published detailed guidance to account for the technical risks relating to insulation improvements (BR 262) to thermal elements. BR 262 provides clear and comprehensive, practical guidance on the types of problems, including those related to moisture, which may occur when thermal insulation is added to buildings. The document, which was last revised almost 20 years ago, needs to be updated to align with current thermal performance standards and best practice in several aspects, including roof insulation. However, it is referenced in the Approved Documents C, E and L and the guidance within BR 262 may be taken as reasonable provision. Note, at the time of writing, BRE have withdrawn this guide but have not provided a timescale for the publication of an updated version.

As is the case for BS 5250: 2021, BR 262 espouses the principle of the ‘whole-building approach’ in that the thermal insulation, heating and ventilation aspects should form part of a total design rather than considering individual elements. A key principle of the guidance is that risk assessments should be made against environmental conditions arising out of the proposed thermal insulation measures.

In relation to roofs insulated at rafter level to create a warm roof, BR 262 highlights a potential moisture risk in cases where "*water vapour from the internal environment can condense on cold surfaces within the construction if it penetrates the insulation layer and cannot permeate through the tiling underlay*". The risks identified in this study, particularly where SFI is applied either to a HR underlay or directly to tiles support this advice.

BR 262 also advises that a vapour permeable (low resistance – LR) membrane should ideally be used as the tiling underlay with a 50mm air path between the tiling and the LR underlay. However, it does not explicitly recommend an air gap between the insulation and the underlay, even though the accompanying diagram suggests there should be a gap, as shown in **Figure 36**. The scenarios modelled in this study identify a significant moisture risk, leading to timber degradation in more severe climates. The guidance in BR 262 is explicit for cases where a HR underlay is present where is recommends a clear 50mm ventilated air path between the HR underlay and the insulation.

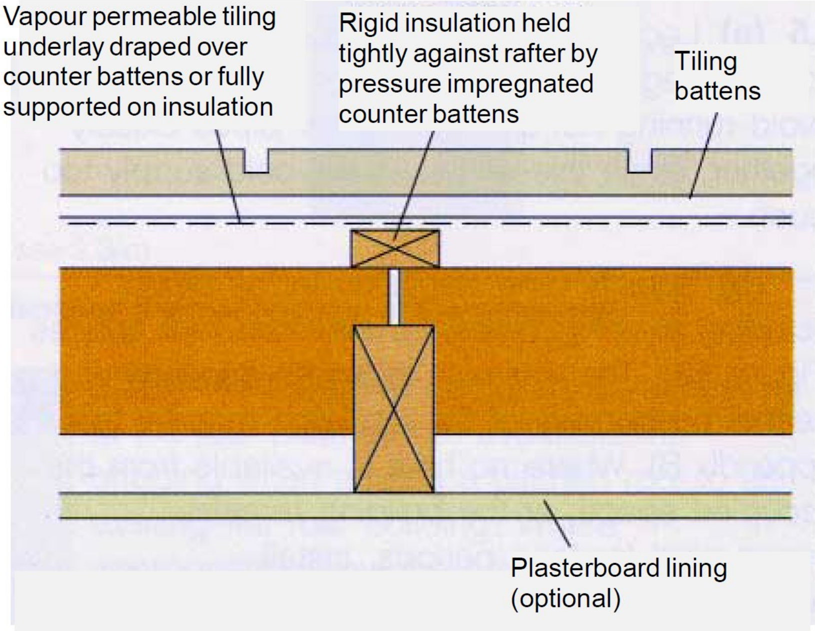

Figure 36. Section through insulation and rafter (from BR 262)

Furthermore, **Figure 36** does not include an AVCL to the warm side of the insulation, but instead recommends the inclusion of an AVCL "*to inclined ceilings enclosing kitchens, bathrooms and showers".* The scenarios modelled in this study, would suggest that there is a benefit of including an AVCL, particularly when open cell insulation is used, across all areas of roof being insulated, irrespective of the rooms enclosed.

If the intention is to update the guidance in a new publication of BR 262, it is recommended that:

- To ensure moisture safety, an air gap of at least 25mm should be provided between the underlay and the insulation, irrespective of resistance, i.e. both LR and HR underlays.
- An AVCL is included to the warm side of the insulation, irrespective of a HR or LR underlay. If closed cell insulation is used then, in theory, an AVCL has less benefit. However, ABIS conditions modelled in this study, such as gaps in the insulation

layer (rigid board may potentially be more prone to this than SFI), would suggest that an AVCL would reduce moisture risks within the insulated roof structure.

These changes would align the publication with the prescriptive guidance in BS 5250: 2021.

Conclusions

This research project considers the moisture risks associated with the application of spray foam insulation in sloping timber roofs in dwellings. The research team has carried out extensive hygrothermal modelling to assess this moisture risk, the risk of mould and condensation occurrence and likelihood of decay to the structural timber roof members embedded within the insulation layer.

Two types of spray foam insulation (SFI) have been considered in this research: open cell and closed cell. The open cell type has been evaluated in greater detail (i.e. using more complex two-dimensional simulations), based upon feedback from industry that this is the most widely used SFI in current practice.

The main models assessed evaluate the risk when SFI is directly applied to a range of substrates, both with and without an AVCL to the warm side of the insulation layer:

- Low resistance (LR) underlays (e.g. breather membrane)
- High resistance (HR) underlays (e.g. bitumen felt)
- Roof tiles

Two different England climate scenarios have been evaluated for each substrate: a severe climate (Newcastle); and a less severe climate (London) as the variations with wind-driven rain, humidity and solar gain will change the severity of risk. The main models assume that, once the SFI is applied, the loft space is within the thermal envelope. Hence, the conditions in the loft space should be equivalent to those in the occupied zone of the dwelling, i.e. the standard conditions modelled.

Further assessments were undertaken to evaluate risks when SFI is applied to these substrates to account for scenarios when the:

- Insulation is not fully continuous (e.g. gaps between the SFI and the timber rafter)
- Original loft/ceiling insulation is retained after the application of SFI, thereby changing the environment from the ‘standard conditions’ in the roof zone

BS 5250 prescriptive guidance assessment

The research indicates that risks are low when an open cell (moisture permeable) insulant is applied in accordance with the prescriptive roof constructions and guidance described in British Standard BS 5250:2021. These constructions include the provision of an air and vapour control layer (AVCL) on the warm side of the insulation and a space left between the insulation and the roof underlay (which needs to be specifically ventilated from the eaves in the case of high resistance underlays). For sprayed foam insulation such spaces can be created by the use of card spacers inserted between rafters or other similar techniques.

Applied directly to low resistance underlay

When insulation is applied directly to a low resistance underlay, for the less severe climate, the simulations resulted in a low moisture risk for both open cell and closed cell SFI. This is due, in part, to the low resistance of the underlay, which will allow moisture diffusion through it and aid preventing moisture accumulation near the cold side.

Conversely, in the severe climate, the predicted moisture conditions from the simulations are such that there was a medium risk of timber rafter deterioration when open cell SFI is used without an AVCL. This risk reduced slightly with the inclusion of an AVCL to the open cell insulation or by using closed cell insulation, but both resulted in a low to medium risk of timber rafter decay within 5 years.

In situations where open cell SFI is installed and the original loft insulation is retained (both climates), there is a significant risk of mould growth on the inner surface of the timber rafters and, to a slightly lesser degree, to the underside of the insulation. Other surfaces and objects in the loft may also be at risk.

Applied directly to high resistance underlay

When insulation is applied directly to a high resistance underlay, for the less severe climate, the simulations resulted in a low moisture risk for closed cell SFI. The risk was also predicted to be low for open cell insulation, provided an AVCL was installed to the warm side of the insulation. Without an AVCL there is a high risk of timber rafter decay within 5-years and a high risk of condensation occurrence, which could accelerate the rate of decay.

For the severe climate, the predicted moisture conditions identify a high risk of timber rafter deterioration when both open cell and closed cell SFI is used. For closed cell SFI, the risk reduced slightly with the inclusion of an AVCL but still results in a medium risk of timber rafter decay within 5-years.

Similar to the low resistance underlay assessment, in situations where open cell SFI is installed and the original loft insulation is retained (both climates), there is a significant risk of mould growth to both the inner surface of the timber rafters and to the underside of the insulation.

Applied directly to roof tiles

For both the severe and the less severe climates, the simulations resulted in a high moisture risk for both types of SFI with or without an AVCL. The predicted moisture levels are sufficiently high such that there is a high risk of timber rafter (and batten) deterioration within 5-years and, for open cell SFI there is also a high risk of condensation, which could accelerate the rate of decay.

Further analysis for situations where SFI is applied directly to the roof tiles considered the impact of an imperfect roof, whereby an amount of rain penetration could penetrate the waterproof layer. This identified, as expected, an even greater condensation risk than the scenarios without rain ingress The simulations are unable to predict where rainwater ingress will accumulate but the rate of decay to the timber rafters would likely accelerate.

Summary of findings

Table 11 and **Table 12** provide an overall summary of the risk for each of the cases for severe climate and less severe climates respectively. These tables are for standard internal boundary condition cases (i.e. the loft conditions are the same as the internal occupied conditions).

Table 11. Summary of cases modelled – severe climate

		Severe Climate (Newcastle)		
		LR	**HR**	**On Tiles**
No Lining	Open Cell	Medium risk of timber degradation	High risk of timber degradation	High risk of timber degradation
	Closed Cell	Medium risk of timber degradation	High risk of timber degradation	High risk of timber degradation
Foil-backed plasterboard	Open Cell	Medium risk of timber degradation	Medium risk of timber degradation	High risk of timber degradation
	Closed Cell	Low risk of timber degradation	Low risk of timber degradation	High risk of timber degradation

Table 12. Summary of cases modelled – less severe climate

		Less Severe Climate (London)		
		LR	**HR**	**On Tiles**
No Lining	Open Cell	Low risk of timber degradation	High risk of timber degradation	High risk of timber degradation
	Closed Cell	Low risk of timber degradation	Low risk of timber degradation	High risk of timber degradation
Foil-backed plasterboard	Open Cell	Low risk of timber degradation	Low risk of timber degradation	High risk of timber degradation
	Closed Cell	Low risk of timber degradation	Low risk of timber degradation	High risk of timber degradation

Summary of varying loft environments

A further set of hygrothermal models were performed to evaluate the risks for situations where the roof had been treated with SFI, but where the original loft insulation at ceiling level had been retained, and where the ventilation conditions in the loft space differed from the rest of the dwelling. This identified a significant risk of mould growth to the internal surface of timber rafters, and, in some cases, to the underside of the SFI. If the retained loft insulation was a thick layer (300mm assessed in the model), this could lead to surface condensation on the internal surfaces of the SFI during warmer periods.

Suitability of hygrothermal assessment methods

As alternatives to following prescriptive guidance, BS 5250:2021 provides further principles to followed to achieve a moisture safe design. This includes a consideration of which hygrothermal modelling tools may be applicable in different circumstances when assessing moisture risk. This outcome of this research indicates that alignment with the BS 5250:2021 requires an assessment of moisture risk using dynamic tools (i.e. BS EN 15026: 2007) rather than the ‘Glaser method’ (BS EN 13788: 2012) using applicable climate conditions relevant for the specific location. Careful consideration is also required for the loft conditions, particularly for cases where ceiling insulation is left in place after the spray foam insulation has been installed.

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