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

Appendices

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Appendix 1: Wood destruction models

The one- and two-dimensional simulations presented in the main report 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. However, further assessment is needed to specifically investigate the risk of decay of timber elements.

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 pure timber materials and 18M-% for timber-based materials (DIN 68800-2:2022[1]).

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 also 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 report for assessing the extent and rate of timber decay, which takes account of both temperature and RH excess duration, is outlined in WTA 6-8[2] and assessed using the VTT timber degradation model[3].

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. More resilient types of timber may be at less risk. The model is based on time-stepping and proposes that the development of decay is modelled as two processes: the activation process and the 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%.

A selection of the VTT models used in the analysis in the main report are presented in the following sections using the RH data from the one-dimensional modelling.

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[1] DIN 68800-2:2022-02 Wood preservation - Part 2: Preventive constructional measures in buildings
[2] 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.
[3] H.Viitanen et al (2010. Towards modelling of decay risk of wooden structures')

Insulation applied to low resistance membranes

Figure 1 presents the results of the wood destruction model when open cell insulation is applied to a low resistance underlay without any AVCL in the one-dimensional study. This shows that after 5 years there is a medium risk (see main report for risk categories) of decay to the outer region of the timber rafters, which may lead to a loss of timber mass. During this period, the rate of decay continues to increase, i.e. it does not level off. Thus, it is probable that degradation would continue in the following years.

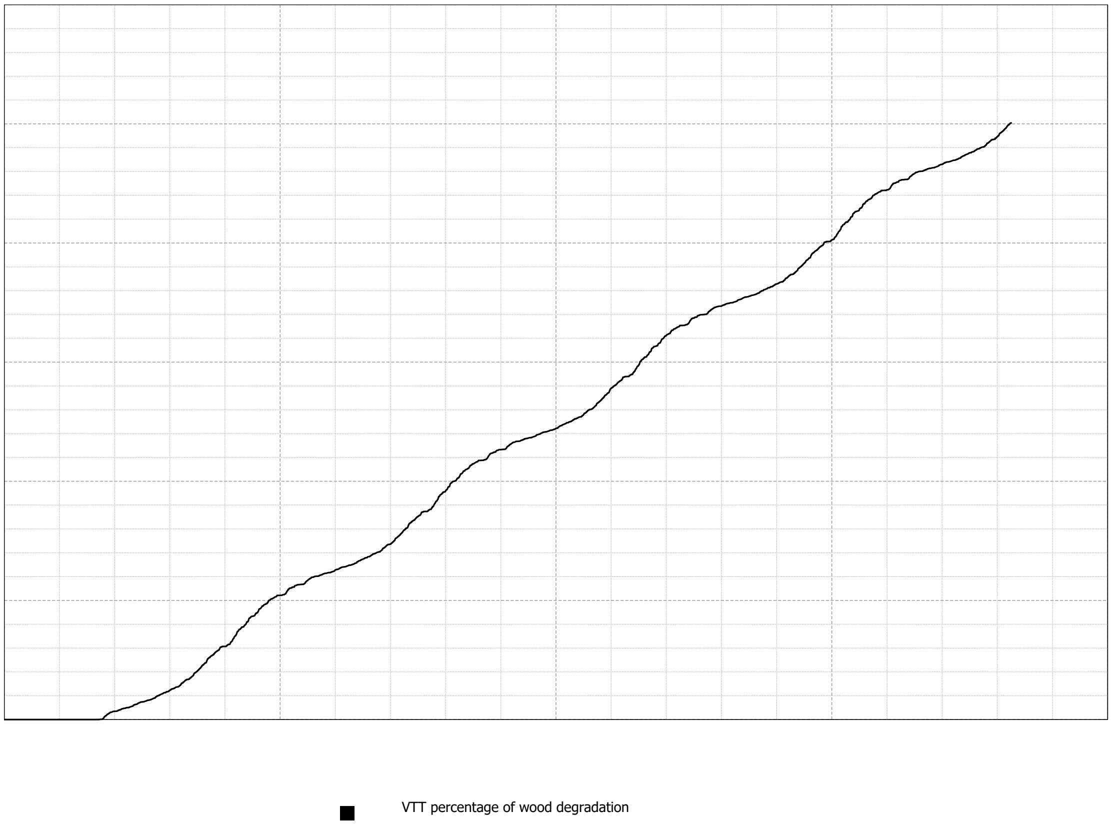

Figure 1. The VTT wood degradation percentage for the outer region of timber rafter in the case with 100mm open cell spray foam insulation installed onto a LR underlay without foil-backed plasterboard in Newcastle.

Insulation applied to high resistance membranes

Figure 2 presents the results of the wood destruction model when open cell insulation is applied to a high resistance underlay without an AVCL to the underside of the rafters in the one-dimensional study. This shows that after around 3.5 years there is a high risk that the outer region of the timber rafters would decay..

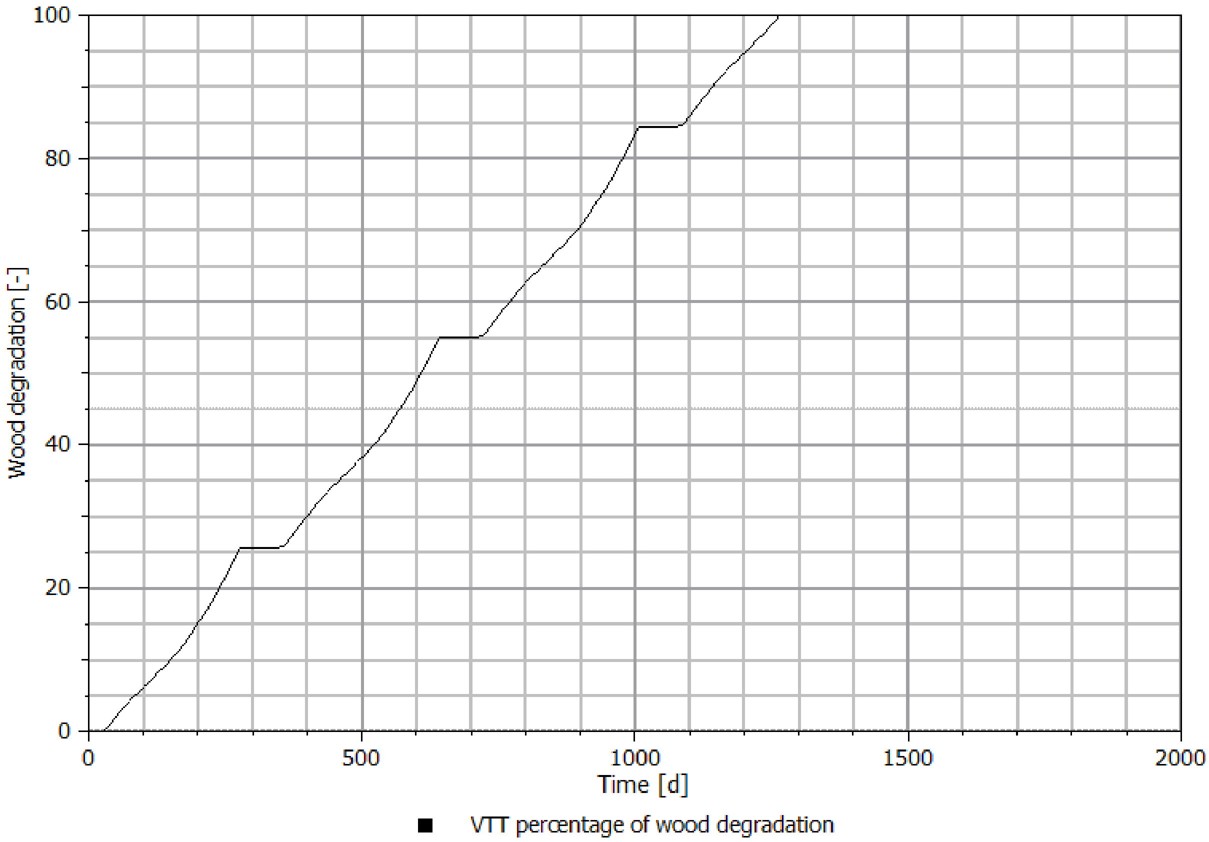

Figure 2 The VTT wood degradation percentage for the outer region of timber rafter in the case with 100mm open cell spray foam insulation installed onto a HR underlay without foil-backed plasterboard in Newcastle.

Figure 3 presents the results of the wood destruction model when open cell insulation is applied to a high resistance underlay in the one-dimensional study. In this case, an AVCL is included to the underside of the rafters. By comparison, this shows that after 5 years there is a risk that the outer region of the timber rafters would decay at a much lesser rate than without an AVCL present. However, this still still results in a loss of mass and is allocated a medium risk categorisation. As the chart shows, the rate of increase does not level off during the 5-year period, and it is probable that degradation would continue beyond the simulated time period. This, nonetheless, demonstrates there is a significant benefit in introducing an AVCL, but is insufficient to mitigate the risk to safe levels.

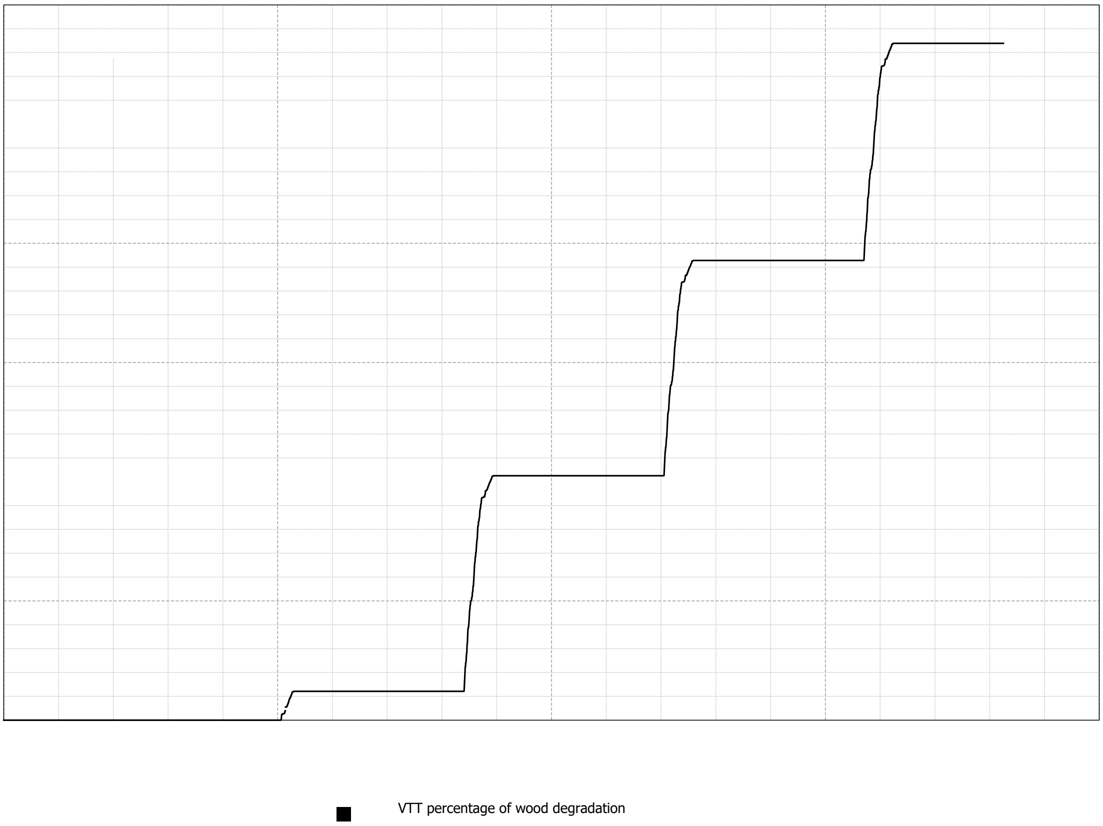

Figure 3. The VTT wood degradation percentage for the outer region of timber rafter in the case with 100mm open cell spray foam insulation installed onto a HR underlay with foil-backed plasterboard in Newcastle

Appendix 2: Condensation risk analysis

The hygrothermal assessments presented in the main report consider the moisture risk when the RH levels exceed a threshold above 85%. In this section, the risk of condensation forming (i.e. 100% RH or saturation) has been assessed for cases where saturation conditions in the hygrothermal models were reached. This occurred when SFI was applied to high resistance underlays and direct to tiles. However, only cases for high resistance underlays have been presented in this section, where the risks of timber decay varied between low and high depending upon climate region or the presence of an AVCL. For situations where SFI is applied directly to tiles, this resulted in a high risk for all climate regions irrespective of an AVCL. Hence, further risk evaluation is unnecessary.

The risk of condensation occurring on the underside of the HR underlay was assessed by means of incorporating a notional layer into the model which allowed any excess moisture to accumulate within. The water content trends in this layer could then be assessed to determine the risk of moisture build-up and condensation in this region.

Insulation applied to high resistance membranes

This assessment evaluates the condensation risk for 100mm of **open cell** insulation when applied onto a HR underlay, both with and without an AVCL. **Figure 4**, shows the risk threshold for condensation (579 kg/m^3). The risk assessments for the Newcastle (severe) climate indicate:

- Without any AVCL, such as foil-backed plasterboard, there is a very high risk of condensation occurrence throughout winter and into early summer. The RH in this scenario is also above 85% for significant periods of the year (see main report), and presents a high risk of timber decay
- Where the foil-backed plasterboard is provided as an AVCL, there is a significant decrease in the water content sufficiently below the condensation threshold, highlighting the benefit of an AVCL. However, whilst the conditions in this layer remain below saturation, the RH is still above the 85% threshold for significant periods (see main report), and there is still a significant risk of timber decay in this region.

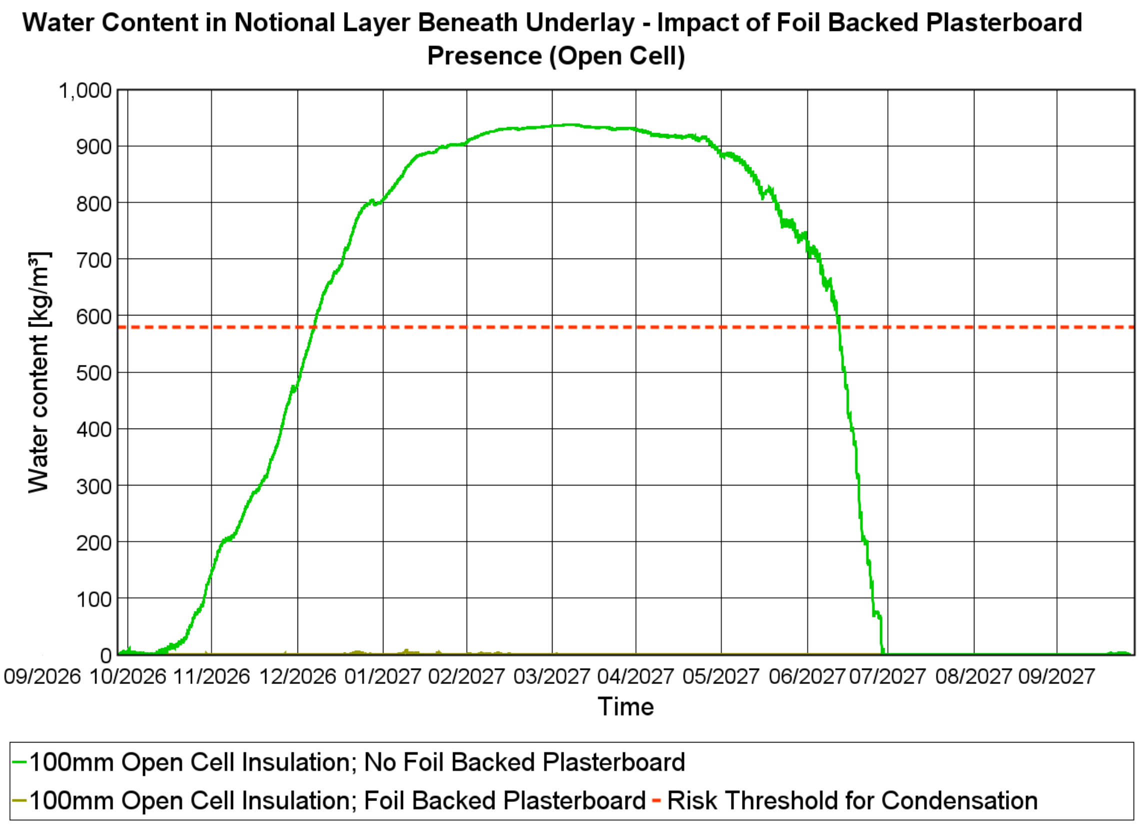

Figure 4. The impact of foil-backed plasterboard presence on the water content on the underside of a HR underlay in Newcastle

Figure 5 show the results for cases with 100mm of **closed cell** insulation applied to a HR underlay. This shows that there is a low risk of condensation occurring on the underside of the HR underlay when closed cell spray foam insulation is installed perfectly both with and without plasterboard. Note, the y-axis scale has been set to the same scale as **Figure 4** to allow comparison.

Despite the low risk of condensation, both with and without an AVCL, the hygrothermal risk assessments in the main report identified a high risk of timber decay when closed cell is used without an AVCL. This is due to RH levels predicted at above 85% for significant periods of the year.

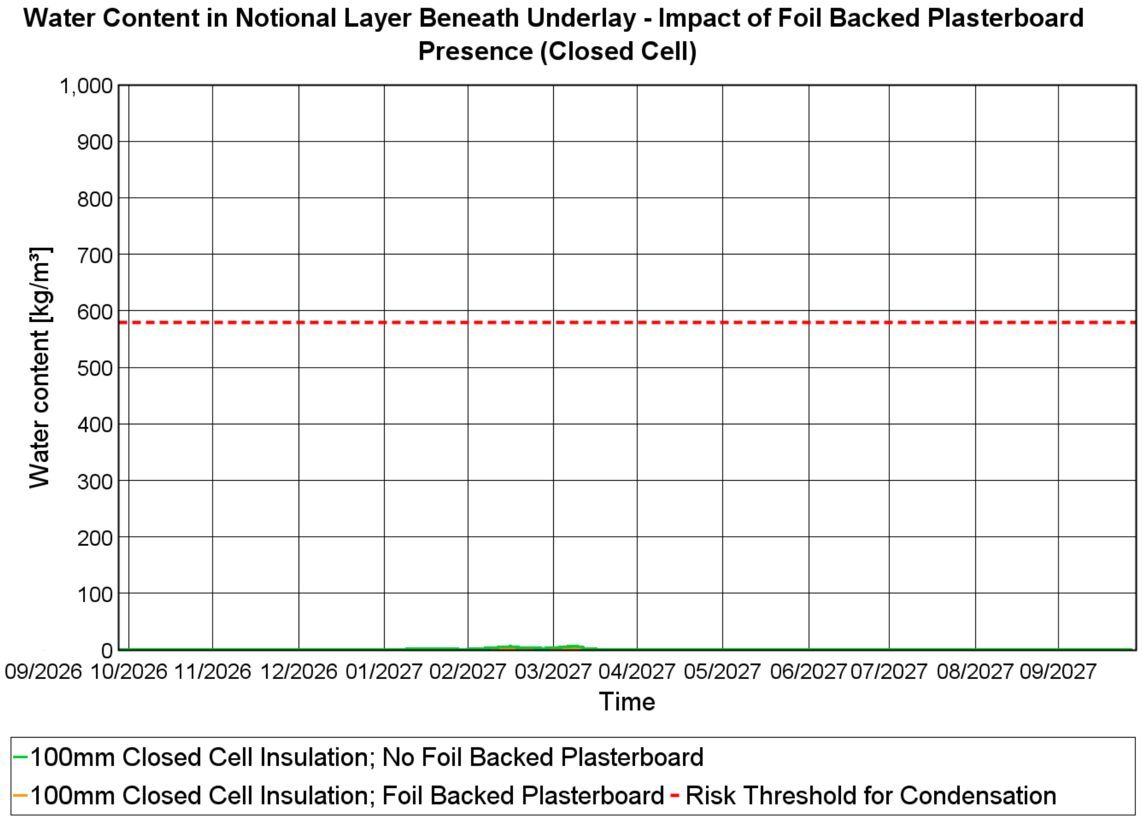

Figure 5. The impact of foil-backed plasterboard presence on the risk of condensation on the underside of the underlay when closed cell insulation is applied on a HR underlay in Newcastle.

Appendix 3: Assessment of different loft conditions

Calculation approach to loft conditions

The main report modelling assessments, unless otherwise stated, assumed that loft conditions were the same as the occupied space, as predicted by the algorithms specified in BS EN 13788: 2012 or BS EN 15026: 2007. The assessments in this section consider a range of situations where the loft conditions differ to those assumptions, and to understand the impact these conditions may have on the overall risk moisture.

The following factors that influence the loft conditions have been investigated, where:

- the original loft insulation (e.g. mineral fibre) is retained after installation of the spray foam insulation
- the original eaves ventilation is insufficiently sealed during the installation of the spray foam insulation
- a combination of the above conditions exist along with variations induced by air leakage from the habitable zone of the dwelling (i.e. via the ceiling)

To estimate these conditions, a simple heat, air and moisture balance tool was created. The internal (habitable space) conditions used in the tool are inferred from the external conditions using the algorithm specified in BS EN 13788: 2007.

The heat gains/losses to/from the loft space are calculated as a sum of:

- conduction through the ceiling
- conduction, including solar gains, through the pitched part of the roof
- air exchange from the occupied space to the loft
- air exchange between the loft and outdoors

The conduction through the ceiling depends on the loft and occupied air temperatures, and the U-value of the ceiling. The conduction through the pitched slope is calculated using the sol-air approach, which considers shortwave and longwave gains and longwave re-radiation as these can cause significant cooling overnight. The sol-air approach calculates an equivalent air temperature, adjusted to account for radiative heat exchanges with respect to the external surface resistance.

The air flow rates from outside and from the occupied space into the loft are assumed to be steady state. Air flow rates through the ceiling are estimated based upon an on a range of dwelling airtightness levels and assume a constant static pressure (i.e. one direction air flow from the conditioned dwelling).

The moisture balance is based upon the absolute humidity of the outside and inside air. The internal (occupied space) moisture generation assumes the vapour pressure excess values (i.e. the difference between the internal and external conditions) given in BS EN 13788: 2012. The absolute humidity (AH) in the loft is taken to be the average of the outside and occupied space, weighted according to estimated air flow rates through the eaves versus the ceiling. This is a simplification which assumes airflow is always upwards through the ceiling. The simplifications also assumes that there are no moisture sources in the loft, and that moisture and heat storage and buffering is negligeable.

Assumptions and Limitations

Modelling in this section is for the open cell spray foam insulation material as described in the main report.

The loft conditions calculated from the heat, air and moisture balance tool provided the boundary conditions for the re-assessment of a selection of Wufi one-dimensional simulation models. Other assumptions were made in relation to dwelling characteristics:

- Ceiling area: 50 m^2
- Pitched area: 80m^2
- Loft volume: 100m^3
- Either 50mm or 300mm mineral wool (conductivity 0.04 W/m.K) at ceiling level
- External ventilation of the loft space: either 0 or 5 ACH
- Air Leakage from the internal occupied space to the loft: either 0.5 or 10 m^3/hr.m^2 @50 Pa
- Humidity class III (BS EN 13788:2012)
- London climate

The model does not account for the following factors, mechanisms and effects:

- Thermal mass or heat storage effects
- Moisture buffering due to hygroscopic materials and surfaces
- Interactions with neighbouring properties
- Differing solar gains on different orientations
- Decrement delays and thermal diffusivity due to thermal storage in the insulating materials
- Ventilation between tiles and underlay is simplified

The following cases are presented within each of the following graphs:

ID	Rafter insulation	Joist insulation	External ventilation	Internal/ceiling leakage
1	100mm	50mm	Low	High
2	100mm	50mm	High	Low
3	100mm	300mm	Low	High

4	100mm	300mm	High	Low
5	100mm	0mm	High	Low
6	0mm	50mm	High	Low
7	200mm	50mm	High	Low
8	200mm	300mm	Low	High

Results of loft conditions

The graphs presented for the various loft conditions consider a one-week period in either winter or summer to investigate which variables have the largest impact on the resulting loft conditions, in particular, the vapour pressure, temperature and relative humidity.

Influence of loft conditions on temperature

Figure 6 and **Figure 7** show the temperature profiles for the external and internal conditions, and for the eight different loft scenarios. The loft temperatures normally lie between the internal and external temperatures. In June, however, solar gains on the roof increase the loft temperatures (for some of the assessed conditions) above the internal temperature during the daytime.

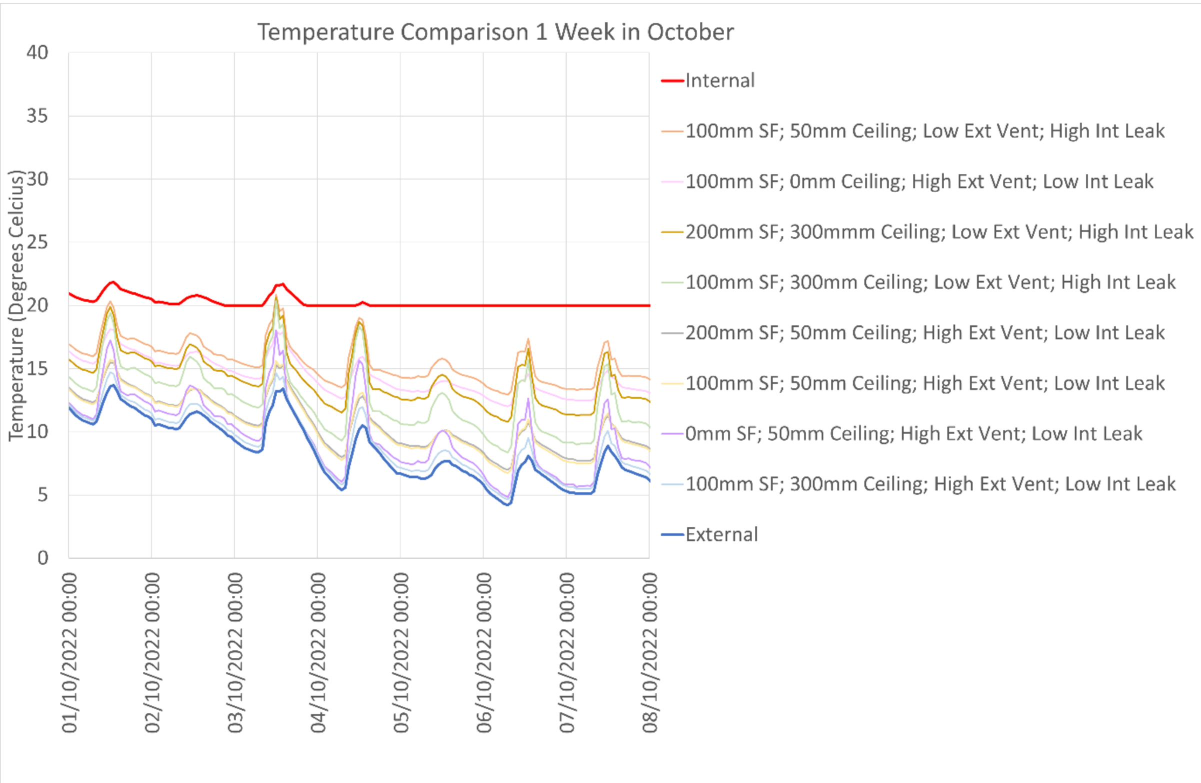

Figure 6. The temperature for all cases during a 1-week period in October in London when open cell SFI is applied.

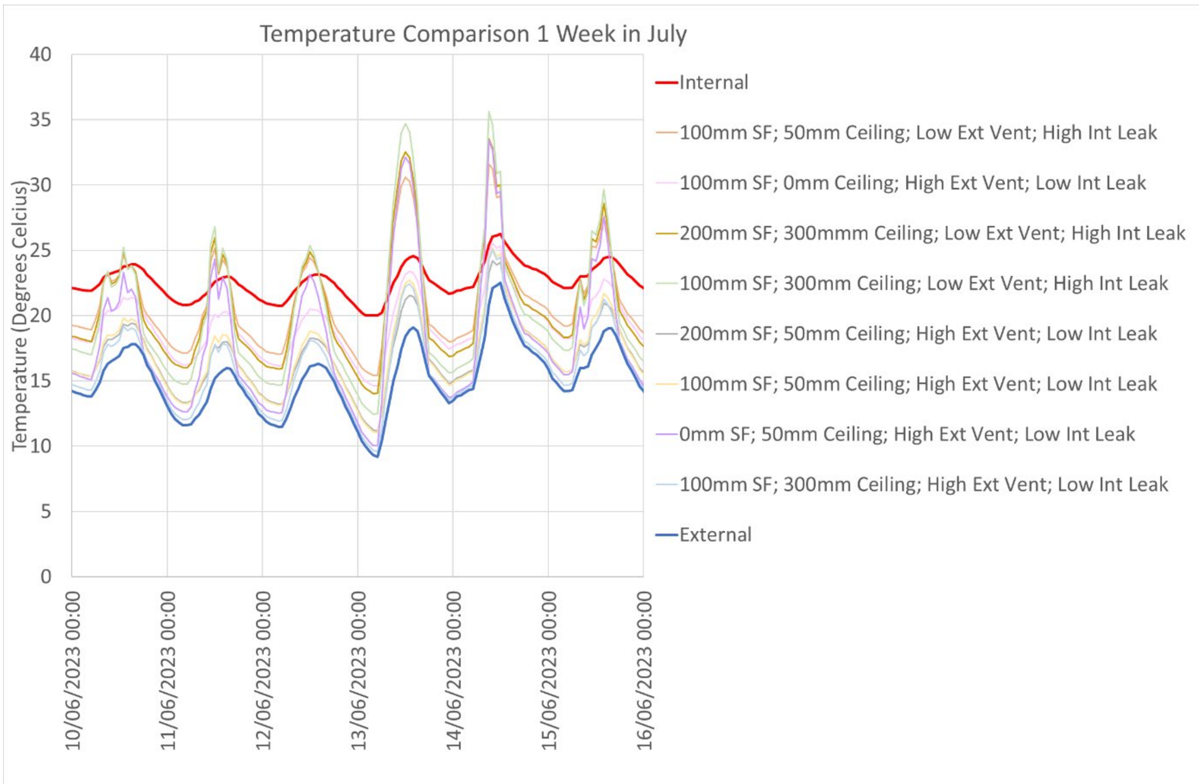

Figure 7. The temperature for all cases during a 1-week period in June in London when open cell SFI is applied.

Influence of loft conditions on relative humidity

Figure 8 and **Figure 9** show the relative humidity for the external, internal and the six different loft condition scenarios. These show that, during October, the relative humidity in the loft is on average higher than the internal relative humidity under all realistic conditions. The extent to which this is higher depends upon eaves ventilation and the insulation thicknesses both at rafter and ceiling level. The RH varies between c.5% lower and c.30% higher than internal. This indicates that there could be a greater risk to the roof structure when these predicted loft conditions are accounted for, particularly when there is high air leakage from the occupied space to the loft, and low air exchange with outside.

During the week in June, the relative humidity within the loft space also tends to be greater than the internal relative humidity during the nights, but lower during the daytime. This is likely a result of the radiative transfer, warming up the loft space during the day and cooling overnight.

The graphs also show that the cases with low external ventilation and high internal ceiling leakage results in higher relative humidities. This could prove problematic as the eave's vents (external ventilation) should be blocked to prevent thermal bypass in order for the applied spray foam to perform well thermally. Increased RH in the loft space could increase the moisture risk to the insulation and the timber elements.

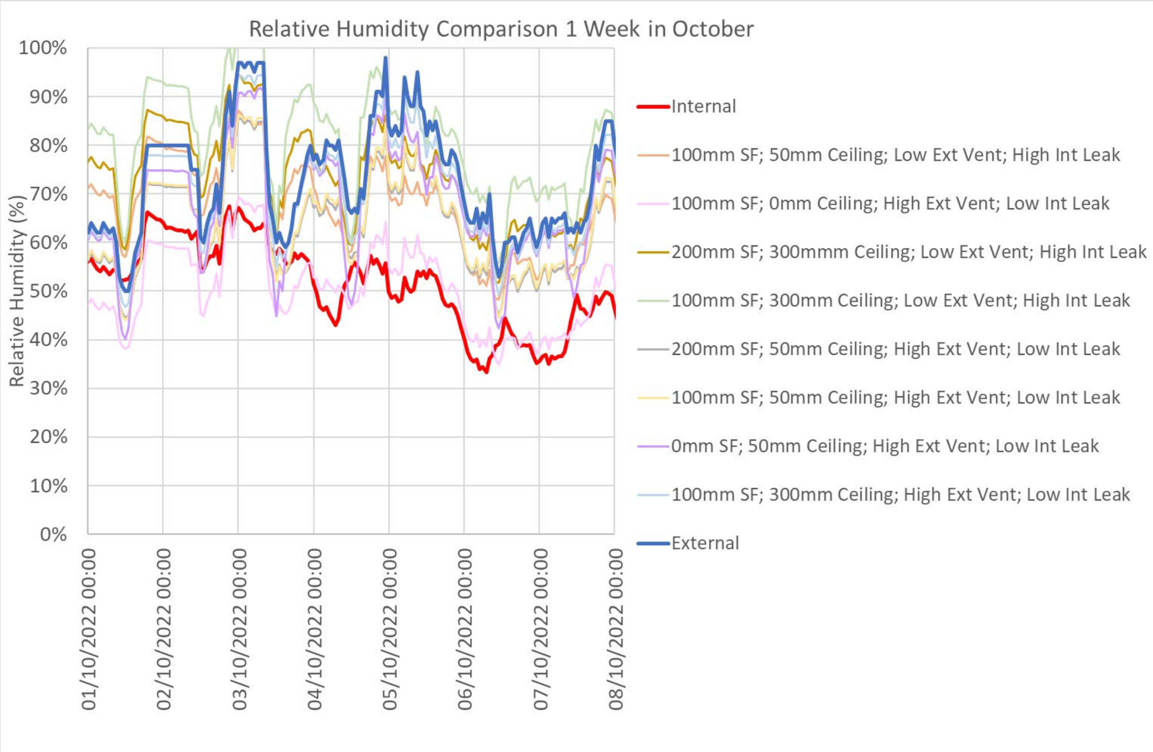

Figure 8. The relative humidity for all cases during a 1-week period in October in London when open cell SFI is applied.

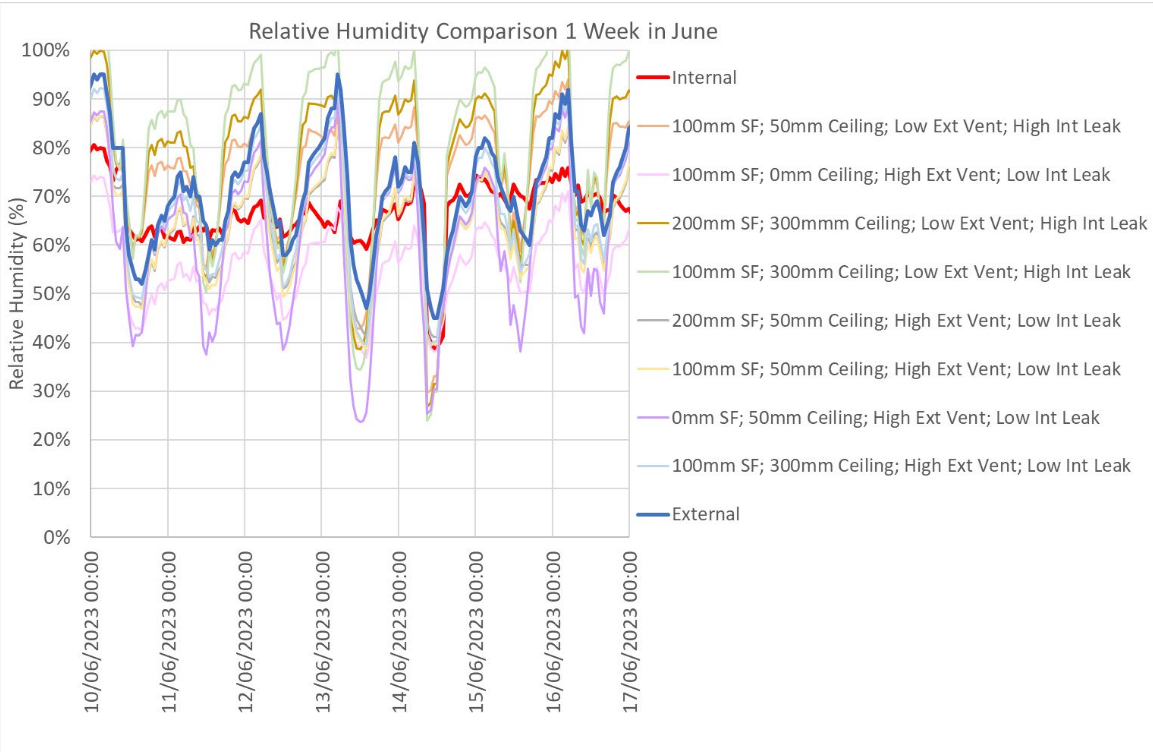

Figure 9. The relative humidity for all cases during a 1-week period in June in London when open cell SFI is applied.

Influence on Vapour Pressure

Figure 10 and **Figure 11** present the vapour pressure for the external and internal conditions, and the six different loft condition scenarios. These show that the ventilation has the largest impact on the resulting vapour pressure seen within the loft space. When there is a high external ventilation and insignificant ceiling leakage, the resulting vapour pressure within the loft space closely follows the external vapour pressure. When there is high ceiling leakage and insignificant eaves ventilation, the vapour pressure in the loft closely tracks the internal vapour pressure.

The impact of ventilation can be seen for both the week in October and the week in June. Comparison between the vapour pressure values for the cases show that there is a higher average vapour pressure in June for all cases. They also show that the internal vapour pressure is always higher than the external vapour pressure, indicative of the net movement of vapour from the internal to external space, likely through the loft if a vapour pathway is present.

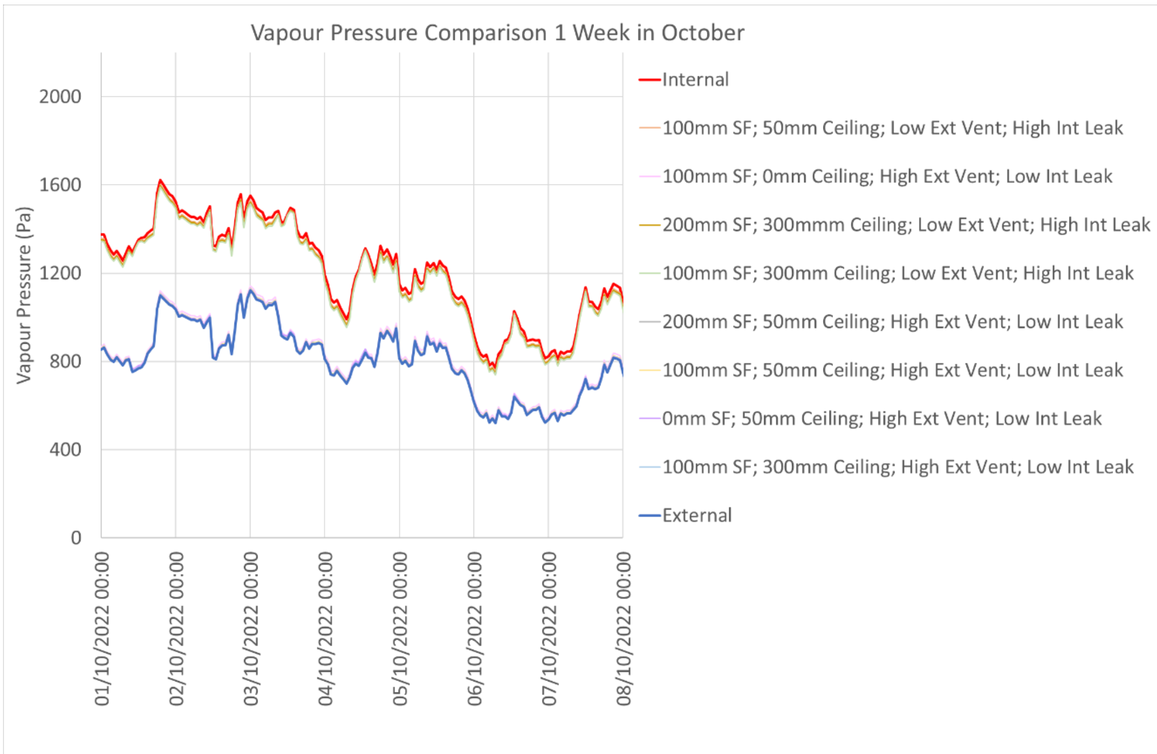

Figure 10. The vapour pressure for all cases during a 1-week period in October in London when open cell SFI is applied.

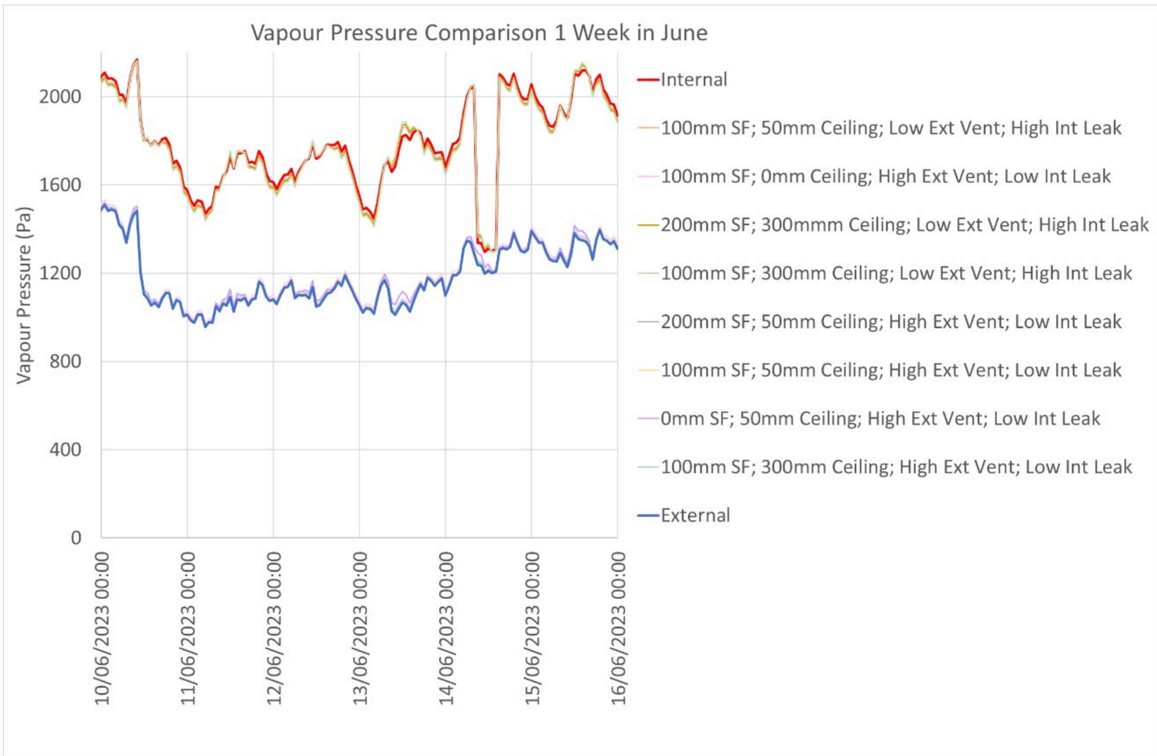

Figure 11. The vapour pressure for all cases during a 1-week period in June in London when open cell SFI is applied.

The same analysis was undertaken for a loft condition generated for a Newcastle climate. These are not presented as the trends were found to be the same as those for a London Climate.

Hygrothermal Risk Assessment for the different loft conditions

Internal temperature and relative humidity conditions used for hygrothermal simulation normally reflect typical heating and moisture generation, and ventilation regimes. For the following scenarios, the simulations in the rafter zone use the hygrothermal conditions assessed in the previous section.

Key Risk Factors

The following outlines the key risk factors taken into account as part of the hygrothermal assessments:

- Mould growth on or within the build-up
- Decay of any timber elements within the build-up
- Moisture accumulation within the build-up

To assess these key risk factors, conditions within specific locations of the build-ups were monitored throughout the simulation.

Assumptions

The same assumptions apply here as those listed in the main report. The simulations presented in this section do not include any AVCL or internal finish.

Results

Impact of Spray Foam Thickness

The initial assessment considered the impact of the thickness of spray foam insulation, i.e. 100mm or 200mm, for a London climate based on two different loft conditions:

- 50mm ceiling insulation; high external ventilation and a low ceiling leakage
- 300mm ceiling insulation; low external ventilation and a high ceiling leakage

These two cases are considered to be the lower and upper limits, with the 50mm case resulting in a loft condition similar to the external climate and the 300mm case resulting in loft conditions similar to the internal environment.

The results are presented for SFI applied to a HR underlay.

Figure 12 to **Figure 14** show the relative humidity in the outer region of spray foam insulation for 100mm and 200mm spray foam insulation within the two loft environments. This shows a minimal influence of the insulation thickness on the conditions within the outer region of insulation during the winter months. During the colder periods, the loft conditions have a much larger influence on the conditions than the insulation thickness. However, during the summer months, the 100mm SFI results in a greater RH fluctuation. Both thicknesses result in higher humidity during the colder night and lower humidity during the warmer daytime.

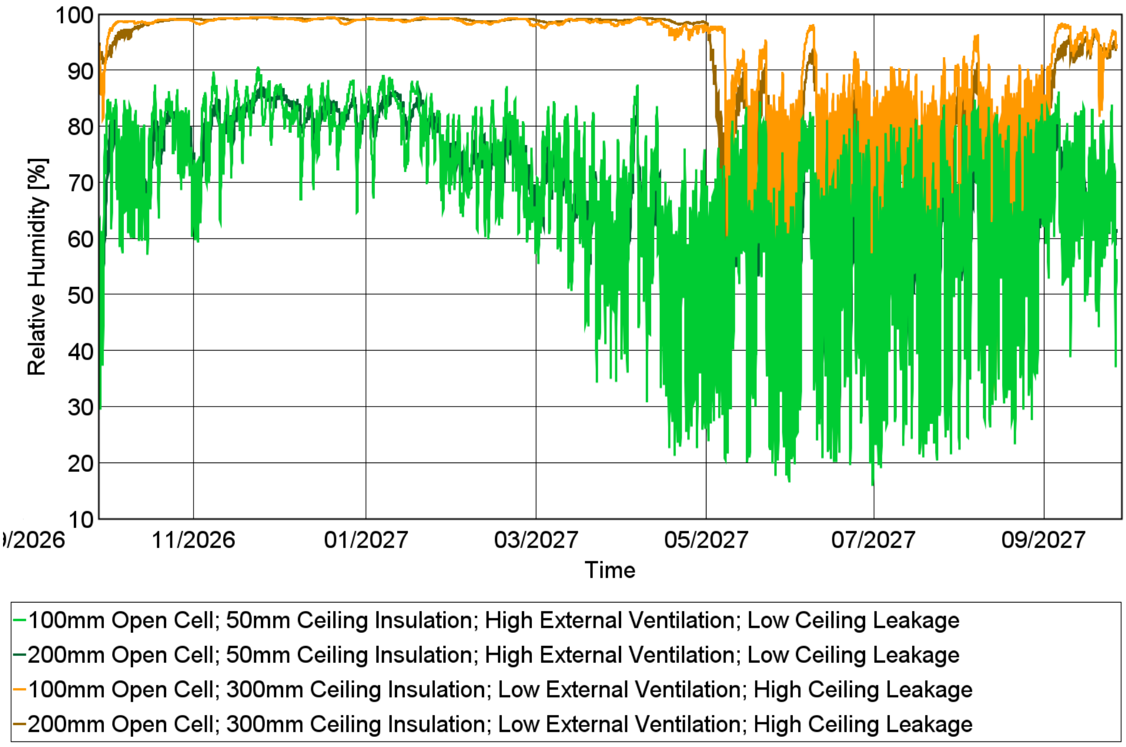

Figure 12. The impact of the insulation thickness on the relative humidity in the outer region insulation over a 1-year period in London when open cell SFI is applied to an HR underlay.

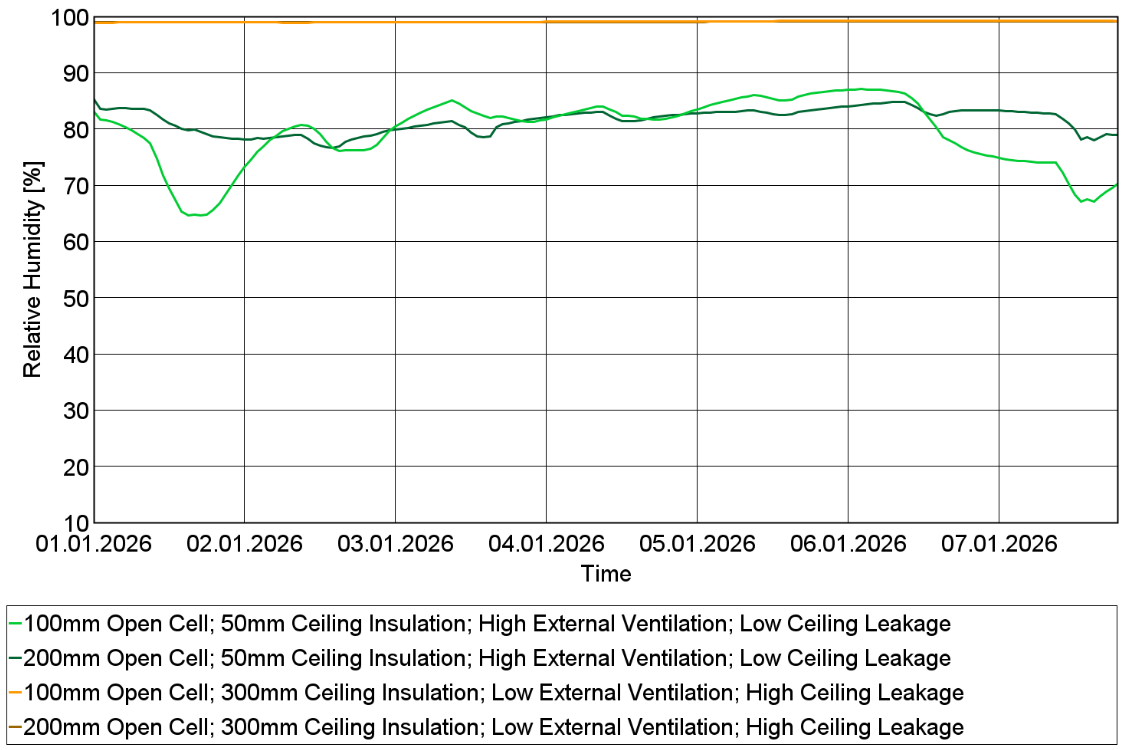

Figure 13. The impact of the insulation thickness on the relative humidity in the outer region insulation over a 1-week period in winter in London when open cell SFI is applied to an HR underlay.

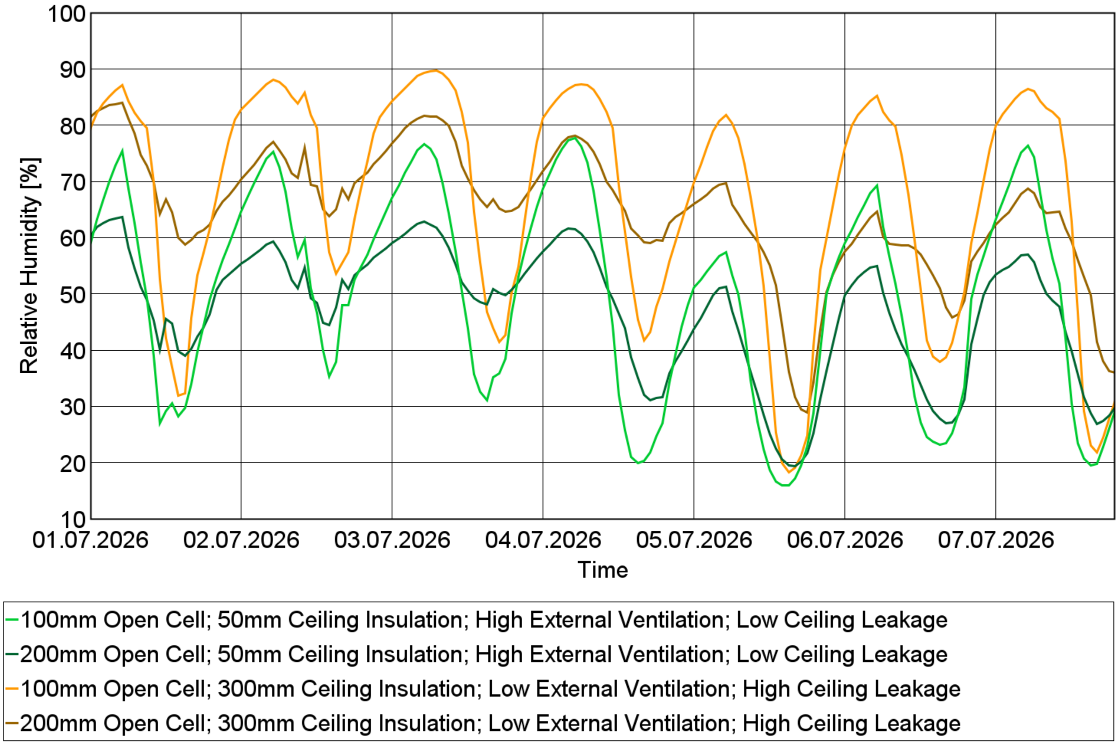

Figure 14. The impact of the insulation thickness on the relative humidity in the outer region insulation over a 1-week period in summer in London when open cell SFI is applied to an HR underlay

The water content on the underside of the underlay was assessed for each of the cases as shown in **Figure 15**. This shows that the two cases with a loft condition more similar to the external climate result in a very low risk of condensation forming on the underside of the underlay (water content remains at or very close to zero). However, when the loft conditions are similar to the internal conditions (e.g. eaves vents sealed) the thickness of spray foam insulation installed has an influence on the risk of condensation occurring on the underside of the underlay. The 200mm of insulation results in a lower water content on the underside of the underlay (below the risk threshold for condensation), whereas the 100mm insulation is above the risk threshold throughout winter and spring periods. The difference between the two thicknesses is likely due to the greater total vapour resistance of the thicker material. Typically, dwellings of a standard size will have rafters with a thickness of around 100-150mm. The use of 200mm thick rafters is unusual for dwellings.

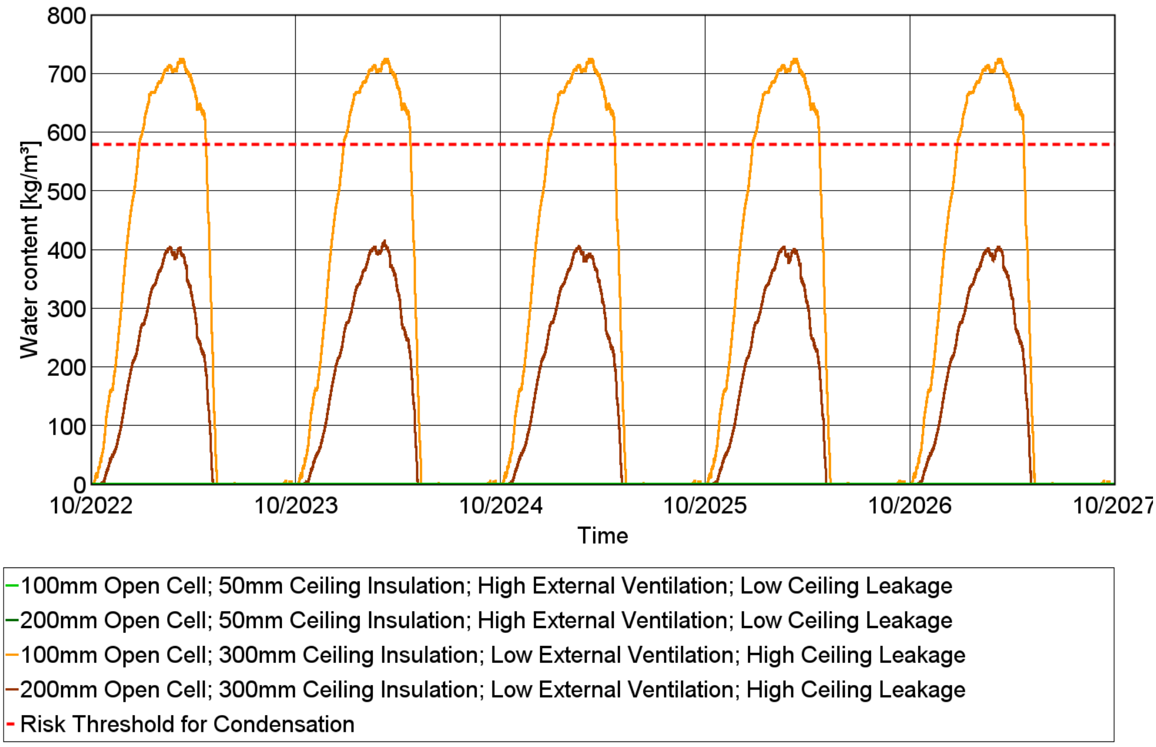

Figure 15. The impact of insulation thickness on the water content on the underside of the underlay in London when open cell SFI is applied.

Based on these initial results the subsequent one-dimensional models were only simulated with 100mm of insulation between the rafters, as this thickness is higher risk and more typical in terms of rafter thickness.

Influence of Loft Conditions in London

<u>Low Resistance Underlay</u>

The influence of the loft conditions on the conditions within the build-up were assessed when 100mm of spray foam insulation was installed onto a LR underlay in London.

Figure 16 to **Figure 18** show the influence of the loft conditions on the outer region of spray foam insulation. This shows that there is a minimal influence of the conditions within the loft on the relative humidity in the outer region of spray foam insulation when there is a LR underlay. This is true for both the winter and summer periods.

The graph also shows that the outer region of spray foam results in high humidity, particularly during the colder winter months. The humidity in these periods remains above 80% which could indicate a risk of mould growth between the underlay and the timber rafters. However, this outer region is likely to experience large temperature swings which may inhibit mould growth.

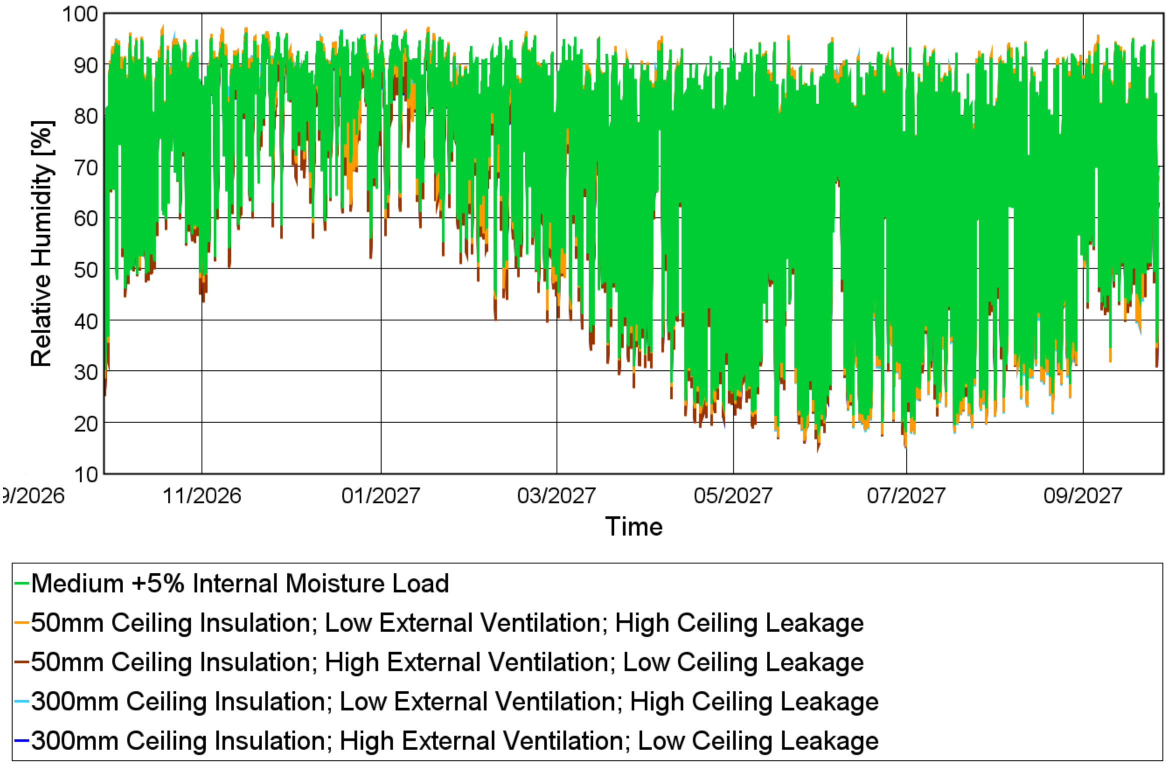

Figure 16. The impact of loft conditions on the relative humidity in the outer region spray foam insulation over a 1-year period in London when there is 100mm of open cell SFI applied to a LR underlay.

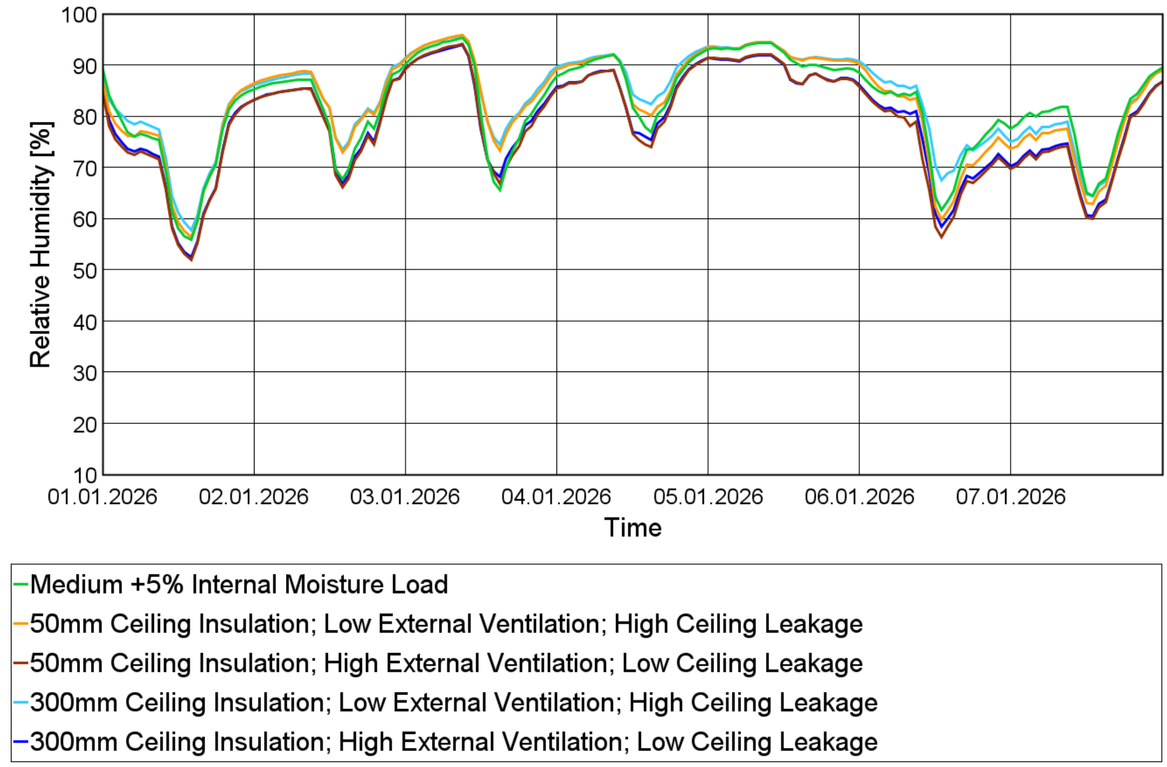

Figure 17. The impact of loft conditions on the relative humidity in the outer region spray foam insulation over a 1-week period in winter in London when there is 100mm of open cell SFI applied to a LR underlay.

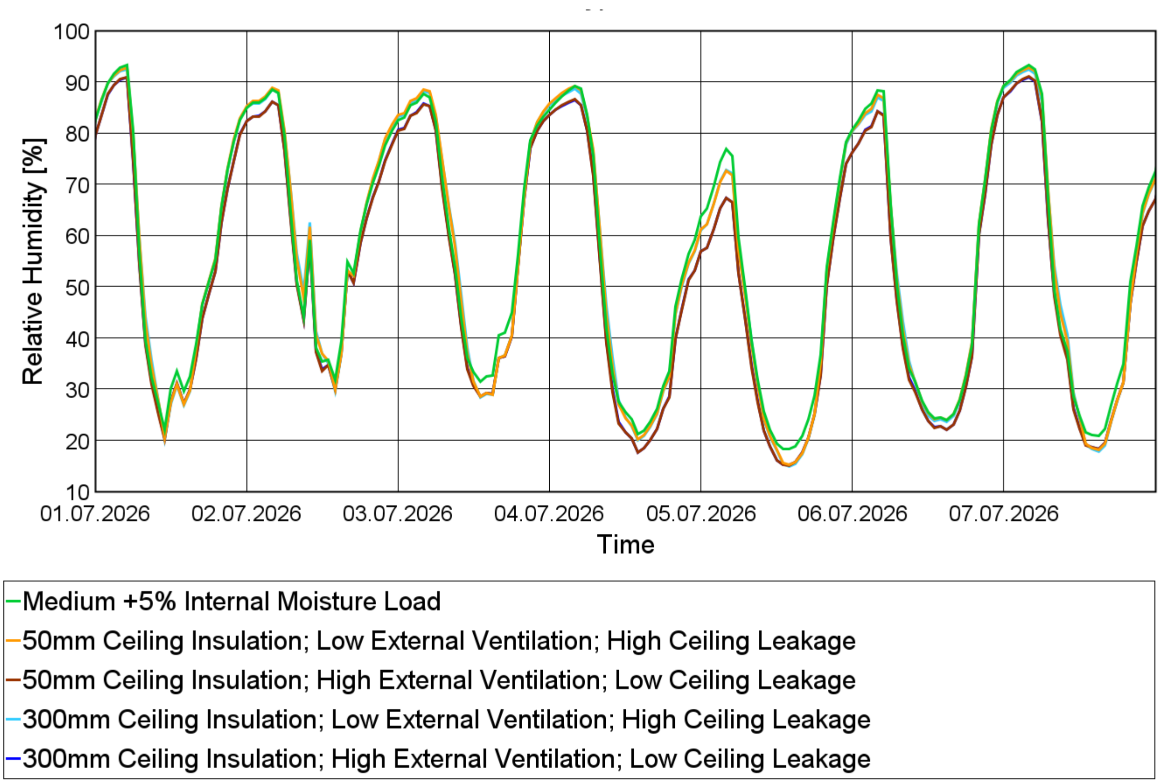

Figure 18. The impact of loft conditions on the relative humidity in the outer region spray foam insulation over a 1-week period in summer in London when there is 100mm of open cell SFI applied to a LR underlay.

The influence of these loft conditions on the internal surface was then assessed. **Figure 19** to **Figure 21** shows that the loft environment has a strong influence on the conditions at and near to the internal surface of the build-up.

The green line indicates the 'medium +5%' internal condition (i.e. the loft conditions are the same as the occupied space – as per the main report). This results in the lowest overall relative humidity at the internal surface of the build-up and hence the lowest risk. The graph shows that a greater thickness of ceiling insulation results in a higher humidity at the internal surface of the rafter level build-up. This is likely due to the scenarios with a greater thickness of ceiling insulation resulting in a generally colder loft space. It also shows that there is only a small influence of the ventilation on the conditions at the internal surface with this LR underlay during the winter months. A high external ventilation and low ceiling leakage results in marginally lower relative humidities at this location (though would impair the thermal performance of the spray foam insulation).

All of the cases where the conditions in the loft have been calculated (i.e. all except the green line) result in a relative humidity at the internal surface which exceeds the 80% risk threshold for mould growth and the 85% risk threshold for decay for periods of time each year. To further investigate the risk of surface mould growth, the results were post processed using the VTT mould model.

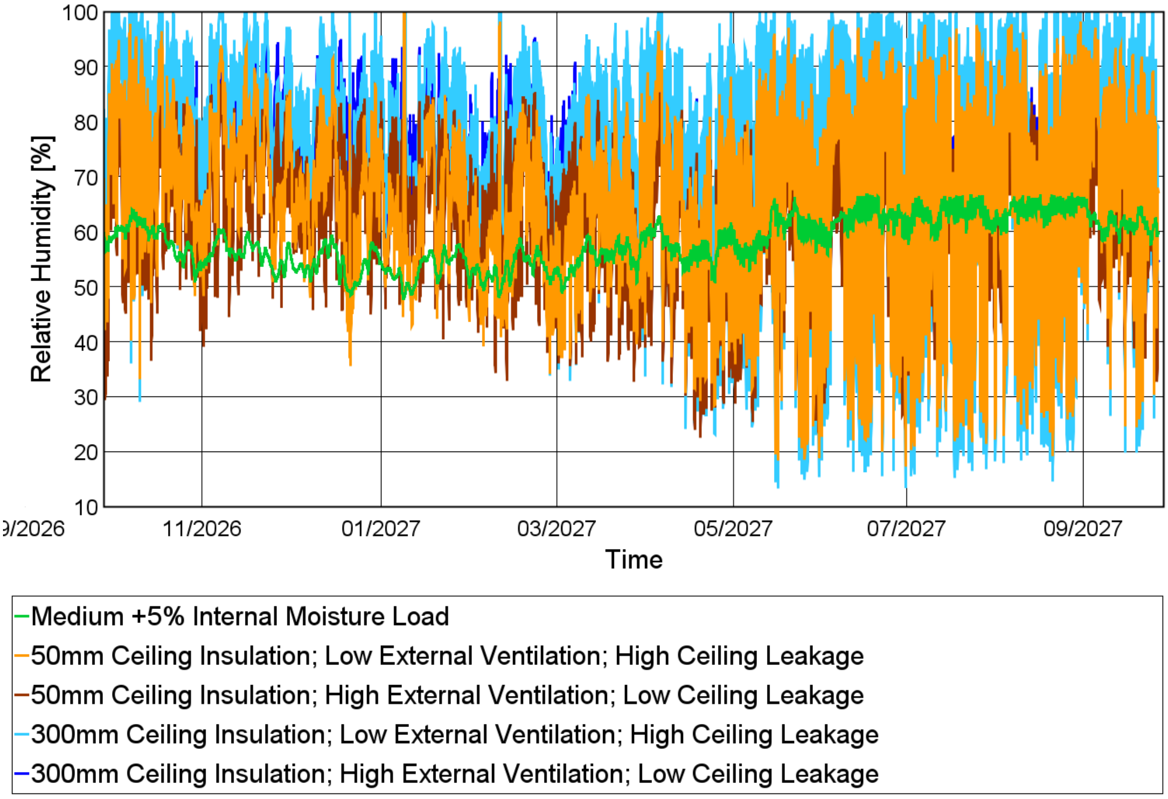

Figure 19. The impact of loft conditions on the relative humidity at the internal surface over a 1-year period in London when there is 100mm of open cell SFI applied to a LR underlay.

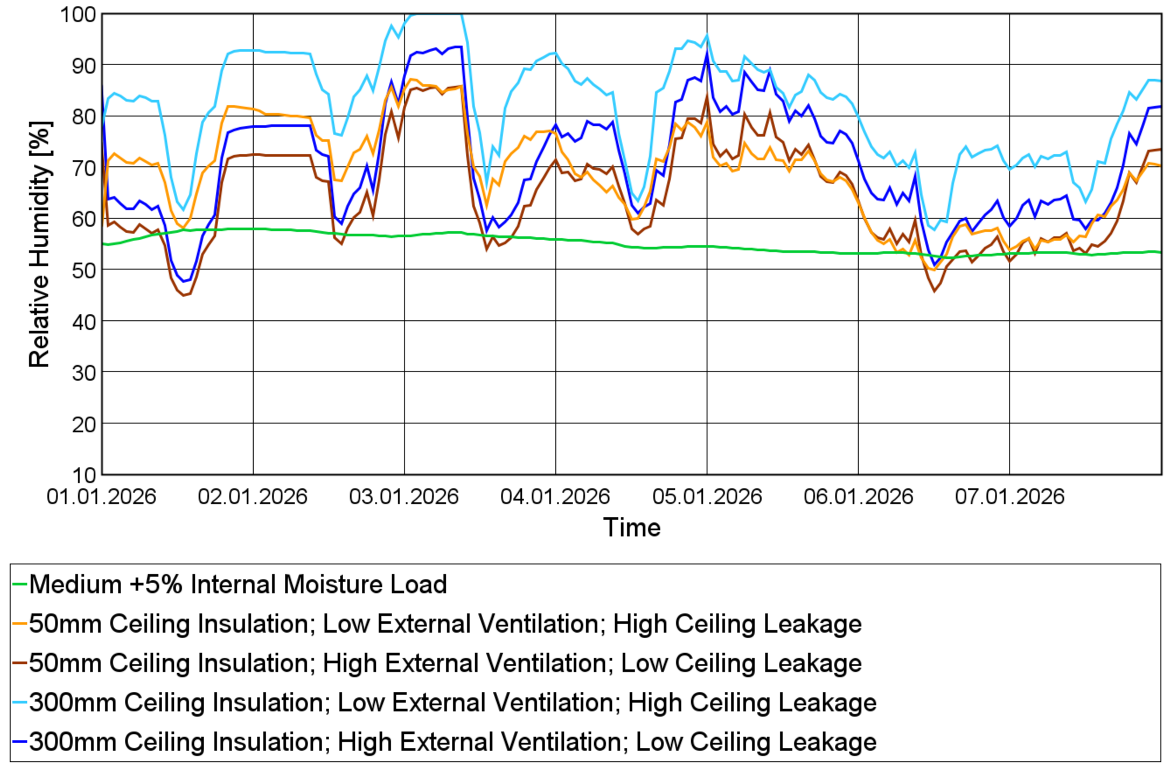

Figure 20. The impact of loft conditions on the relative humidity at the internal surface over a 1-week period in winter in London when there is 100mm of open cell SFI applied to a LR underlay.

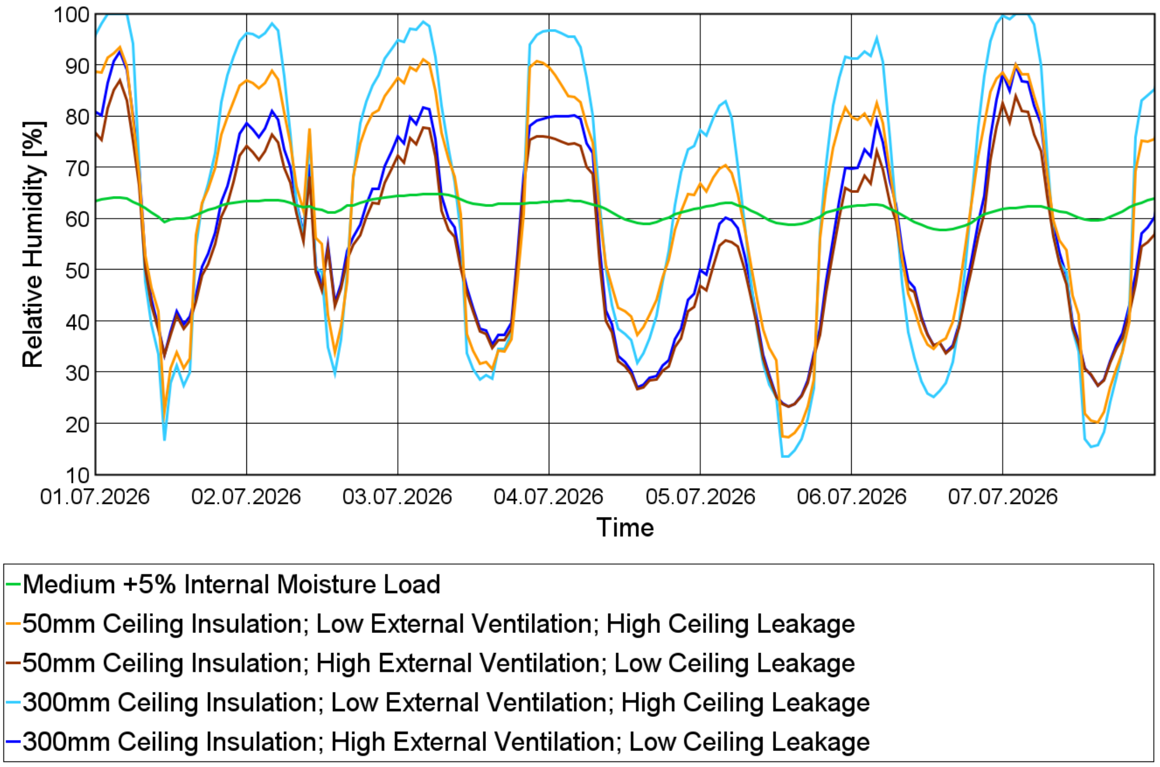

Figure 21. The impact of loft conditions on the relative humidity at the internal surface over a 1-week period in summer in London when there is 100mm of open cell SFI applied to a LR underlay.

Figure 22 shows the mould growth index graph for each of the five cases, assuming a timber substrate. The loft space could be considered isolated from the living space but may be used to store possessions sensitive to mould and therefore a mould growth index of 1 has been used as the risk threshold. This indicates that both cases with 300mm of ceiling insulation and both cases with a low external ventilation result in mould growth index above this threshold. Both cases with low levels of external ventilation (i.e. good sealing at eaves) result in a high levels of mould risk within the loft when ceiling insulation is retained. The risk is reduced where there is higher ventilation to outside, but this would undermine the thermal performance of the SFI. As well as timber rafters, other similar materials in the space will be at comparable risk, such as other timber components, and possessions stored in the space.

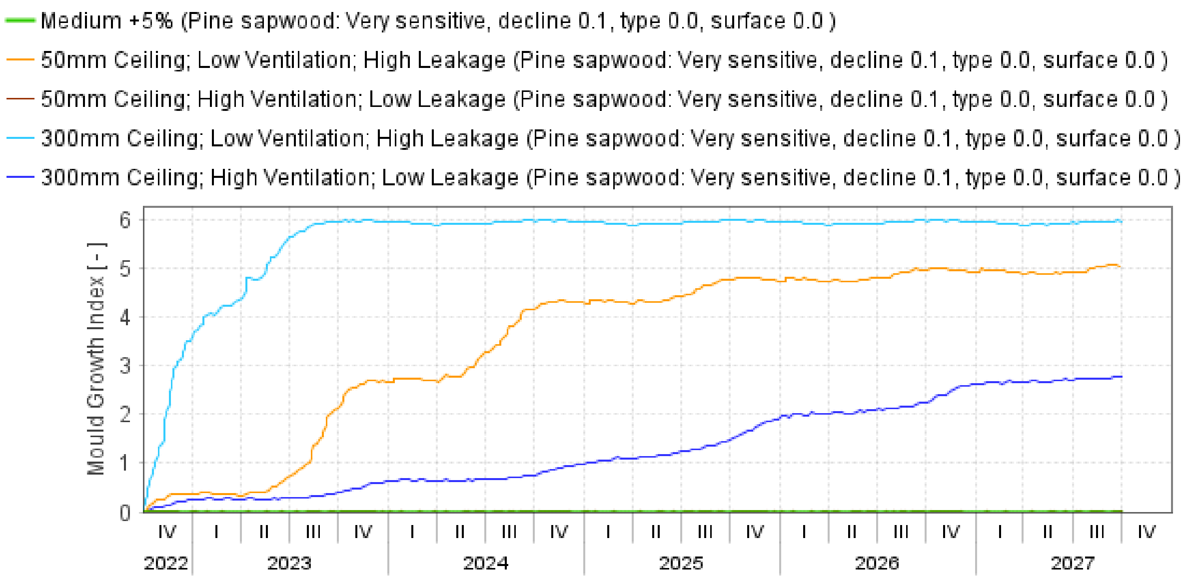

Figure 22. the impact of loft conditions on the mould growth index of the timber rafter at the internal surface in London when there is 100mm of open cell SFI applied to a LR underlay.

The same assessment was undertaken but assuming that the spray foam insulation is the substrate. This is shown in **Figure 23**. A low risk of mould growth (i.e. a mould growth index below 1) is only achieved without ceiling insulation or with adequate ventilation to the outside. However, external ventilation would negate the benefit of the spray foam insulation as the external air would be introduced on the inside of the spray foam. Note that the standard loft condition as assessed in the main report (i.e. ceiling insulation removed, and eaves assumed sealed) shows this condition would result in a low mould growth risk.

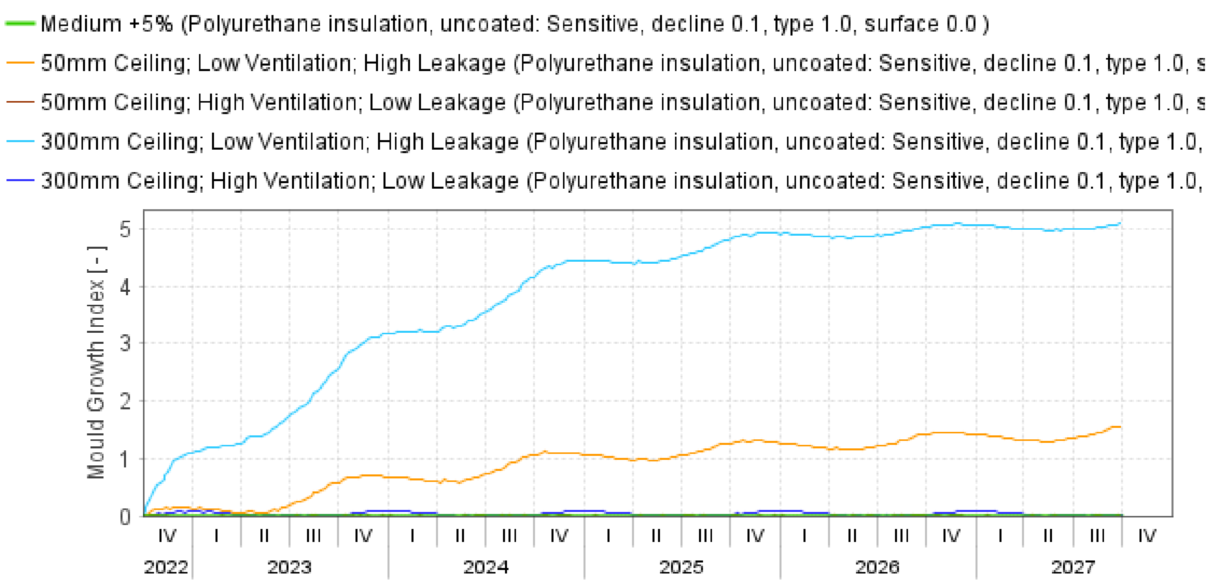

Figure 23. The impact of the loft conditions on the mould growth index of the spray foam at the internal surface in London when there is 100mm of open cell SFI applied to a LR underlay

High Resistance Underlay

The influence of the loft conditions on the conditions within the build-up were also assessed when 100mm of spray foam insulation was installed onto a HR underlay in London.

Figure 24 to **Figure 26** show the influence of the loft conditions on the outer region of spray foam insulation for a five-year simulation period, a winter week period and a summer week period, respectively. This shows that the ventilation of the loft space to both the inside and outside have a large influence on the conditions in the outer region of spray foam insulation. The relative humidity in this region is higher and exceeds 95% during the winter months when there is low external ventilation and high ceiling ventilation, or when the loft condition is the same as the internal conditions. Therefore, these conditions could result in a high risk of mould growth and decay of the timber rafters in this region.

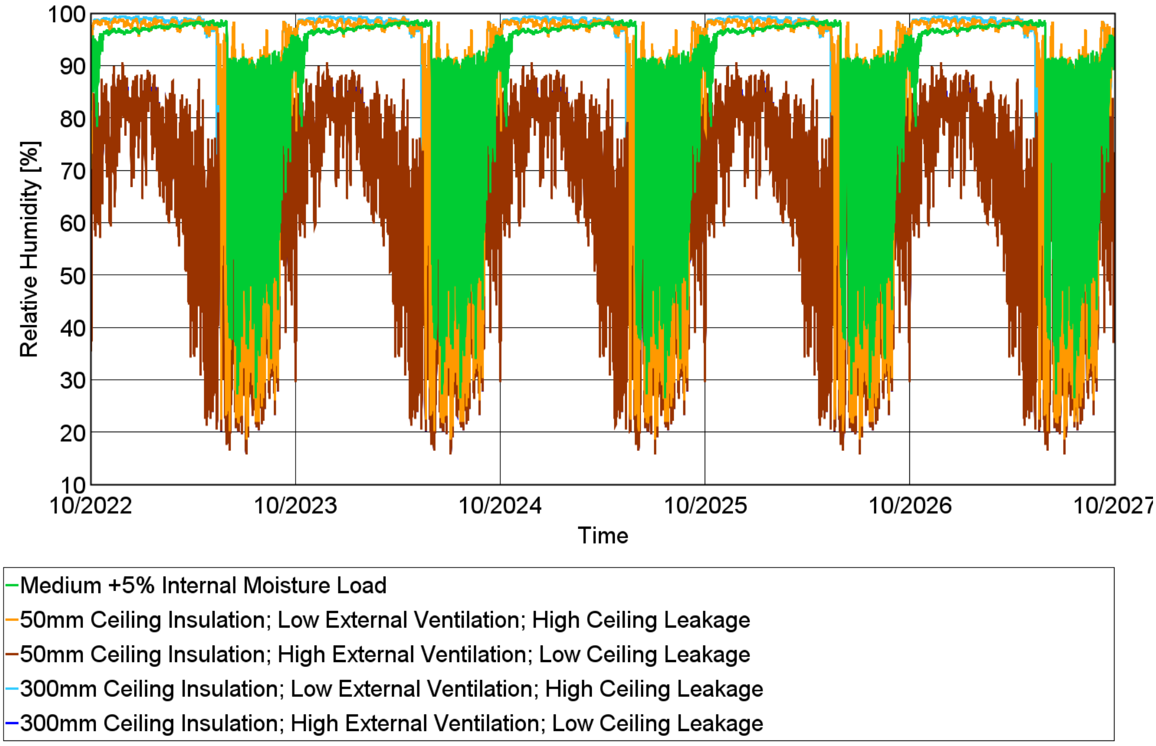

Figure 24. The impact of the loft conditions on the relative humidity in the outer region of insulation over a 5-year period in London when there is 100mm of open cell SFI applied to a HR underlay.

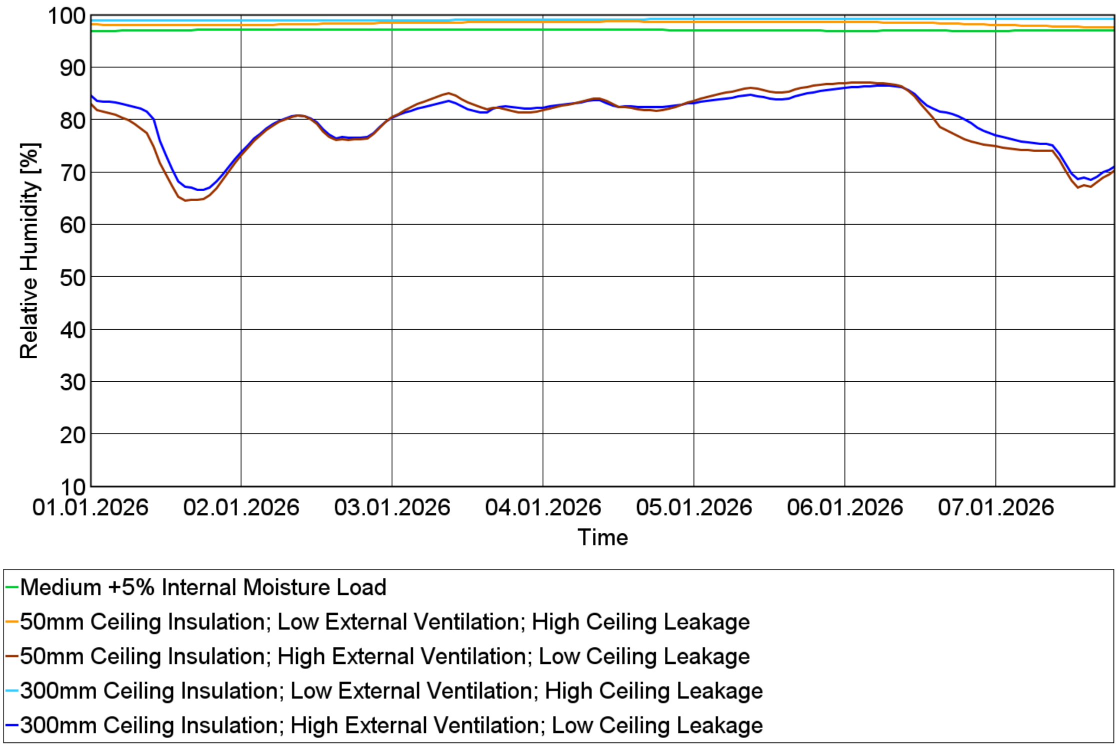

Figure 25. The impact of the loft conditions on the relative humidity in the outer region of insulation over a 1-week period in winter in London when there is 100mm of open cell SFI applied to a HR underlay.

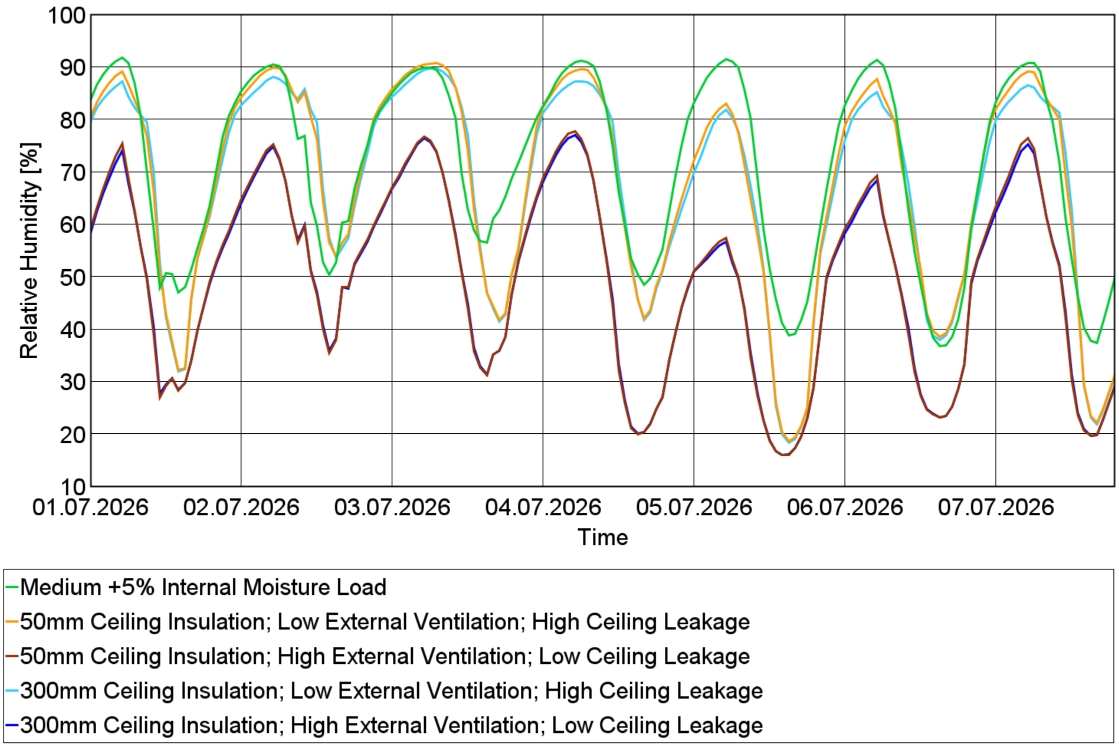

Figure 26. The impact of the loft conditions on the relative humidity in the outer region of insulation over a 1-week period in summer in London when there is 100mm of open cell SFI applied to a HR underlay.

The water content within this outer layer was assessed to determine the risk of condensation occurring on the underside of the underlay. **Figure 27** shows the water content for each of the five cases. This shows that in order to result in a low risk of condensation occurring on the HR underside of the underlay in London, there needs to be high external ventilation and low ceiling leakage. Under these conditions the water content remains at or close to zero. However, a high external ventilation is likely to negate the benefit of the spray foam insulation.

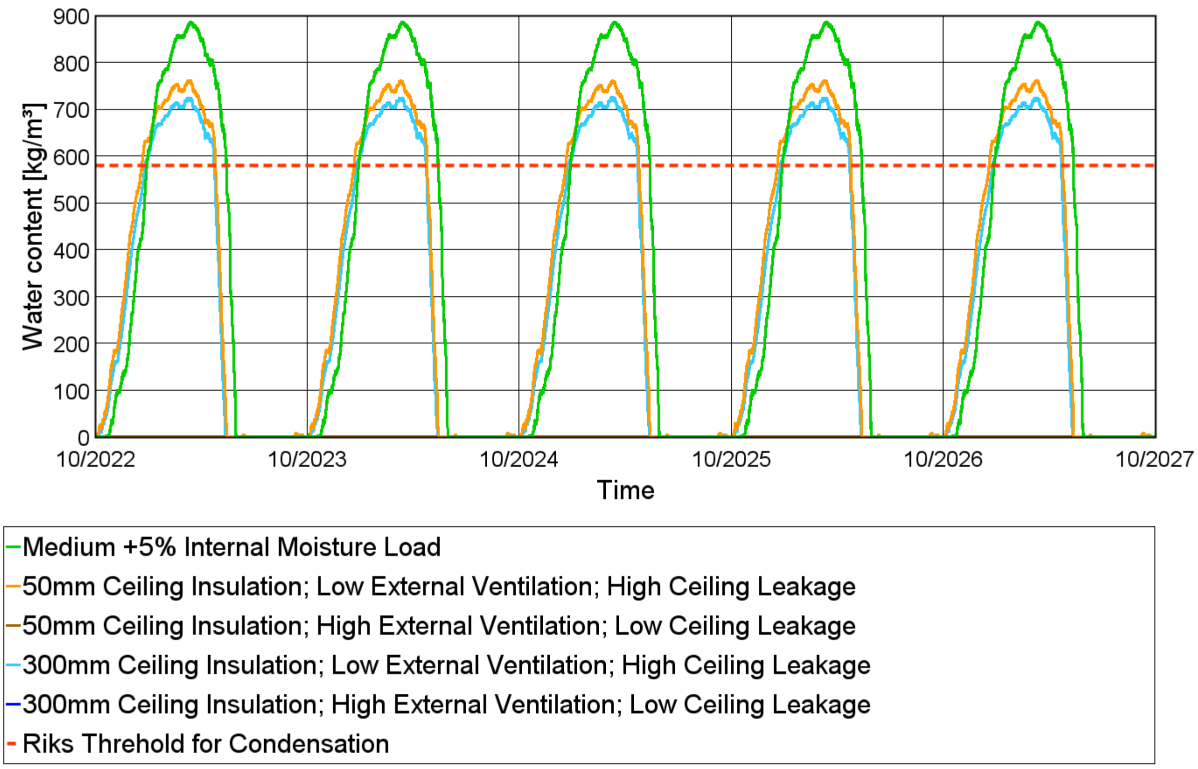

Figure 27. The impact of the loft conditions on the water content on the underside of the underlay in London when there is 100mm of open cell SFI applied to a HR underlay.

The same investigation was undertaken for the internal surface. **Figure 28** to **Figure 30** shows a similar trend to that presented for a LR underlay. This shows that a thicker layer of insulation at ceiling level results in a higher relative humidity at the internal surface. All cases (except the scenario in which the loft conditions are assumed to be the same as the internal conditions – green line) exceed the 80% risk threshold for mould growth for periods of time each year.

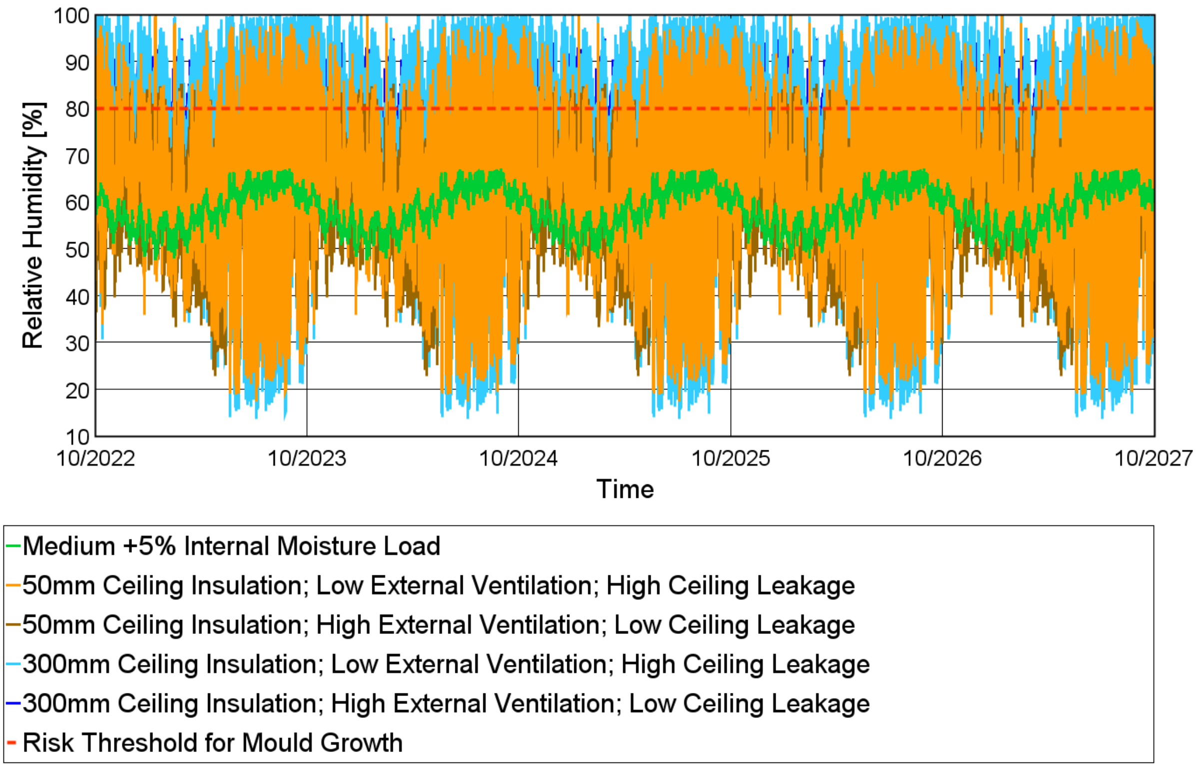

Figure 28. The impact of the loft conditions on the relative humidity at the internal surface over a 5-year period in London when there is 100mm of open cell SFI applied to a HR underlay.

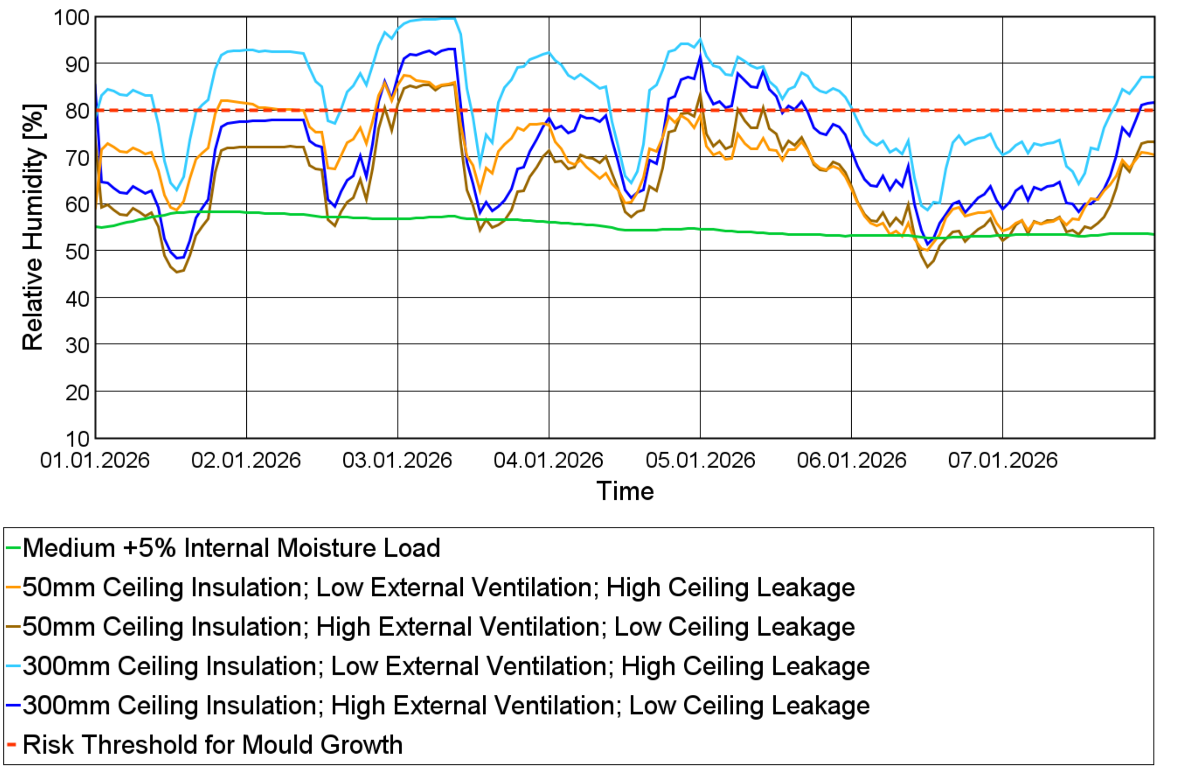

Figure 29. The impact of the loft conditions on the relative humidity at the internal surface when over a 1-week period in winter in London when there is 100mm of open cell SFI applied to a HR underlay.

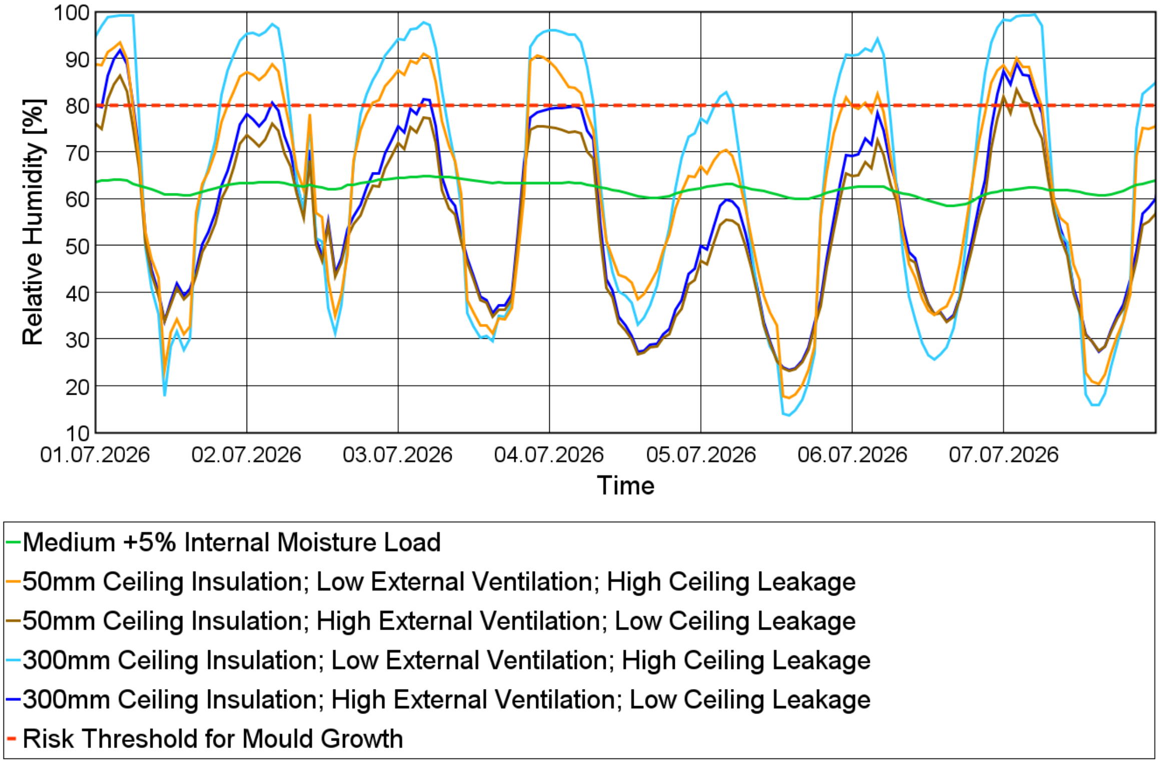

Figure 30. The impact of the loft conditions on the relative humidity at the internal surface over a 1-week period in summer in London when there is 100mm of open cell SFI applied to a HR underlay.

<u>Comparison of Underlay Properties</u>

The influence of installing 100mm open cell spray foam insulation onto a LR versus HR underlay is shown in **Figure 31** to **Figure 33**. These present the relative humidity in the outer region of spray foam insulation for each underlay type. This shows that the underlay properties have a larger influence on the conditions in the outer region of insulation when there is a thicker layer of insulation at ceiling level and poor external ventilation. At the internal surface, the underlay properties have a minimal influence, and the conditions are more heavily influenced by the resulting loft conditions.

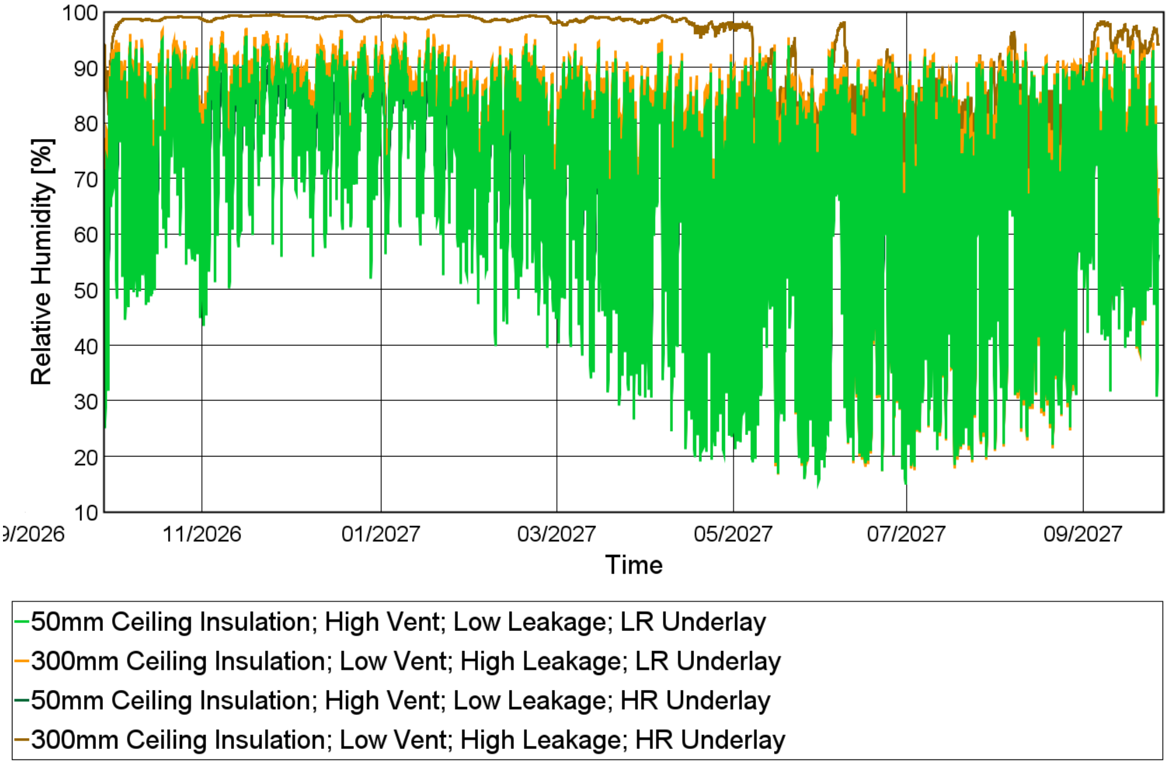

Figure 31. The impact of the underlay properties on the relative humidity in the outer region of insulation over a 5-year period in London when 100mm of open cell SFI is applied.

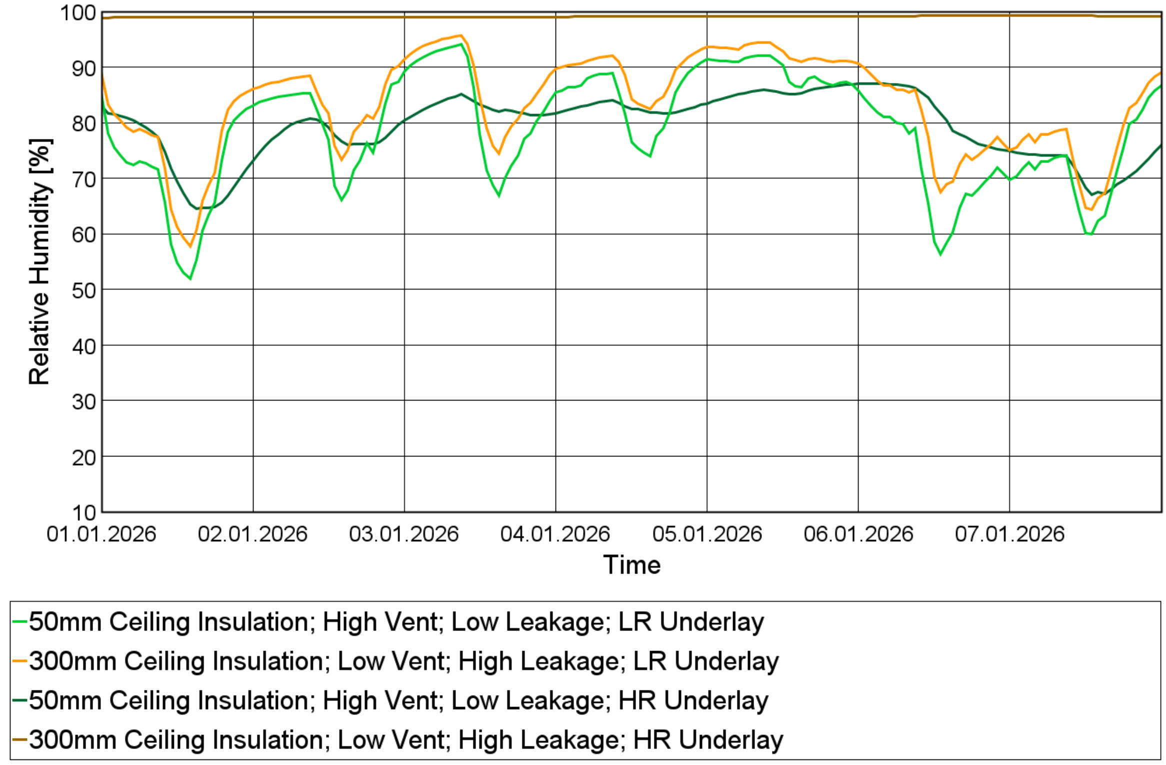

Figure 32. the impact of the underlay properties on the relative humidity in the outer region of insulation over a 1-week period in winter in London when 100mm of open cell SFI is applied.

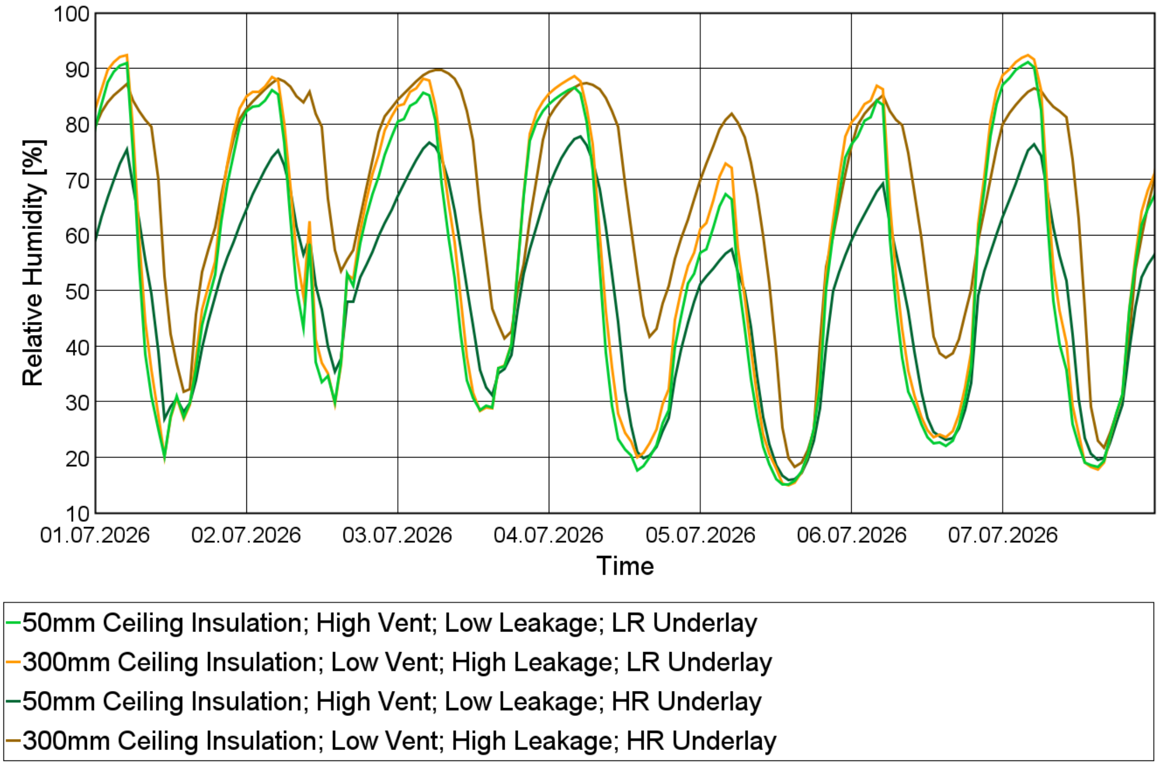

Figure 33. The impact of the underlay properties on the relative humidity in the outer region insulation over a 1-week period in summer in London when 100mm of open cell SFI is applied.

Influence of Loft Conditions in Newcastle

LR Underlay

The influence of the loft conditions on the conditions within the build-up were also assessed when 100mm of spray foam insulation was installed onto a LR underlay in Newcastle.

Figure 34 to **Figure 36** show the influence of the loft conditions on the outer region of spray foam insulation for a single year once equilibrium has been reached. As with the results for London, this shows that the conditions within the loft have a minimal influence on the relative humidity in the outer region of spray foam insulation when there is a LR underlay.

The graph also shows that high humidities occur in the outer region of the foam, particularly during the colder winter months. The humidity in these periods remains above 80% which could indicate a risk of mould growth between the underlay and the timber rafters.

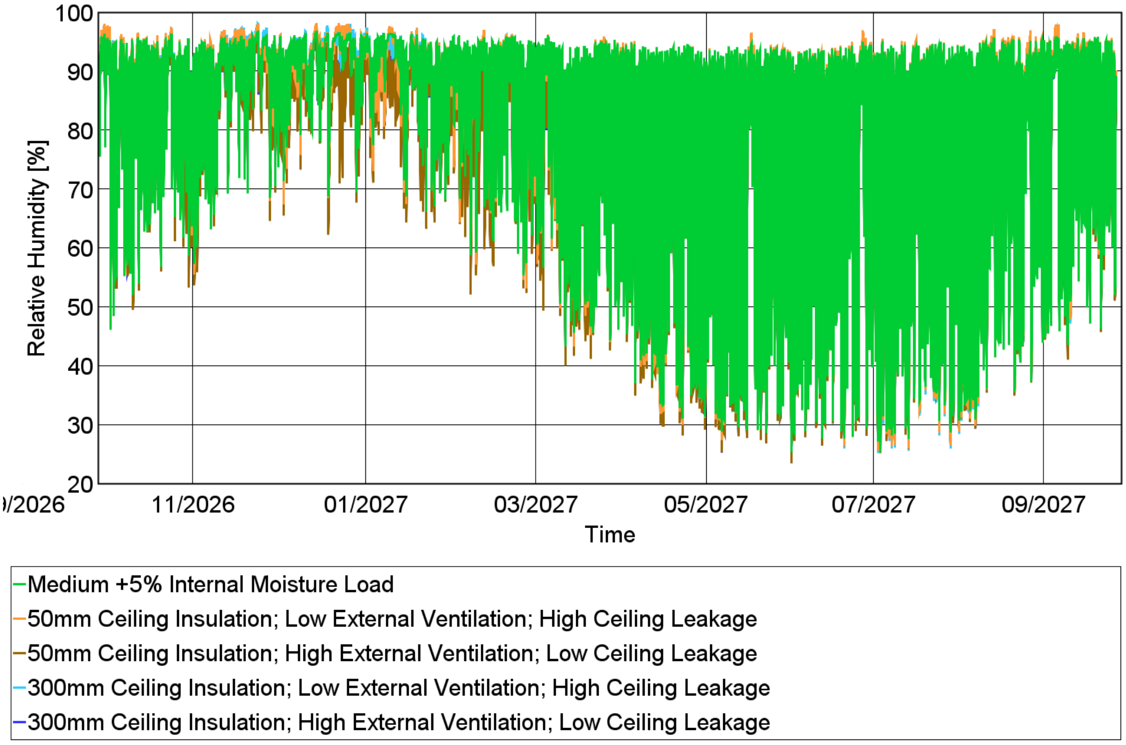

Figure 34. the impact of the loft conditions on the relative humidity in the outer region spray foam insulation over a 1-year period in Newcastle when 100mm of open cell SFI is applied to a LR underlay.

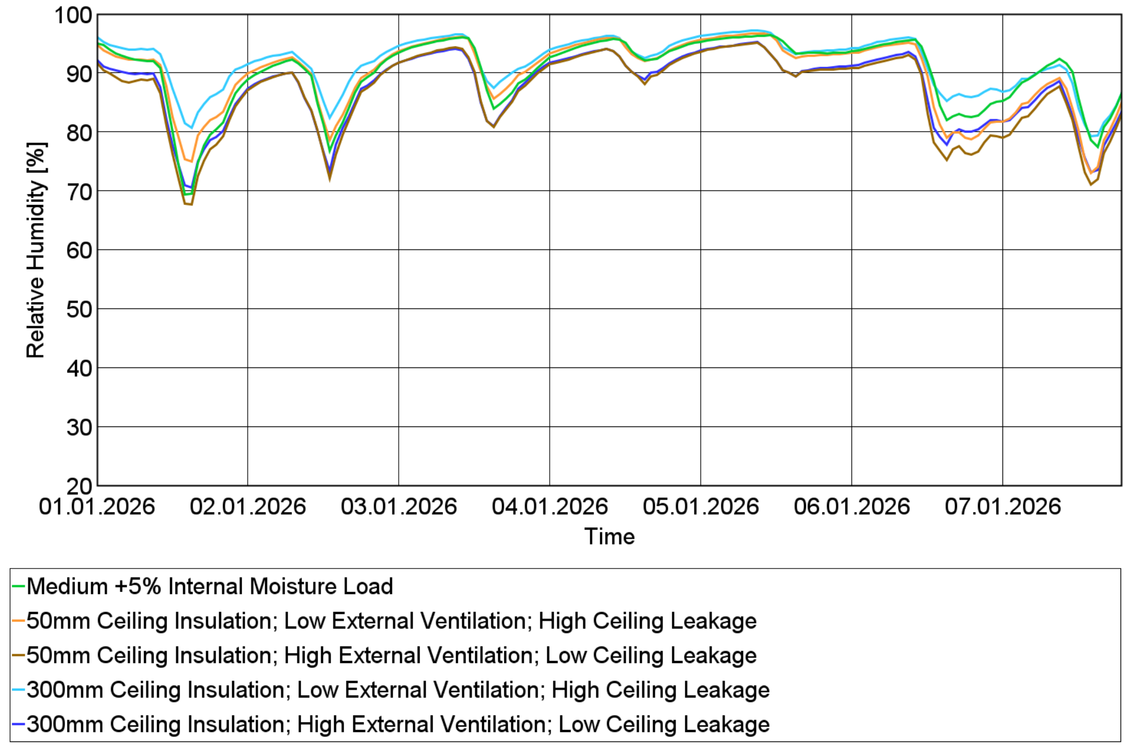

Figure 35. the impact of the loft conditions on the relative humidity in the outer region spray foam insulation over a 1-week period in winter in Newcastle when 100mm of open cell SFI is applied to a LR underlay.

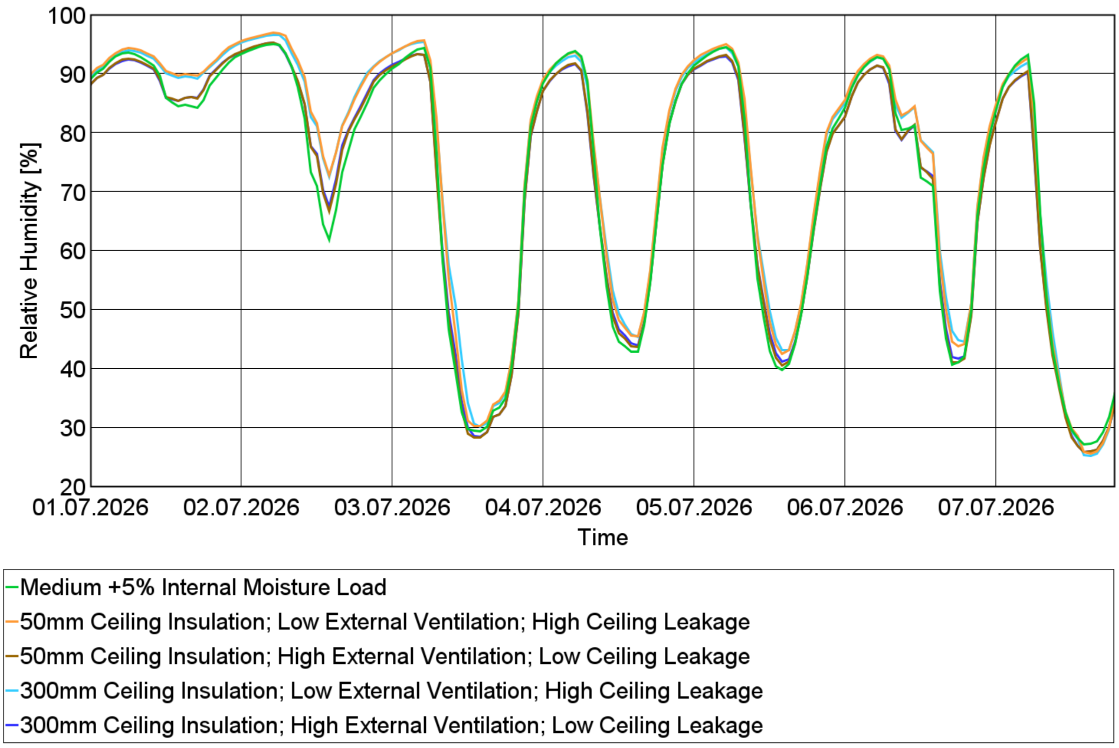

Figure 36. the impact of the loft conditions on the relative humidity in the outer region spray foam insulation over a 1-week period in summer in Newcastle when 100mm of open cell SFI is applied to a LR underlay.

The influence of these loft conditions on the conditions on the internal surface of the build-up was then assessed. The results are shown in **Figure 37** to **Figure 39** which shows that the loft conditions have a strong influence on the conditions at and near to the internal surface of the build-up. The green line indicates a medium +5% internal moisture load i.e. the loft conditions are the same as the occupied space. This results in the lowest overall relative humidity at the internal surface of the build-up and hence the lowest risk.

The graph shows that a the presence of thicker insulation at ceiling level results in a higher humidity at the internal surface of the rafter. This is because the scenarios with a thicker ceiling level insulation have a generally colder loft space. It also shows that there is only a small influence of the ventilation on the conditions at the internal surface. A high external ventilation and low ceiling leakage results in marginally lower relative humidities at this location.

All of the cases where the conditions in the loft have been calculated (i.e. all except the green line) result in a relative humidity at the internal surface which exceeds the 80% risk threshold for mould growth and the 85% risk threshold for decay for periods of time each year.

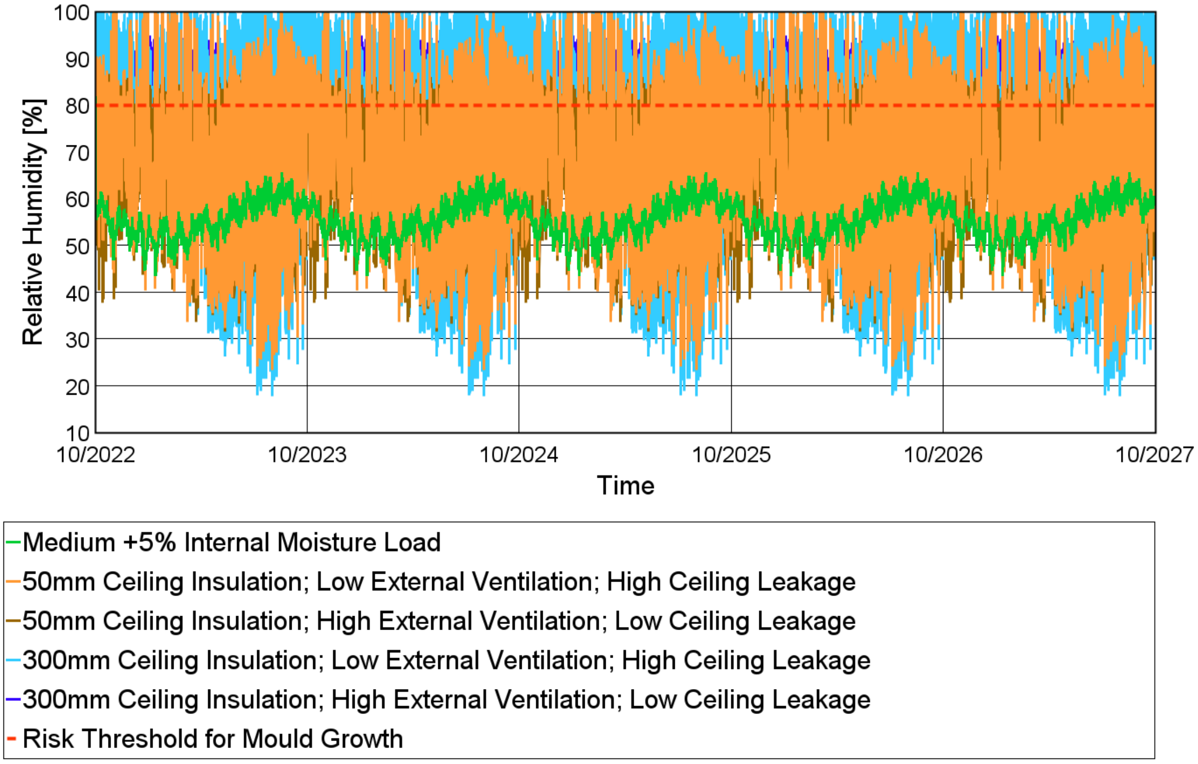

Figure 37. The impact of the loft conditions on the relative humidity at the internal surface over a 5-year period in Newcastle when 100mm of open cell SFI is applied to a LR underlay.

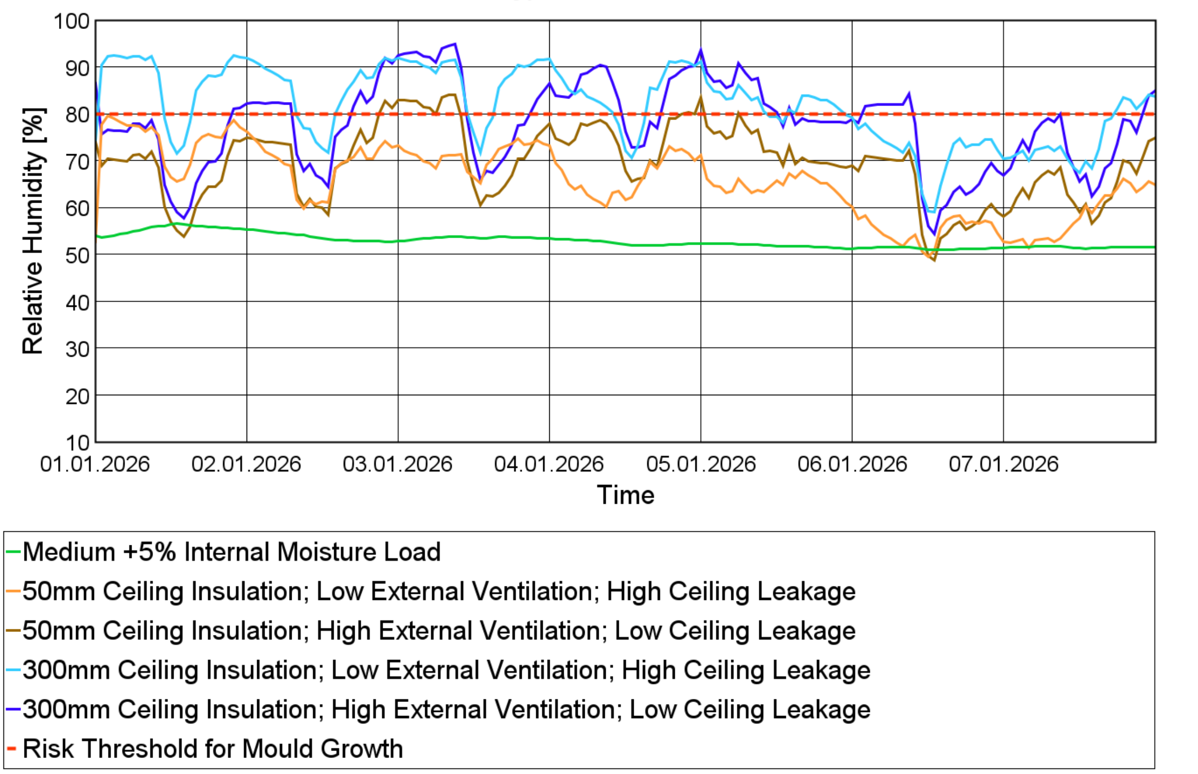

Figure 38. The impact of the loft conditions on the relative humidity at the internal surface over a 1-week period in winter in Newcastle when 100mm of open cell SFI is applied to a LR underlay.

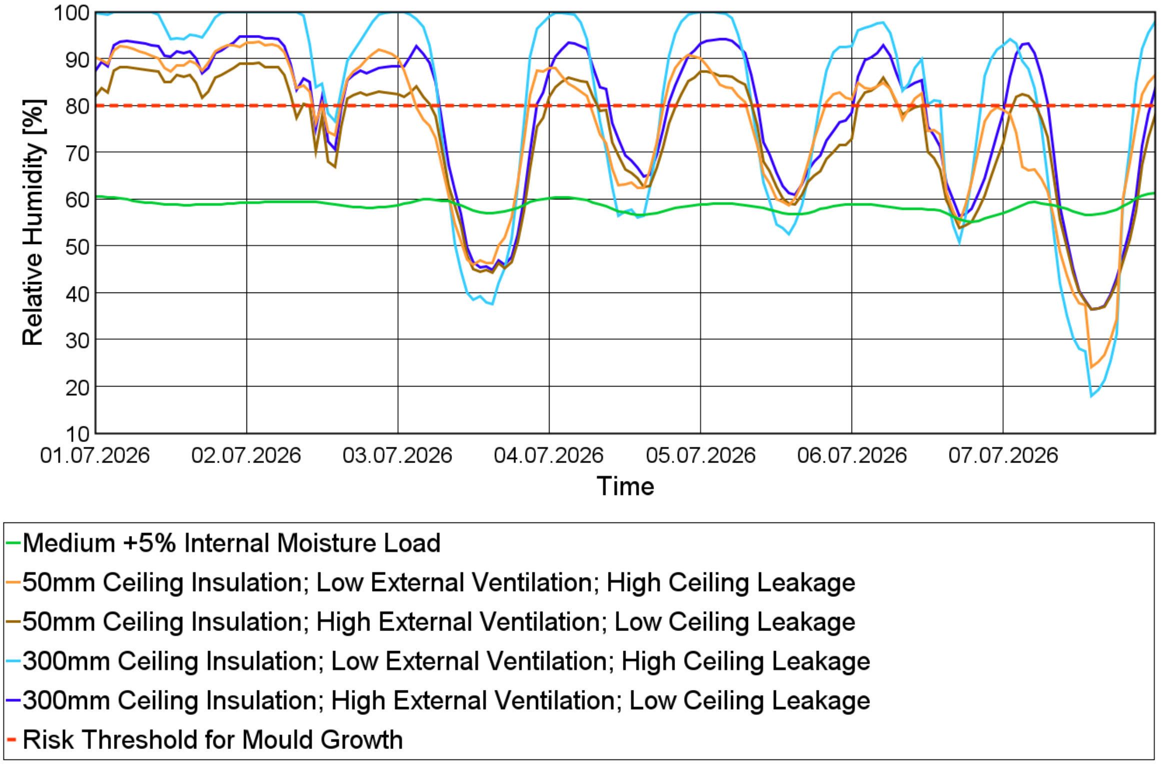

Figure 39. The impact of the loft conditions on the relative humidity at the internal surface over a 1-week period in summer in Newcastle when 100mm of open cell SFI is applied to a LR underlay.

To further investigate the risk of surface mould growth, the results were post processed using the VTT mould model. **Figure 40** shows the mould growth index graph for each of the five cases, assuming a timber substrate. As the area of concern in this instance if the internal surface, a mould growth index of 1 is used as the risk threshold. This graph indicates that both cases with 300mm of ceiling insulation and both cases with a low external ventilation result in a high risk of mould growth on the timber rafters.

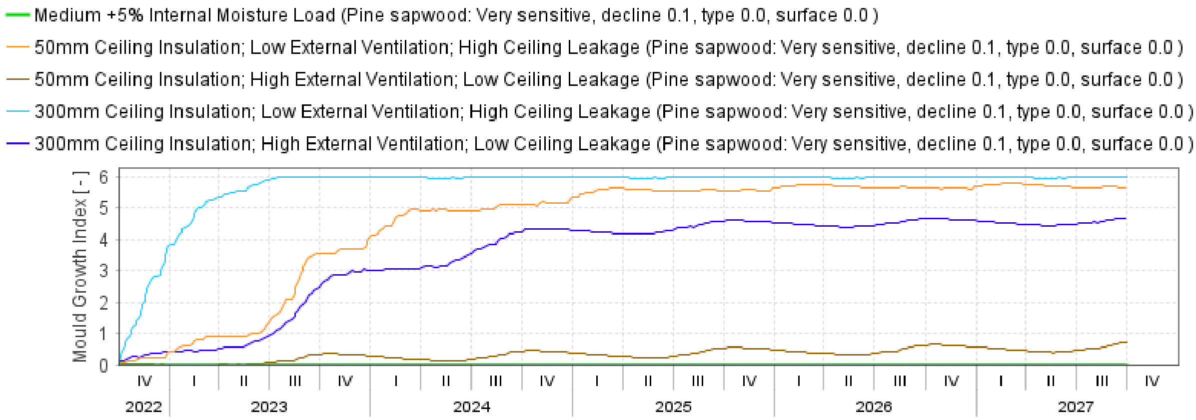

Figure 40. The impact of the loft conditions on the mould growth index of the timber rafter at the internal surface in Newcastle when 100mm of open cell SFI is applied to a LR underlay.

The same assessment was undertaken but assuming that the spray foam insulation is the substrate. This is shown in **Figure 41**, which shows that both cases with a low external ventilation result in a high risk of mould growth on the internal surface of the spray foam insulation.

A low risk of mould growth (i.e. a mould growth index below 1) is only achieved without ceiling insulation or with adequate ventilation to the outside. The problem with the latter point is that this external ventilation would negate the benefit of the spray foam insulation as the external air would be introduced on the inside of the spray foam and hence bypass the elements thermal resistance and lead to sizeable heat losses.

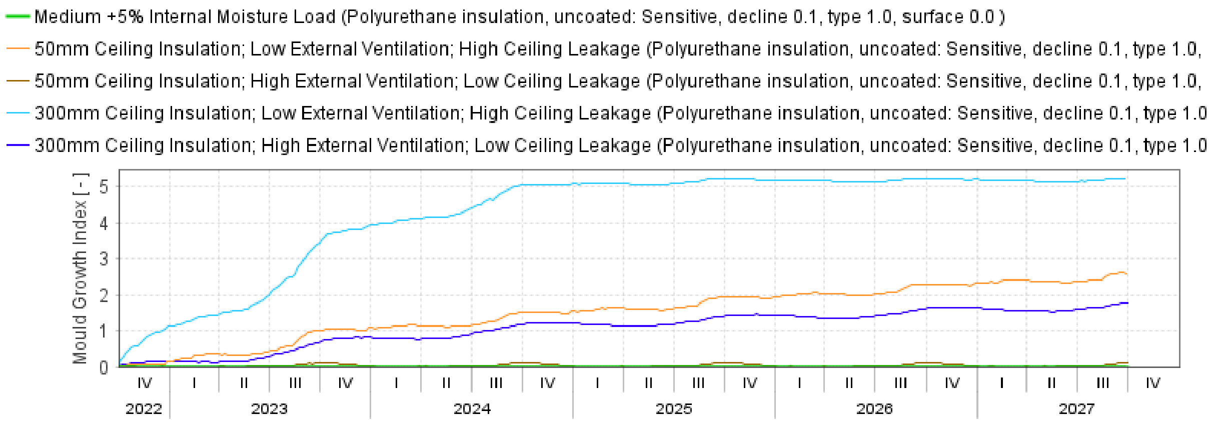

Figure 41. The impact of the loft conditions on the mould growth index of the spray foam insulation at the internal surface in Newcastle when 100mm of open cell SFI is applied to a LR underlay.

<u>High Resistance Underlay</u>

The influence of the loft conditions on the humidity within the build-up were assessed when the spray foam insulation was installed onto a HR underlay in Newcastle.

Figure 42 to **Figure 44** show the influence of the loft conditions on the outer region of spray foam insulation for a five-year simulation period, a winter week period and summer week period, respectively. This shows that the ventilation of the loft space to both the inside and outside have a strong influence on the conditions in the outer region of spray foam insulation. The relative humidity in this region is higher, and exceeds 95%, when there is low external ventilation and high ceiling ventilation or when the loft condition is the same as the occupied space. Therefore, these conditions could result in a high risk of mould growth and decay of the timber rafters in this region.

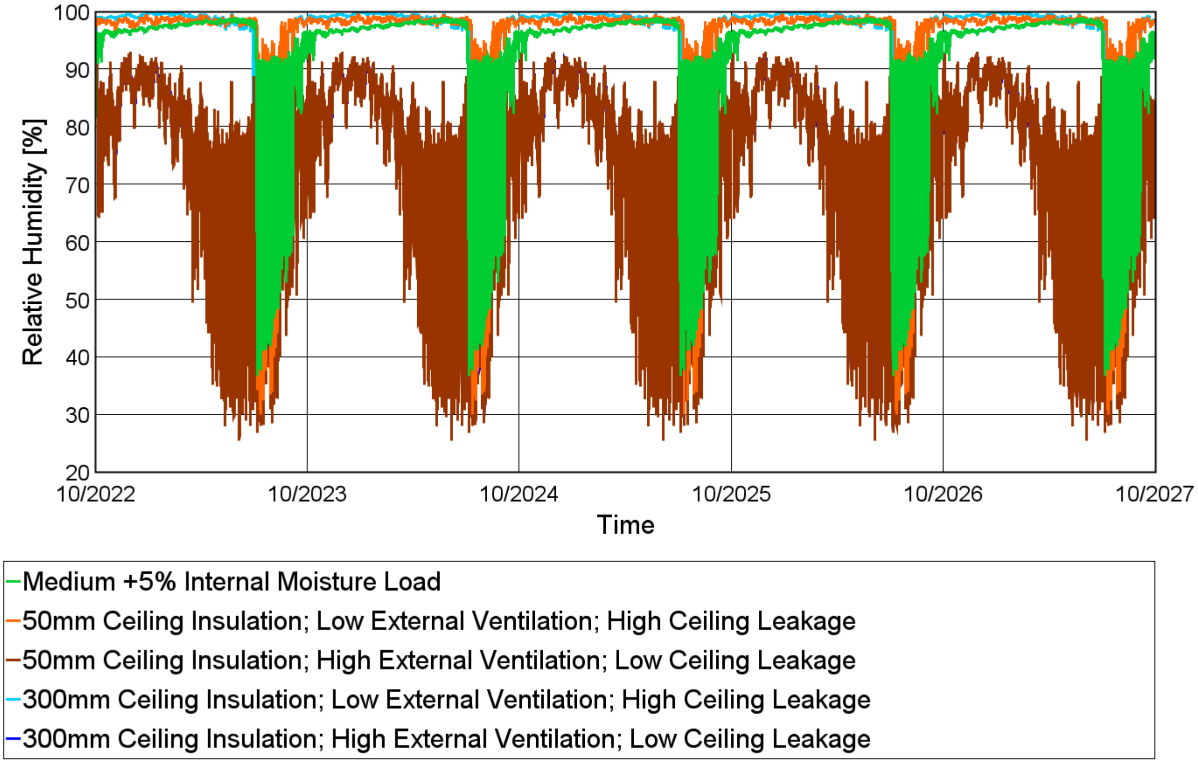

Figure 42. The impact of the loft conditions on the relative humidity in the outer region spray foam insulation over a 5-year period in Newcastle when 100mm of open cell SFI is applied to a HR underlay.

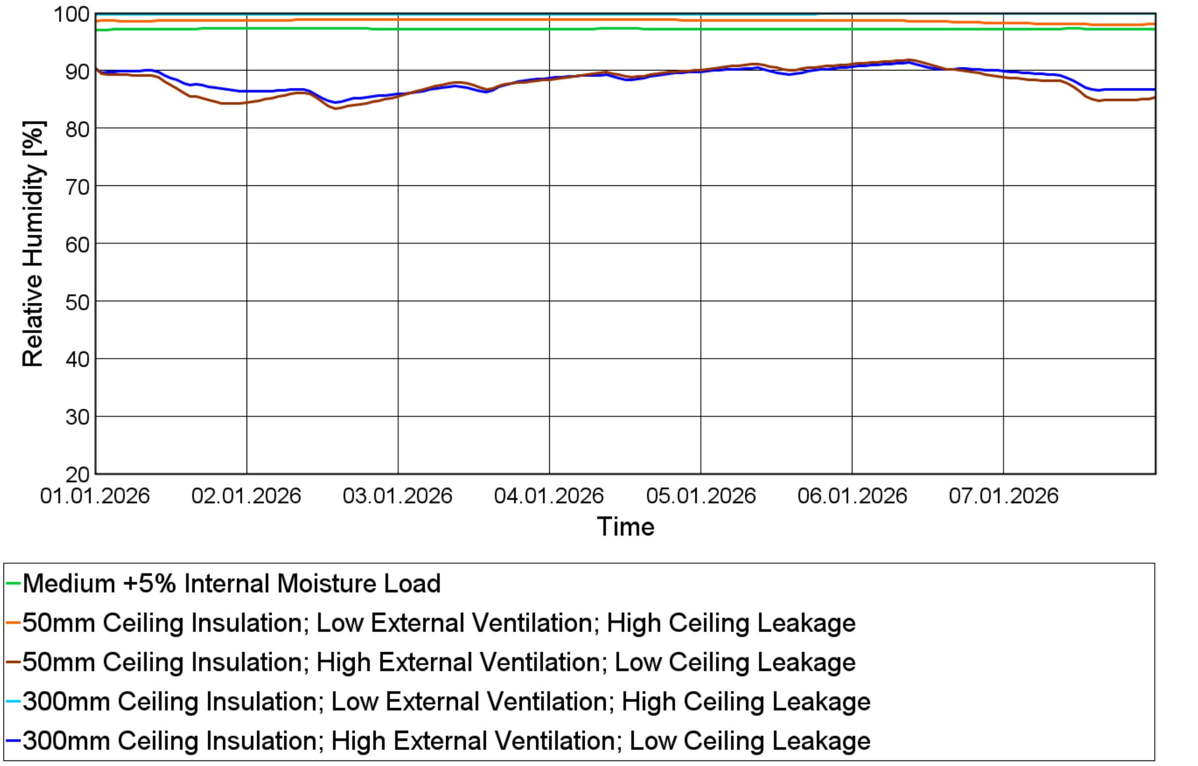

Figure 43. The impact of the loft conditions on the relative humidity in the outer region spray foam insulation over a 1-week period in winter in Newcastle when 100mm of open cell SFI is applied to a HR underlay.

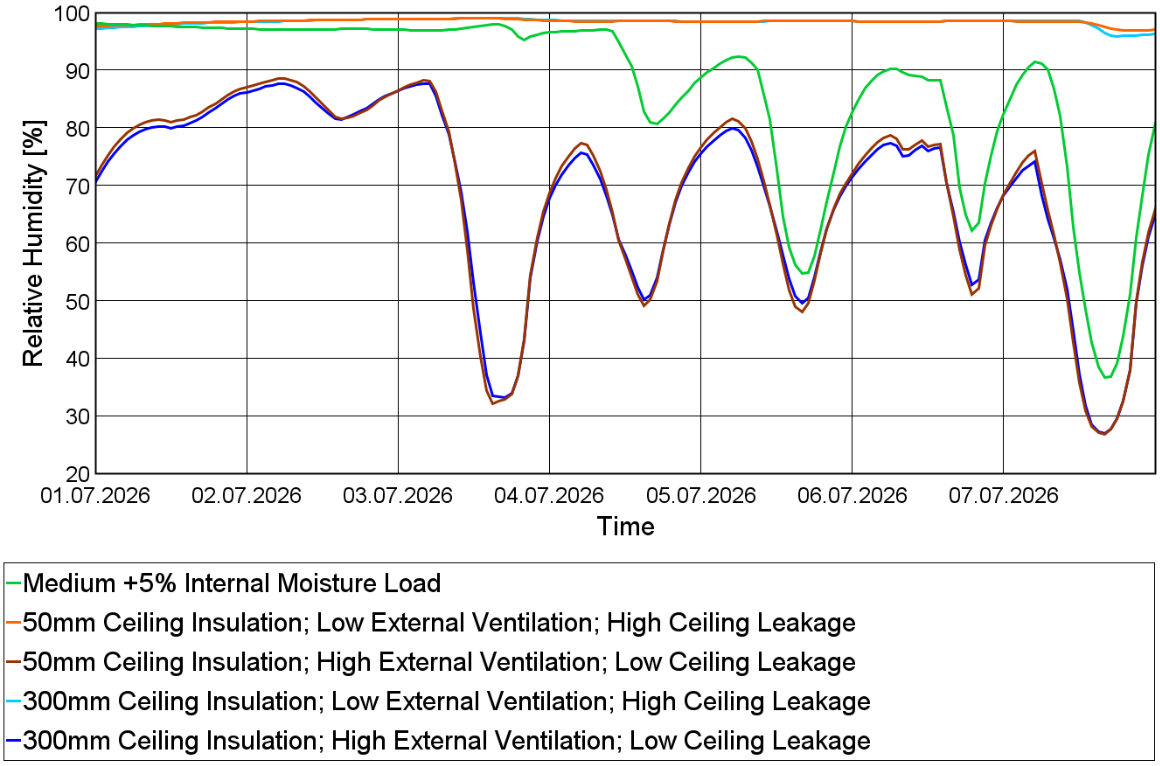

Figure 44. The impact of the loft conditions on the relative humidity in the outer region spray foam insulation over a 1-week period in summer in Newcastle when 100mm of open cell SFI is applied to a HR underlay.

The water content within this layer was then assessed to determine the risk of condensation occurring on the underside of the underlay. **Figure 45** shows the water content in the outer layer for each of the five cases. This shows that in order to result in a low risk of condensation occurring on the HR underside of the underlay in Newcastle, there needs to be high external ventilation and low ceiling leakage (which results in a water content at or near zero). A high level of external ventilation will, however, be likely to negate the thermal benefit of the spray foam insulation.

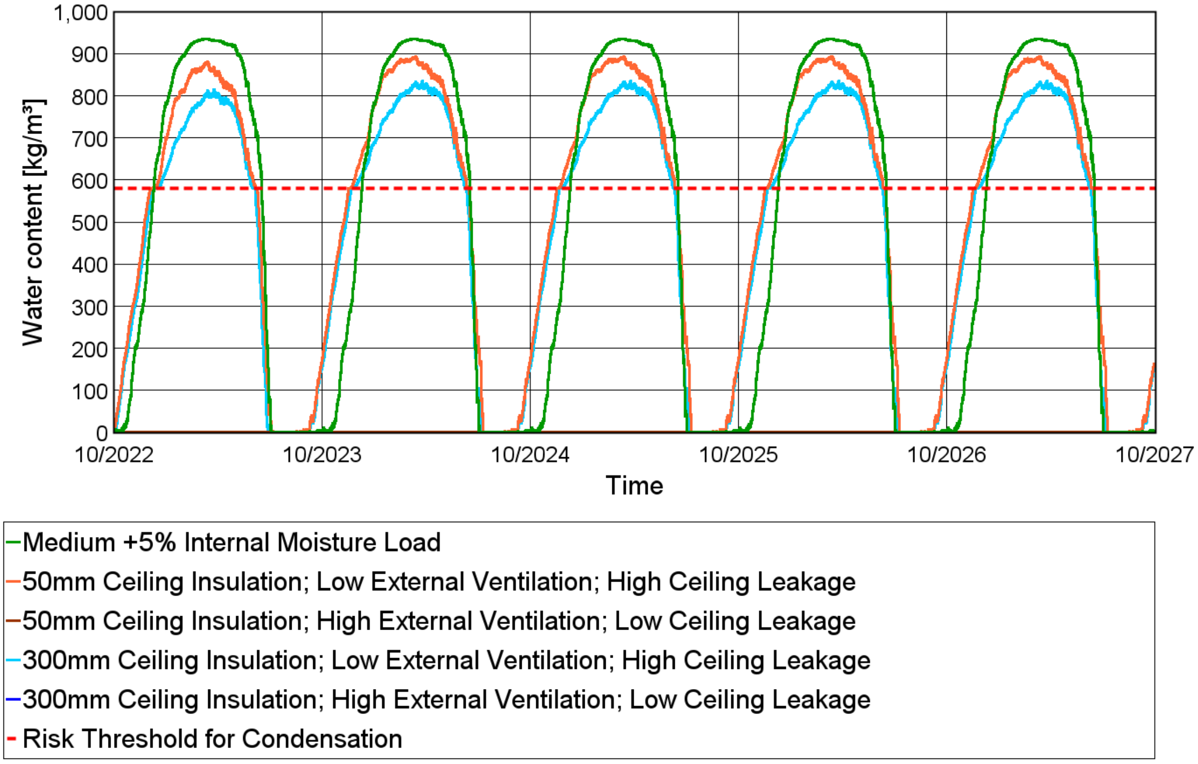

Figure 45. The impact of the loft conditions on the water content on the underside of the underlay in Newcastle when 100mm of open cell SFI is applied to a HR underlay.

The conditions at the internal surface of the rafters for this case was also considered. This is shown in **Figure 46** to **Figure 48** for a single year of simulation once dynamic equilibrium was reached, a typical winter week and a typical summer week, respectively. The charts show a similar trend as presented with a LR underlay, indicating the type of underlay has a negligible effect. A thicker layer of insulation at ceiling level results in a higher relative humidity at the internal surface. All cases (except the scenario in which the loft conditions are assumed to be the same as the occupied space – green line) exceed the 80% risk threshold for mould growth for large periods of time each year.

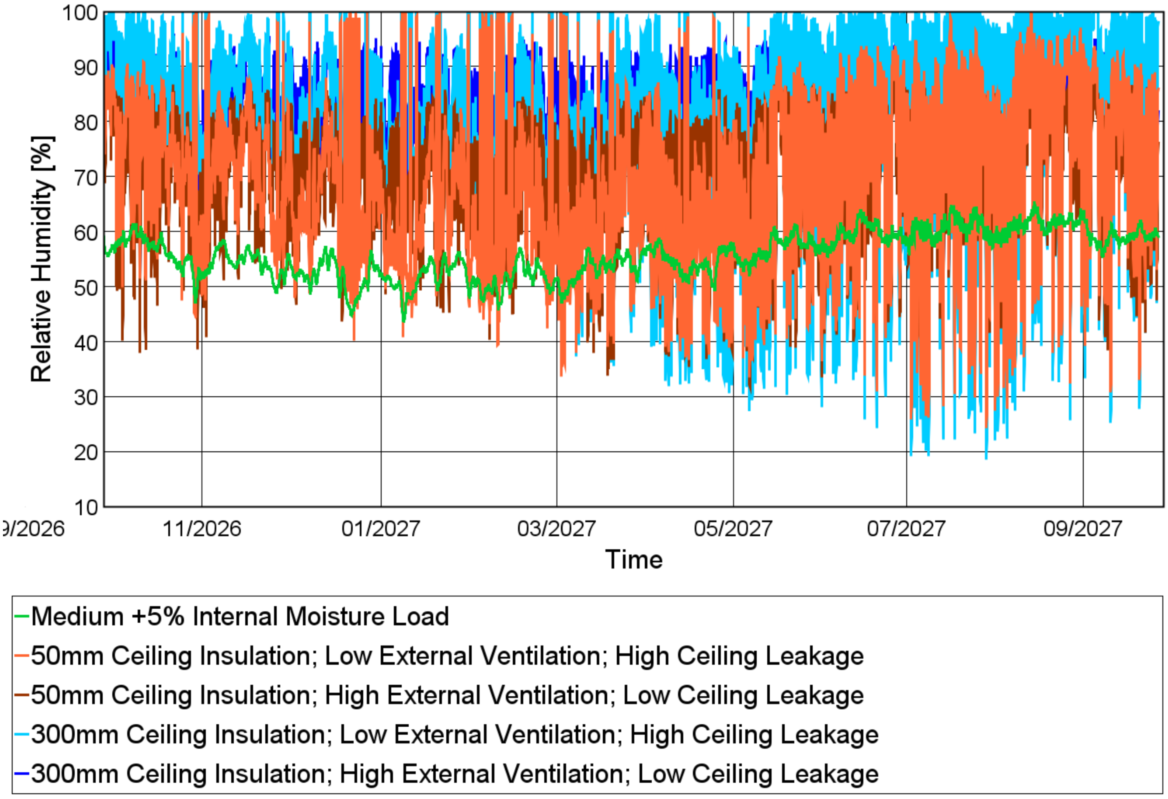

Figure 46. the impact of the loft conditions on the relative humidity at the internal surface over a 5-year period in Newcastle when 100mm of open cell SFI is applied to a HR underlay.

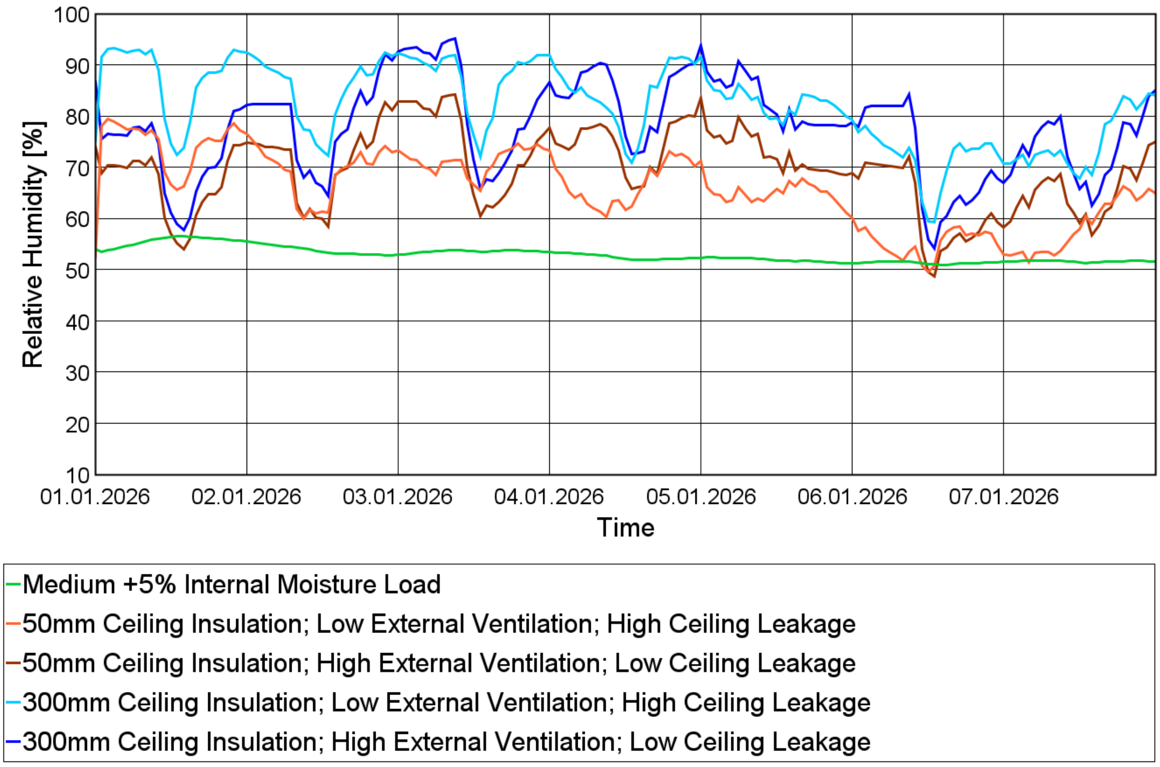

Figure 47. the impact of the loft conditions on the relative humidity at the internal surface over a 1-week period in winter in Newcastle when 100mm of open cell SFI is applied to a HR underlay.

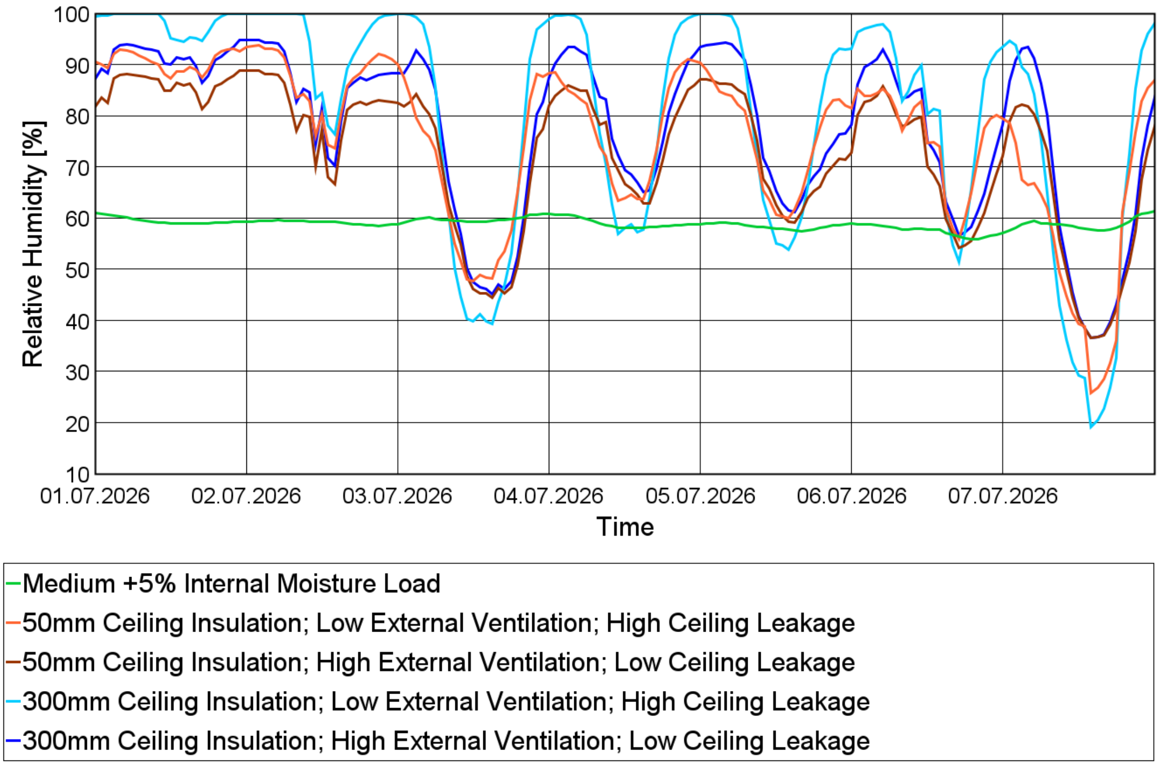

Figure 48. the impact of the loft conditions on the relative humidity at the internal surface over a 1-week period in summer in Newcastle when 100mm of open cell SFI is applied to a HR underlay.

<u>Comparison of Underlay Properties</u>
The influence of installing 100mm open cell spray foam insulation onto a LR versus HR underlay was investigated. **Figure 49** to **Figure 51** present the relative humidity in the outer region of spray foam insulation for each underlay type. This shows that the underlay properties have a larger influence on the conditions in the outer region of insulation when there is a thicker layer of insulation at ceiling level and poor external ventilation.

At the internal surface, the underlay properties have a minimal influence, and the conditions are more heavily influenced by the resulting loft conditions.

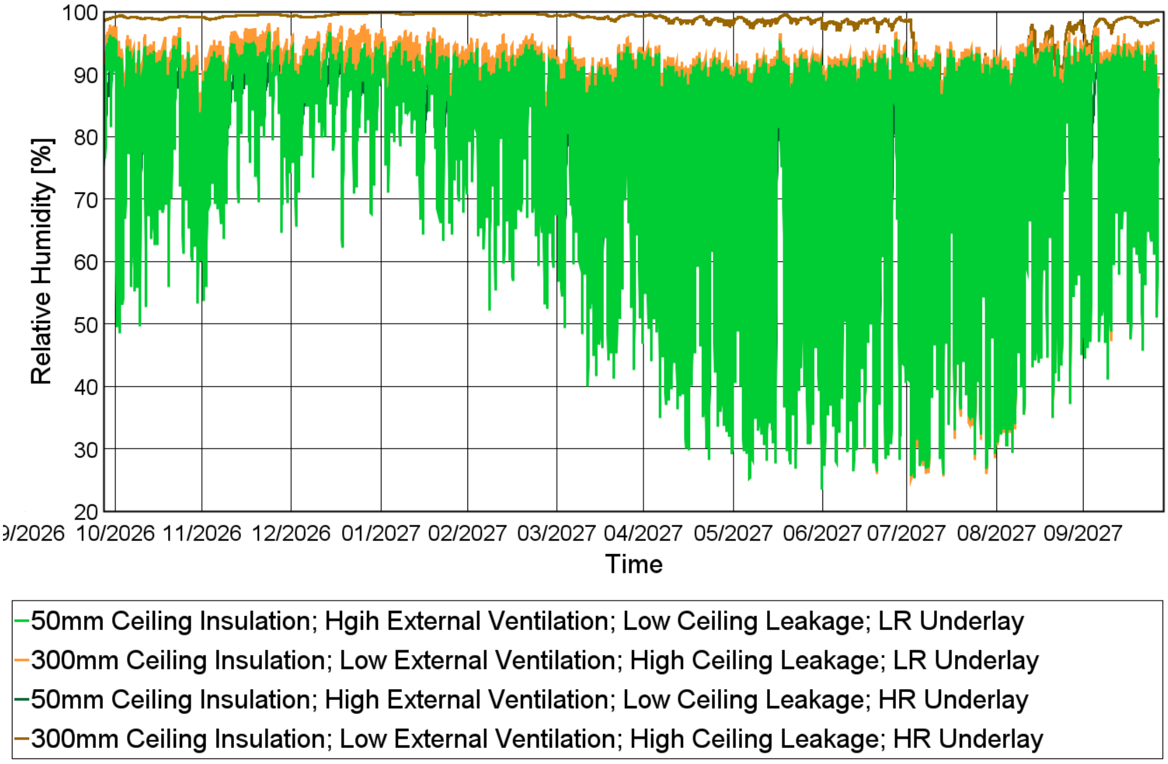

Figure 49. The impact of the underlay properties on the relative humidity in the outer region of spray foam insulation over a 5-year period in Newcastle when 100mm of open cell SFI is applied.

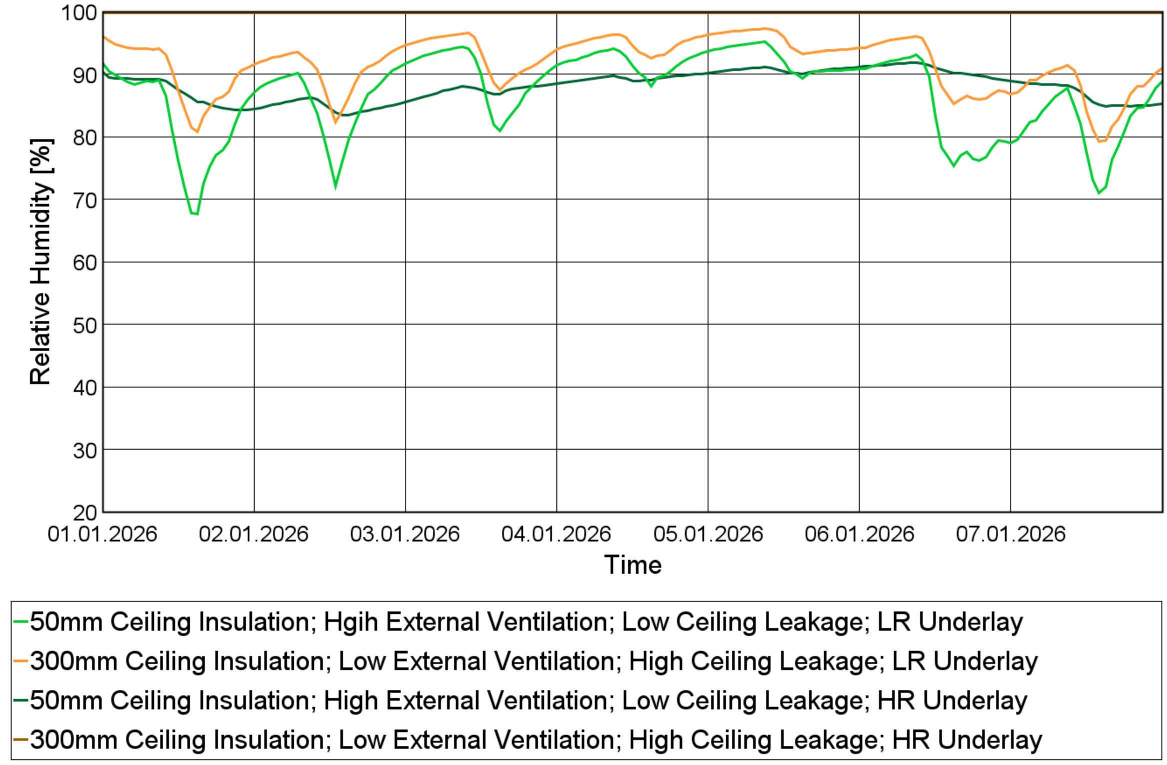

Figure 50. The impact of the underlay properties on the relative humidity in the outer region of spray foam insulation over a 1-week period in winter in Newcastle when 100mm of open cell SFI is applied.

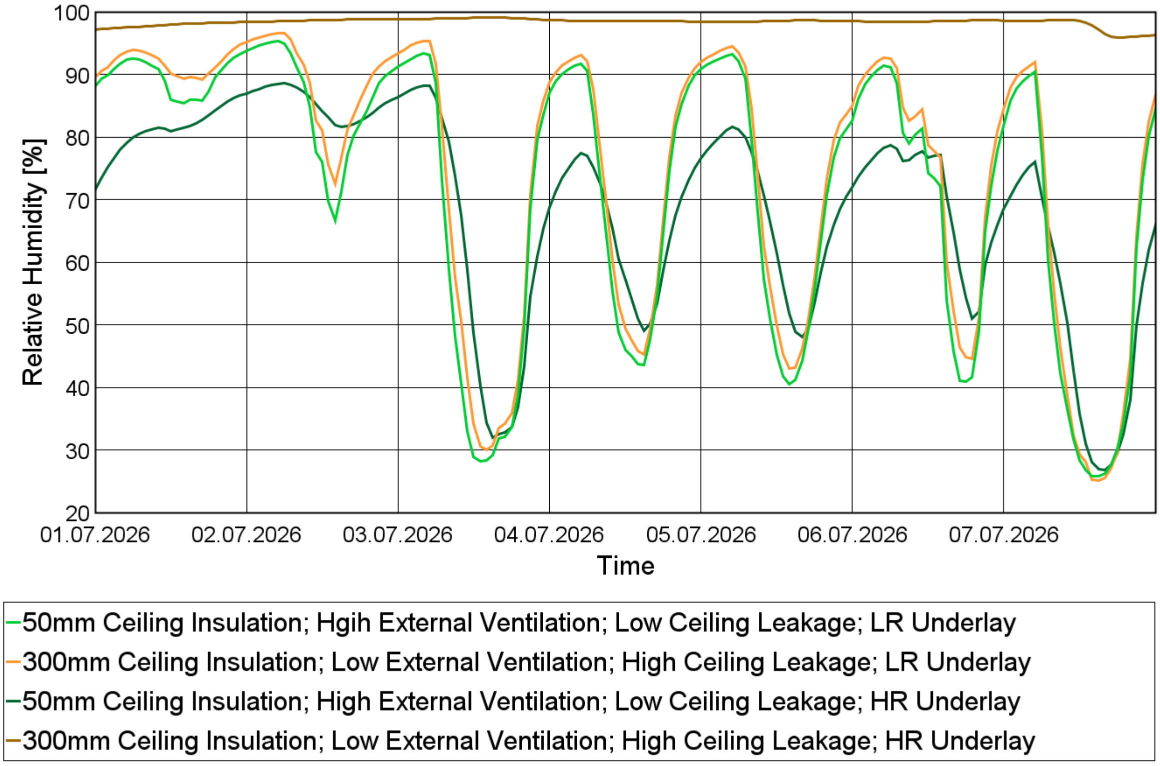

Figure 51. The impact of the underlay properties on the relative humidity in the outer region of spray foam insulation over a 1-week period in summer in Newcastle when 100mm of open cell SFI is applied.

Summary – impact of various loft conditions

Tables 1 and 2 present a summary of the risks identified in this sub-study. The tables are colour coded to identify the risk level:

- green indicates a low risk for all risk factors assessed
- orange indicates a possible risk to one of the key risk factors assessed
- red indicates multiple key risk factors or a probable risk to one or more key risk factors.

Table 1: Summary of results - London climate

	Loft Conditions Identical to Occupied Space	50mm Ceiling		300mm Ceiling	
		Low External Ventilation and High Ceiling Leakage	**High External Ventilation and Low Ceiling Leakage**	**Low External Ventilation and High Ceiling Leakage**	**High External Ventilation and Low Ceiling Leakage**
LR Underlay	Low mould risk to internal	Significant mould risk to internal	Low mould risk to internal	Significant mould risk to internal	Medium mould risk to internal

	surface of rafters Low risk to outer region of timber rafters Low risk of condensation Low mould risk to the insulation	surface of rafters Low risk to outer region of timber rafters Low risk of condensation Significant risk of mould on insulation	surface of rafters Low risk to outer region of timber rafters Low risk of condensation Low mould risk to the insulation	surface of rafters Low risk to outer region of timber rafters Low risk of condensation Significant risk of mould on insulation	surface of rafters Low risk to outer region of timber rafters Low risk of condensation Low mould risk to the insulation
HR Underlay	Low mould risk to internal surface of rafters Significant risk to outer region of timber rafters Significant condensation risk Significant risk of mould on insulation	Possible mould risk to internal surface of rafters Significant risk to outer region of timber rafters Significant condensation risk Significant risk of mould on insulation	Medium mould risk to internal surface of rafters Low risk to outer region of timber rafters Low risk of condensation Low mould risk to the insulation	Medium mould risk to internal surface of rafters Significant risk to outer region of timber rafters Significant condensation risk Significant risk of mould on insulation	Medium mould risk to internal surface of rafters Significant risk to outer region of timber rafters Low risk of condensation Low mould risk to the insulation

Table 2: summary of risks - Newcastle climate

	No Ceiling Loft Conditions Identical to Occupied Space	50mm Ceiling		300mm Ceiling	
		Low External Ventilation and High Ceiling Leakage	**High External Ventilation and Low Ceiling Leakage**	**Low External Ventilation and High Ceiling Leakage**	**High External Ventilation and Low Ceiling Leakage**
LR Underlay	Low mould risk to internal surface of rafters Low risk to outer region of timber rafters Low risk of condensation	Significant mould risk to internal surface of rafters Low risk to outer region of timber rafters Low risk of condensation	Medium mould risk to internal surface of rafters Low risk to outer region of timber rafters Low risk of condensation	Significant mould risk to internal surface of rafters Low risk to outer region of timber rafters Low risk of condensation	Medium mould risk to internal surface of rafters Low risk to outer region of timber rafters Low risk of condensation

	Low mould risk to the insulation	Medium risk of mould on insulation	Low mould risk to the insulation	Significant risk of mould on insulation	Low mould risk to the insulation
HR Underlay	Low mould risk to internal surface of rafters Significant risk to outer region of timber rafters Significant condensation risk Medium risk of mould on insulation	Medium mould risk to internal surface of rafters Significant risk to outer region of timber rafters Significant condensation risk Significant risk of mould on insulation	Significant mould risk to internal surface of rafters Low risk to outer region of timber rafters Low risk of condensation Low mould risk to the Insulation	Significant mould risk to internal surface of rafters Significant risk to outer region of timber rafters Significant condensation risk Significant risk of mould on insulation	Significant mould risk to internal surface of rafters Low risk to outer region of timber rafters Low risk of condensation Low mould risk to the Insulation

A select number of cases were run with 200mm of open cell insulation and it was found that there was a minimal influence of this increased thickness of spray foam insulation on the results for LR underlay. When there was a HR underlay, there was a minimal influence of the spray foam thickness on the conditions within the insulation, but a thicker layer of insulation resulted in a lower risk of condensation occurring on the underside of the underlay.

Appendix 4: U-value calculations

U-value modelling has been completed to illustrate the performance of rafter level loft insulation when applied to an unheated loft space. This follows the conventions in the Building Research Establishment's BR443[4]. Section 5 of BR443 outlines how U-values should be calculated for elements adjacent to an unheated space, such as ceiling below an unheated loft.

The boundary used for energy assessments consists of all the building elements separating heated space from

a. external environments
b. adjacent dwellings
c. unheated spaces

For a dwelling with an unheated loft, therefore, the ceiling is the boundary of heated space and the U-value as calculated at ceiling level.

The heat transfer from a building to the external environment via unheated spaces is calculated according to ISO 13789. Alternatively, when the external envelope of the unheated space is not insulated, sections 6.10.2 and 6.10.3 of BS EN ISO 6946 provide simplified procedures, treating the unheated space as a thermal resistance. These state that:

> *When a building has an unheated space adjacent to it, the thermal transmittance between the internal and external environments can be obtained by treating the unheated space together with its external construction components as if it were an additional homogeneous layer with thermal resistance R_u. When all elements between the internal environment and the unheated space have the same thermal transmittance, R_u is given by:*
>
> $$R_u = \frac{A_i}{\sum\left(A_{e;k} \cdot U_{e;k}\right) + 0{,}33 \times n \cdot V}$$
>
> *Where:*
> *R_u is the thermal resistance of the unheated space, in m^2K/W;*
> *A_i is the total area of all elements between the internal environment and the unheated space, in m^2;*
> *$A_{e;k}$ is the area of element k between the unheated space and the external environment, in m^2;*
> *$U_{e;k}$ is the thermal transmittance of the element k between the unheated space and the external environment, in $W/(m^2K)$;*
> *0,33 is the value of the thermal capacity of air, in $Wh/(m^3K)$;*
> *n is the ventilation rate of the unheated space, in air changes per hour;*
> *V is the volume of the unheated space in m^3;*

[4] BR443 (2019) Conventions for U-value calculations. Anderson, B & Kosmina,L.

The thermal resistance of the unheated loft space is, therefore, dependent on a combination of the area of the ceiling, the area and thermal transmittance of the elements at rafter level, the volume of the loft space and the ventilation rate of the loft space (expressed in air changes per hour).

U-value modelling has been completed to illustrate the performance of rafter level loft insulation in an unheated loft space, using the example of a semi-detached house. Insulation was modelled at thermal conductivities (lambda value) of 0.039 and 0.026, applied with thicknesses of 100mm, 150mm and 200mm and at two different ventilation rates of 0.5, and 3 air changes per hour.

The results of the analysis are shown in **Table 3** below.

Table 3: Insulation applied at rafter level with no existing joist insulation (0.5 and 3 air changes per hour in loft space).

Thickness of insulation at joist level (mm)	Number of air changes in loft space (air changes per hour)[2]	Thickness of insulation at rafter level (mm)	Thermal conductivity of rafter level insulation	Resistance of loft space including rafter level insulation	Final U-value (W/m^2K)
0mm (uninsulated)[1]	0.5	100	0.39	0.804	1.00
			0.26	0.886	0.92
		150	0.39	0.914	0.90
			0.26	0.987	0.84
		200	0.39	0.987	0.84
			0.26	1.060	0.79
0mm (uninsulated)[1]	3	100	0.39	0.450	1.54
			0.26	0.474	1.49
		150	0.39	0.482	1.47
			0.26	0.502	1.43
		200	0.39	0.502	1.43
			0.26	0.520	1.39

1 = Resultant U-value at ceiling of 2.24 W/m^2K
2 = n.b. BR443 states that a default value of n=3 should be used where the airtightness of the unheated space is unknown.

Further analysis considered a situation where there was some existing ceiling/joist level insulation (assumed 100mm mineral wool) in place and rafter level insulation was also applied into the unheated loft space above this insulation. These results are shown in **Table 4** below.

Table 4: Insulation applied at rafter level with 100mm of existing joist insulation (0.5 and 3 air changes per hour in loft space).

Thickness of insulation at joist level (mm)	Number of air changes in loft space (air changes per hour) [2]	Thickness of insulation at rafter level (mm)	Thermal conductivity of rafter level insulation	Resistance of loft space including rafter level insulation	Final U-value (W/m²K)
100mm of mineral wool[1]	0.5	100	0.39	0.804	0.34
			0.26	0.886	0.33
		150	0.39	0.914	0.32
			0.26	0.987	0.32
		200	0.39	0.987	0.32
			0.26	1.060	0.31
100mm of mineral wool[1]	3	100	0.39	0.450	0.38
			0.26	0.474	0.38
		150	0.39	0.482	0.38
			0.26	0.502	0.37
		200	0.39	0.502	0.37
			0.26	0.520	0.37

1 = Resultant U-value at celling of 0.41 W/m²K
2 = n.b. BR443 states that a default value of n=3 should be used where the airtightness of the unheated space is unknown