Historic England

Building and Landscape Conservation

A Study of the Roof Environment in Four Domestic Buildings

Brian Ridout, Iain McCaig and Soki Rhee-Duverne

Discovery, Innovation and Science in the Historic Environment

Research Report Series no. 6/2022

Research Report Series 6/2022

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ISSN 2059-4453 (Online)

SUMMARY
This report presents the findings of a project carried out to investigate the behaviour of heat, moisture and air in domestic pitched 'cold roofs' under the influence of internal and external environmental loads. The aim of the project was to better understand the factors affecting the risk of condensation and moisture accumulation, the influence of roofing underlays and air and vapour control layers (AVCLs) on roof environments, and the role of ventilation in managing the risk of condensation.

The four buildings selected for this study represent a range of typical domestic roofs. Two had undergone recent energy saving renovations, including the introduction of AVCLs at ceiling level, cellulose insulation (hygroscopic) and vapour-permeable roofing underlays. A third roof had no AVCL at ceiling level, glass fibre insulation (non-hygroscopic) – which was increased in thickness during the monitoring period – and no roofing underlay. The fourth roof had no AVCL at ceiling level, glass fibre insulation and impermeable BS 747 Type 1F roofing underlay.

The four roofs were monitored continuously over four years. Sensors were installed to provide an upward profile of air temperature and relative humidity from the room below the roof space to the roof covering. This included sensors below and above the insulation in the roof space, at high level and between the roof covering and the roofing underlay (where one existed). Surface temperatures on the underside of roof coverings were also recorded, as were air velocities at low and high levels within the roof space. In one roof, the moisture content of timber was recorded, too. Weather stations were used to monitor exterior conditions.

Due to the large amount of data obtained, the analysis presented in this report is limited to comparing the roof environments during winter (January/February) and summer (July/August). The data demonstrated a seasonal consistency in the environments in each of the roofs over the monitoring period. In winter, the relative humidity in the roofs was high and all the roofs were liable to moisture absorption in porous materials and condensation on impermeable surfaces to varying degrees. Condensation was generally a transitory event, with moisture evaporating and rejoining gases in the air as the roof environment warmed as the day progressed. Daily evaporation of absorbed moisture and surface condensation requires a decreasing vapour pressure gradient away from the surface. If the relative humidity within the roof space remains high, there is little, if any, gradient and the rate of evaporation declines. During prolonged periods of very cold weather, the moisture content of porous materials increases and condensate on impermeable surfaces accumulates until it forms droplets. In some buildings, where moist air from the building enters the attic and/or there is restricted air exchange between the attic and the exterior, this phenomenon might be exacerbated by adding insulation. This appeared to be the case in Building 4 'Long Compton'.

In Building 3, the thickness of insulation was increased from 100mm to 300mm partway through the monitoring period. The lack of a roofing underlay allowed air exchange through the plain tile roof coverings, which enabled the roof environment to equilibrate readily with the exterior. The additional insulation had little effect in

reducing air temperature within the roof space and we could not demonstrate that it exacerbated condensation.

Differences between the insulation systems did not appear to have any significant effect on the potential for condensation. The environment between the tiles and vapour-permeable roofing underlay in Building 1 showed the greatest temperature variation and tendency towards dew point during the day, caused largely by solar gain. However, there was no evidence of dampness and the attic space remained dry. It is probable that condensate was absorbed by the roof tiles. AVCLs and hygroscopic insulation materials appear useful in controlling and buffering moisture entering the attic from the building. Most of the buffered moisture is released back into the air in the roof space as the roof covering warms. In winter, the relative humidity of roof spaces is generally so high that only a small drop in temperature results in increased equilibrium moisture contents and condensation. To avoid accumulation, moisture must be able to escape by diffusion through vapour-permeable roofing underlays or air exchange to the exterior environment, where vapour pressures are generally lower.

CONTRIBUTORS

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ACKNOWLEDGEMENTS
The support of the following is gratefully acknowledged in producing this report:
The owners of the properties investigated during this research programme
Bill Bordass

ARCHIVE LOCATION
Historic England Archive
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DATE OF RESEARCH
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FOREWORD

The UK has the oldest housing stock in Europe. In England, about 20% of homes – nearly 5 million – were built before 1919. Some 2 million of these are in conservation areas, and at least 320,000 are listed buildings. For the most part, these older buildings have survived because they are durable, maintainable and adaptable, and they have an essential role to play in fighting climate change. Continuing to adapt, upgrade, repair and maintain them so they go on being useful and viable makes good social, economic and environmental sense. However, unsuitable improvements may not deliver the energy savings and carbon reductions predicted, and may harm the building and the health and well-being of its occupants.

The project described in this report is part of an ongoing programme of research investigating the effects of retrofit measures on the performance of building elements of traditional construction, particularly the risk of moisture accumulation in building fabric. The aim of this research is to contribute to an evidence base that will enable better-informed decisions to be made about improving the energy and carbon performance of buildings of traditional construction.

1. INTRODUCTION

The requirement to improve the thermal resistance of roofs to save energy has introduced a range of different insulating materials and associated air and vapour control layers (AVCLs). These may be used on an ad hoc basis according to availability and the designer's judgement, or as a system recommended by a manufacturer. However, while their ability to reduce heat loss is predictable, the consequences for the roof environment are less clear. It is not unusual now to hear that an extra layer of insulation added above ceiling joists in a cold roof resulted in condensation within a roof that was previously dry (*see* 5.0 Building 4 'Long Compton').

Historic England set out to investigate these environmental consequences by posing and testing the null hypothesis that 'condensation is likely to form on the underside of the roof covering in a cold roof, whatever the type and thickness of thermal insulation'. This condensate may be visible or it may be absorbed into porous construction materials.

This hypothesis was investigated by monitoring the roof environments in four dwellings with a low level of occupancy (generally two persons) between 2015 and 2019.

Two roofs had undergone major renovations; two had piecemeal changes. All were pitched cold roofs with insulation at ceiling joist level. Two had hygroscopic cellulose insulation and two had the more familiar glass fibre. Two had AVCLs beneath the insulation (one vapour permeable, one impermeable) and two did not. Two had vapour-permeable underlays, one had a bituminous BS 747 Type 1F underlay and one had no underlay. In addition, monitoring at Building 1 was carried out both before and after occupancy, thereby allowing the consequences of domestic activity to be investigated. At Building 3, the thickness of insulation was increased from 100mm to 300mm partway through the monitoring period, which allowed the influence of this change to be observed.

The choice of buildings for comparative monitoring is never likely to be ideal because building availability is limited, construction is variable and local environmental conditions may not be comparable. Nevertheless, the four buildings monitored represent a useful range of typical domestic roofs from which to glean basic data.

Monitoring four buildings for four years yielded a vast quantity of data. Therefore, the analysis in this report has been limited to comparing data from January/February (winter environment) and July/August (summer environment).

Sensors were installed to provide an upward profile of air temperature and relative humidity from the room below the roof space to the roof covering. This included sensors in the roof space below and above the insulation, at high level and between the roof covering and the roofing underlay (where one existed). The surface temperature on the underside of the roof covering was also recorded and a weather station was used to monitor exterior conditions.

1.1 Equipment

Surface temperature, air temperature and relative humidity were recorded with Eltek GD10 transmitters and Eltek RX250AL receivers.

Air velocity was measured with E + E Elektronik E660 sensors connected to a GS41AV Eltek transmitter.

Meteorological data were recorded at each building using a Vaisala WXT536 weather station connected to an Eltek TMET transmitter.

2.0 BUILDING 1 'ADDISON' (HAMPSHIRE)

2.1 Roof construction

The roof at Building 1 was constructed using plain tiles on softwood battens, with Tyvek Enercor underlay directly beneath. (This is described by the manufacturer as a vapour-permeable membrane with a metallised surface to control heat gain and loss.) The roof construction below the membrane is of softwood, and unventilated. Blown cellulose insulation and an AVCL – Tyvek AirGuard – are incorporated in the attic floor construction. The general construction is shown in Figure 1; the attic floor construction is shown in Figure 2.

Fig 1: Building 1 'Addison' attic interior

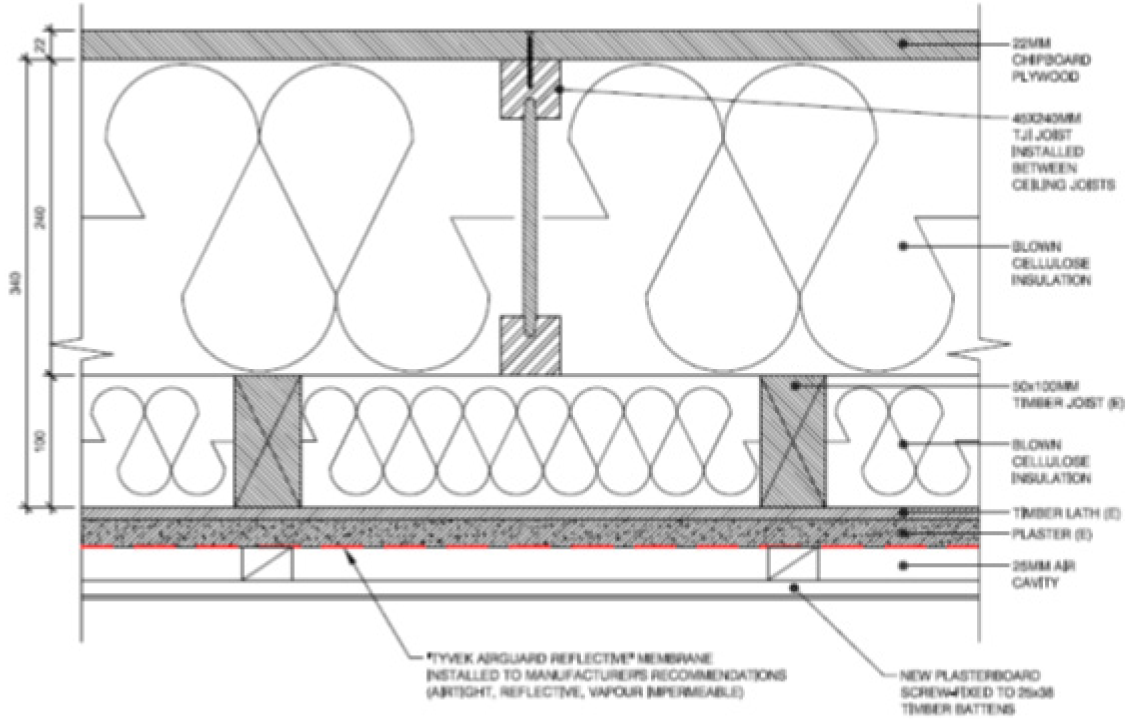


Fig 2: Attic floor construction (copyright Arboreal Architecture)

2.2 Sensor type and location

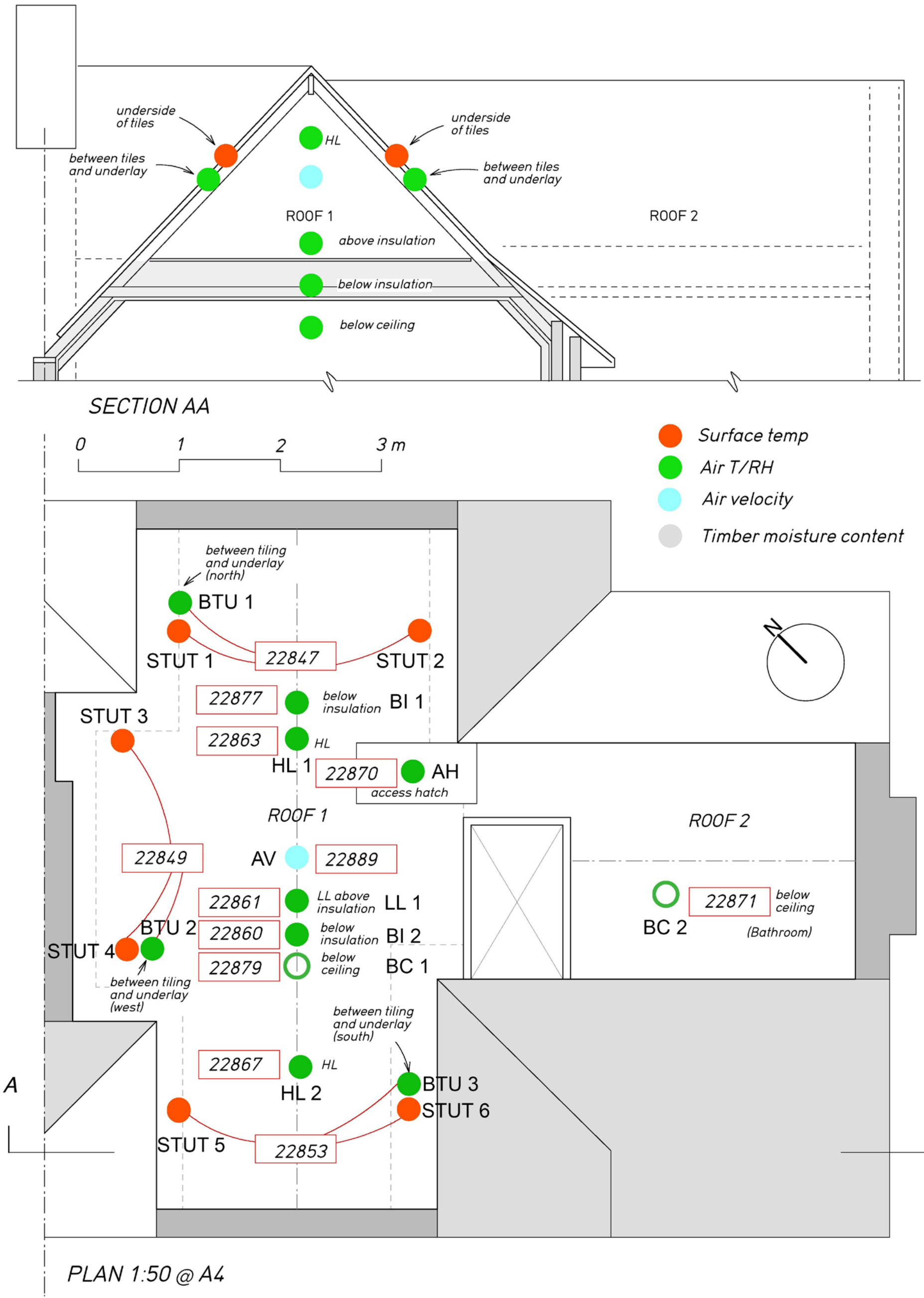


Fig 3: Sensor types and locations

Key to Figure 3
BTU = between tiles and underlay temperature (T)/relative humidity (RH)
STUT = surface temperature under tiles
HL = high level temperature/relative humidity
LL = low level temperature/relative humidity
BI = below insulation temperature/relative humidity
BC = below ceiling temperature/relative humidity
AV = air velocity
AH = access hatch

2.3 Data analysis: Winter (January/February 2016–2019)

The building had been renovated and was unoccupied until 11 January 2016. The air velocity sensors did not record any air movement in the roof space at any time during the monitoring period.

2.3.1 Roof slope orientation and sensor position

Temperature (T) and relative humidity (RH) statistics for the months of January and February over four consecutive years are shown in Tables 1 to 3.

Table 1: January/February air temperature (°C) and relative humidity (%) comparisons between tiles and underlay (BTU, see *Fig 2) for 2016 to 2019*

		2016 Jan/Feb	2017 Jan/Feb	2018 Jan/Feb	2019 Jan/Feb
BTU1 T (North)	Maximum	15.9	16	13	17.5
	Minimum	-4.5	-3.8	-1.5	-4.4
	Median	5.8	6.0	5.9	6.2
	IQR	5.2	6.1	4.4	5.4
BTU2 T (West)	Maximum	25.9	23	19.1	29.6
	Minimum	-3.8	-2.9	-0.8	-3.6
	Median	7.0	7.2	7.1	7.4
	IQR	5.6	5.8	4.8	5.2
BTU3 T (South)	Maximum	22.1	19.8	No data	No data
	Minimum	-5.2	-4.4	No data	No data
	Median	6.6	6.6	No data	No data
	IQR	6.1	6.4	No data	No data
BTU1 RH (North)	Maximum	100	99.1	99.2	98.6
	Minimum	77.1	72.9	85.5	84.0
	Median	97.6	97.7	96.3	95.7
	IQR	2.2	1.7	1.8	2.6
BTU2 RH (West)	Maximum	98.4	97	97.0	96.3
	Minimum	61.8	67.5	67.3	44.2
	Median	91.9	91.8	90.6	89.1
	IQR	5.5	3.5	3.8	4.7
BTU3 RH (South)	Maximum	99.2	98.2	No data	No data
	Minimum	66.9	70.4	No data	No data
	Median	94.2	94.3	No data	No data
	IQR	5.3	2.8	No data	No data

The south and west roof slopes become warmer and, therefore, less humid underneath than the north slope. Humidity variation (interquartile range [IQR]) under the north slope is lower than the other orientations. Median values for each sensor remain rather consistent for each of the four years, although maximum and minimum temperatures are more variable. Relative humidities are very high and approach 100%.

These conclusions are illustrated with box plots in Figures 4 and 5 using the data from 2016.

Box and whisker plots

The box itself is the interquartile range, which contains the central 50% of the ordered data values and is crossed by the median line. The 'whisker' lines from the box are the data values that are not in the central 50% range, but exclude more extreme values (outliers). The maximum of these included values is the short crossbar that terminates the top whisker and the minimum included value is the bottom crossbar. Outliers are presented as dots outside of the whiskers.

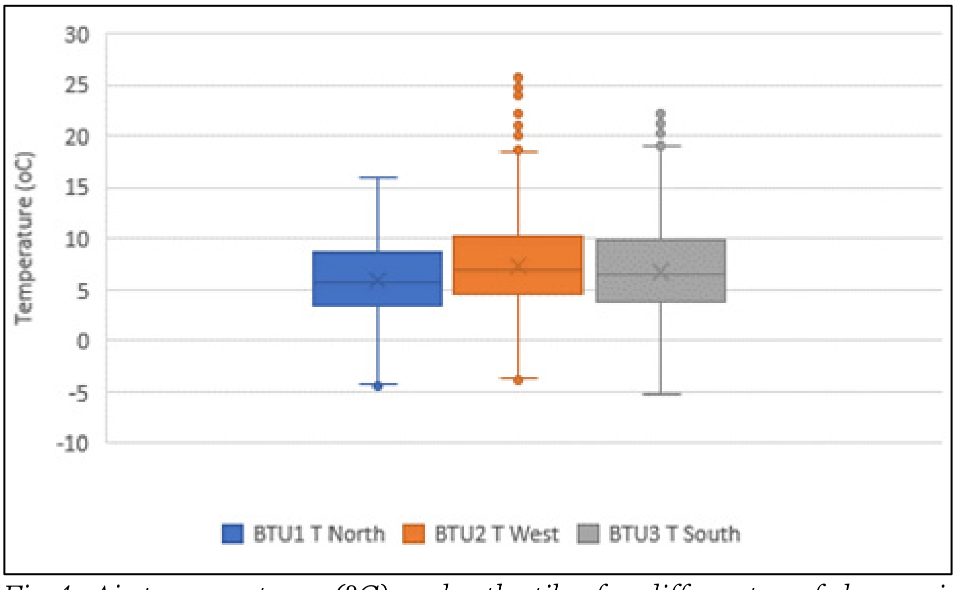


Fig 4: Air temperatures (°C) under the tiles for different roof slope orientations. The upper outliers (dots) are solar gain

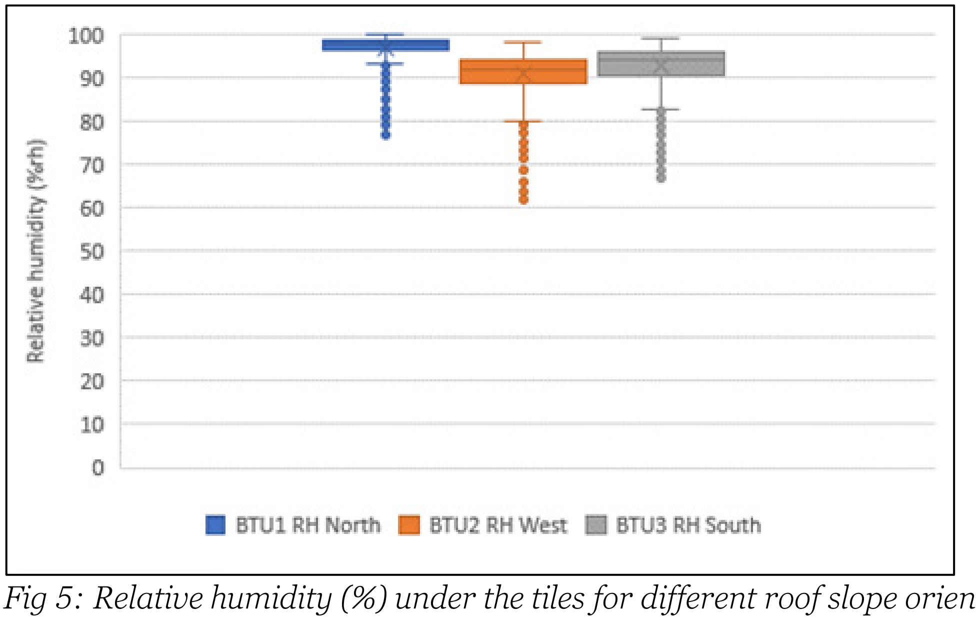


Fig 5: Relative humidity (%) under the tiles for different roof slope orientations. The humidity under the north slope is the highest and least variable

Table 2: January/February air temperature (°C) and relative humidity (%) comparisons between high level (HL) and low level (LL) for 2016 to 2019

		2016 Jan/Feb	2017 Jan/Feb	2018 Jan/Feb	2019 Jan/Feb
HL1 T	Maximum	14.4	15	12.5	16.4
	Minimum	-1.7	-0.8	1.3	-1.2
	Median	6.8	6.9	6.9	7.6
	IQR	4.1	5.2	3.5	4.3
HL2 T	Maximum	15.2	15.3	12.6	17
	Minimum	-1.5	-0.5	1.5	-1
	Median	7.0	7.1	7.2	7.7
	IQR	4.2	5.2	3.5	4.3
LL1 T	Maximum	12.1	13.9	11.6	13.7
	Minimum	-1.6	-0.8	1.4	-0.9
	Median	6.4	6.6	6.6	7.3
	IQR	3.9	5.3	3.2	4.3
HL1 RH	Maximum	96.5	95.9	95.4	95.1
	Minimum	85.5	85.4	86.2	81.7
	Median	92.5	91.2	90.4	89.3
	IQR	2.2	1.5	1.7	2.3
HL2 RH	Maximum	97.5	96.2	95.8	95.8
	Minimum	83.9	82.3	85	77.4
	Median	92.0	90.8	89.9	88.7
	IQR	2.7	1.7	2.0	2.4
LL1 RH	Maximum	95.4	94.2	94.6	93.3
	Minimum	86.1	82.5	85.3	84.4
	Median	91.6	90.9	90.0	88.9
	IQR	2.5	2.1	2.4	2.6

The high-level sensors are both along the mid-line of the roof and there is very little difference between their medians and their interquartile ranges. The low level sensor provides consistently lower median temperatures. However, the difference between high level and low level results is very small and does not have any practical significance. Medians are rather consistent over the four years.

The high level medians and interquartile ranges are compared with the exterior values in Table 3 and Figures 6 and 7.

Table 3: January/February air temperature (°C) and relative humidity (%) comparisons between high level (HL) and exterior (Ext) for 2016 to 2019

		2016 Jan/Feb	2017 Jan/Feb	2018 Jan/Feb	2019 Jan/Feb
HL1 T	Median	6.8	6.9	6.9	7.6
	IQR	4.1	5.2	3.5	4.3
HL2 T	Median	7.0	7.1	7.2	7.7
	IQR	4.2	5.2	3.5	4.3
Ext T	Median	6.4	6.3	6.2	6.2
	IQR	5.6	6.4	5.0	6.9
HL1 RH	Median	92.5	91.2	90.4	89.3
	IQR	2.2	1.5	1.7	2.3
HL2 RH	Median	92.0	90.8	89.9	88.7
	IQR	2.7	1.7	2.0	2.4
Ext RH	Median	83.0	86.0	80.0	83.0
	IQR	18	11.2	16.0	14.0

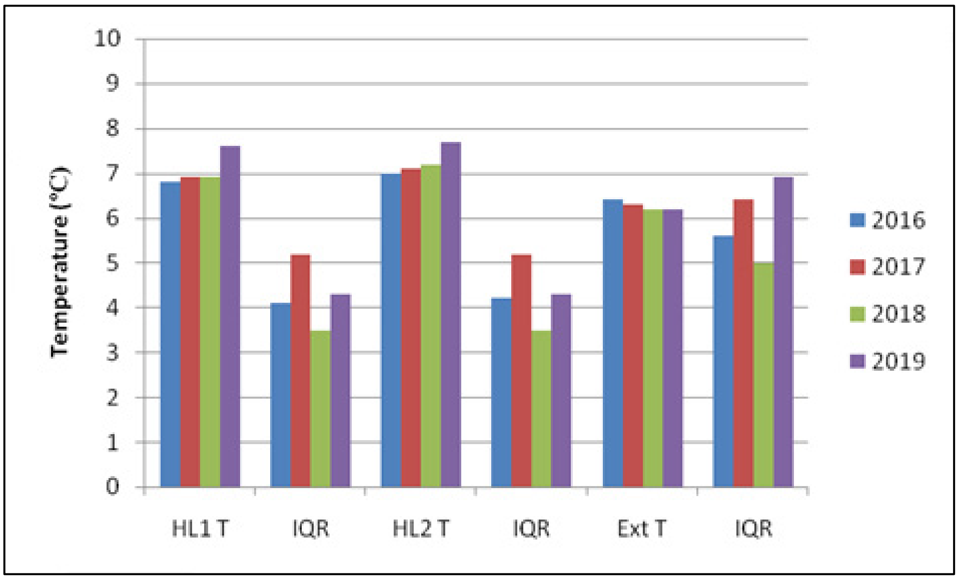


Fig 6: A comparison between high level (HL) and exterior (Ext) median temperatures (°C) and their interquartile ranges (IQR) for January/February 2016 to 2019

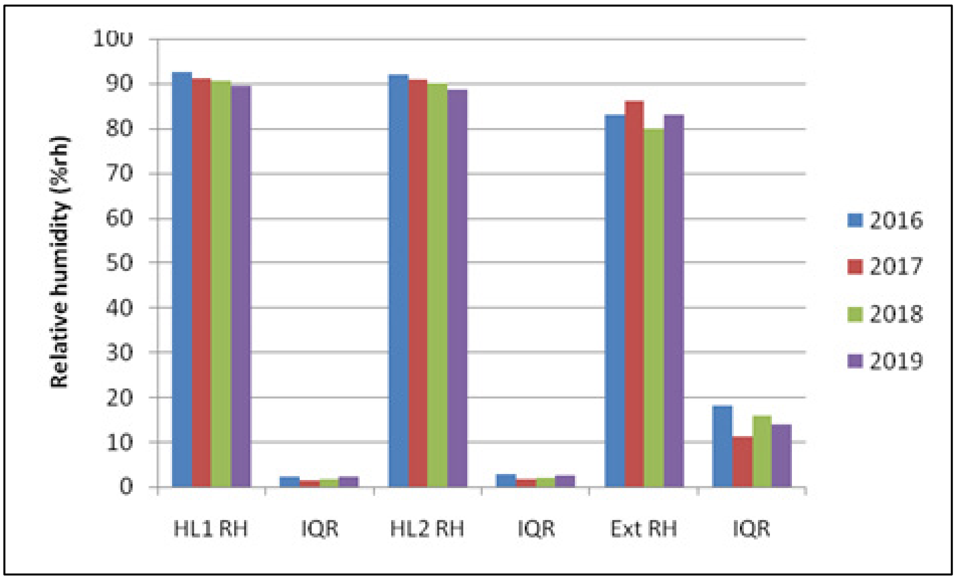


Fig 7: A comparison between high level (HL) and exterior (Ext) median relative humidities (%) and their interquartile ranges (IQR) for January/February 2016 to 2019

Median January/February temperatures within the roof vary by less than 1°C over the four years and remain consistently higher than exterior temperatures. Relative humidities at high level are high each year with a low interquartile range.

2.3.2 Roof covering temperature and condensation

The data have indicated that the air beneath the tiles is warmer on the south and west sides than it is on the sheltered north side. However, the comparative risk of condensation for each orientation depends on the surface temperature on the underside of the tiles. Statistics are provided in Table 4.

Table 4: January/February surface temperature (°C) under tiles (STUT) for 2016 to 2019

		2016 Jan/Feb	2017 Jan/Feb	2018 Jan/Feb	2019 Jan/Feb
STUT1 (North)	Maximum	16.9	16.2	12.9	18.6
	Minimum	-6.8	-6.1	-3.6	-6.7
	Median	5.0	5.1	4.8	5.2
	IQR	6.1	6.8	5.2	6.3
STUT2 (East)	Maximum	23.1	21.9	23.7	28.8
	Minimum	-6.5	-5.6	-3.4	-6.2
	Median	5.9	6.0	5.8	6.1
	IQR	6.5	6.7	5.5	6.1
STUT3 (NW)	Maximum	30.3	26.7	21.8	34.6
	Minimum	-6	-5.1	-3	-5.9
	Median	6.3	6.4	6.1	6.4
	IQR	6.5	6.6	5.5	6.1
STUT4 (West)	Maximum	13	15.6	12.8	13.9
	Minimum	-6.2	-5.2	-3	-6.2
	Median	5.1	5.4	5.1	5.5
	IQR	5.6	6.6	4.8	5.9
STUT5 (SW)	Maximum	26.4	22.5	No data	No data
	Minimum	-6.8	-6.1	No data	No data
	Median	6.3	6.3	No data	No data
	IQR	7.0	7.0	No data	No data
STUT6 (South)	Maximum	18.9	16.8	No data	No data
	Minimum	-6.2	-5.2	No data	No data
	Median	5.4	5.5	No data	No data
	IQR	6.2	6.7	No data	No data

Median values and interquartile ranges are fairly consistent for each year, but maximum and minimum temperatures are more variable. Data for 2016 are plotted in Figure 8, where it can be seen that the outliers, which are indicators of solar gain, are not sensibly ranked according to roof surface orientation. For example, data from the north-west (3) and the south-west (5) are more variable than from the west (4). The ranking is, however, consistent for each year (where there is data) and must be influenced by the local positioning of the sensors. Heating of the roof covering in each slope orientation is evidently not uniform in winter.

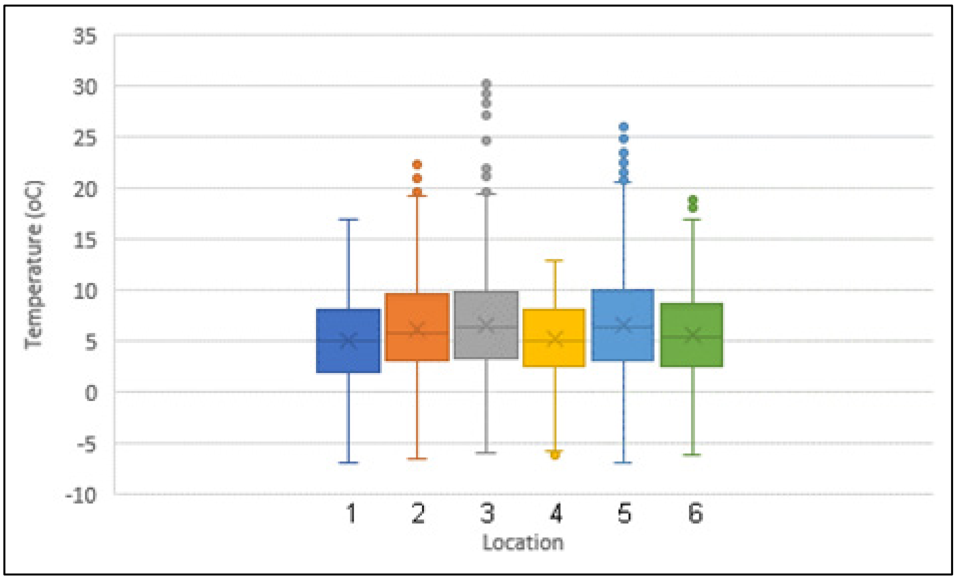


Fig 8: A comparison of minimum temperatures (°C), interquartile ranges, medians and outliers for January/February 2016 on the undersides of the tiles

Key to Figure 8
1 = north
2 = east
3 = north-west
4 = west
5 = south-west
6 = south

The minimum results in Table 4 demonstrate that condensation beneath the tiles is likely. The bottom bars (minimum temperatures) on the whiskers in Figure 8 show that minimum temperatures are similar for each box, but north is slightly lower.

The effect that location has on this risk can be demonstrated by subtracting the calculated dew points obtained from BTU1 T, BTU2 T and BTU3 T (see Fig 4) from the surface temperatures (STUT1, STUT4 and STUT6). Condensation could occur if the resulting temperatures dip below zero. This is shown by a red line in Figures 9 to 11.

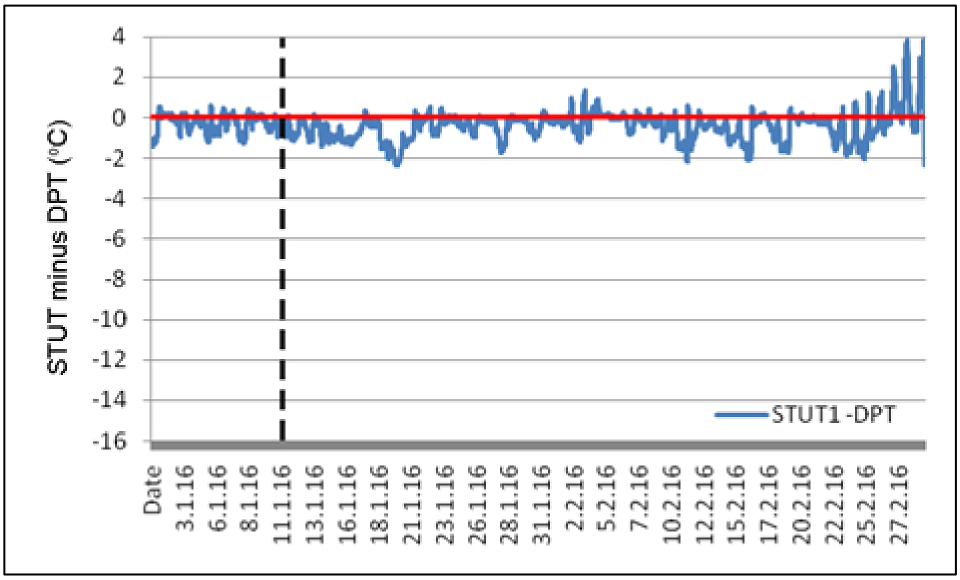


Fig 9: Condensation risk (under red line) in north corner of roof January/February 2016 obtained by subtracting dew point temperature (DPT) from surface temperatures under tiles (STUT). The dotted line is the date occupancy commenced

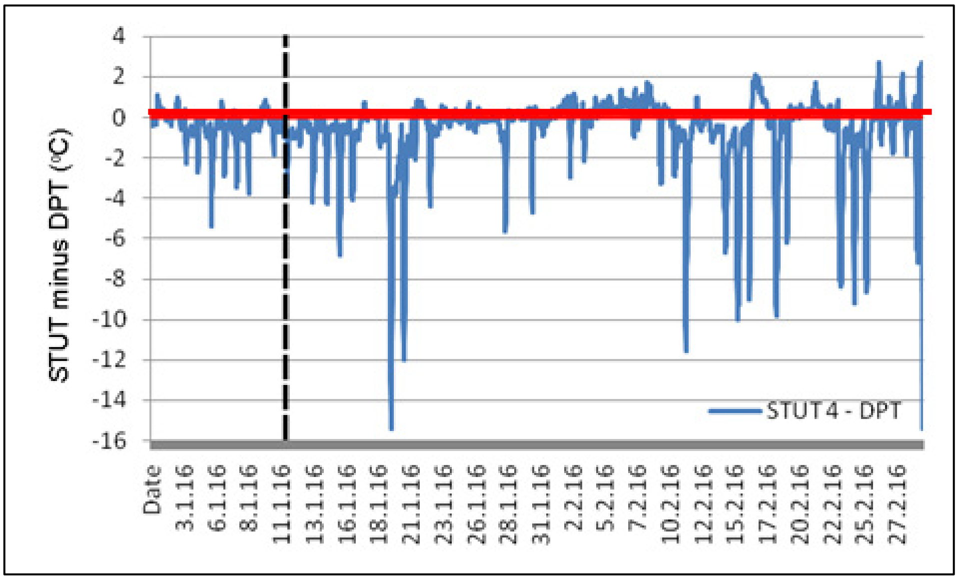


Fig 10: Condensation risk (under red line) in west corner of roof January/February 2016 obtained by subtracting dew point temperature (DPT) from surface temperatures under tiles (STUT). The dotted line is the date occupancy commenced

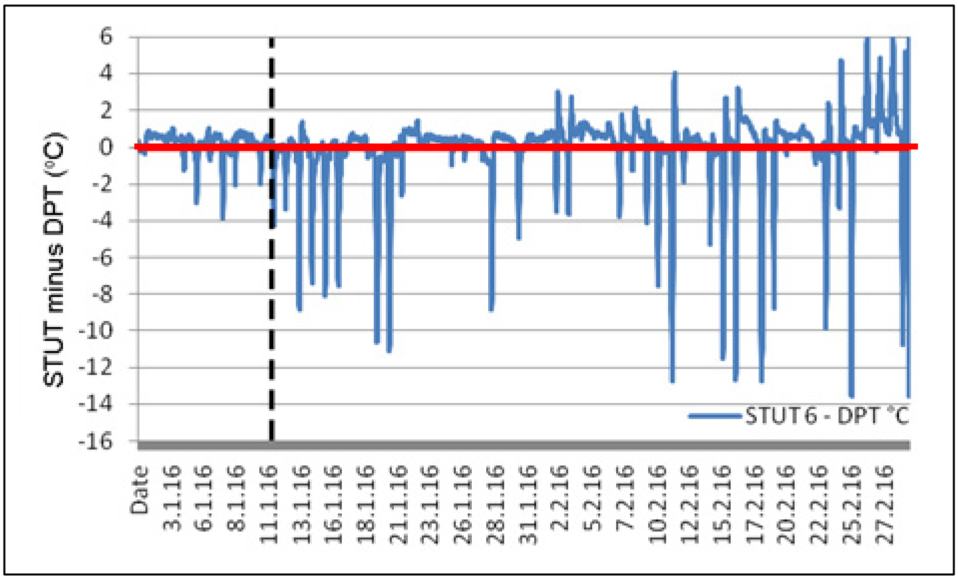


Fig 11: Condensation risk (under red line) in south corner of roof January/February 2016 obtained by subtracting dew point temperature (DPT) from surface temperatures under tiles (STUT). The dotted line is the date occupancy commenced

Results show that condensation forming on the underside of the tiles is a strong possibility throughout January and February in each of the corners, but less so on the sheltered north side.

2.3.3 When does condensation occur?

Figure 12 compares the air moisture content or absolute humidity (AH) below the tiles (obtained from BTU3) in the south corner with the exterior absolute humidity for January/February 2016.

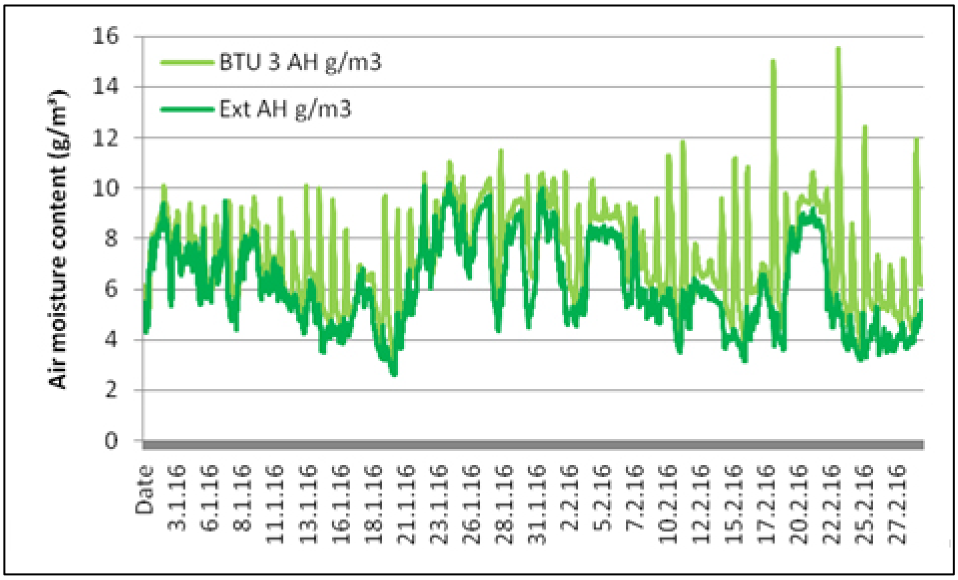


Fig 12: Air moisture content (g/m³) between tiles and underlay (BTU) compared with exterior (Ext) during January and February 2016

The basic shape of the traces is similar, but the air moisture content beneath the tiles shows regular spikes (light green trace). These spikes are also apparent if dew point temperatures are plotted (Fig 13).

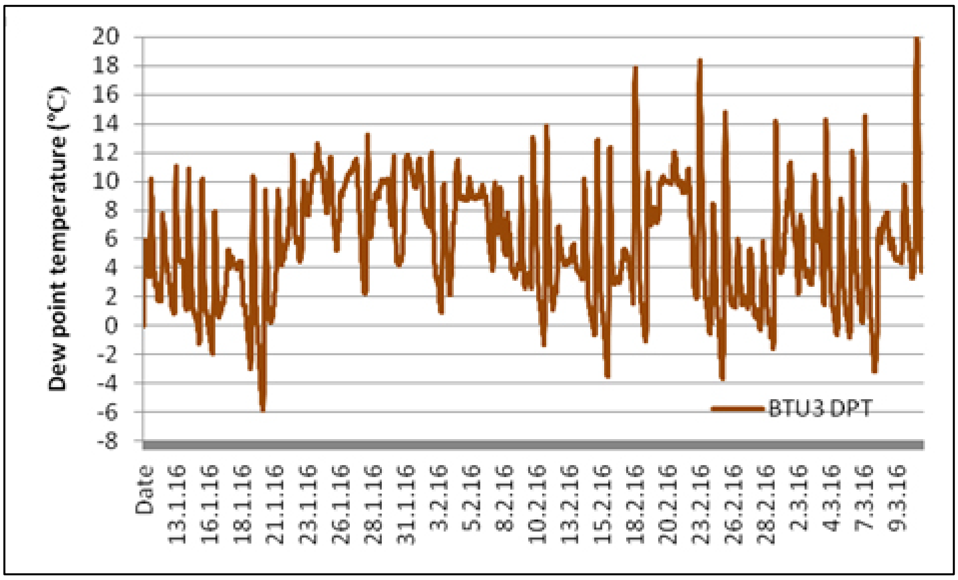


Fig 13: Dew point temperature (DPT) fluctuations recorded by BTU3 during January and February 2016

The spikes can be understood by restricting the data to a three-day period, as shown in Figure 14, and changing the x axis to time.

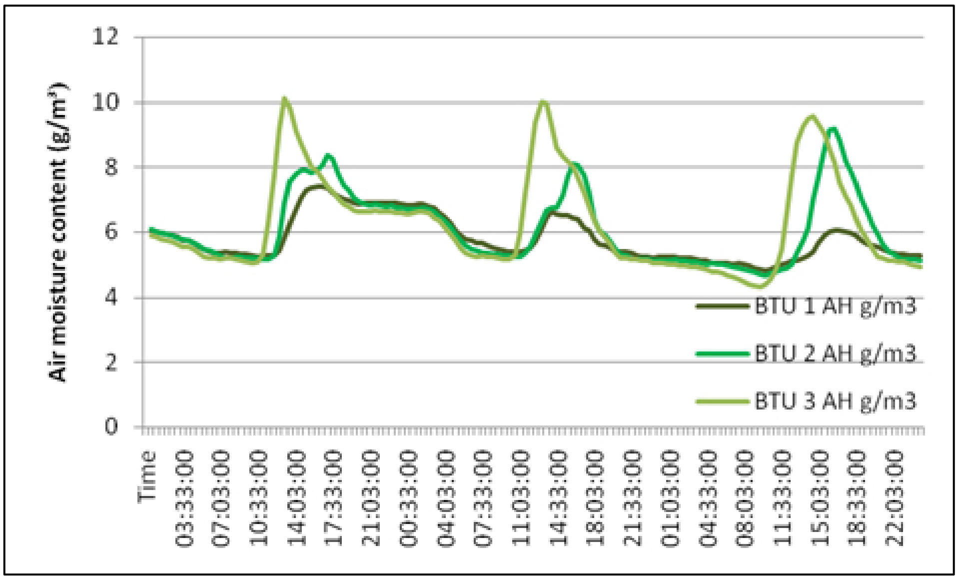


Fig 14: Afternoon spikes in air moisture content (g/m³) under tiles, from Figure 12 data

All of the spikes occur between late morning and early evening. They do not occur in the exterior data, as shown in Figure 12, and so they must either be fluctuations in air moisture content within the main roof environment or moisture recycled by daily solar gain under the roof covering. The first possibility can be investigated by plotting high level air moisture readings or dew points in the roof space with the adjacent underlay (BTU) readings (Figs 15 and 16).

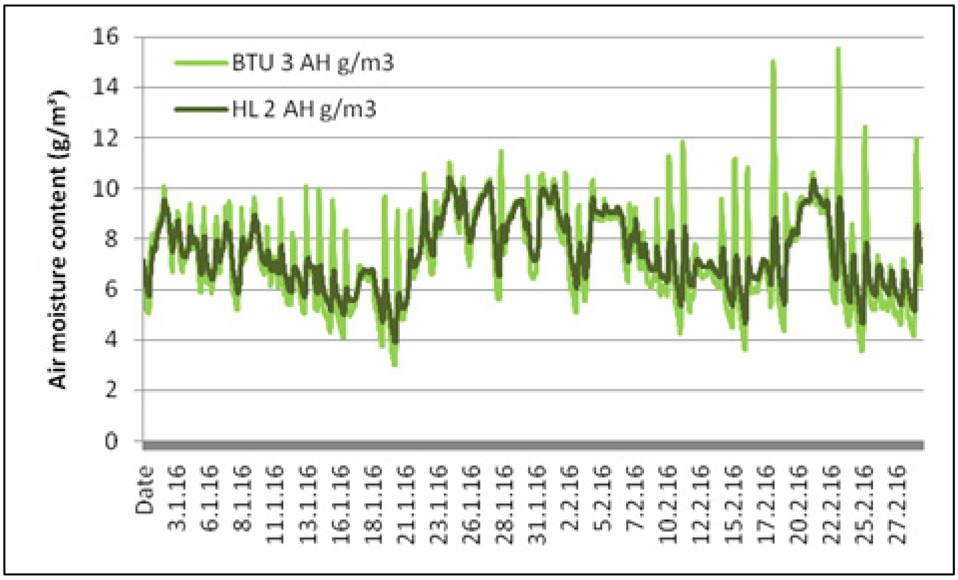


Fig 15: A comparison between air moisture content (g/m³) at high level (HL) and between tile and underlay (BTU) in the south corner during January and February 2016

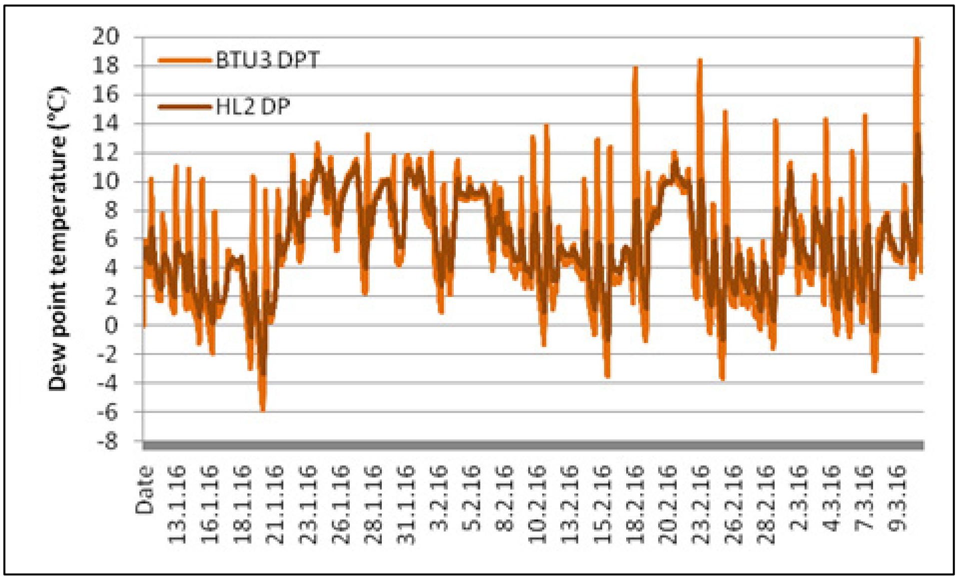


Fig 16: A comparison between dew point temperatures (°C) at high level (HL) and between tile and underlay (BTU) in the south corner during January and February 2016

Figures 15 and 16 show that the underlying shape of the traces (between HL and BTU) is similar, but that the afternoon spikes in air moisture content and dew points are most prominent in the space below the tiles. This means that the spikes are not caused by the general building environment and must be caused by solar gain.

The same effect is found at the north corner, although far more muted (Fig 17) because this is less exposed to the sun.

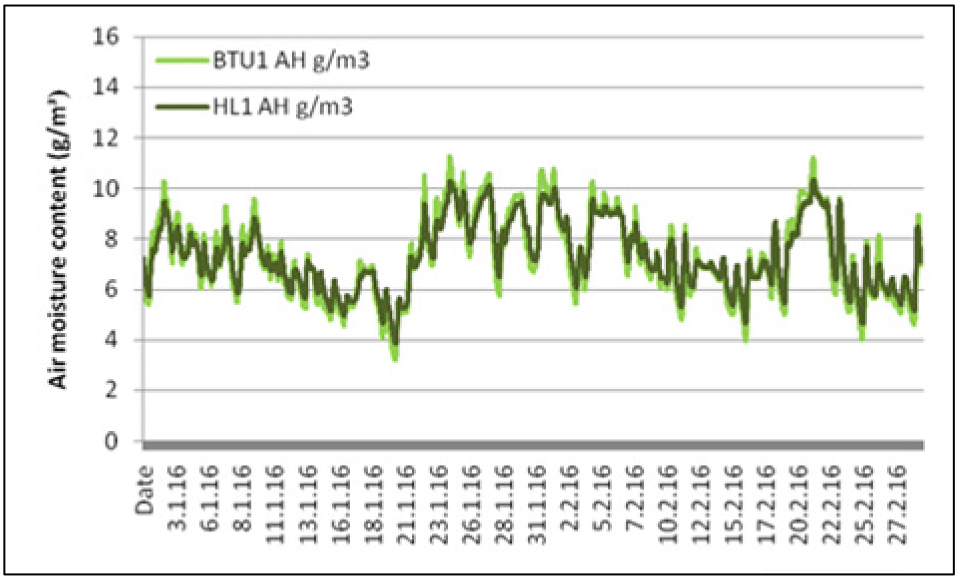


Fig 17: A comparison between air moisture content (g/m³) at high level (HL) and between tile and underlay (BTU) in the north corner during January and February 2016

Figure 18 compares temperature with irradiance, which produces solar gain.

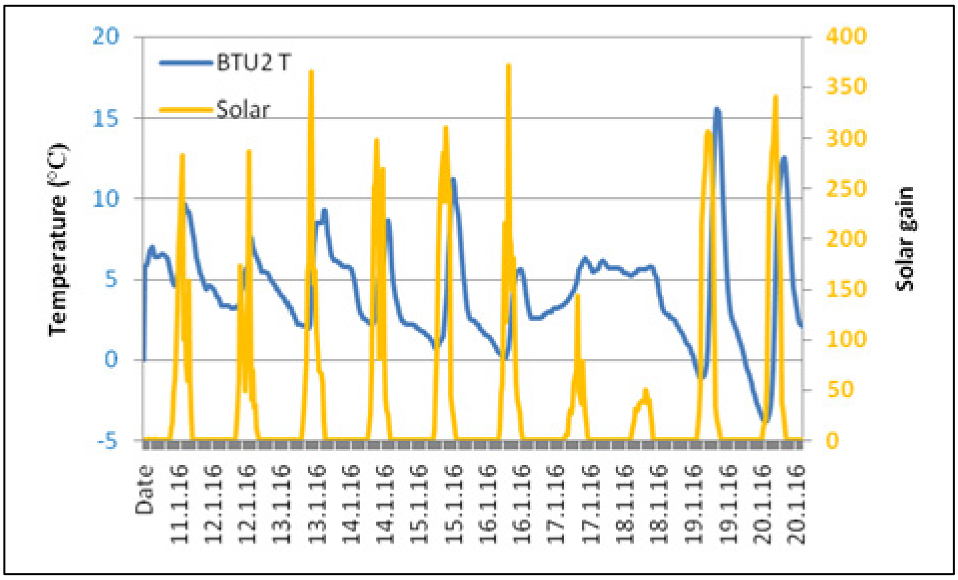


Fig 18: A comparison between afternoon temperature spikes (°C) and solar gain (irradiance W/m²) in January 2016

These spikes draw more moisture from the surrounding surfaces and structure (Fig 19), raising the relative humidity and the dew point. However, the air temperature increases faster than the temperature of the tile undersides (Fig 20) so the dew point is easily reached (Fig 21) and condensation or moisture sorption will occur.

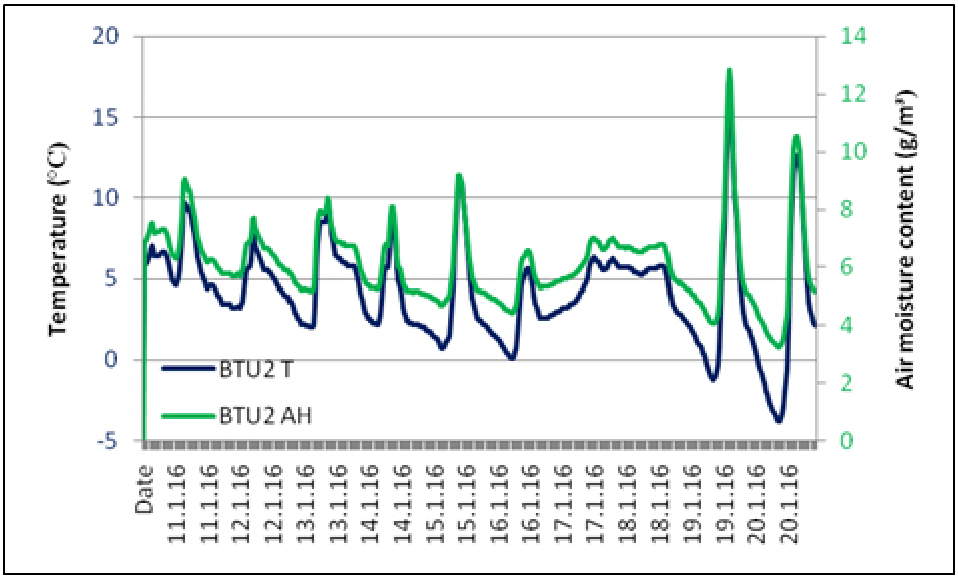


Fig 19: The afternoon spikes in temperature in January 2016 increase the air moisture content

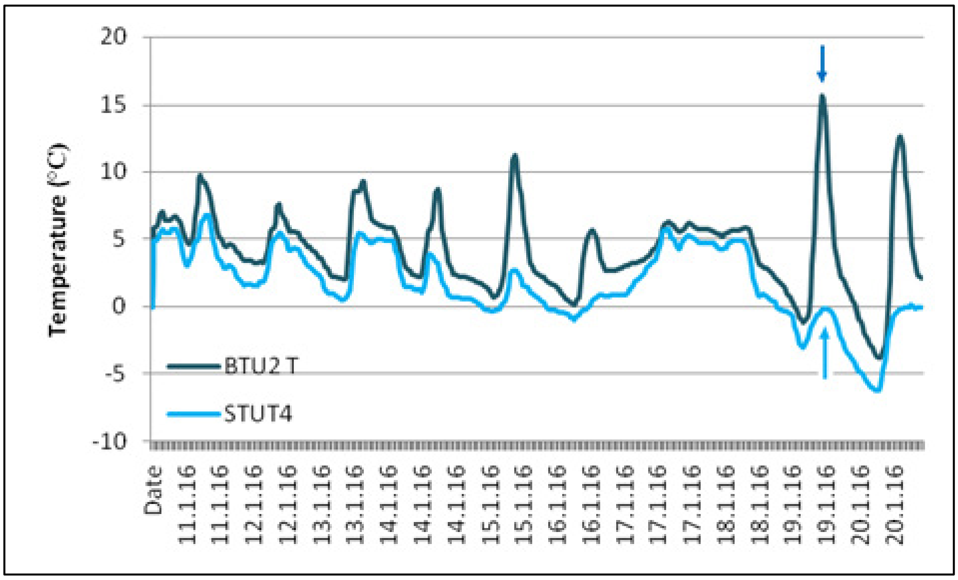


Fig 20: The arrows show that the underside (STUT = light blue trace) does not reach the same temperature as the air (BTU = dark trace)

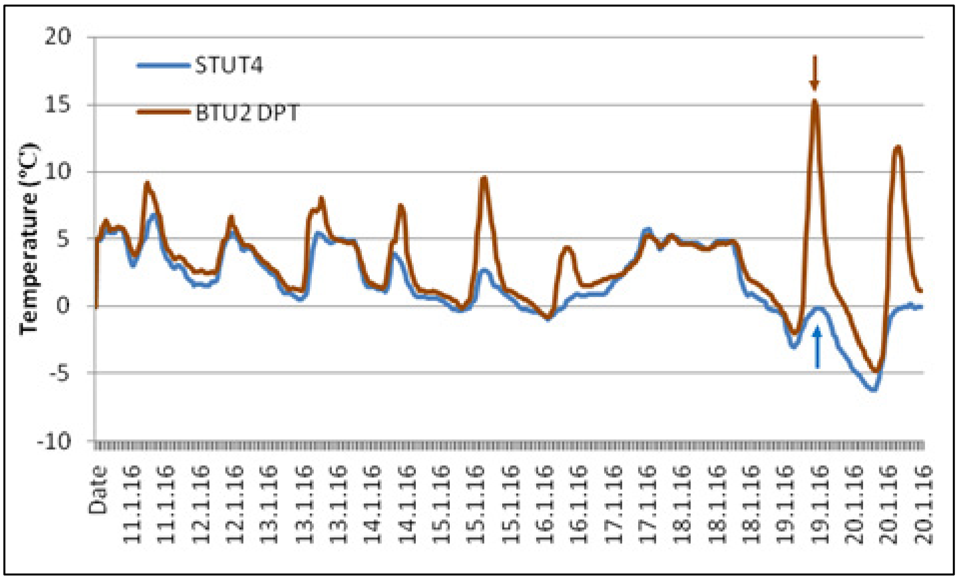


Fig 21: The afternoon spikes in temperature increase the air moisture content and, therefore, the dew point, particularly on the afternoon of 19 January 2016 (arrows)

Moisture condenses on the undersides of the tiles or is absorbed by them when the temperature dips below dew point. This seems to be a rather consistent event, so that condensation is not confined to cold night-times.

2.3.4 Occupancy and insulation

Data from BC1 show that the heating system was switched on during the afternoon of 11 January 2016. This provides a comparison between unheated and heated periods, and the event is shown by a dotted line in Figure 22 within a four-month monitoring period.

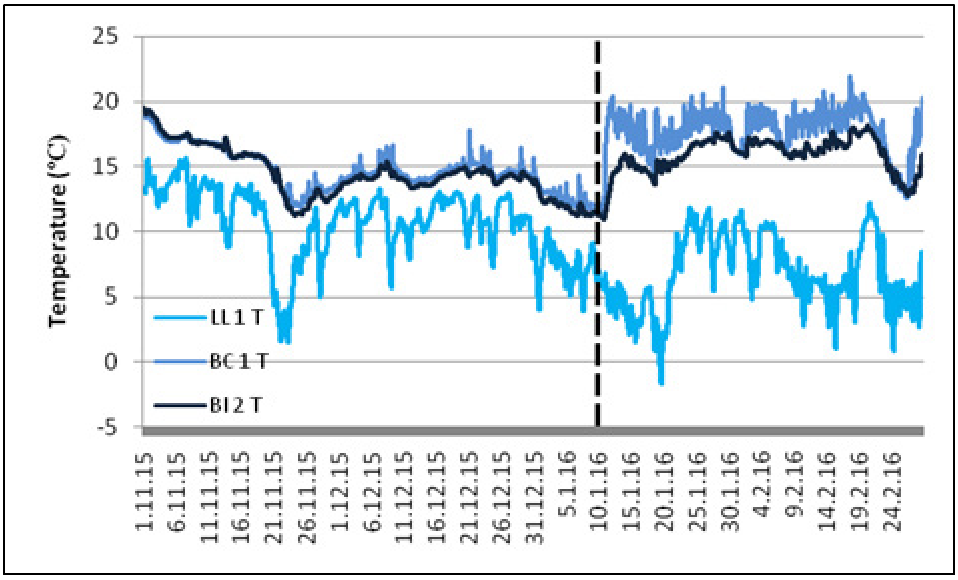


Fig 22: Occupancy (dotted line) and its effects on temperature (°C) below the ceiling (BC), below the insulation (BI) and at low level (LL) within the roof

The rapid increase in room temperature (BC1) is slowly accompanied by a rise in temperature below the insulation (BI2) but, as expected, has no effect on the temperature within the roof space above the insulation (LL1).

More information may be gleaned from box plots, and the temperature data for 11 November 2015 to 10 January 2016 (before occupancy) are shown in Figure 23. These will be compared with data from 11 January to 29 February 2016 in Figure 24.

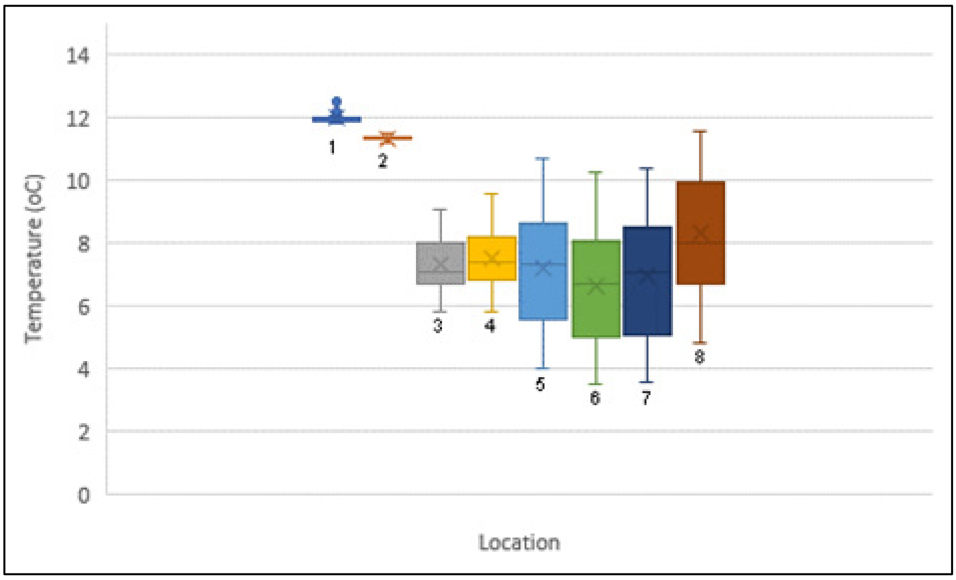


Fig 23: A comparison of median and interquartile range temperatures from the room (BC1) through the roof space to the exterior from 11 November 2015 to 10 January 2016

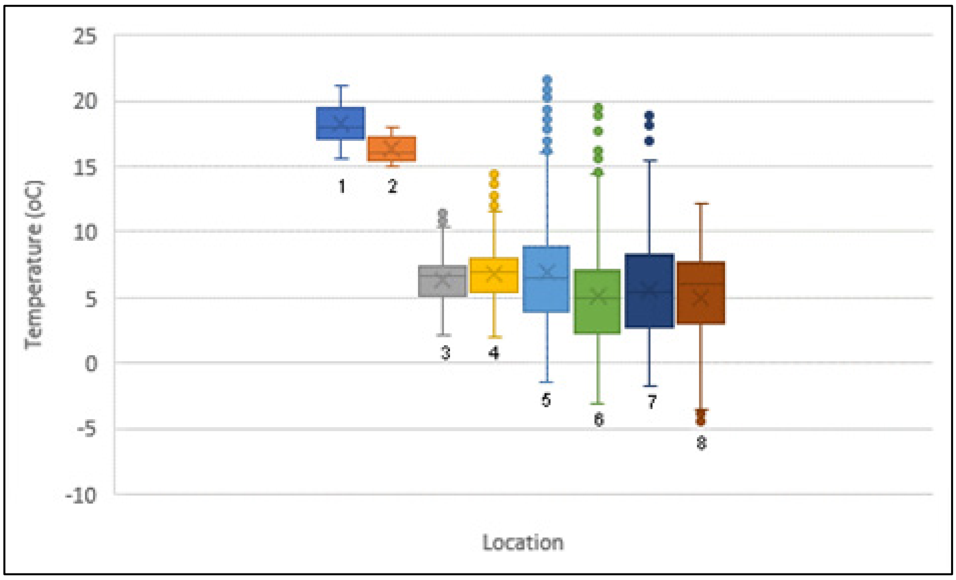


Fig 24: A comparison of median and interquartile range temperatures from the room (BC1) through the roof space to the exterior from 11 January to 29 February 2016

Key to Figures 23 and 24
1 = below ceiling (BC1)
2 = below insulation (BI2)
3 = low level (LL1)
4 = high level (HL1)
5 = between tiles and underlay (BTU3)
6 = dew point (BTU3 DPT)
7 = surface temperature under tiles (STUT6)
8 = exterior (Ext)

Boxes 1 and 2 (the interquartile ranges) in both barely overlap because of the temperature drop through the ceiling construction. The whisker lines from the boxes are short, indicating a small total range of variation, particularly before occupancy (Fig 23). These are fairly stable environments.

There is then a wide gap between boxes 2 and 3, which is the temperature drop caused by the insulation. The temperature range increases from low level (box 3) to just under the tiles (box 5) and there are progressively more outliers during January and February (Fig 24), which are caused by solar gain. The dew point interquartile range box (box 6) during both monitoring periods considerably overlaps box 5 and is mostly included within the interquartile range of tile underside temperatures (box 7), indicating a considerable likelihood of condensation.

Figure 25 illustrates the relationship between box 6 and box 7 data.

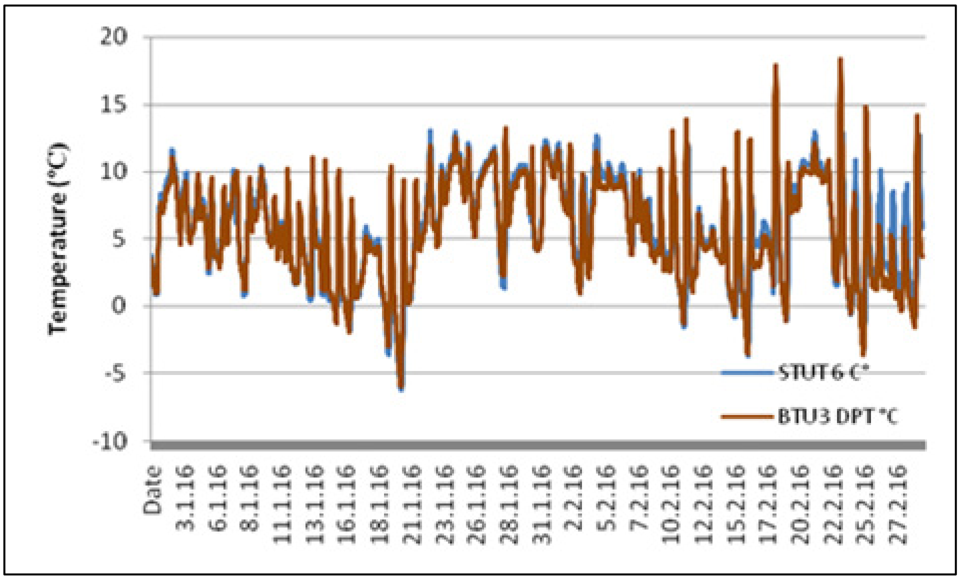


Fig 25: A comparison of dew point (BTU3 DPT) with surface temperature on the underside of the tiles (STUT6) for January/February 2016, showing that they overlap. Condensation would be a frequent event

Figures 26 and 27 compare relative humidity before and after occupancy.

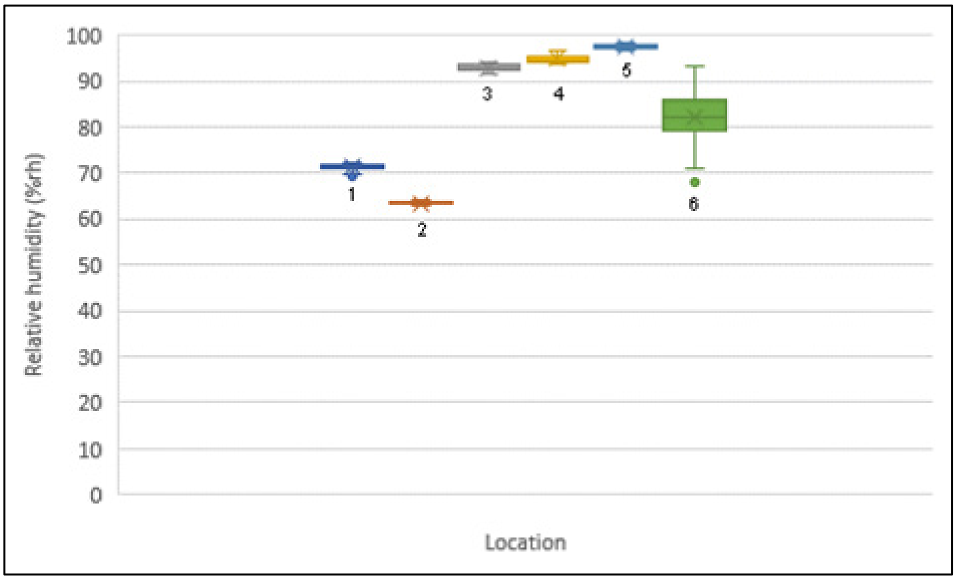


Fig 26: A comparison of median and interquartile range relative humidities (%) from the room (BC1) through the roof space to the exterior for November/December 2015

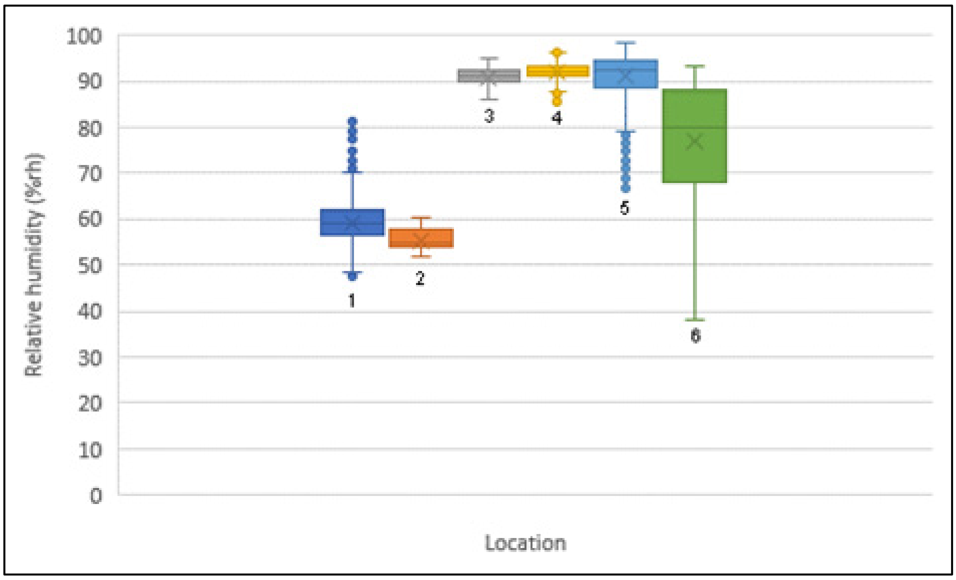


Fig 27: A comparison of median and interquartile range relative humidities (%) from the room (BC1) through the roof space to the exterior for January/February 2016

Key to Figures 26 and 27
1 = below ceiling (BC1)
2 = below insulation (BI2)
3 = low level (LL1)
4 = high level (HL1)
5 = between tiles and underlay (BTU3)
6 = exterior (Ext)

Relative humidities within the room (box 1) and between the ceiling and the insulation (box 2) are far lower than in the roof space above, both before and after occupancy. However, there are numerous upper outliers in the room data (BC1) in Figure 27, which will be caused by domestic activities. This extra moisture cannot penetrate the vapour barrier in the ceiling construction, and the relative humidity beneath the insulation (box 2) must be controlled by the heat that is transferred through the ceiling (*see* Fig 24). This will mobilise some moisture that is available within the ceiling construction and within the insulation, but the environment under the insulation remains dry and stable before and after occupancy.

The relative humidity within the roof space is high and occupancy does not make it higher. However, stability declines towards the exterior in January/February with more outliers (box 3 to box 5 in Fig 27), probably because the thermal gain through the roof covering (*see* Fig 24) lowers the relative humidity. The exterior humidity (box 6) is far more variable, but the interquartile range is below that found in the roof space during both monitoring periods. The high humidity within the roof is present before occupancy and is presumably a consequence of embodied moisture and the buffering of the roof construction. This also suggests that air exchange is limited. The variability of the room environment after occupancy compared with the stable high humidity within the roof is shown in Figure 28.

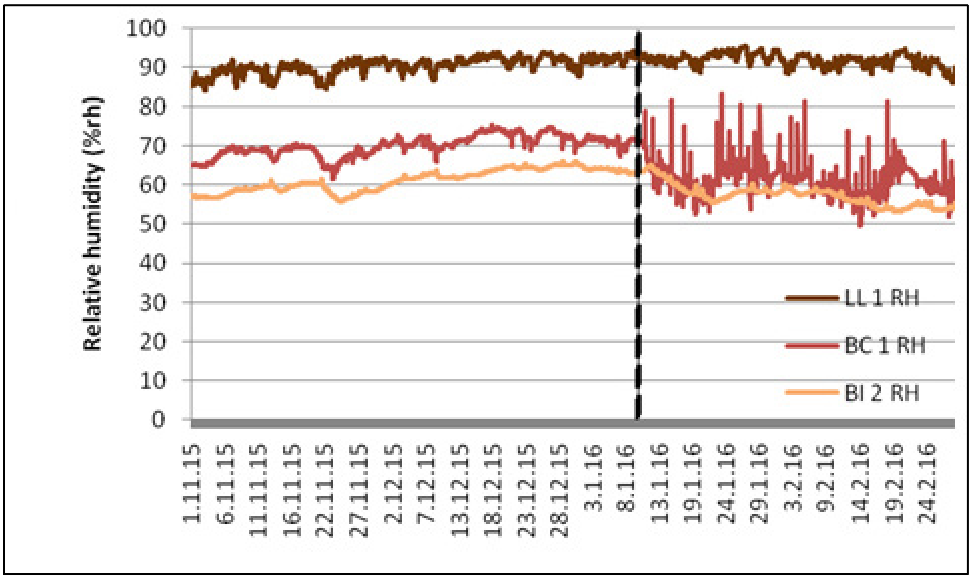


Fig 28: Occupancy (dotted line) and its effects on relative humidity (%) below the ceiling (BC), below the insulation (BI) and at low level (LL) within the roof

Figure 28 shows that the increase in temperature below the ceiling and below the insulation lowers the relative humidity in those locations, but the roof space relative humidity remains consistently high.

Figures 29 and 30 compare air moisture content before and after occupancy.

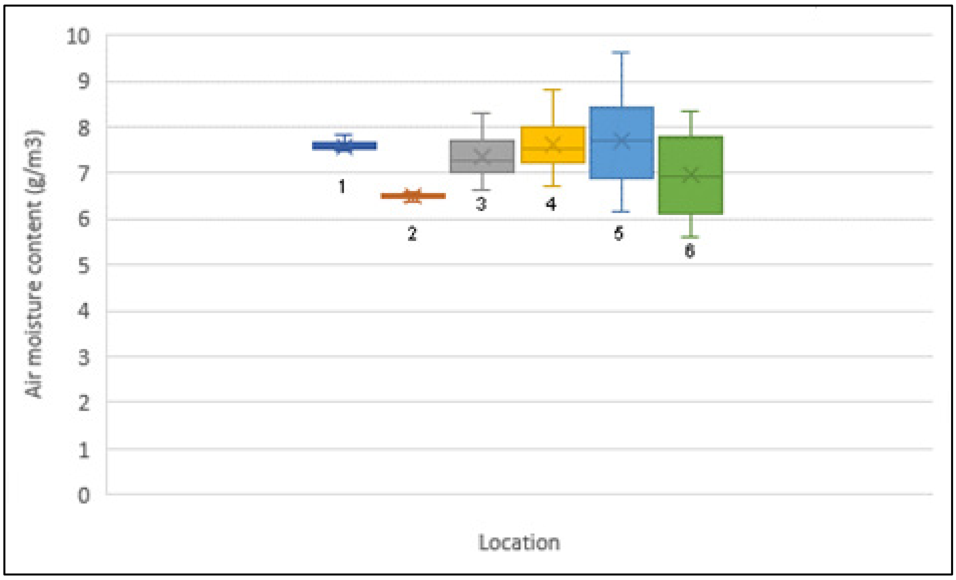


Fig 29: A comparison of median and interquartile range air moisture contents (g/m³) from the room (BC1) through the roof space to the exterior for November/December 2015

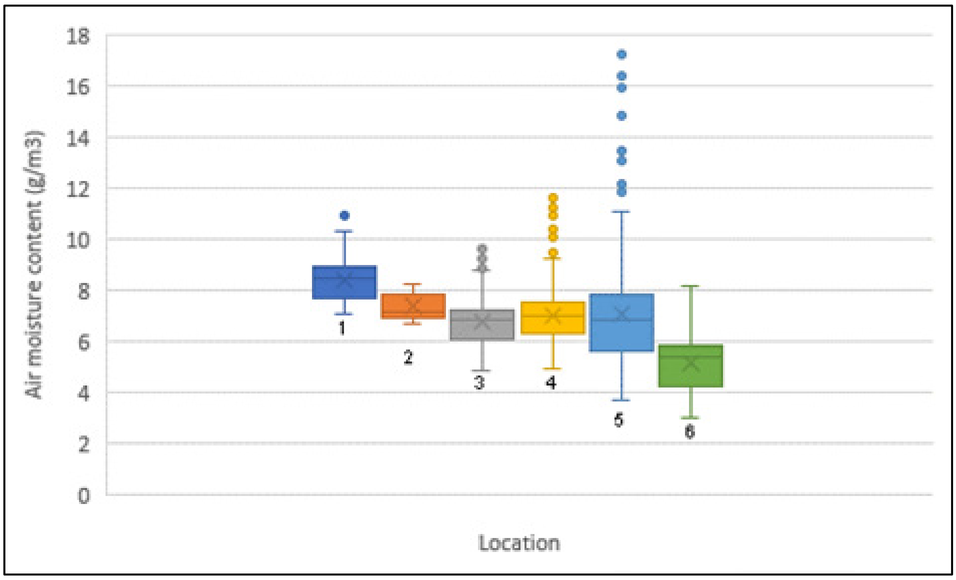


Fig 30: A comparison of median and interquartile range air moisture contents (g/m³) from the room (BC1) through the roof space to the exterior for January/February 2016

Key to Figures 29 and 30
1 = below ceiling (BC1)
2 = below insulation (BI2)
3 = low level (LL1)
4 = high level (HL1)
5 = between tiles and underlay (BTU3)
6 = exterior (Ext)

Occupancy produces a rise in air moisture content within the room and below the insulation, but has no apparent effect on air moisture content within the roof (box 3), which seems to drop. The thermal recycling of moisture is apparent from the outliers in box 5. This response of air moisture content to occupancy is shown in Figure 31.

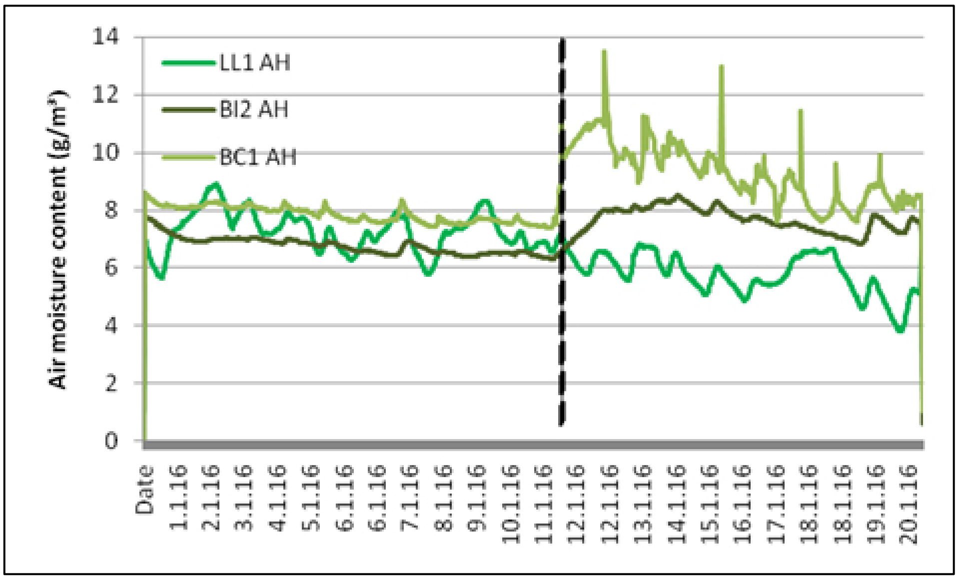


Fig 31: Occupancy (dotted line) and its effects on air moisture contents (g/m³) below the ceiling (BC), below the insulation (BI) and at low level (LL) within the roof

As shown by the box plots, a rise in air moisture content in the room is accompanied by a rise under the insulation, but has no effect on the low level absolute humidity. The attic floor construction includes an AVCL (*see* Fig 2), which should resist vapour movement from below. So, the increase in air moisture content under the insulation is likely to be caused largely by moisture drawn from the hygroscopic insulation material.

Figure 32 compares air moisture contents below the insulation, at low level within the roof space and outside of the building. The low level and exterior traces are the same shape, but the below insulation trace is different. Figure 33 shows that the below insulation trace is similar to the below ceiling trace, despite the AVCL. As noted earlier, this must be because air moisture fluctuations have a basic dependency on air temperature. The underlying response will be the same, with the level of moisture depending on the source available. Figure 24 shows that room temperature controls the above ceiling/below insulation temperature.

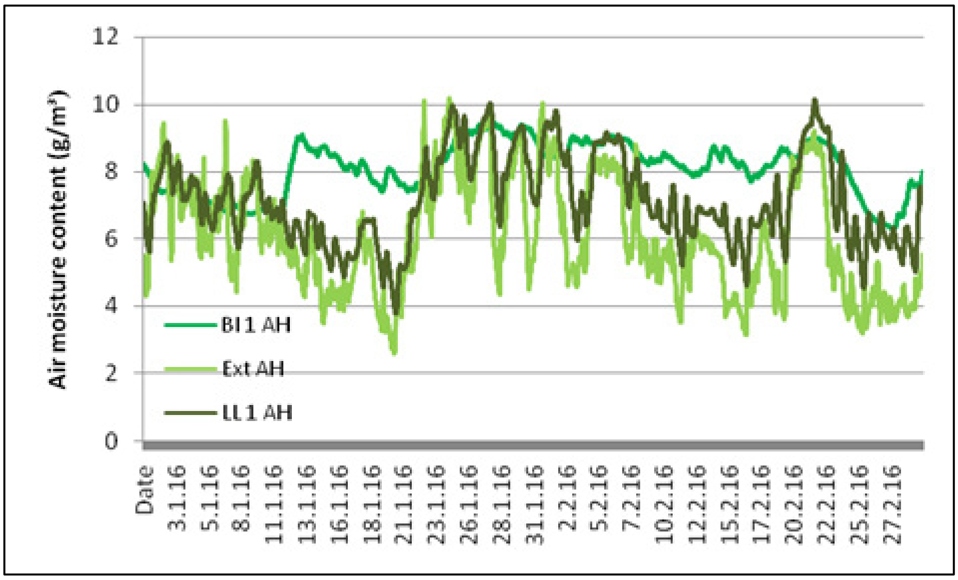


Fig 32: The low level (LL) trace in the roof space is responding to exterior (Ext) air moisture fluctuations, but the below insulation (BI) trace is responding differently

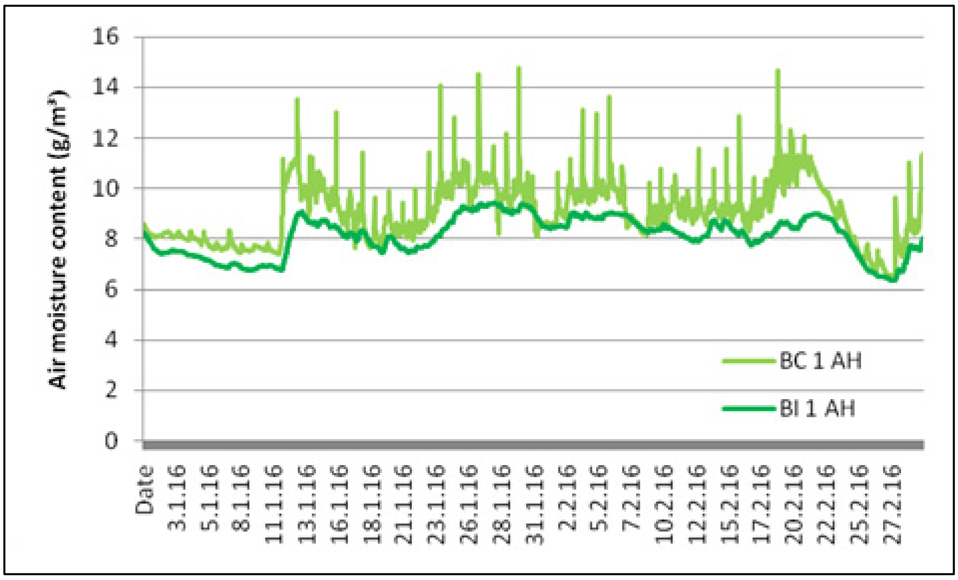


Fig 33: A comparison of the air moisture content (g/m³) below the ceiling (BC) and below the insulation (BI). The underlying trace shapes are similar

2.4 Data analysis: Summer (July/August 2015–2017)

Roofing works had already been completed and windows installed by the time the monitoring system was put in place. This means that data from summer 2015, following installation but prior to occupancy, can be used in Tables 5 to 8. No data were logged for July/August 2018.

In winter, the temperature is generally higher beneath the ceiling and insulation than it is within the roof (Fig 34), but in summer, solar gain can make the roof extremely hot (Fig 35).

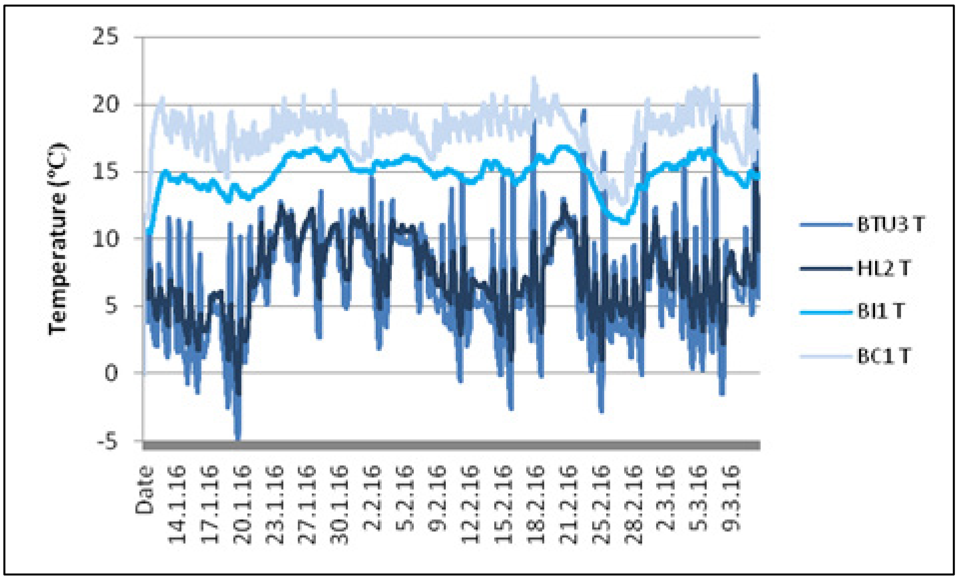


Fig 34: January/February within roof – below the insulation (BI), high level (HL), between tiles and underlay (BTU) – and below ceiling (BC) temperature comparisons for 2016

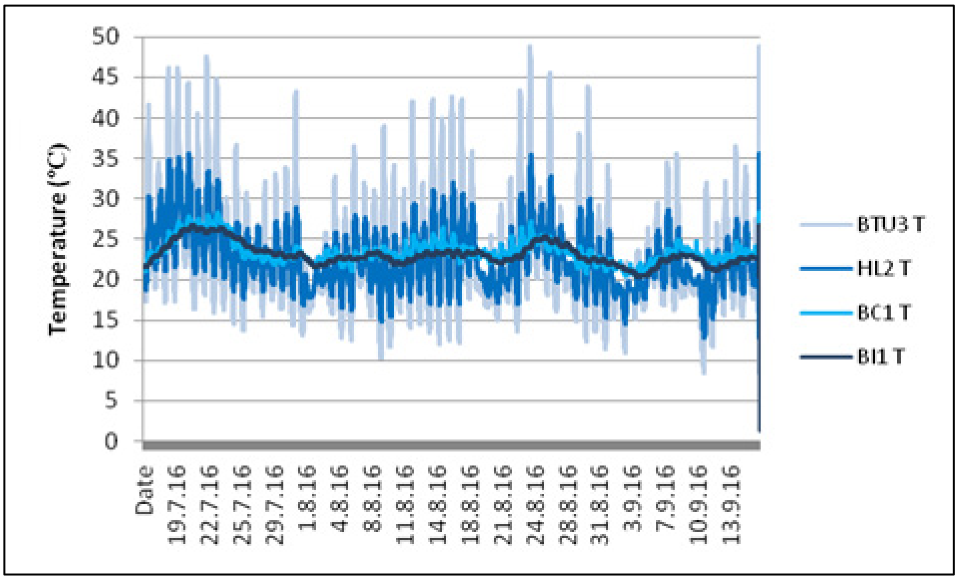


Fig 35: July/August within roof – below the insulation (BI), high level (HL), between tiles and underlay (BTU) – and below ceiling (BC) temperature comparisons for 2016

Median and interquartile range values for air temperatures beneath the tiles for July/August 2015 to 2017 are presented in Table 5.

Table 5: July/August air temperatures (°C) and relative humidity (%) between tiles and underlay (BTU) for 2015 to 2017

		2015 July/August	2016 July/August	2017 July/August
BTU1 T (North)	Maximum	37.8	41.8	42.2
	Minimum	9.2	9.3	9.4
	Median	19.5	20.5	19.6
	IQR	6.3	7.2	7.1
BTU2 T (West)	Maximum	48.6	48.6	47.8
	Minimum	9.4	9.4	9.6
	Median	19.6	20.6	19.4
	IQR	7.3	8.8	8.1
BTU3 T (South)	Maximum	48.8	48.8	47.2
	Minimum	8.2	8.5	8.6
	Median	19.7	20.8	19.6
	IQR	7.7	9.2	8.6
BTU1 RH (North)	Maximum	91.6	91.3	91.7
	Minimum	29.7	26.2	27.5
	Median	69.2	66.5	69.0
	IQR	19.2	19.4	19.3
BTU2 RH (West)	Maximum	92.5	92.1	92.6
	Minimum	20.4	19.1	19.2
	Median	64.5	61.7	65.1
	IQR	21.2	23.2	22.1
BTU3 RH (South)	Maximum	92.6	90.8	92.1
	Minimum	17.3	17.3	18.1
	Median	65.8	63.7	67.2
	IQR	20.7	21.7	21.5

Readings for each year are consistent. The minimum temperature under the north slope is lower than under the west and south slopes, but the medians are similar. The median relative humidity is lower than during the winter months.

The general comparability of the data from year to year means that it is reasonable to select data from 2016 to illustrate these observations. Figures 36 and 37 compare data from the winter (January/February) and summer (July/August) monitoring periods.

Figure 36 shows that the interquartile ranges (boxes) are greater in summer than in winter. The median cross-lines are skewed from the centre in summer because of the outliers caused by solar gain.

Figure 37 shows that summer relative humidity drops with the increased temperature and the interquartile ranges increase considerably compared with the winter. The roof becomes far less humid.

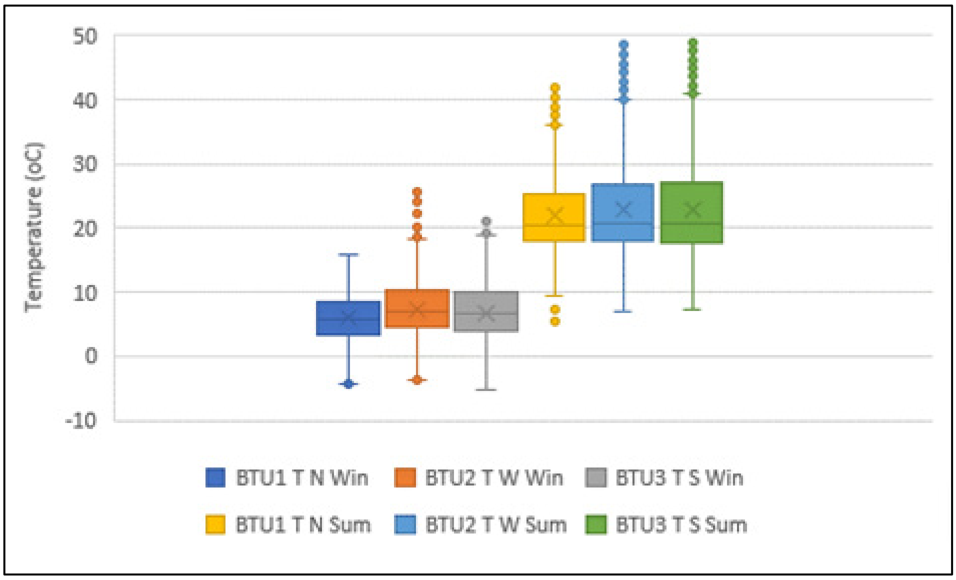


Fig 36: A comparison of winter (Win) and summer (Sum) air temperatures (°C) for the space between the tiles and the underlay (BTU) during 2016

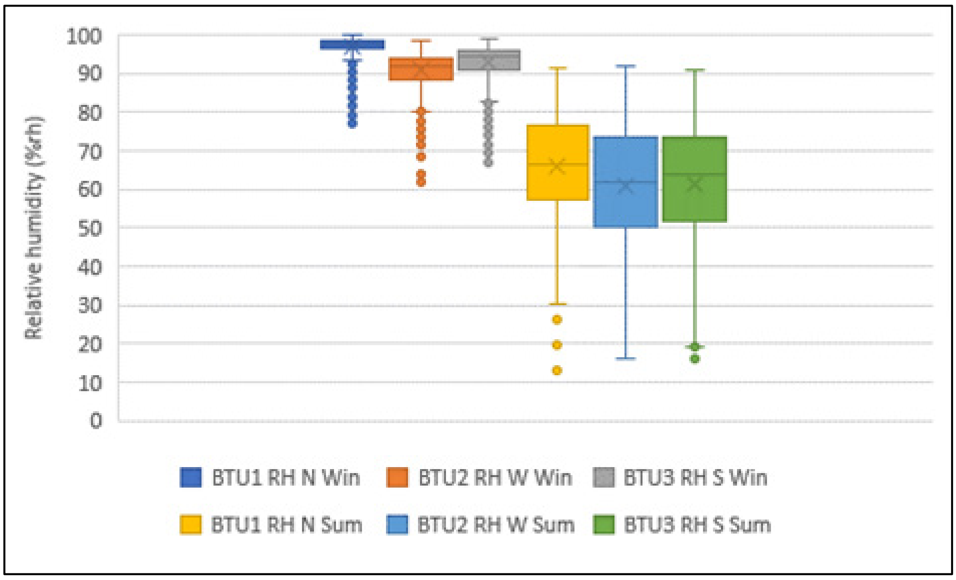


Fig 37: A comparison of winter (Win) and summer (Sum) air relative humidity (%) for the space between the tiles and the underlay (BTU) during 2016

Table 6 compares summer temperature and relative humidity statistics for high and low level in the roof space and allows a comparison with the environment directly under the tiles (see Table 5). Maximum temperatures are lower at high level than just under the tiles, but the monthly medians are the same. There is little difference between high level and low level readings.

Table 6: July/August high level (HL) and low level (LL) comparisons between temperature (°C) and relative humidities (%) for 2015 to 2017

		2015 July/August	2016 July/August	2017 July/August
HL1 T	Maximum	34.6	35	36
	Minimum	12.7	12.7	12.4
	Median	20.6	21.6	20.6
	IQR	4.5	5.6	5.2
HL2 T	Maximum	35.4	35.6	36.4
	Minimum	12.8	12.8	12.5
	Median	20.7	21.7	20.7
	IQR	4.6	5.7	5.3
LL1 T	Maximum	29.8	31.4	31.9
	Minimum	12.8	12.9	12.6
	Median	20.1	21.1	20.1
	IQR	3.7	4.4	4.0
HL1 RH	Maximum	85.6	85.6	84.7
	Minimum	38.2	39.9	39.9
	Median	65.5	63.1	67.4
	IQR	13.3	13.6	12.2
HL2 RH	Maximum	85.9	85.8	84.7
	Minimum	36.4	37.6	38.4
	Median	64.8	62.7	66.8
	IQR	13.5	14.1	12.4
LL1 RH	Maximum	83.3	83.3	84.8
	Minimum	40.2	51.1	47.5
	Median	66.7	65.7	69.0
	IQR	12.0	11.8	10.7

Table 7 compares the surface temperatures under the tiles for the summer months.

Table 7: July/August surface temperature (°C) under tiles (STUT) for 2015 to 2017

		2015 July/August	2016 July/August	2017 July/August
STUT1 (North)	Maximum	40.1	45.1	45.1
	Minimum	7	7.2	7.3
	Median	18.7	19.5	18.5
	IQR	7.2	8.4	8.2
STUT2 (East)	Maximum	48.3	50.4	48.6
	Minimum	7.1	7.2	7.5
	Median	19.4	20.6	19.3
	IQR	8.8	10.5	9.8
STUT3 (NW)	Maximum	53	53	51.6
	Minimum	7.1	7.5	7.5
	Median	18.9	19.7	18.5
	IQR	8.7	10.4	9.6
STUT4 (West)	Maximum	31.8	36.5	35.8
	Minimum	7.4	7.9	7.9
	Median	19.1	20.1	19.1
	IQR	6.9	7.7	7.7
STUT5 (SW)	Maximum	53.7	53.7	51.2
	Minimum	6.8	7	7.2
	Median	19.3	20.4	19.0
	IQR	9.1	10.9	10.0
STUT6 (South)	Maximum	42.2	47.9	47.9
	Minimum	6.9	7.2	7.3
	Median	18.9	19.6	18.5
	IQR	7.6	8.8	8.1

Statistics for the summer months are compared with those from the winter months in Figure 38.

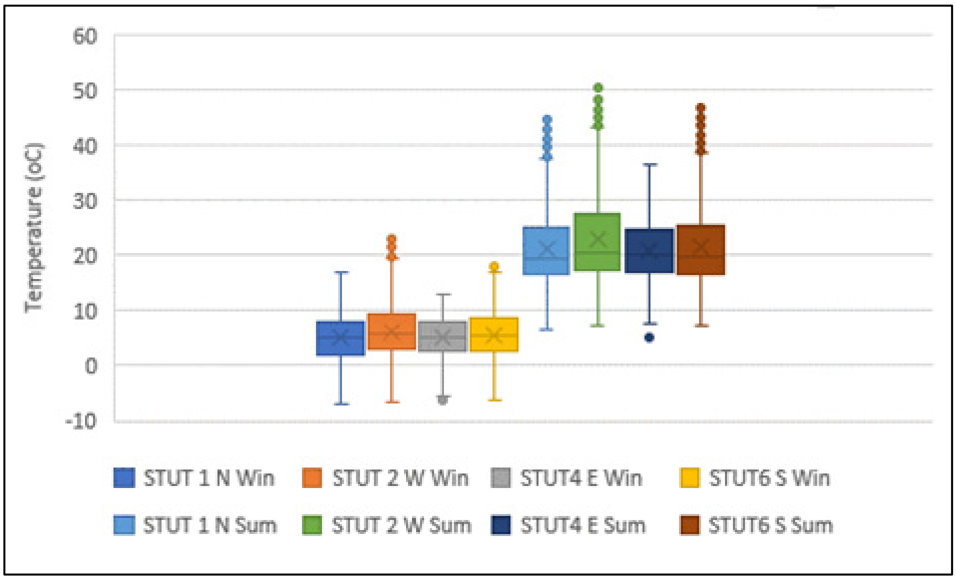


Fig 38: A comparison of winter (Win) and summer (Sum) surface temperatures (°C) for the undersides of the tiles

Surface temperatures are warmer and more variable in summer, particularly on the slope facing west (STUT2). This presumably receives the most irradiance from the sun.

2.5 Predictability of seasonal data

The temperature distribution from the room to the underside of the tiles is compared for summer and for winter, with the statistics presented in Table 8.

Table 8: Winter and summer temperature comparisons for 2015 to 2018

		2015 July/Aug	2016 Jan/Feb	2016 July/Aug	2017 Jan/Feb	2017 July/Aug	2018 Jan/Feb
BTU3 T	Maximum	48.8	22.1	48.8	19.8	47.2	19.1
	Minimum	8.2	-5.2	8.5	-4.4	8.6	-0.8
	Median	13.6	5.6	14.7	6.6	14.3	7.1
	IQR	4.9	6.1	4.5	6.4	4.6	4.8
HL2 T	Maximum	35.4	15.2	35.6	15.3	36.4	12.6
	Minimum	12.8	-1.5	12.8	-0.5	12.5	1.5
	Median	20.7	7.0	21.7	7.1	20.7	7.2
	IQR	4.6	4.0	5.7	5.2	5.3	3.5
BI2 T	Maximum	31.4	18.1	28.3	17.7	25.6	17.4
	Minimum	18.6	10.9	21.2	9.7	20	13.1
	Median	22.8	16.1	22.8	15.2	22.8	15.9
	IQR	1.6	1.7	1.2	2.4	1.8	1.3
BC1 T	Maximum	31.6	21.9	28.2	22.1	26.2	21.8
	Minimum	18.8	11.6	20.4	10.8	19.3	14.6
	Median	22.5	18.2	23.2	17.2	22.5	17.5
	IQR	1.5	1.9	1.4	2.6	1.7	1.4

Summer temperatures (July/August) are compared with winter (January/ February) in Figures 39 to 41 to illustrate the similarity in roof data from year to year.

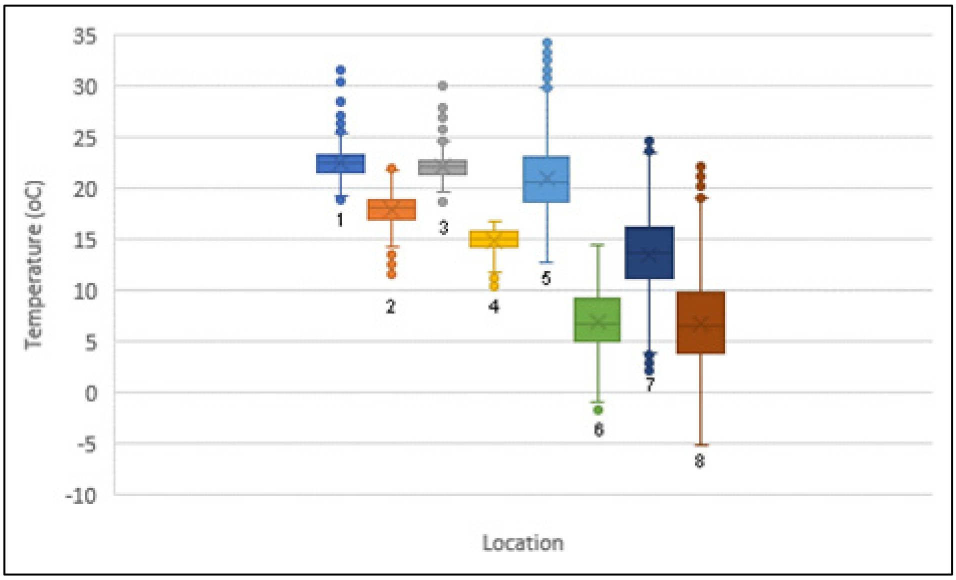


Fig 39: A comparison of temperature distribution for July/August 2015 (boxes 1, 3, 5, 7) and January/February 2016 (boxes 2, 4, 6, 8)

Key to Figure 39
1 = below ceiling (BC1) summer 2015
2 = below ceiling (BC1) winter 2016
3 = below insulation (BI2) summer 2015
4 = below insulation (BI2) winter 2016
5 = high level (HL2) summer 2015
6 = high level (HL2) winter 2016
7 = between tiles and underlay (BTU3) summer 2015
8 = between tiles and underlay (BTU3) winter 2016

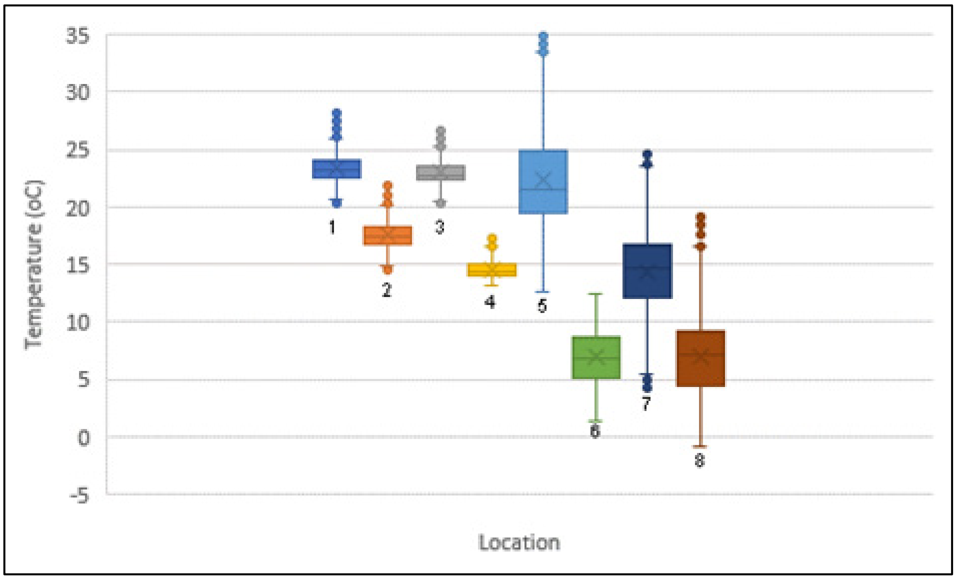


Fig 40: A comparison of temperature distribution for July/August 2016 (boxes 1, 3, 5, 7) and January/February 2017 (boxes 2, 4, 6, 8)

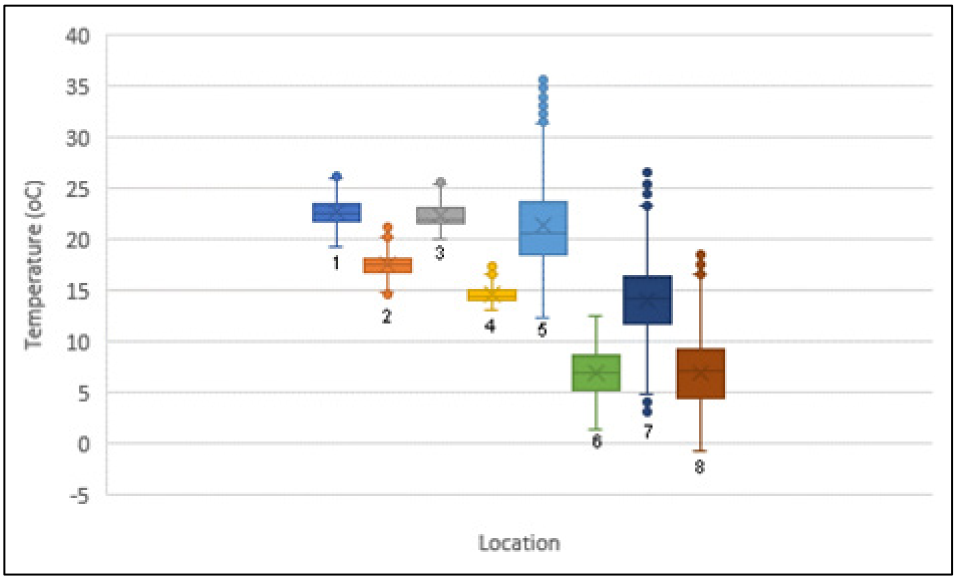


Fig 41: A comparison of temperature distribution for July/August 2017 (boxes 1, 3, 5, 7) and January/February 2018 (boxes 2, 4, 6, 8)

Key to Figures 40 and 41
1 = below ceiling (BC1) summer
2 = below ceiling (BC1) winter
3 = below insulation (BI2) summer
4 = below insulation (BI2) winter
5 = high level (HL2) summer
6 = high level (HL2) winter
7 = between tiles and underlay (BTU3) summer
8 = between tiles and underlay (BTU3) winter

The similarity between Figures 39, 40 and 41 suggests that the temperature distribution from year to year is rather predictable. There is little difference between the below ceiling (box 1) and the below insulation (box 3) interquartile ranges in summer, presumably because both are responding to ambient temperatures. Both are within the interquartile temperature range of the high level roof space environment (box 5) and there is no heat from below producing a winter temperature difference across the ceiling and insulation, as demonstrated by boxes 2, 4 and 6 in all three tables.

Figures 42 to 44 compare relative humidities.

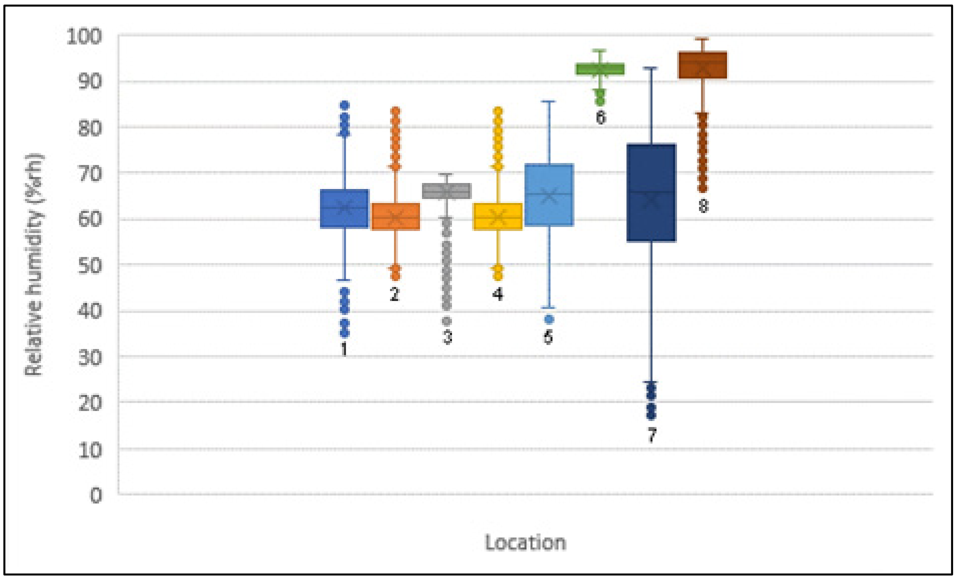


Fig 42: A comparison of relative humidity (%) distribution for July/August 2015 (boxes 1, 3, 5, 7) and January/February 2016 (boxes 2, 4, 6, 8)

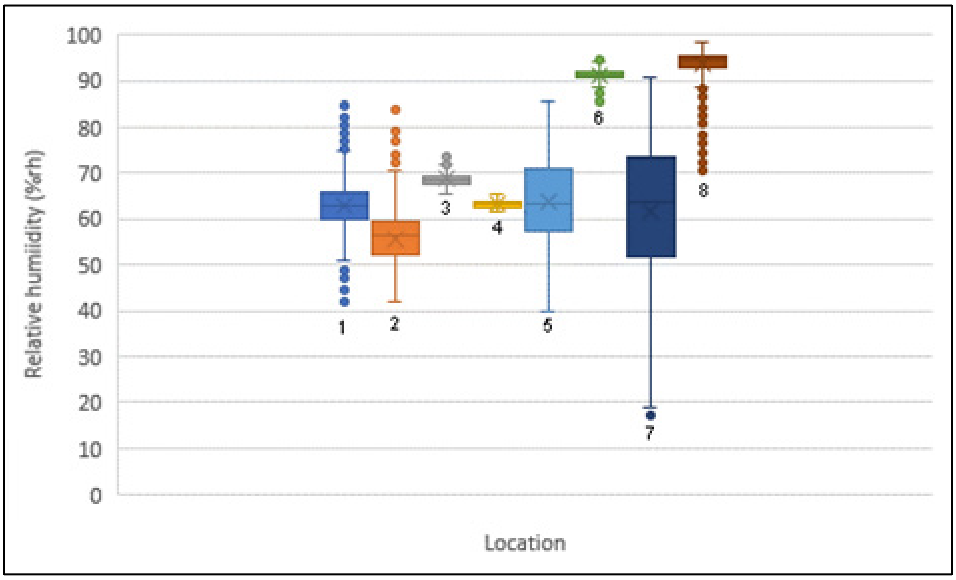


Fig 43: A comparison of relative humidity (%) distribution for July/August 2016 (boxes 1, 3, 5, 7) and January/February 2017 (boxes 2, 4, 6, 8)

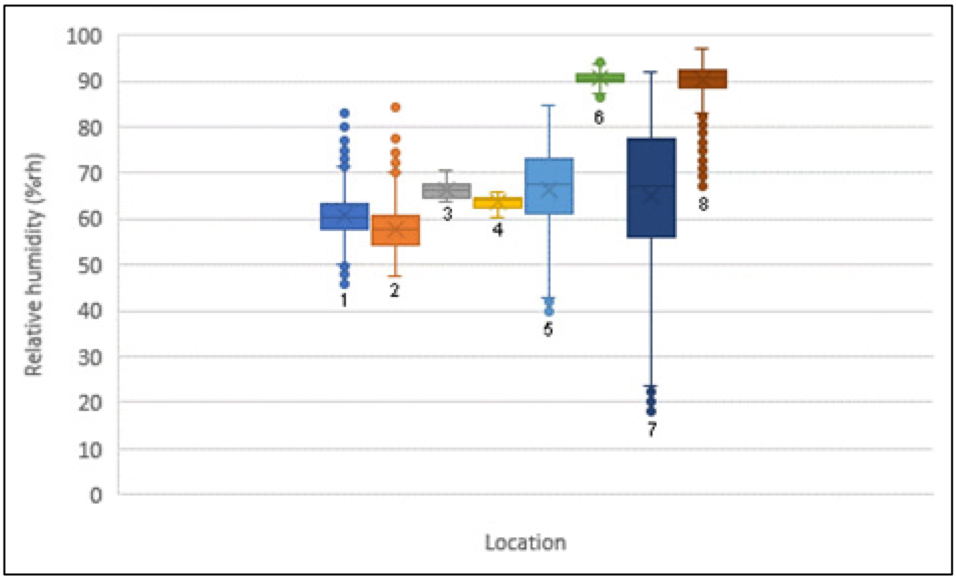


Fig 44: A comparison of relative humidity (%) distribution for July/August 2017 (boxes 1, 3, 5, 7) and January/February 2018 (boxes 2, 4, 6, 8)

Key to Figures 42, 43 and 44
1 = below ceiling (BC1) summer
2 = below ceiling (BC1) winter
3 = below insulation (BI2) summer
4 = below insulation (BI2) winter
5 = high level (HL2) summer
6 = high level (HL2) winter
7 = between tiles and underlay (BTU3) summer
8 = between tiles and underlay (BTU3) winter

In summer, the interquartile humidity range beneath the insulation (box 3 in Figures 42, 43 and 44) is a little higher than in the room below, perhaps because of retained moisture within the insulation. However, it is within the relative humidity range for the roof space (box 5). Humidity under the tiles is very variable in summer (box 7), but the roof is essentially dry. In winter, the relative humidity in the roof space increases to around 90% because the temperature drops.

2.6 Building 1 'Addison' – Summary

The attic floor contains an AVCL and a thick layer of hygroscopic insulation. Heating within the house during the winter months raises the temperature above the ceiling and AVCL (but under the insulation). This draws moisture from the insulation and timber roof structure so that the room and the below insulation sensors record a similar pattern of relative humidity, even though there is no moisture movement through the AVCL.

The insulation halts further heat transfer into the roof void so that the roof environment is discrete – cooler and far more humid. There were no indications from the data obtained that moisture from occupancy made any obvious difference to the humidity in the roof space, which remained around 90% during the winter months (January/February).

Humidity between the underlay and the tiles frequently reached dew point when the night temperatures dropped and also during the daytime when solar gain increased air temperature and moisture content faster than it raised surface temperatures. The environment between the tiles and underlay would seem to be damp in winter.

In summer, when there is no incremental heat from below, the temperatures in the room, below the insulation and in the roof void tend to equalise. Relative humidity below the insulation tends to be a little higher than below the ceiling, probably because of residual moisture within the insulation. Relative humidity within the roof void drops as temperature increases, and the seasonal consequences for dew point and condensation are shown in Figure 45.

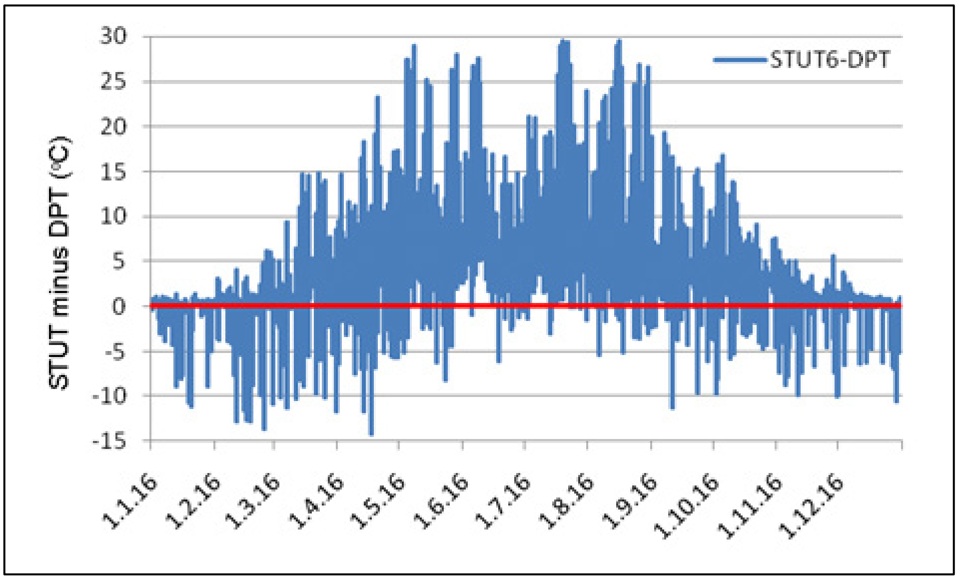


Fig 45: The condensation risk (below red line) shows seasonal trends during 2016 obtained by subtracting the dew point temperature (DPT) beneath the tiles and underlay from the surface temperature of the underside of the tiles (STUT)

Dew point is easily reached during the winter months, but still occurs in summer.

Box plots of temperature and relative humidity from below ceiling to the exterior illustrate the basic predictability of the seasonal environment from year to year (see Figs 39 to 44).

3.0 BUILDING 2 ‘RECTORY’ (LONDON)

3.1 Roof construction

Building 2 ‘Rectory’ differs from Building 1 ‘Addison’ in having two parallel shallow pitched roofs (Fig 46). Further construction details, together with sensor types and locations, are provided in Figures 49 and 50.

Fig 46: Slate covered roofs and weather station at Building 2 ‘Rectory’

The unventilated softwood roof is slated and has a vapour-permeable underlay – Pro Clima Solitex – beneath the battens. The attic floor is insulated and covered with particle board (Fig 47). A vapour-permeable AVCL –Pro Clima Intello Plus – is incorporated in the attic floor construction.

Fig 47: Building 2 'Rectory' attic

Fig 48: The underlay was slit to allow sensors to be installed behind, then sealed with Tescon Vana tape

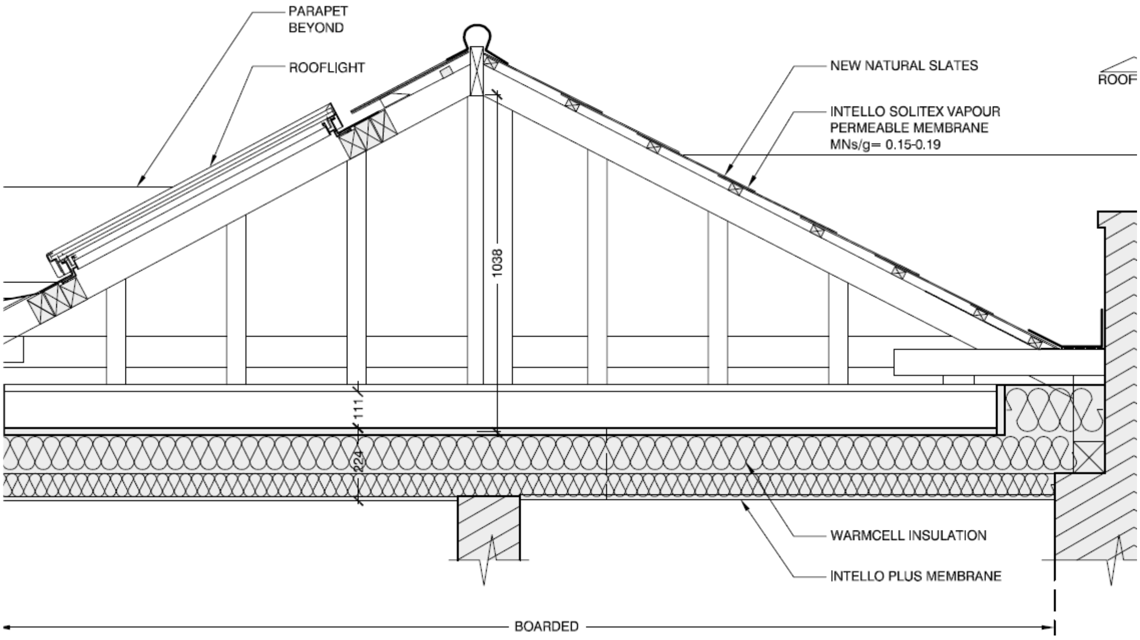


Fig 49: Cross section through attic (Roof 1) (copyright Arboreal Architecture)

The Intello Plus membrane is described by the manufacturers as a 'humidity-variable vapour retarder'. The description indicates that the molecular structure acts as a seal against moisture movement in winter and becomes more open in summer. Warmcell is a cellulose insulation made from waste paper and should, therefore, act similarly to the blown cellulose insulation used in Building 1.

3.2 Sensor type and location

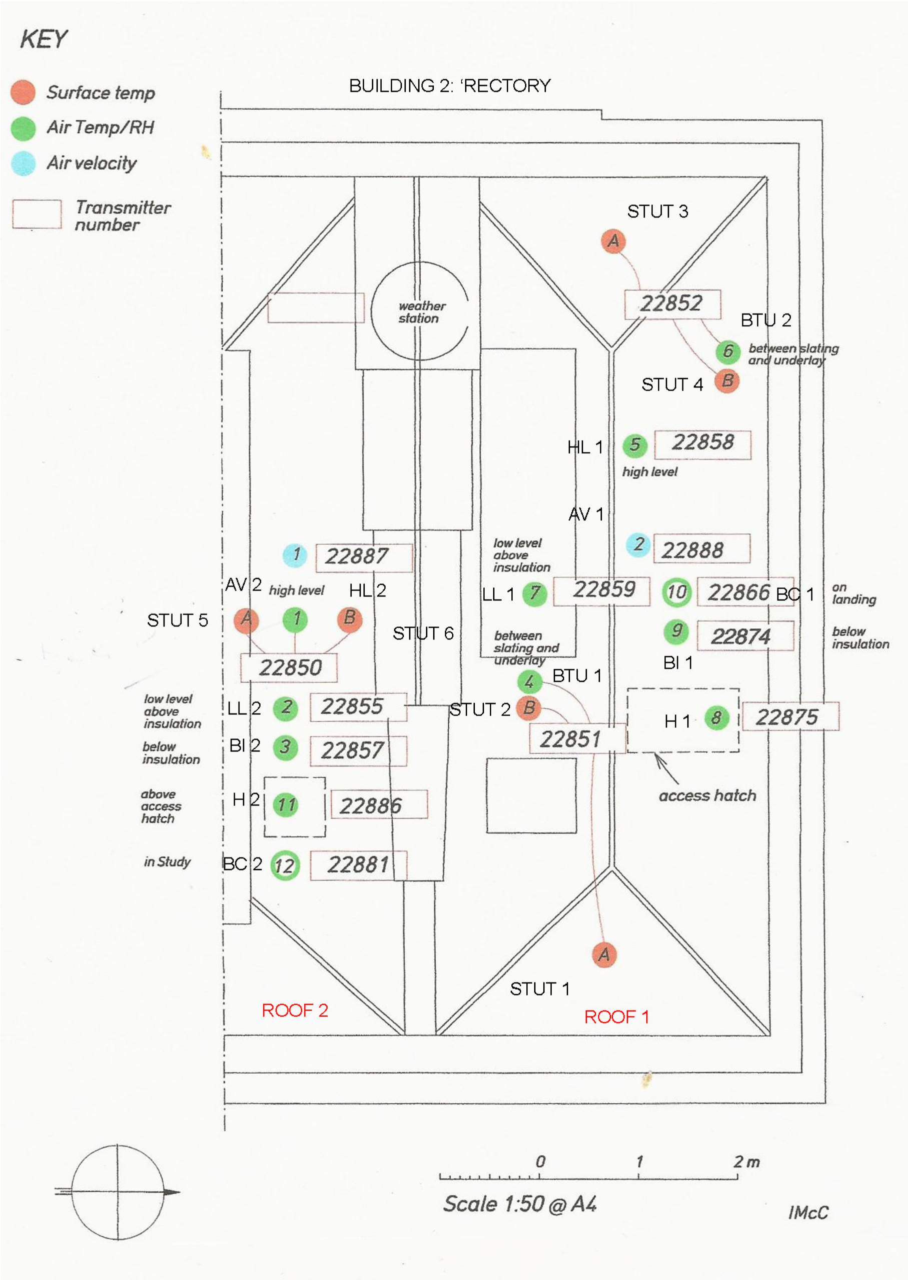


Fig 50: Plan of roof showing sensor positions

Key to Figure 50
BTU = between slates and underlay temperature (T)/relative humidity (RH)
STUT = surface temperature under slates
HL = high level temperature/relative humidity
LL = low level temperature/relative humidity
BI = below insulation temperature/relative humidity
BC = below ceiling temperature/relative humidity
AV = air velocity

3.3 Data analysis: Winter (January/February 2016–2019)

3.3.1 Roof slope orientation and sensor position

Orientation and location data are presented in Tables 9 and 10.

Table 9: January/February air temperature (°C) between slates and underlay (BTU) comparisons for 2016 to 2019

		2016 Jan/Feb	2017 Jan/Feb	2018 Jan/Feb	2019 Jan/Feb
BTU1 T (North)	Maximum	17.6	19.3	14.5	23.5
	Minimum	-3.2	-3.7	-3.8	-4.9
	Median	6.7	5.8	5.8	6.5
	IQR	5.1	6.4	4.3	5.1
BTU2 T (South)	Maximum	17.3	19.4	14.5	20
	Minimum	-4.5	-4.6	-4.2	-5.3
	Median	6.3	5.8	5.7	6.4
	IQR	5.4	6.5	4.6	5.1
Ext T	Maximum	15.3	17.5	13.8	20.1
	Minimum	-1.7	-1.5	-4.2	-1.8
	Median	6.9	6.0	5.9	7.1
	IQR	4.7	5.7	4.1	4.7
BTU1 RH (North)	Maximum	96.1	96.6	96.6	95.3
	Minimum	34.5	42.8	41.3	33.7
	Median	84.0	87.1	80.1	81.1
	IQR	14.4	7.8	13.8	12.1
BTU2 RH (South)	Maximum	93.4	94.4	94.3	93.5
	Minimum	44.6	50	48	45.3
	Median	85.7	87.8	82.2	82.5
	IQR	10.5	5.2	8.6	6.8
Ext RH	Maximum	90	90	89.0	88
	Minimum	34	32	36.0	23
	Median	75.0	78.0	70.0	71.0
	IQR	15.0	12.0	15.0	14.0

The median temperatures (T) under the slates are lower than outside and the relative humidity (RH) is a little higher.

Table 10: January/February high level (HL) and low level (LL) temperature (°C) and relative humidity (%) for 2016 to 2019

		2016 Jan/Feb	2017 Jan/Feb	2018 Jan/Feb	2019 Jan/Feb
HL1T	Maximum	16.6	19	15.4	23.2
	Minimum	-1.4	-1.6	-1	-1.8
	Median	7.8	7.2	7.1	8.0
	IQR	4.6	5.5	3.7	4.5
HL2T	Maximum	15.2	16.4	13.3	14.7
	Minimum	0.2	0.2	0.1	0
	Median	8.2	7.7	7.4	8.4
	IQR	3.8	5.1	3.3	4.1
LL1T	Maximum	15	16.5	13.1	16.3
	Minimum	-1.7	-2.1	-1.3	-2.4
	Median	7.2	6.9	6.6	7.6
	IQR	4.2	5.7	3.6	4.5
LL2T	Maximum	15.1	16	13.4	14.5
	Minimum	-0.7	-0.3	-0.2	-0.7
	Median	7.9	7.5	7.2	8.7
	IQR	3.9	5.3	3.4	4.1
HL1RH	Maximum	90	88.7	90	88.1
	Minimum	62.4	66.7	58.6	55.1
	Median	83.0	83.7	80.9	80.3
	IQR	4.8	3.0	3.5	3.0
HL2RH	Maximum	86.7	84.1	84.4	85.1
	Minimum	72.9	71.9	75.2	76.4
	Median	82.0	82.4	80.1	80.5
	IQR	3.6	1.4	2.3	2.7
LL1RH	Maximum	88.3	87.3	85.6	87.6
	Minimum	71.1	76.3	71.9	77.4
	Median	83.6	84.3	81.5	81.6
	IQR	3.1	2.2	2.4	2.7
LL2RH	Maximum	88.2	86.6	86.6	85.9
	Minimum	74.1	72.9	76.6	77
	Median	84.3	84.5	82.5	82.7
	IQR	3.0	1.5	2.2	2.7

The sensors for HL1 and HL2 are in different roofs. HL1 is in Roof 1 which is more exposed, so maximum temperatures are a little higher and minimum temperatures are lower (Fig 51), but the medians are similar. Temperatures and relative humidities are compared with exterior in Figures 52 and 53.

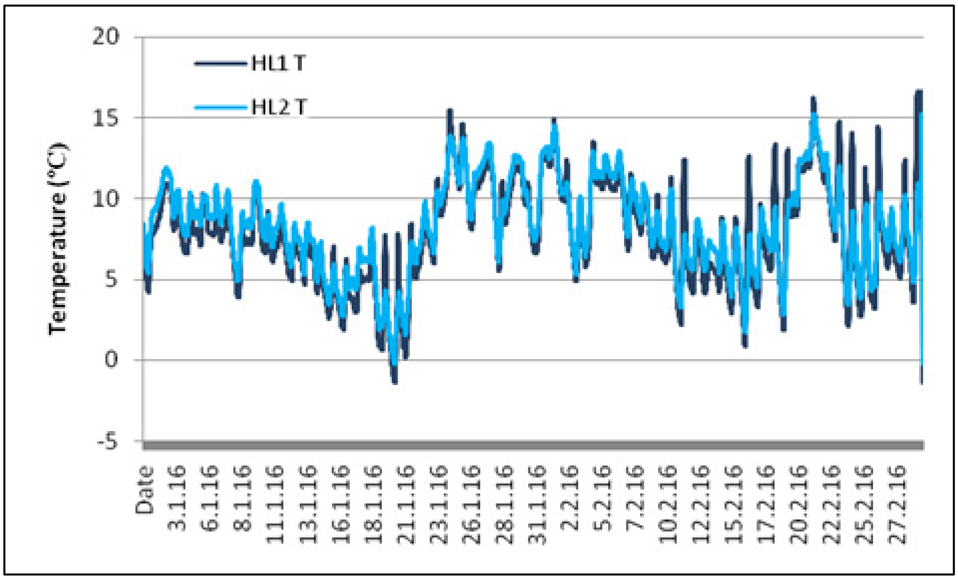


Fig 51: January/February 2016 temperatures (°C) in Roof 1 (HL1) and Roof 2 (HL2)

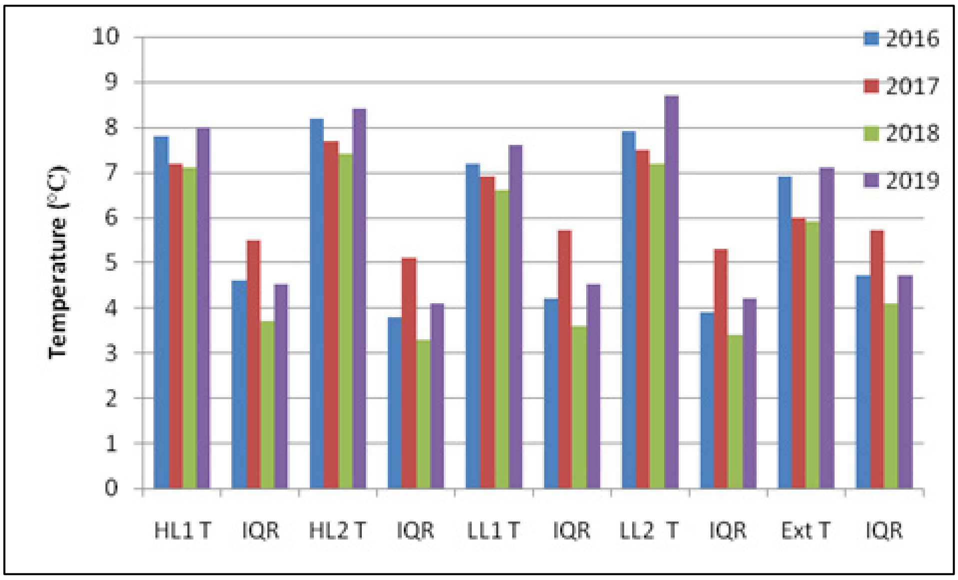


Fig 52: January/February median temperatures (°C) at high (HL) and low (LL) levels, with their interquartile ranges (IQR) compared with exterior (Ext) for 2016 to 2019

Yearly patterns are quite similar for individual parameters and yearly medians vary by only about 1°C. Roof space temperatures tend to be a little higher than exterior. Temperature data for 2016 are presented as a box plot in Figure 53 and relative humidity for 2016 in Figure 54.

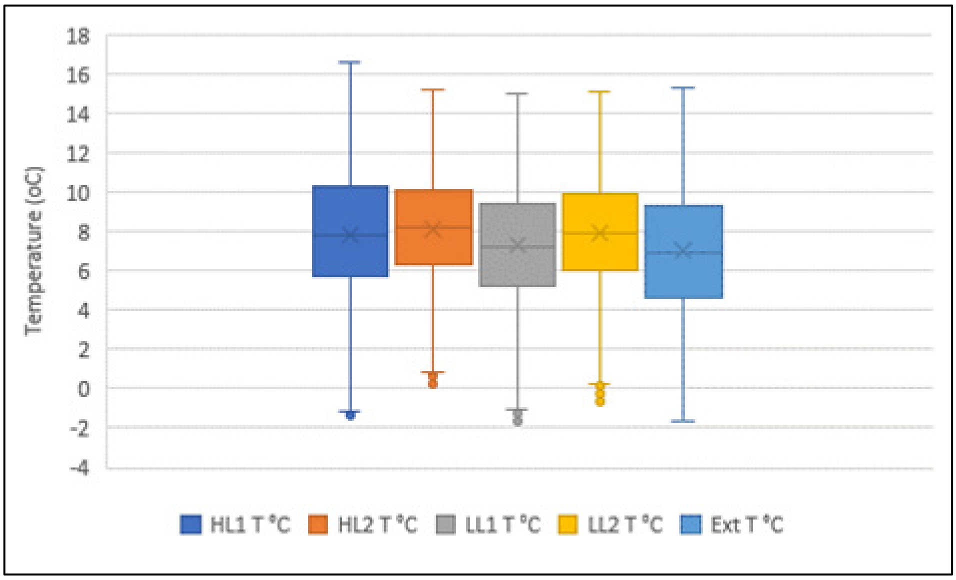


Fig 53: January/February median temperatures (°C) at high (HL) and low (LL) levels, with their interquartile ranges compared with exterior (Ext) for 2016

High level temperatures are a little higher than low level and exterior temperatures. There are no upper outliers that would be caused by solar gain.

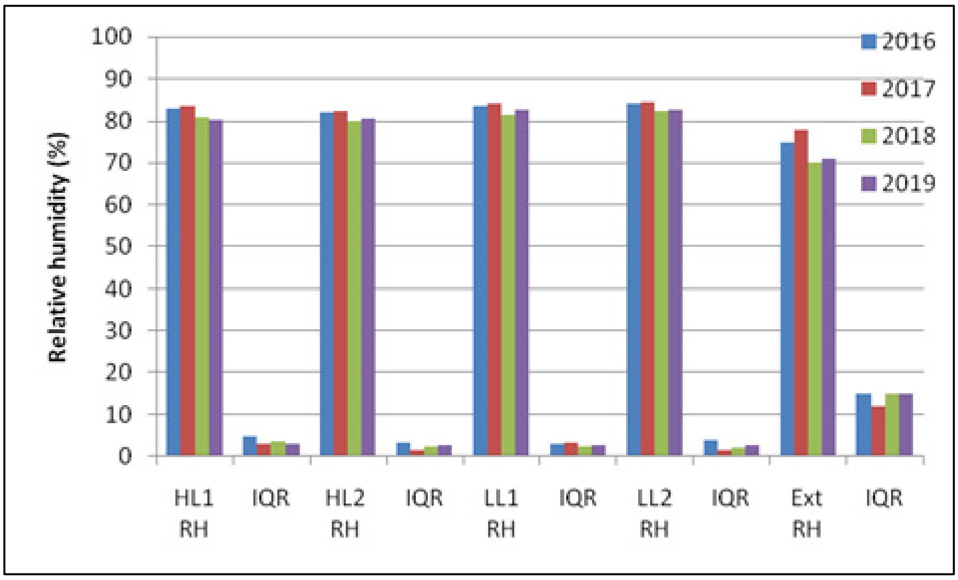


Fig 54: January/February relative humidity (%) at high (HL) and low (LL) levels, with their interquartile ranges (IQR) compared with exterior (Ext) for 2016 to 2019

Figure 54 shows that relative humidities remain rather constant during January/February for each of the four years. Data from 2016 are presented as a box plot in Figure 55 to provide more information.

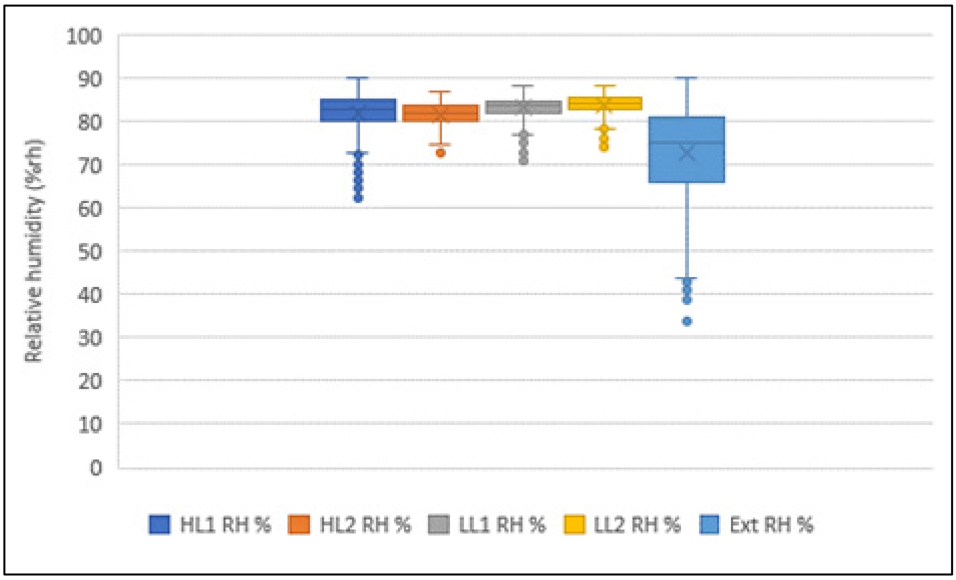


Fig 55: A comparison of high (HL) and low level (LL) relative humidity (%) with exterior (Ext) for January/February 2016

Relative humidities are rather uniform throughout the roofs and their interquartile ranges indicate a more humid and less variable environment than the exterior range.

3.3.2 Roof covering temperature and condensation

Slate underside temperatures for January/February are provided in Table 11.

Table 11: January/February surface temperature (°C) under slates (STUT) for 2016 to 2019

		2016 Jan/Feb	2017 Jan/Feb	2018 Jan/Feb	2019 Jan/Feb
STUT1 (East – Roof 1)	Maximum	22.8	27.2	26.8	34.3
	Minimum	-5.6	-5.2	-5.1	-6.5
	Median	6.3	5.8	5.7	6.4
	IQR	5.4	6.5	4.6	5.1
STUT2 (South – Roof 1)	Maximum	27.1	27.9	22	40
	Minimum	-5	-5.6	-4.9	-6.6
	Median	6.2	5.5	5.3	6.2
	IQR	6.4	7.1	5.6	5.9
STUT3 (West – Roof 1)	Maximum	27	26.7	25.3	38.2
	Minimum	-5.2	-6.1	-5.8	-6.6
	Median	6.2	5.2	5.4	6.0
	IQR	5.9	6.7	5.1	5.5
STUT4 (North – Roof 1)	Maximum	18	20.3	15.2	20
	Minimum	-5.7	-5.8	-5.8	-6.8
	Median	6.3	5.7	5.5	6.3
	IQR	6.1	7.0	5.5	5.7
STUT5 (South – Roof 2)	Maximum	14.8	15.4	13.6	14
	Minimum	1.9	1.9	2.2	1.9
	Median	8.2	7.7	7.4	8.4
	IQR	3.8	5.1	3.3	4.1
STUT6 (North – Roof 2)	Maximum	17.8	19.7	15.4	16.2
	Minimum	-5.4	-5.4	-5.2	-6.6
	Median	6.9	6.7	6.5	6.9
	IQR	1.8	2.2	1.5	1.8

The medians and interquartile ranges are compared in Figure 56.

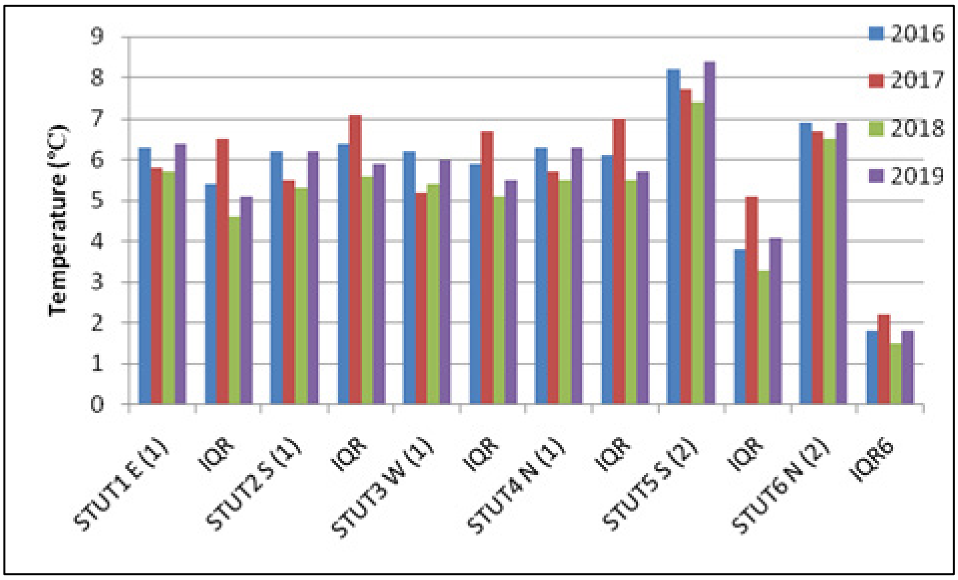


Fig 56: Median surface temperatures (STUT) and their interquartile ranges (IQR) for January/February 2016 to 2019

Surface temperatures mostly vary by less than 2°C for each year, the greatest difference being between Roof 1 and Roof 2. In each case, the interquartile range is a high percentage of the median. Data for 2016 are presented as a box plot in Figure 57 to provide information on distribution and outliers.

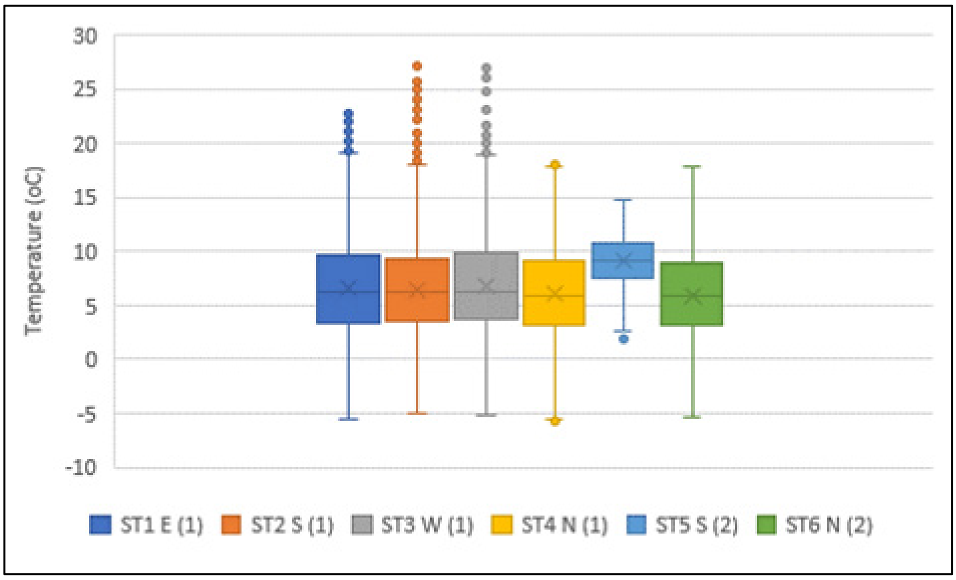


Fig 57: Box plot of surface temperature under slate (°C) for January/February 2016

The median for STUT5 in Roof 2 is the highest, but the range between maximum and minimum temperatures (upper and lower bars on the whiskers) is the shortest, and there are no upper outliers. The latter suggests that the roof slope at the sensor position is sheltered.

Minimum temperatures are fairly consistent and the risk from condensation under the slates can be demonstrated by using data from 2016 (Roof 1) as examples. Calculated dew points are subtracted from surface temperatures and condensation may occur if the resulting temperature drops below zero (red line in Figures 58 and 59).

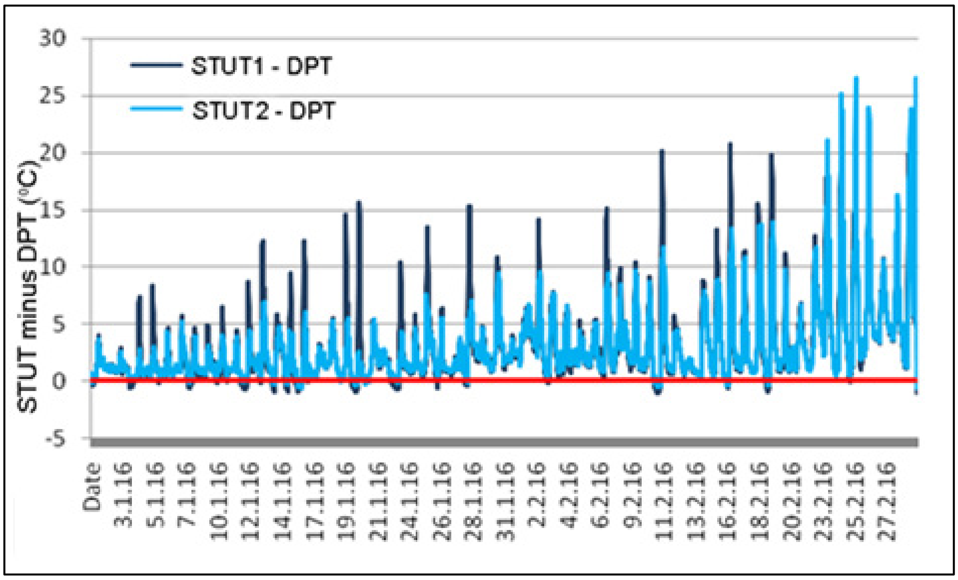


Fig 58: Condensation risk (below red line) for January/February 2016 obtained by subtracting dew point temperature (DPT) from surface temperatures 1 and 2 (east and south) under slates (STUT)

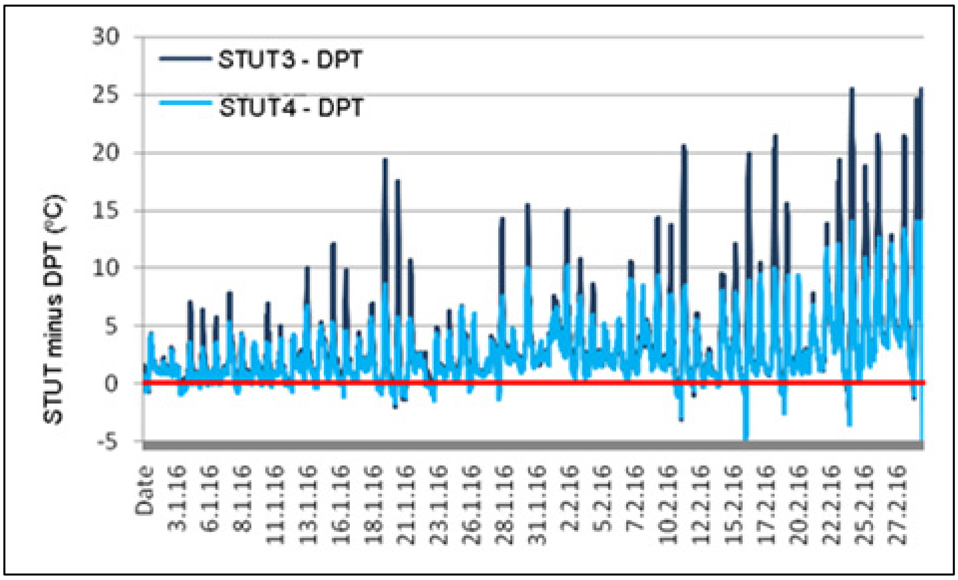


Fig 59: Condensation risk (below red line) for January/February 2016 obtained by subtracting dew point temperature (DPT) from surface temperatures 3 and 4 (west and north) under slates (STUT)

Figures 58 and 59 show that condensation is likely on the undersides of the slates. Afternoon spikes are present, as at Building 1 ‘Addison’, but the temperature differential is much smaller. Dew point is compared with surface temperature in Figure 60. It can be seen that the temperature may drop to dew point but, unlike Building 1 (see Figs 10 and 11), it does not linger there and condensation is likely to be a transient event.

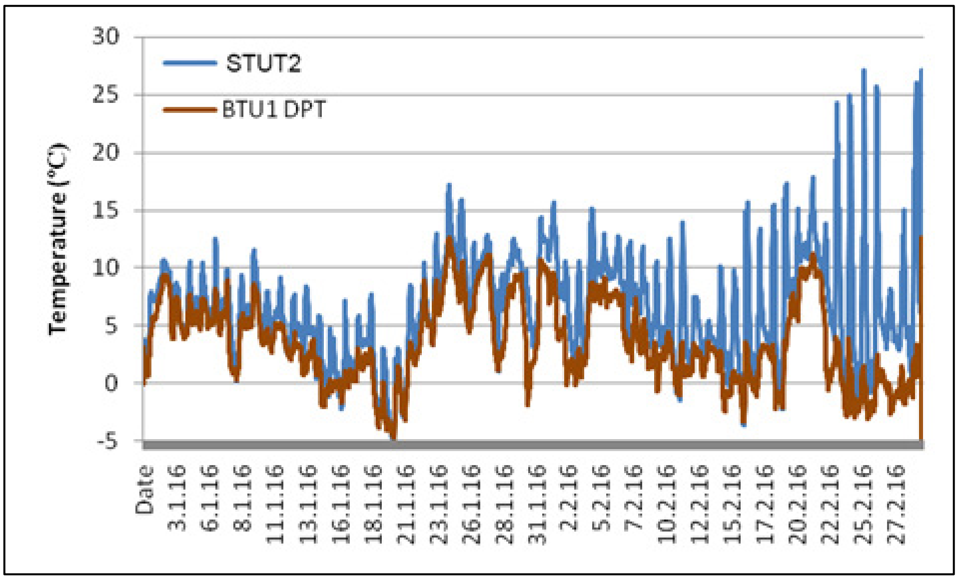


Fig 60: Surface temperature (STUT2) compared with dew point temperature (DPT) for January/February 2016

If winter 2016 data are plotted, it can be shown – as at Building 1 – that high level air moisture contents follow a similar trend to below slate moisture contents and both are similar to exterior moisture contents (Fig 61). High-level moisture content peaks, however, tend to be a little higher than the exterior peaks.

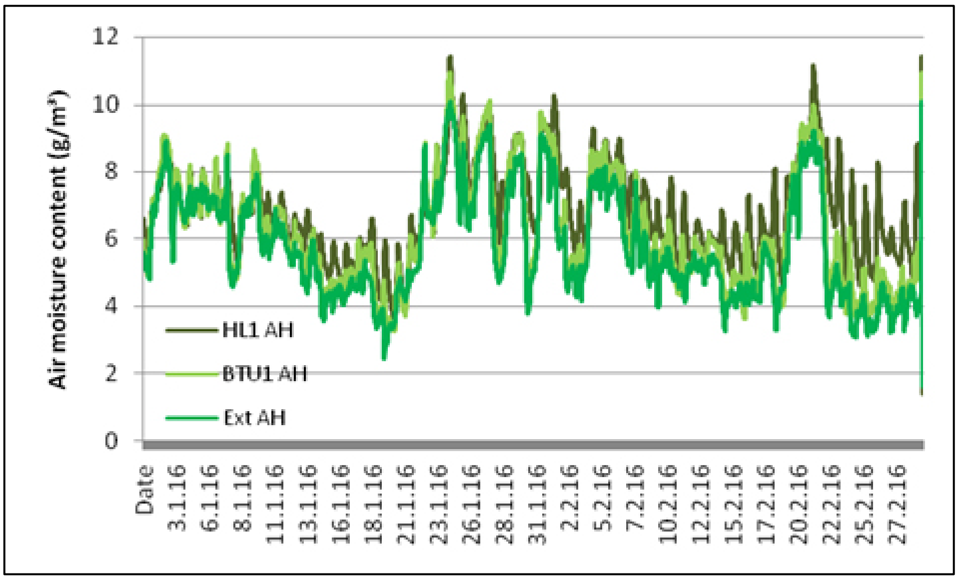


Fig 61: Air moisture content (g/m^3) at high level (HL), between slates and underlay (BTU) and exterior (Ext) for January/February 2016

3.3.3 Occupancy and insulation

Figures 62 to 65 demonstrate the temperature and relative humidity profiles from the room, through the ceiling and roof constructions, to the exterior for Roof 1.

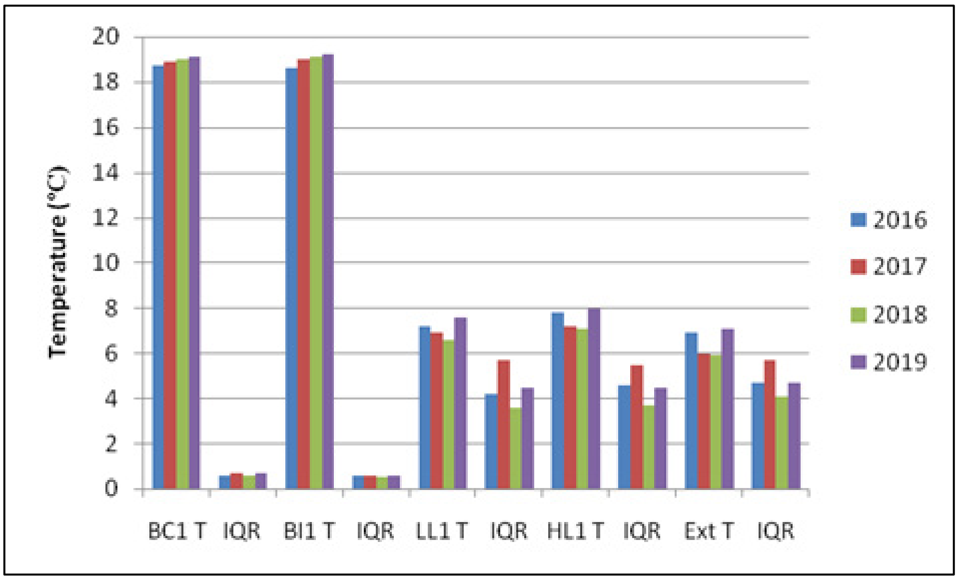


Fig 62: January/February average temperatures (°C) and interquartile ranges (IQR) in the room (BC), below insulation (BI), Roof 1 (HL and LL) and the exterior (Ext) for 2016 to 2019

Figure 62 shows that the median temperatures and their interquartile ranges beneath the insulation and beneath the ceiling are very similar, with little variation. High level, low level and exterior statistics are similar, with high level being the warmest and exterior the coolest. A box plot for 2016 is provided in Figure 63.

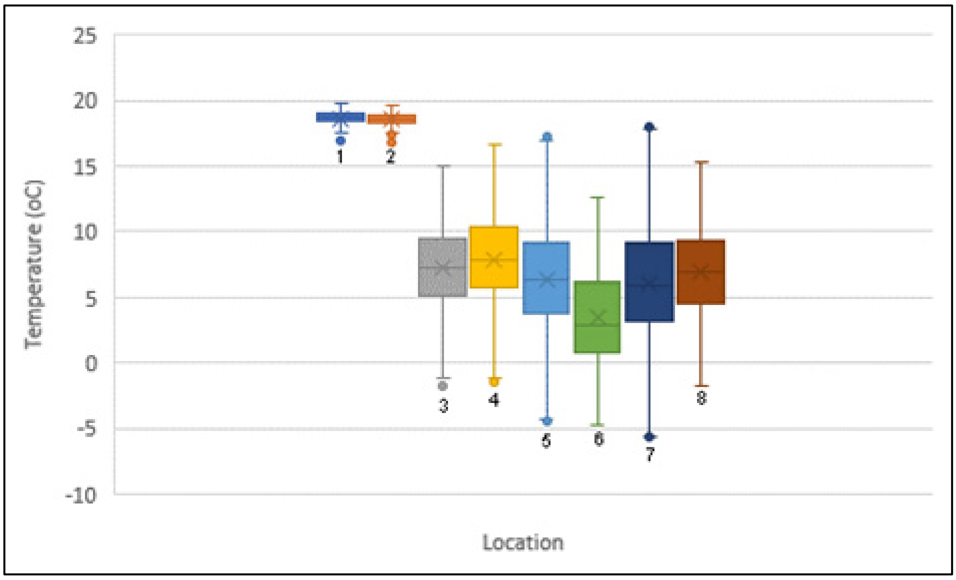


Fig 63: A comparison of median and interquartile range temperatures from the room (BC1) through the roof space to the exterior for January/February 2016

Key to Figure 63
1 = below ceiling (BC1)
2 = below insulation (BI1)
3 = low level (LL1)
4 = high level (HL1)
5 = between slates and underlay (BTU2)
6 = dew point (BTU2 DPT)
7 = surface temperature under tiles (STUT4)
8 = exterior (Ext)

Figure 63 box plots also include air temperature between the slates and the underlay, dew point and the temperature on the underside of the slates. The interquartile range for the dew point is below the median for the surface temperature. This suggests that condensation would be a less common event than at Building 1, where the interquartile ranges overlapped and the dew point and surface temperatures were similar.

Figure 64 compares relative humidity distribution for the four years.

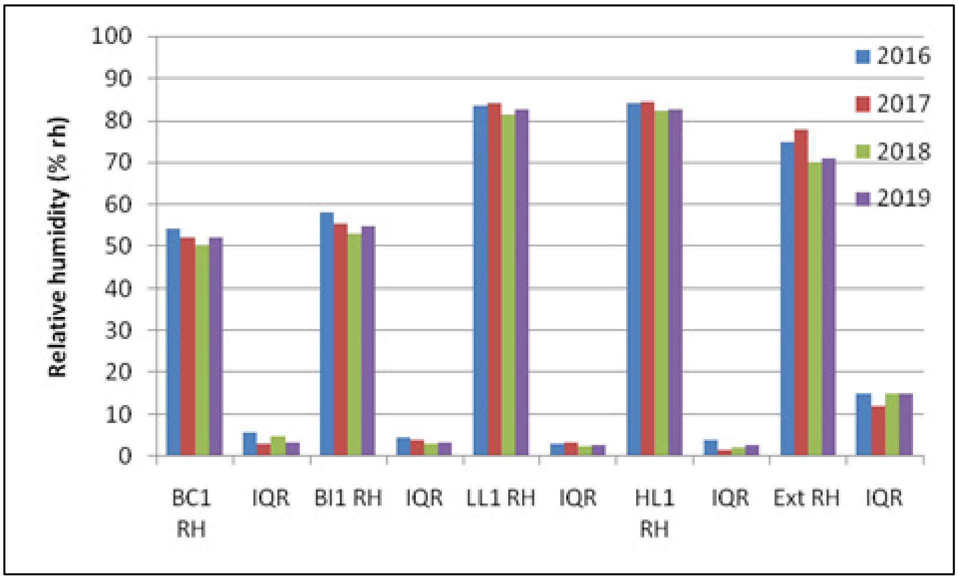


Fig 64: January/February median humidity (%) and interquartile ranges (IQR) in the room (BC), below insulation (BI), Roof 1 (HL and LL) and the exterior (Ext) for 2016 to 2019

Results are again consistent within a few percent for each year, and data from 2016 are used to construct the box plot provided in Figure 65.

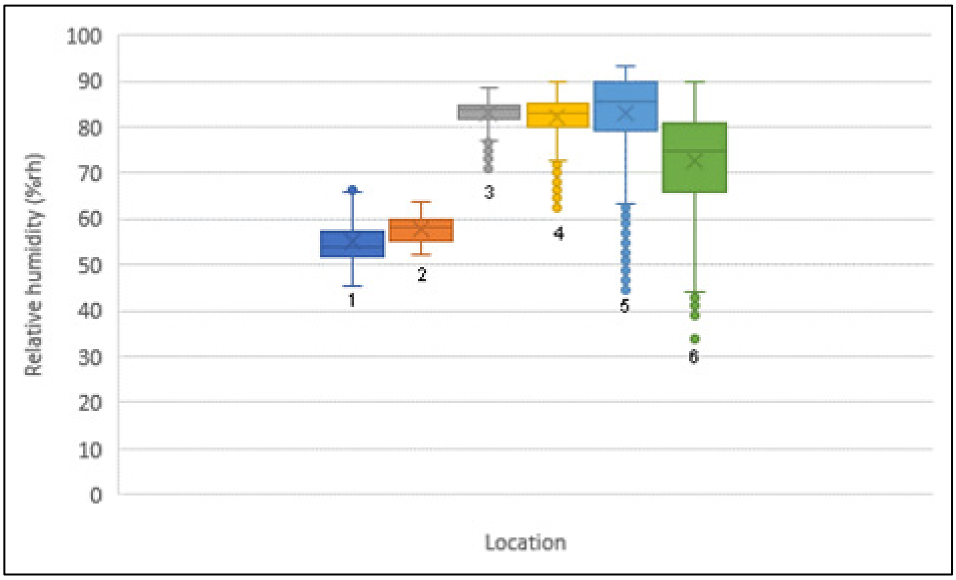


Fig 65: A comparison of median and interquartile range relative humidities (%) from the room (BC1) through the roof space to the exterior for January/February 2016

Key to Figure 65
1 = below ceiling (BC1)
2 = below insulation (BI1)
3 = low level (LL1)
4 = high level (HL1)
5 = between slates and underlay (BTU4)
6 = exterior (Ext)

Figure 63 (boxes 1 and 2) shows that there was only a slight drop in temperature through the ceiling. Figure 65 shows that this is accompanied by a rise in relative humidity, which may be caused by a little more moisture in the hygroscopic insulation.

Table 12 presents the air moisture content medians and interquartile ranges for Roofs 1 and 2, together with the room below and the exterior.

Table 12: January/February air moisture (g/m³) statistics for Roofs 1 and 2 high and low level (HL and LL), below insulation (BI), the room (BC) and the exterior (Ext) for 2016 to 2019

		2016 Jan/Feb	2017 Jan/Feb	2018 Jan/Feb	2019 Jan/Feb
HL1 AH	Maximum	11.41	12.1	10	12.2
	Minimum	3.61	3.51	3.42	3.38
	Median	6.7	6.5	6.3	6.7
	IQR	1.9	2.4	1.6	1.9
HL2 AH	Maximum	10.59	11.18	9.39	10.4
	Minimum	4	3.98	3.77	3.83
	Median	6.8	6.6	6.4	6.8
	IQR	1.7	2.1	1.4	1.8
LL1 AH	Maximum	10.73	11.63	9.52	11.06
	Minimum	3.58	3.45	3.39	3.3
	Median	6.5	6.4	6.2	6.6
	IQR	1.8	2.3	1.6	1.9
LL2 AH	Maximum	10.5	10.95	9.69	10.26
	Minimum	3.92	4.01	3.85	3.87
	Median	6.9	6.7	6.5	6.9
	IQR	1.8	2.2	1.5	1.8
BI1 AH	Maximum	10.42	10.38	9.89	10.17
	Minimum	7.82	7.47	7.42	7.73
	Median	9.1	9.0	8.9	9.0
	IQR	0.75	0.82	0.6	0.6
BI2 AH	Maximum	8.95	9.1	8.39	8.45
	Minimum	5.2	4.83	4.76	5.15
	Median	6.7	6.7	6.7	7.0
	IQR	1.5	1.3	0.9	1.0
BC1 AH	Maximum	10.31	10.3	10.39	10.43
	Minimum	7.09	6.89	6.52	6.96
	Median	8.7	8.4	8.1	8.5
	IQR	1.0	0.7	0.8	0.7
BC2 AH	Maximum	10.5	9.55	9.4	11.23
	Minimum	7.65	7.07	6.35	7.23
	Median	9.0	8.8	8.3	8.8
	IQR	0.8	0.7	0.7	0.5
Ext AH	Maximum	10.07	9.39	9.35	8.36
	Minimum	2.44	2.32	1.82	2.74
	Median	5.3	5.5	5.0	5.4
	IQR	2.6	2.2	1.8	1.9

The highest median air moisture content each year during January/February is under the insulation (Fig 66). This insulation, as with Building 1, is hygroscopic with a huge surface area and should readily accumulate moisture. There is an AVCL within the ceiling construction, but the manufacturer states that this is only a vapour retardant and that the molecular structure becomes more open in summer when temperatures are higher. If this has any validity, then presumably the membrane is vapour permeable in the ceiling construction when there is warmth permeating from the room below.

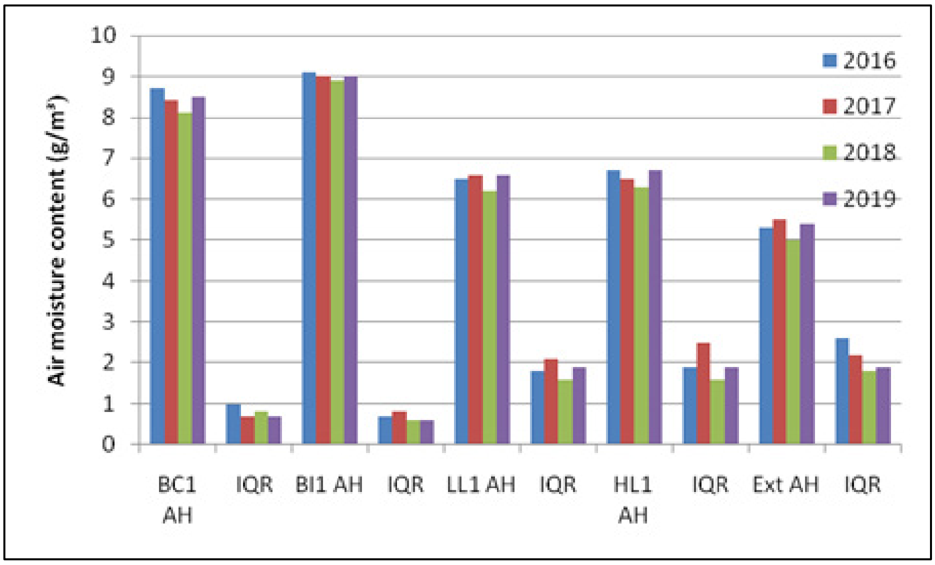


Fig 66: January/February air moisture (g/m³) medians and interquartile ranges (IQR) in the room (BC), below insulation (BI), Roofs 1 and 2 (HL and LL) and the exterior (Ext) for 2016 to 2019

A box plot for 2016 is presented in Figure 67.

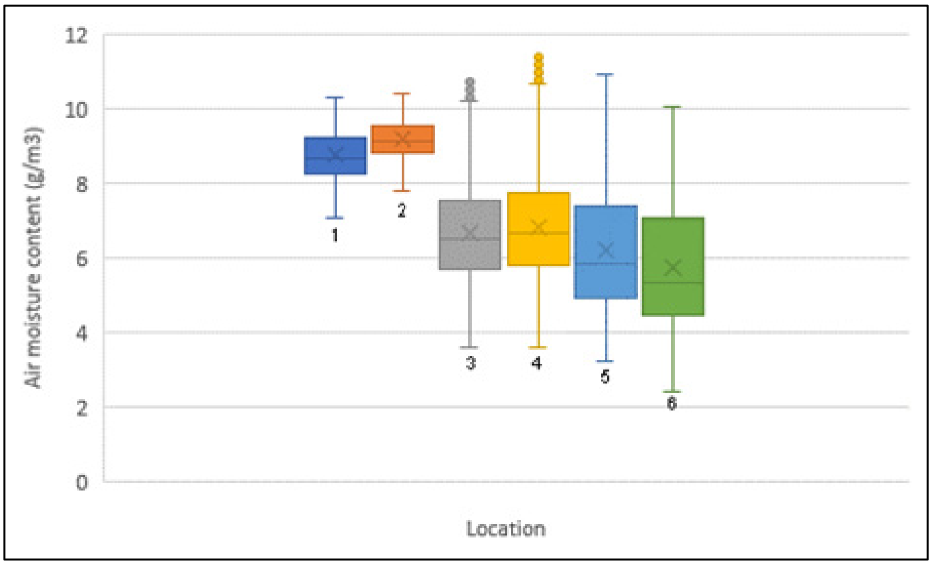


Fig 67: A comparison of median and interquartile range air moisture contents (g/m³) from the room (BC1) through the roof space to the exterior for January/February 2016

Key to Figure 67
1 = below ceiling (BC1)
2 = below insulation (BI2)
3 = low level (LL1)
4 = high level (HL1)
5 = between slates and underlay (BTU2)
6 = exterior (Ext)

3.4 Data analysis: Summer (July/August 2015–2018)

Temperature and relative humidity statistics are compared in Table 13 and Figures 68 and 69.

Table 13: July/August temperatures (°C) and relative humidities (RH) in Roof 1 (HL and LL), below insulation (BI), room (BC), and the exterior (Ext) for 2015 to 2018

		2015 July/August	2016 July/August	2017 July/August	2018 July/August
HL1 T	Maximum	45.1	48.8	48.1	50.1
	Minimum	14	14	12	12.1
	Median	23.3	25.0	23.7	26.4
	IQR	8.8	9.3	8.7	11.3
HL2 T	Maximum	38.3	39.5	39.2	40.3
	Minimum	14.4	14.5	13.6	13.2
	Median	22.4	22,4	22.4	25.1
	IQR	6.2	6.2	6.2	8.3
LL1 T	Maximum	40.4	43.6	43.4	45.4
	Minimum	13.6	13.8	11.9	12
	Median	22.6	24.0	22.7	25.6
	IQR	7.3	7.4	7.4	9.8
LL2 T	Maximum	36.4	37.1	37.4	38.7
	Minimum	13.7	13.7	12.7	12.5
	Median	22.0	22.0	22.0	24.5
	IQR	5.8	5.8	5.8	7.9
BI1 T	Maximum	30.6	29.8	29.4	31
	Minimum	22.2	22.2	21.4	22.2
	Median	25.2	24.6	24.2	25.7
	IQR	2.1	1.6	1.9	3.1
BI2 T	Maximum	30.2	29.7	29.3	31
	Minimum	22.4	22.5	21.5	22.3
	Median	25.4	25.4	24.5	26.0
	IQR	2.0	2.0	1.7	2.8
BC1 T	Maximum	30.7	29.4	29.4	30.7
	Minimum	22.1	21.6	21.5	22.2
	Median	25.0	25.0	24.1	25.3
	IQR	2.2	2.2	1.9	2.8
BC2 T	Maximum	30.9	29.7	29.9	31.2
	Minimum	22.7	22.8	21.8	22.3
	Median	25.6	25.6	24.5	26.1
	IQR	2.1	2.1	1.7	3.0
Ext T	Maximum	31.5	31.0	30.5	33.7
	Minimum	10.3	10.9	9.8	8.7
	Median	18.0	18.0	18.2	20.0
	IQR	4.2	4.2	4.5	6.0

		2015 July/August	2016 July/August	2017 July/August	2018 July/August
HL1 RH	Maximum	69.4	67.2	68.6	66.4
	Minimum	23.5	28.5	27.2	22.7
	Median	46.32	49.1	49.4	41.2
	IQR	11.7	10.3	11.2	12.9
HL2 RH	Maximum	69.8	68.1	68.3	64.8
	Minimum	36.3	46	39.7	33.4
	Median	51.8	55.6	56.9	46.5
	IQR	8.7	5.6	8.3	10.8
LL1 RH	Maximum	70.6	68.1	68	64
	Minimum	30.4	38.9	32.2	29.1
	Median	48.7	52.1	52.4	43.5
	IQR	10	8.2	9.3	11.6
LL2 RH	Maximum	72.1	72.2	70.9	67.5
	Minimum	38.2	49	41.7	35.6
	Median	54.0	54.0	54.0	49.1
	IQR	9.0	9.0	9.0	10.6
BI1 RH	Maximum	64.6	69.9	63.8	62.8
	Minimum	44.3	50.4	46.3	40.9
	Median	51.0	56.7	53.6	51.6
	IQR	3.8	4.4	4.4	5.7
BI2 RH	Maximum	57.7	69	62.2	58.3
	Minimum	39.1	49.5	43.7	37.5
	Median	47.9	55.3	47.9	48.6
	IQR	4.5	4.8	4.5	5.4
BC1 RH	Maximum	61.1	67.3	66.9	61.7
	Minimum	28.5	35.1	36.5	27.9
	Median	47.1	51.3	50.7	47.6
	IQR	6.8	5.5	5.5	8.6
BC2 RH	Maximum	62.3	59	62.7	57.9
	Minimum	34.7	30.5	38.7	28.3
	Median	36.6	50.2	46.6	45.3
	IQR	5.6	3.9	5.6	7.0
Ext RH	Maximum	91	90	89	87
	Minimum	18	17	26	22
	Median	67.0	63.0	65.0	58.0
	IQR	25.0	24.0	23.0	26.0

In winter, the below ceiling and below insulation temperatures were much higher than low level, high level and exterior (Fig 66), which were comparable. In summer (Fig 68), the within building medians are all roughly comparable, with the greatest variation being at high level. The exterior median temperature is now lower. This becomes clearer with a box plot, and the data from 2016 are presented in Figure 69.

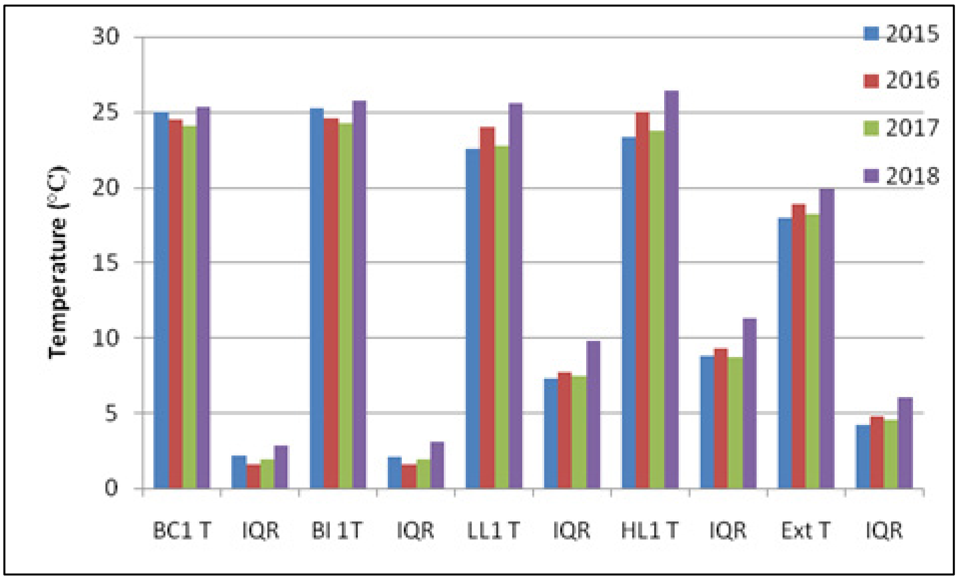


Fig 68: January/February median temperatures (°C) and their interquartile ranges (IQR) in the room (BC), below insulation (BI), Roof 1 (HL and LL) and the exterior (Ext) for 2016 to 2019

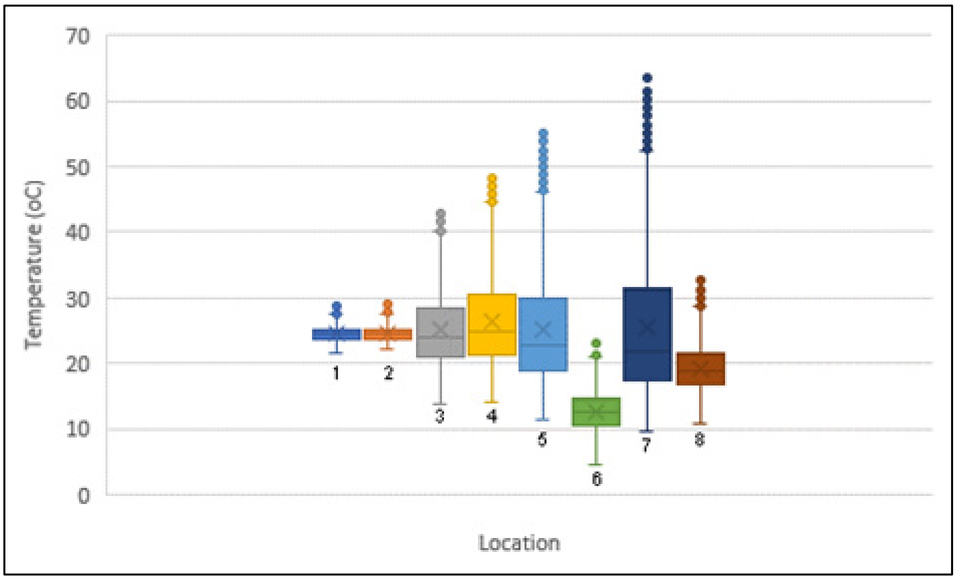


Fig 69: Box plot of temperature distribution from the room (BC1) across the roof to the exterior for 2016

Key to Figure 69
1 = below ceiling (BC1)
2 = below insulation (BI1)
3 = low level (LL1)
4 = high level (HL1)
5 = between states and underlay (BTU1)
6 = dew point (BTU1 DPT)
7 = surface temperature under slates (STUT4)
8 = exterior (Ext)

Below ceiling and below insulation temperatures are identical and their medians are similar to those at low and high level in the roof space. The temperature interquartile ranges and outliers increase from low level to below the slates. The surface temperature under the slates can be very high and the risk from condensation is very small.

Figure 70 compares relative humidity medians and interquartile ranges during July/August 2015 to 2018.

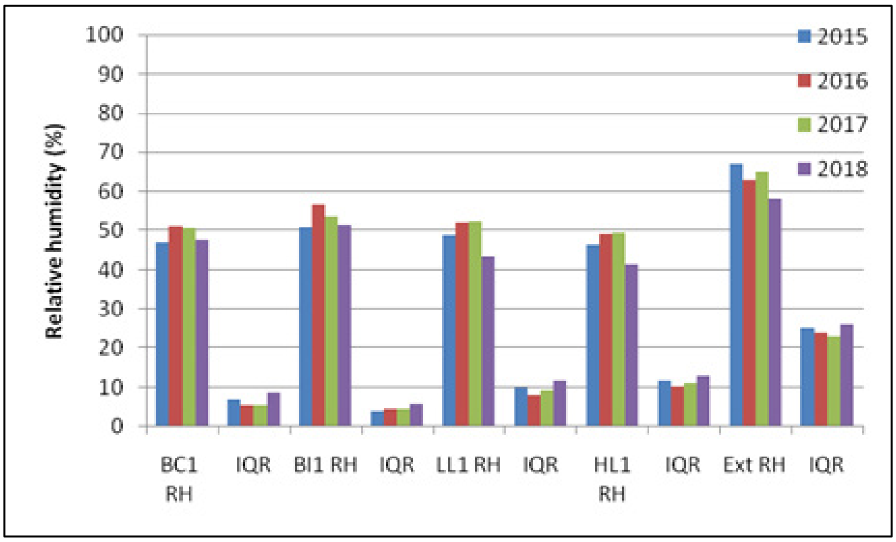


Fig 70: July/August median relative humidity (%) and interquartile ranges (IQR) in the room (BC), below insulation (BI), Roof 1 (HL and LL) and the exterior (Ext) for 2015 to 2018

All interior median relative humidities are comparable to within 10% during the summer months (Fig 70) and lower than exterior. Data for 2016 are presented in Figure 71 as a box plot.

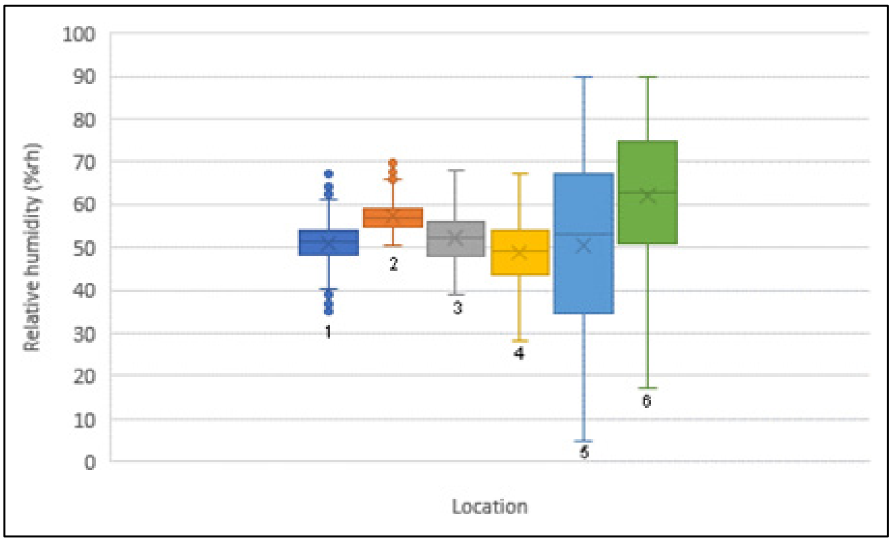


Fig 71: Box plot of relative humidity (%) distribution from the room (BC1) across the roof to the exterior

Key to Figure 71
1 = below ceiling (BC1)
2 = below insulation (BI1)
3 = low level (LL1)
4 = high level (HL1)
5 = between slates and underlay (BTU1)
6 = exterior (Ext)

The humidity under the insulation (box 2) is higher than under the ceiling or at low level within the roof. This is probably due to moisture held within the hygroscopic insulation material. The humidity range increases from low level to beneath the slates and becomes very variable, with a total range (maximum to minimum) of 82%. This is greater than the exterior total range (73%) and is presumably a consequence of the high temperatures caused by solar gain (*see* Fig 69).

3.5 Building 2 'Rectory' – Summary

Condensation is a possibility on the underside of the slates during most of the year, because of afternoon spikes in temperature, but particularly during the winter months. However, the periods when temperatures drop below dew point do not seem to be sustained (*see* Figs 58 and 59) and so condensation, at least during the periods monitored, would be a transient event. Dew point under the slates is plotted against surface temperature in Figures 60 and 72.

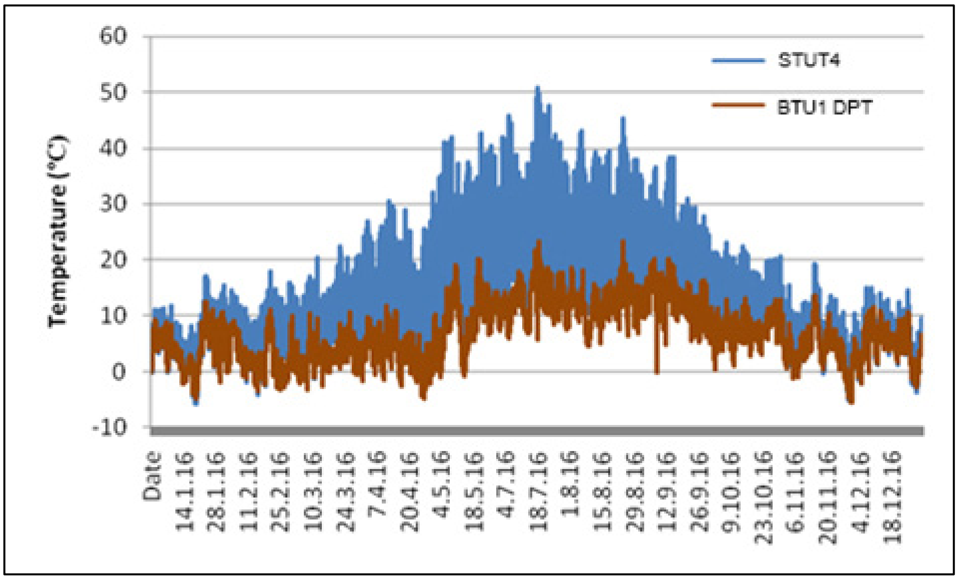


Fig 72: Dew point (DPT) and surface temperature under slates (STUT) for 2016

Surface temperatures frequently dip into dew point zone from November to January, but infrequently during the remainder of the year. This is demonstrated in Figure 73 by subtracting surface temperature on the north side of the building (STUT4) from high level dew point.

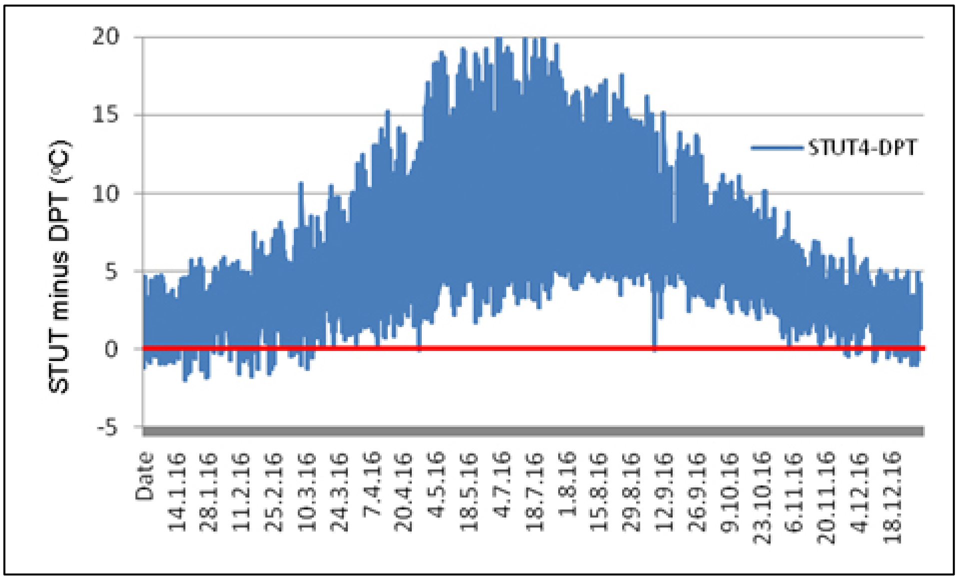


Fig 73: The condensation risk (below red line) on the north slope of the roof during 2016, obtained by subtracting dew point (DPT) from surface temperature under slates (STUT)

4.0 BUILDING 3 'WOODBURY' (HAMPSHIRE)

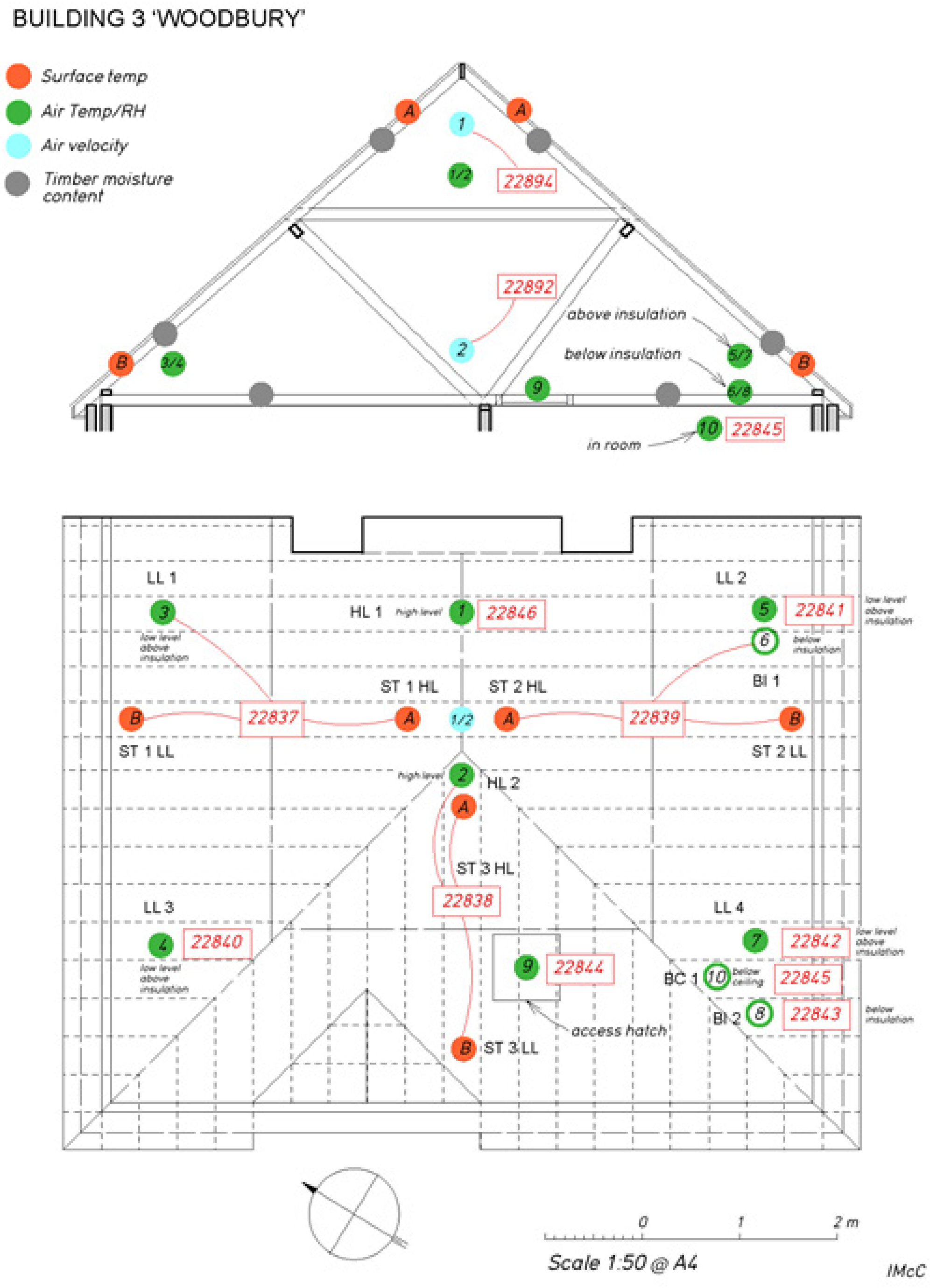
4.1 Roof construction

The roof of Building 3 'Woodbury' is constructed from softwood, covered with plain clay tiles without an underlay. This construction is shown in Figure 75.

The attic floor had a 100mm layer of fibre glass insulation between the joists when monitoring commenced, and this was increased to 300mm in March 2016. The floor is covered with particle board.

Fig 74: Building 3 'Woodbury' attic

4.2 Sensor type and location



Key to Figure 75
STUT = surface temperature under tiles
HL = high level temperature/relative humidity
LL = low level temperature/relative humidity
BI = below insulation temperature/relative humidity
BC = below ceiling temperature/relative humidity
AV = air velocity

4.3 Data analysis: Winter (January/February 2015–2018)

4.3.1 Roof slope orientation and sensor position

A comparison of sensor statistics for temperature (T) for January/February 2015 to 2018 is given in Table 14.

Table 14: January/February high level (HL) and low level (LL) temperature (°C) comparisons for 2015 to 2018

		2015 Jan/Feb	2016 Jan/Feb	2017 Jan/Feb	2018 Jan/Feb
HL1 T Ridge	Maximum	16.6	17.5	20.6	18.5
	Minimum	-0.5	0	0	-1.8
	Median	6.7	7.1	7.1	6.4
	IQR	4.2	4.0	4.6	4.0
HL2 T Gable	Maximum	13.1	12.8	15.8	15.8
	Minimum	-0.8	-2.2	-2.7	-4.4
	Median	6.0	6.4	6.2	5.6
	IQR	4.1	4.4	5.4	4.4
LL1 T North	Maximum	12.8	12.5	15.8	12.3
	Minimum	-2.7	-3.4	-2.4	-4.6
	Median	5.6	6.2	5.8	5.4
	IQR	4.5	4.5	6.0	4.4
LL2 T East	Maximum	13.1	13.1	No data	No data
	Minimum	-1.3	-2.3	No data	No data
	Median	5.9	6.9	No data	No data
	IQR	4.4	3.9	No data	No data
LL3 T South	Maximum	13.7	13.2	16.5	15.3
	Minimum	-0.3	-2.3	-2.5	-4.4
	Median	6.4	6.3	6.5	5.7
	IQR	4.0	4.5	5.4	4.4
LL4 T West	Maximum	13	12.5	16.2	12.6
	Minimum	-1.3	-2.3	-2.4	-4.5
	Median	6.2	6.6	6.3	5.7
	IQR	3.8	4.5	5.3	4.1

Median temperatures and interquartile ranges, excluding the incomplete data from 2017 for LL2 but including exterior temperature, are shown in Figure 76.

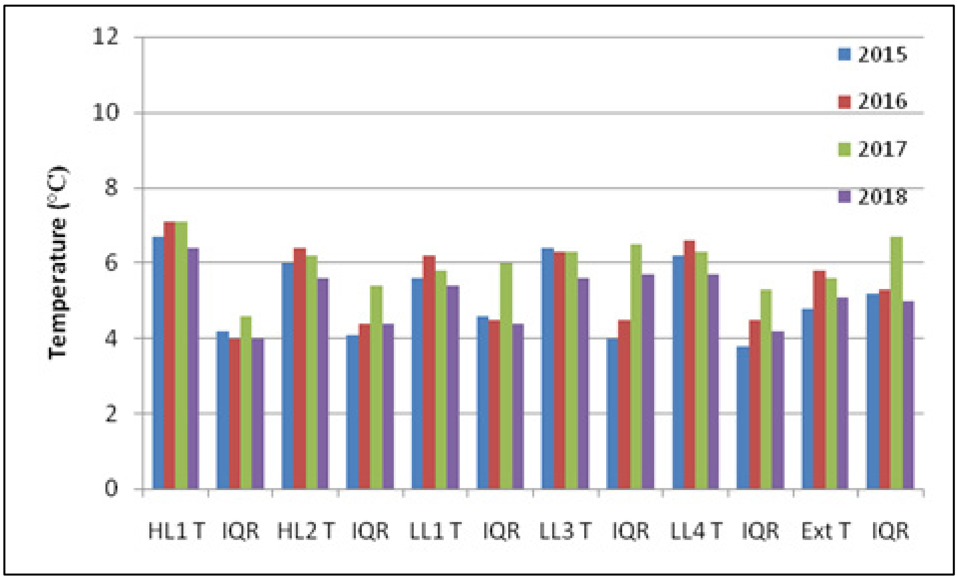


Fig 76: January/February median temperatures (°C) and interquartile ranges (IQR) at different levels and orientations for high level (HL), low level (LL) and exterior (Ext)

Results are rather uniform, and median temperatures vary each year by less than 2°C. Figure 77 presents the data from 2016 as a box plot to demonstrate the similarity between locations. HL1 is slightly warmer and prone to solar gain.

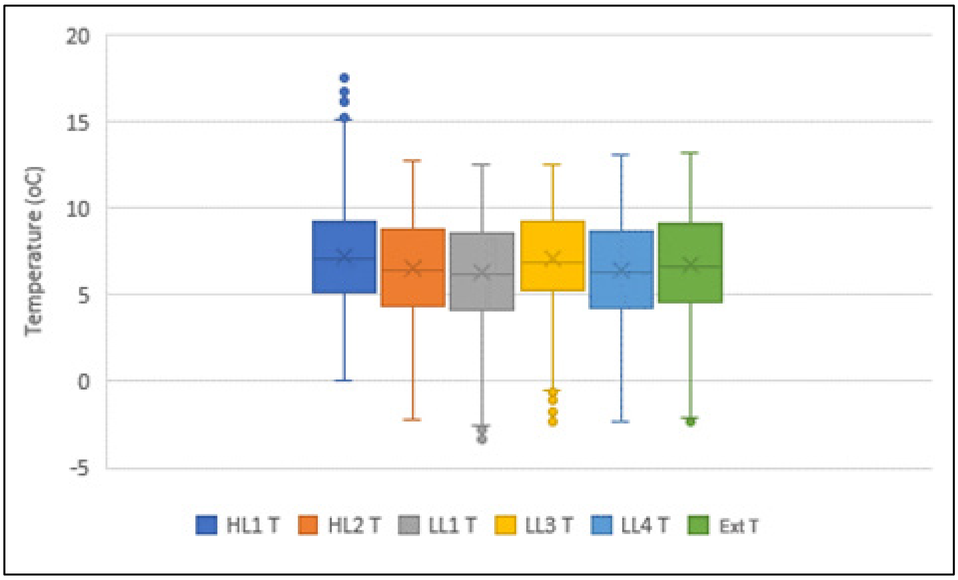


Fig 77: A comparison of median temperatures (°C) and interquartile ranges at high (HL) and low (LL) levels and the exterior (Ext) for January/February 2016

Table 15 and Figure 78 compare the relative humidities (RH).

Table 15: January/February high (HL) and low level (LL) relative humidity (%) comparisons for 2015 to 2018

		2015 Jan/Feb	2016 Jan/Feb	2017 Jan/Feb	2018 Jan/Feb
HL1 RH Ridge	Maximum	97.7	97.0	97.8	97.4
	Minimum	44.5	45.6	40.7	28.1
	Median	86.3	89.2	88.2	86.4
	IQR	9.9	12.6	8.8	11.6
HL2 RH Gable	Maximum	97.5	97.8	97.5	97.7
	Minimum	58.6	52	61.1	45.9
	Median	87.9	90.5	90.8	89.4
	IQR	8.7	10.1	6.2	10.0
LL1 RH North	Maximum	97.7	98.2	97.1	98.1
	Minimum	62.4	56.4	63.1	49.7
	Median	89.4	91.2	92.0	90.3
	IQR	7.0	8.0	4.6	7.6
LL2 RH East	Maximum	96.6	97	No data	No data
	Minimum	58.6	54.5	No data	No data
	Median	67.4	90.4	No data	No data
	IQR	8.7	9.8	No data	No data
LL3 RH South	Maximum	97.3	97.9	97.9	98.1
	Minimum	58.4	53.2	53.2	39.2
	Median	87.4	90.4	81.0	90.2
	IQR	8.7	0.8	7.3	10.2
LL4 RH West	Maximum	96.5	97.2	97.2	97.2
	Minimum	64.8	59.2	59.2	43.6
	Median	86.0	91.0	90.5	89.6
	IQR	8.2	9.9	7.0	9.0

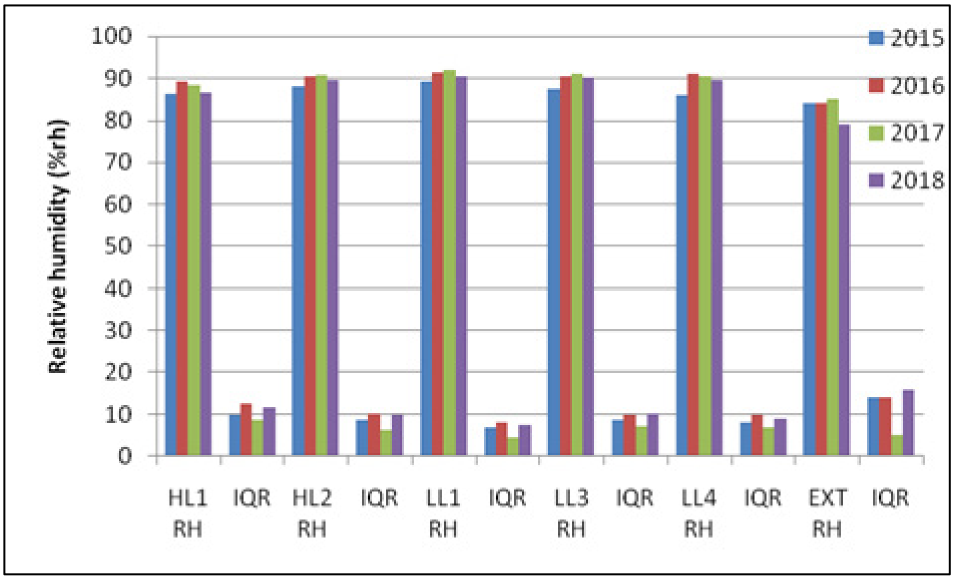


Fig 78: January/February medians and interquartile ranges (IQR) of relative humidity (%) at different levels and orientations

Median and interquartile range relative humidities are very consistent and only slightly higher than those recorded by the exterior weather station. Lack of a felt underlay may mean that there is good air exchange.

4.3.2 Roof covering temperature and condensation

Surface temperatures on the underside of the tiles are presented in Table 16 and Figure 79. High level sensors were located at A and low level at B, as shown in Figure 75.

Table 16: January/February surface temperature (ST) °C under tiles at high (HL) and low levels (LL) for 2015 to 2018

		2015 Jan/Feb	2016 Jan/Feb	2017 Jan/Feb	2018 Jan/Feb
STUT1 HL NW slope	Maximum	14	14.7	18.5	15.6
	Minimum	-1.7	-2.3	-1.6	-4
	Median	5.8	6.1	6.1	5.3
	IQR	4.7	4.8	5.7	4.5
STUT2 HL SE slope	Maximum	20.7	20.5	23.6	17.8
	Minimum	-1.2	-2.1	-1.5	-3.2
	Median	6.1	6.3	6.5	5.9
	IQR	4.9	5.0	5.5	4.2
STUT3 HL SW slope	Maximum	17.8	21.5	22.8	23.5
	Minimum	-0.3	-0.8	-0.3	-3
	Median	6.3	6.5	6.8	5.9
	IQR	4.5	4.5	5.4	4.4
STUT1 LL NW slope	Maximum	12.6	12.8	16.2	12.6
	Minimum	-4.4	-5.6	-5.2	-6.7
	Median	4.7	5.4	4.7	5.2
	IQR	5.1	5.3	5.2	6.6
STUT2 LL SE slope	Maximum	18.6	23	23.4	24.9
	Minimum	-3.7	-5	-5	-6.6
	Median	5.9	6.9	6.3	5.2
	IQR	4.4	3.9	6.5	5.3
STUT3 LL SW slope	Maximum	18.5	21.2	23.1	21.7
	Minimum	-1.7	-3.4	-3	-4.9
	Median	5.9	6.1	6.3	5.5
	IQR	4.5	5.0	5.5	4.6

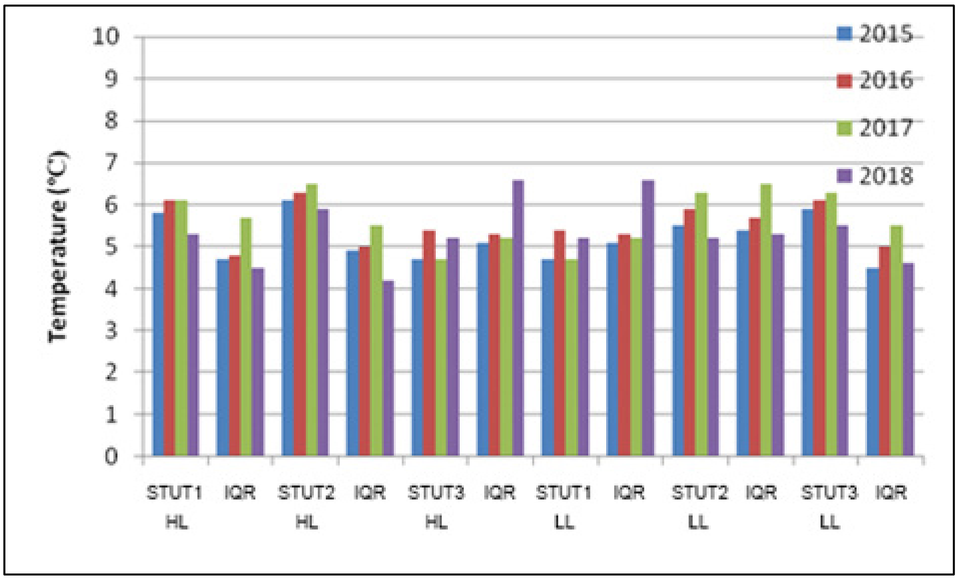


Fig 79: Median and interquartile ranges (IQR) for surface temperatures (°C) at high (HL) and low levels (LL) for January/February 2015 to 2018

Medians and interquartile ranges are similar and do not vary between years by much more than 1°C. Data for 2016 are presented as a box plot in Figure 80.

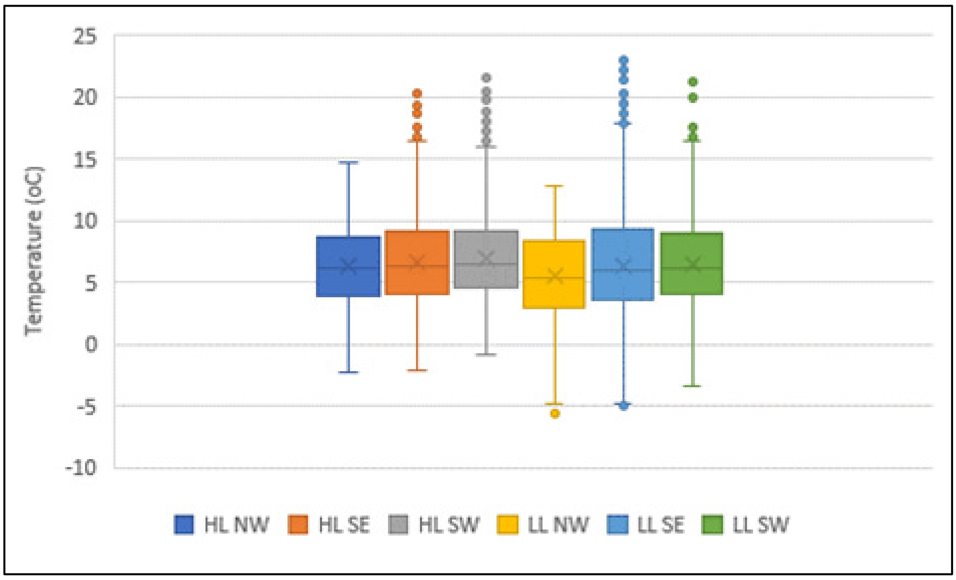


Fig 80: A comparison of high level (HL) and low level (LL) surface temperatures under tiles for January/February 2016

High level and low level interquartile boxes are similar, but the low level sensors record lower minimum values.

Dew point is plotted against surface temperature in Figure 81. Afternoon spikes in temperature raise the dew point, as found in the other roofs, but the dew point spikes remain lower than the temperature spikes so afternoon condensation does not occur. However, condensation is a frequent occurrence at night when temperatures drop.

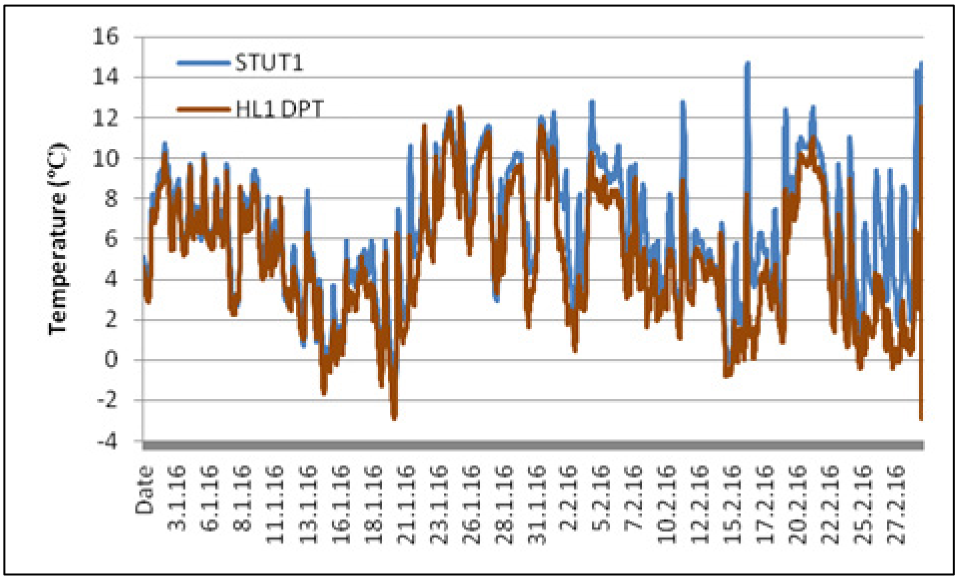


Fig 81: A comparison between high level dew point (HL1 DPT) and surface temperature under the tiles (STUT1)

4.3.3 Condensation and insulation

There was 100mm of glass fibre insulation between the tiles in 2015 and 2016, which was increased to 300mm before winter 2017.

Figures 82 to 89 demonstrate condensation events for January/February of the different years for the north side (STUT1) and the south side (STUT2), when the value obtained from subtracting high level dew point temperature from surface temperature dipped below zero.

Figures 82 to 85 show the environment when there was 100mm of insulation on the joists. Figures 86 to 89 show the condensation events when the insulation was increased to 300mm.

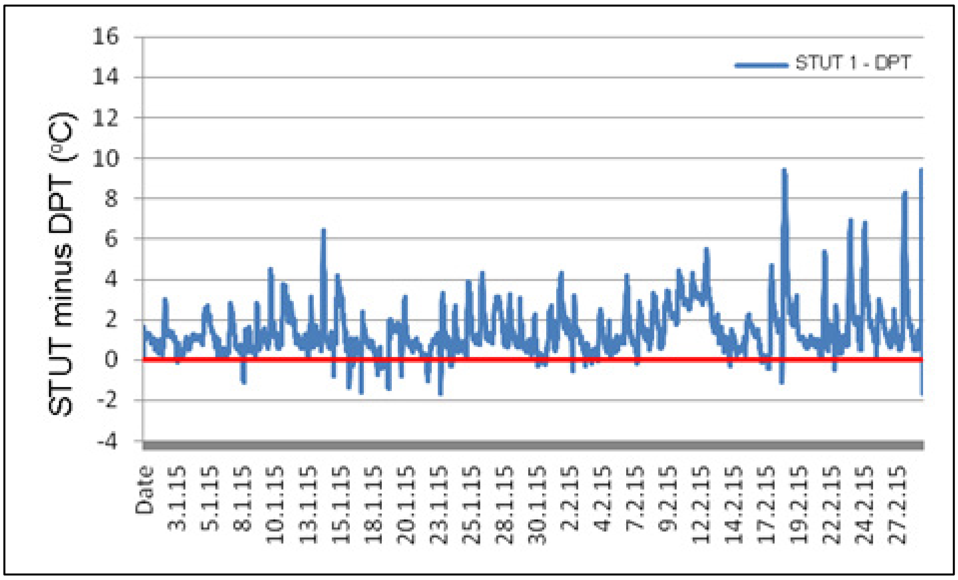


Fig 82: Condensation risk (below red line) on the north slope for January/February 2015 obtained by subtracting dew point (DPT) from surface temperature under tiles (STUT). There was 100mm of insulation between the joists

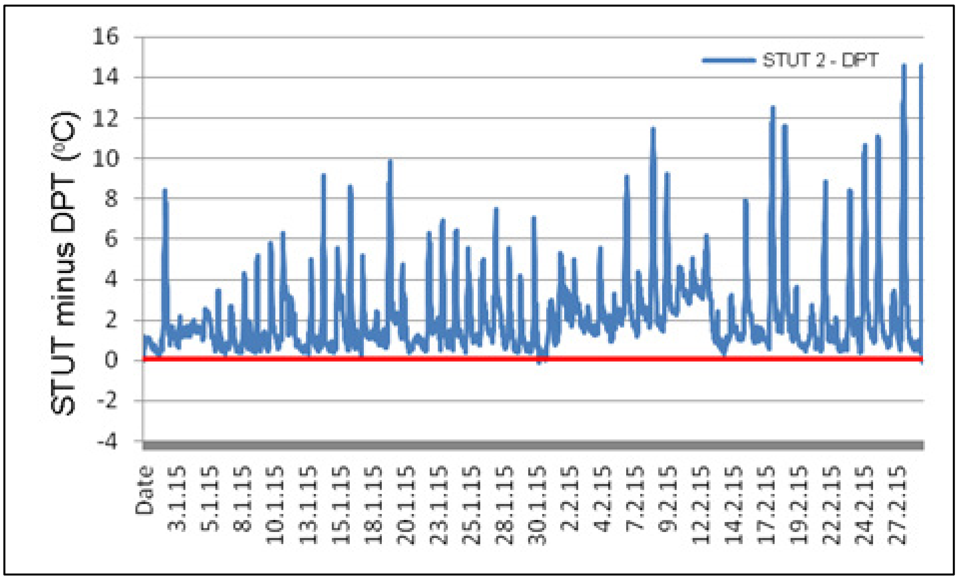


Fig 83: Condensation risk (below red line) on the south slope for January/February 2015 obtained by subtracting dew point (DPT) from surface temperature under tiles (STUT). There was 100mm of insulation between the joists

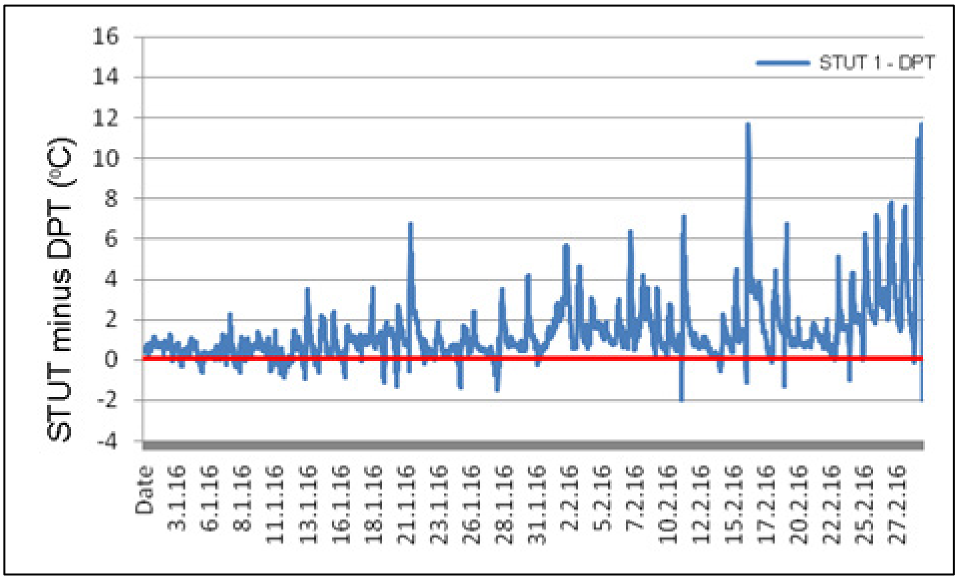


Fig 84: Condensation risk (below red line) on the north slope for January/February 2016 obtained by subtracting dew point (DPT) from surface temperature under tiles (STUT). There was 100mm of insulation between the joists

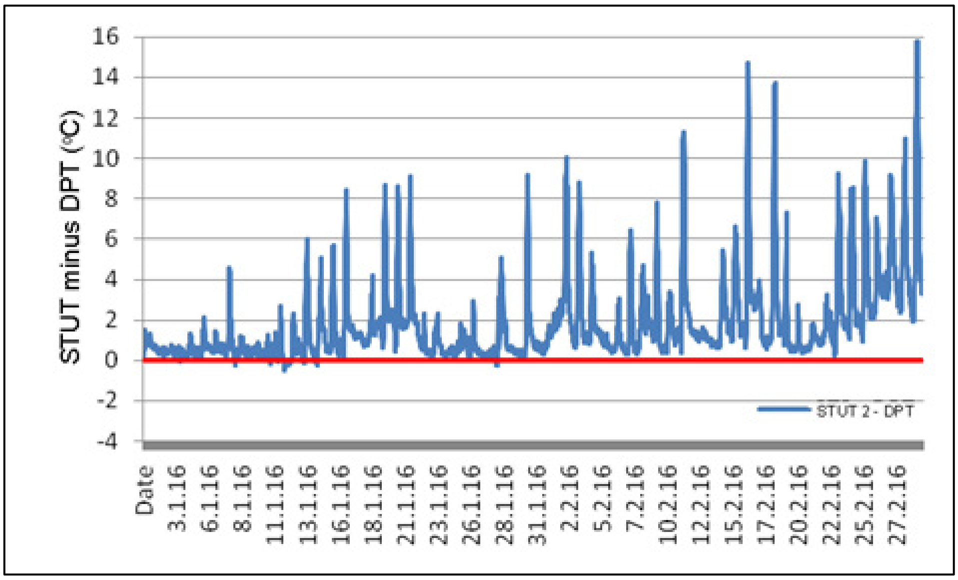


Fig 85: Condensation risk (below red line) on the south slope for January/February 2016 obtained by subtracting dew point (DPT) from surface temperature under tiles (STUT). There was 100mm of insulation between the joists

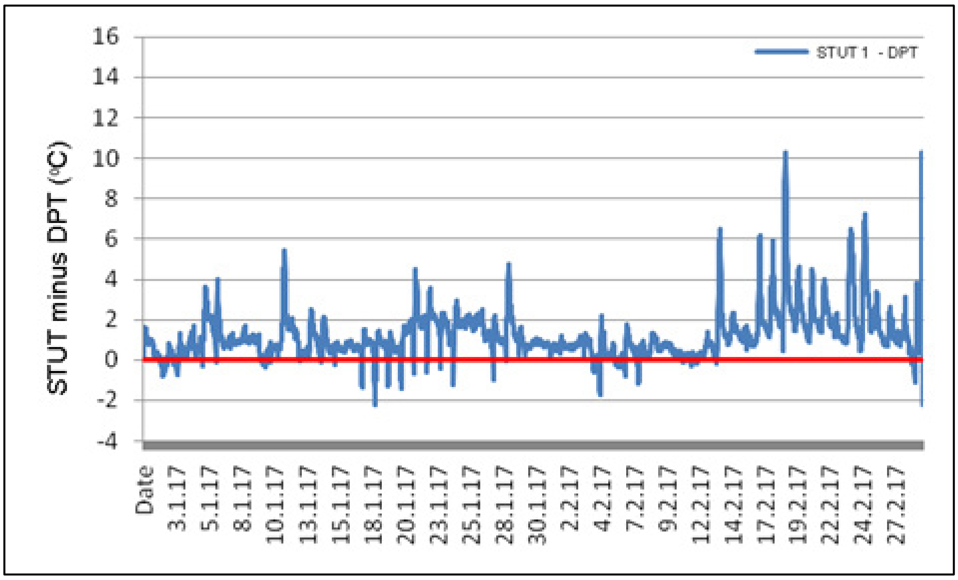


Fig 86: Condensation risk (below red line) on the north slope for January/February 2017 obtained by subtracting dew point (DPT) from surface temperature under tiles (STUT). The thickness of insulation was 300mm

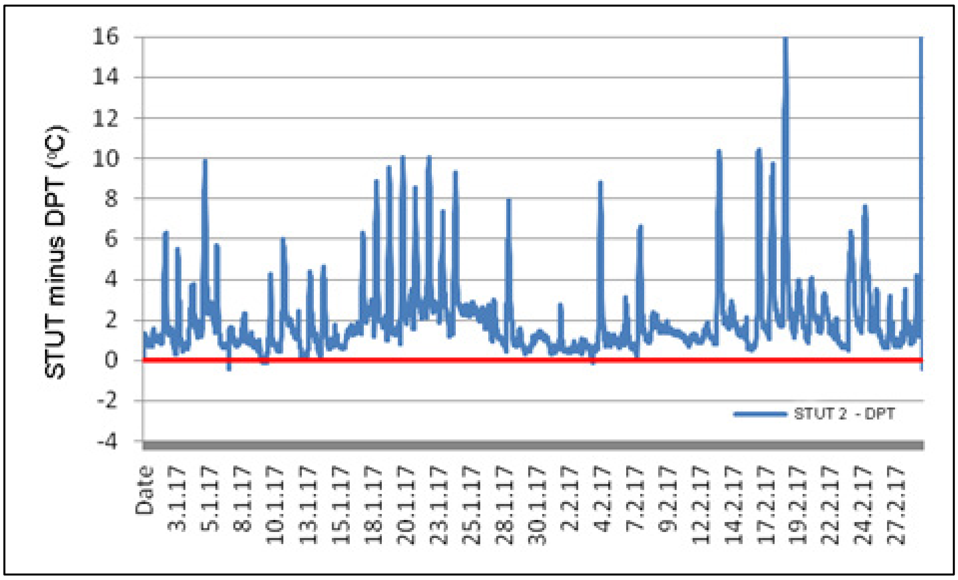


Fig 87: Condensation risk (below red line) on the south slope for January/February 2017 obtained by subtracting dew point (DPT) from surface temperature under tiles (STUT). The thickness of insulation was 300mm

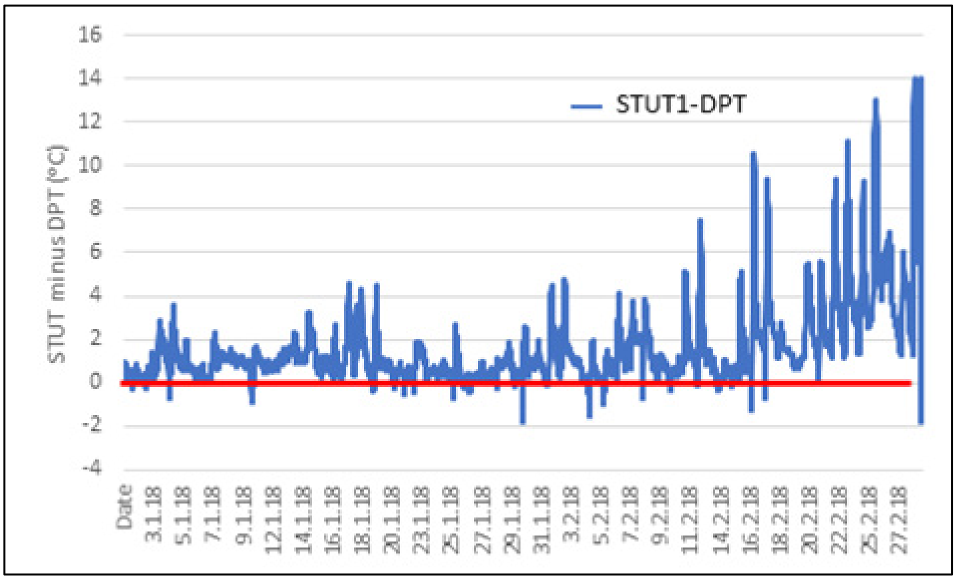


Fig 88: Condensation risk (below red line) on the north slope for January/February 2018 obtained by subtracting dew point (DPT) from surface temperature under tiles (STUT). The thickness of insulation was 300mm

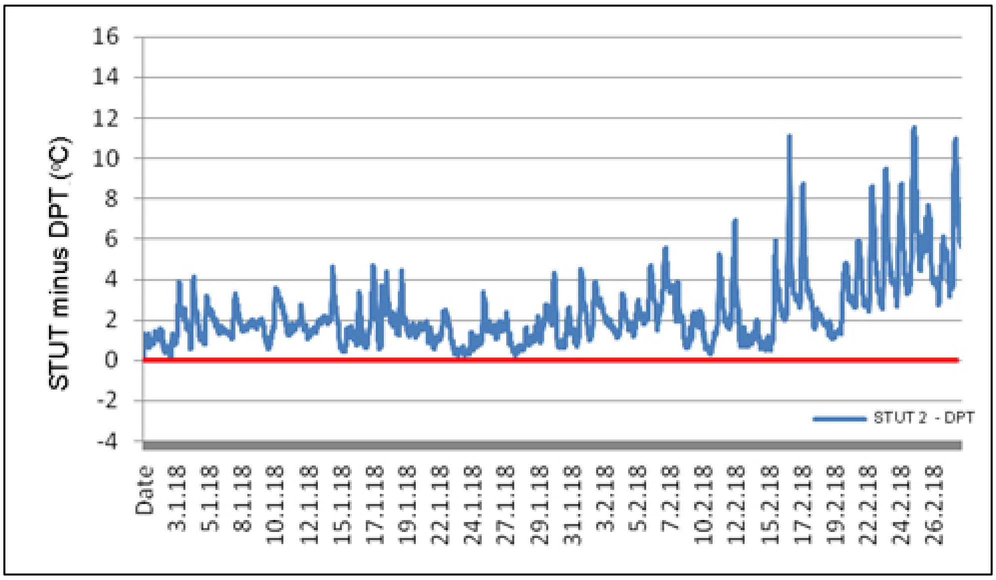


Fig 89: Condensation risk (below red line) on the south slope for January/February 2018 obtained by subtracting dew point (DPT) from surface temperature under tiles (STUT). The thickness of insulation was 300mm

Condensation seems to occur on the north side of the roof, but is a rare event on the south side. There are no indications that deepening the insulation had any significant impact. There is no roofing underlay, so any condensing moisture is probably rapidly absorbed into the tiles and evaporates back into the air as the day progresses.

Table 17 contains the weather data statistics for the four years (January/February 2015–2018), together with the number of readings (at half-hourly intervals) that were negative when dewpoint temperature was subtracted from surface temperature.
These data allow a broad comparison between winter temperatures over four years and condensation events. Results are shaded for the two years when there was only 100mm thickness of insulation and unshaded where this was increased to 300mm.

Table 17: January/February number of negative readings that would result in condensation for 2015 to 2018

Year	Exterior temperature			Number of negative readings	
	Min	Max	Average	NW side	SE side
2015	-3.4	13.6	4.6	122	1
2016	-7.0	13.6	5.7	201	51
2017	-7.1	16.1	5.1	186	11
2018	-7.1	13.8	4.8	108	0

These results suggest that the winter temperatures were generally comparable, although very low readings were not reached in 2015. There is no indication that increasing the thickness of the insulation (years in red) increased the frequency of condensation events.

The consequences of increasing the insulation thickness can also be evaluated by considering the effects on air temperature in the roof. High level temperatures and relative humidities recorded by HL1 are compared for the four years (January/February) in Figures 90 and 91. There are no indications from these box plots that the extra insulation had any effect upon the air temperature in the roof.

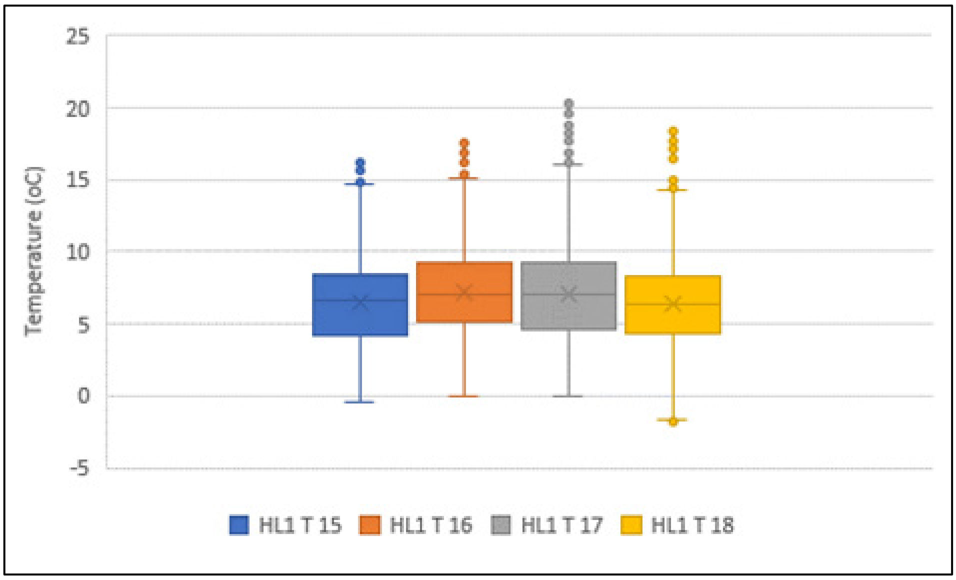


Fig 90: A comparison of high level (HL) temperatures (January/February) for 2015/16, when there was 100mm of insulation between the joists, and 2017/18, when the thickness had been increased to 300mm

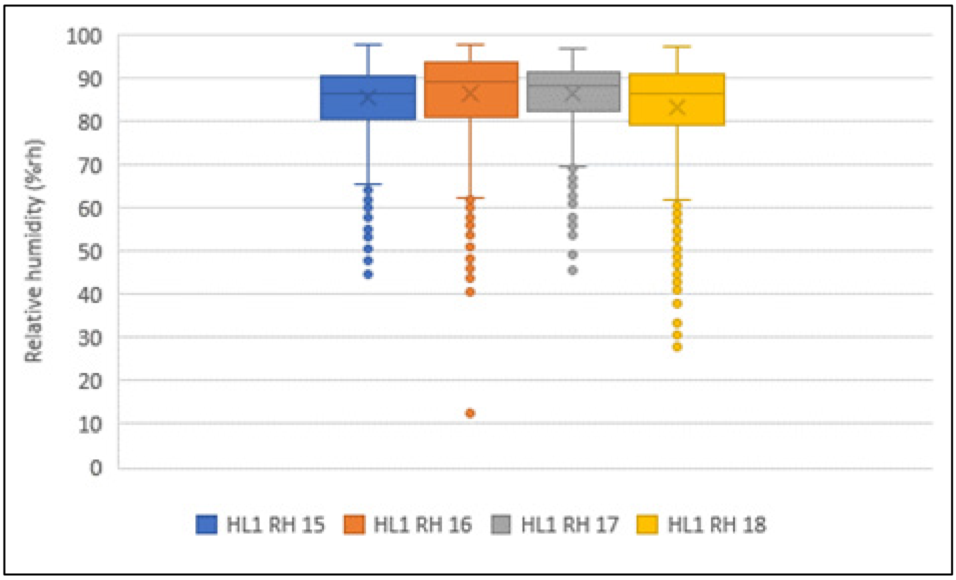


Fig 91: A comparison of high level (HL) relative humidities (January/February) for 2015/16, when there was 100mm of insulation between the joists, and 2017/18, when the thickness had been increased to 300mm

4.3.4 Occupancy and insulation

Below insulation, below ceiling and exterior temperature statistics are compared in Table 18 and Figures 92 and 93.

Table 18: Average temperatures (°C) and relative humidities (%) at high level (HL), low level (LL), below insulation (BI), in the room (BC), and the exterior (Ext) for 2015 to 2018

		2015 Jan/Feb	2016 Jan/Feb	2017 Jan/Feb	2018 Jan/Feb
HL1 T	Maximum	16.6	17.5	20.6	18.5
	Minimum	-0.5	0	0	-1.8
	Median	6.7	7.1	7.1	6.7
	IQR	4.2	4.0	4.6	4.2
LL1 T	Maximum	12.8	12.5	15.8	12.3
	Minimum	-2.7	-3.4	-2.4	-4.6
	Median	5.6	6.2	5.8	5.4
	IQR	4.5	4.5	6.0	4.4
BI1 T	Maximum	21.3	20.1	21.6	22.1
	Minimum	11.4	11.9	13.5	13.3
	Median	18.2	17.4	17.5	17.9
	IQR	2.4	2.1	2.0	1.7
BC1 T	Maximum	25.2	22.6	22.6	21.7
	Minimum	12.3	12.7	14.8	14.2
	Median	19.1	18.4	18.6	17.8
	IQR	2.5	1.7	1.6	1.7
Ext T	Maximum	14.5	13.6	16.1	13.8
	Minimum	-6.1	-7	-7.1	-7.1
	Median	4.8	5.8	5.6	5.1
	IQR	5.2	5.3	6.7	5.0

		2015 Jan/Feb	2016 Jan/Feb	2017 Jan/Feb	2018 Jan/Feb
HL1 RH	Maximum	97.7	97.8	97	97.4
	Minimum	44.5	40.7	45.6	28.1
	Median	86.3	89.2	88.2	86.4
	IQR	9.9	12.6	8.8	11.6
LL1 RH	Maximum	97.7	98.2	97.1	98.1
	Minimum	62.4	56.4	63.1	49.7
	Median	89.4	91.2	92.0	90.3
	IQR	7.0	8.0	4.6	7.6
BI1 RH	Maximum	57.8	64.6	60.4	60.9
	Minimum	31	35.5	38.8	32.5
	Median	42.2	49.1	48.7	47.6
	IQR	7.4	4.8	5.7	7.6
BC1 RH	Maximum	59.2	65	66.3	70.6
	Minimum	28.4	34.4	28.7	21.3
	Median	42.0	51.5	49.2	49.3
	IQR	7.8	7.5	9.9	10.0
Ext RH	Maximum	94	92	93	91
	Minimum	43	42	41	34
	Median	84.0	84.0	85.0	79.0
	IQR	14.0	14.0	9.0	16.0

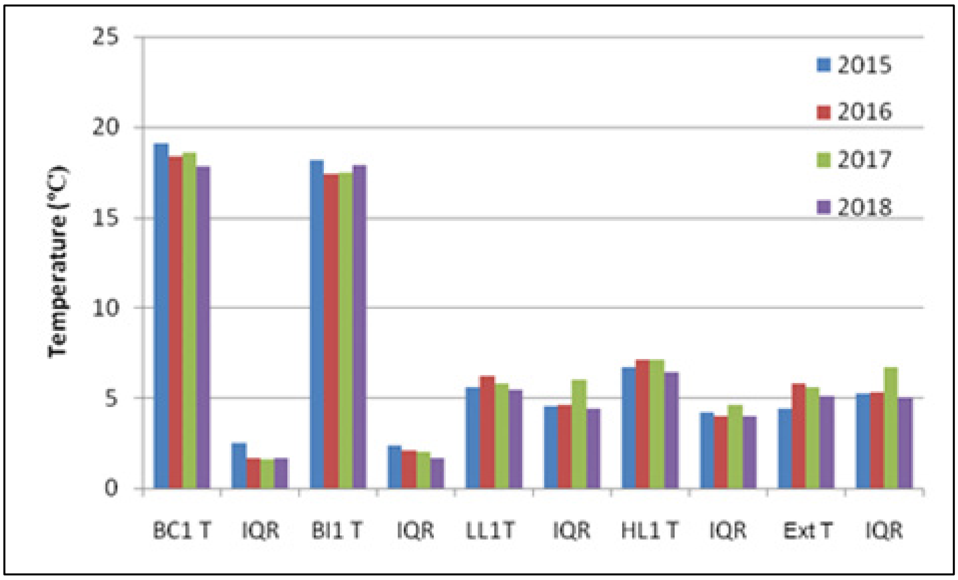


Fig 92: January/February median temperatures (°C) and their interquartile ranges (IQR) in the room (BC), below insulation (BI), low level (LL), high level (HL) and the exterior (Ext) for 2015 to 2018

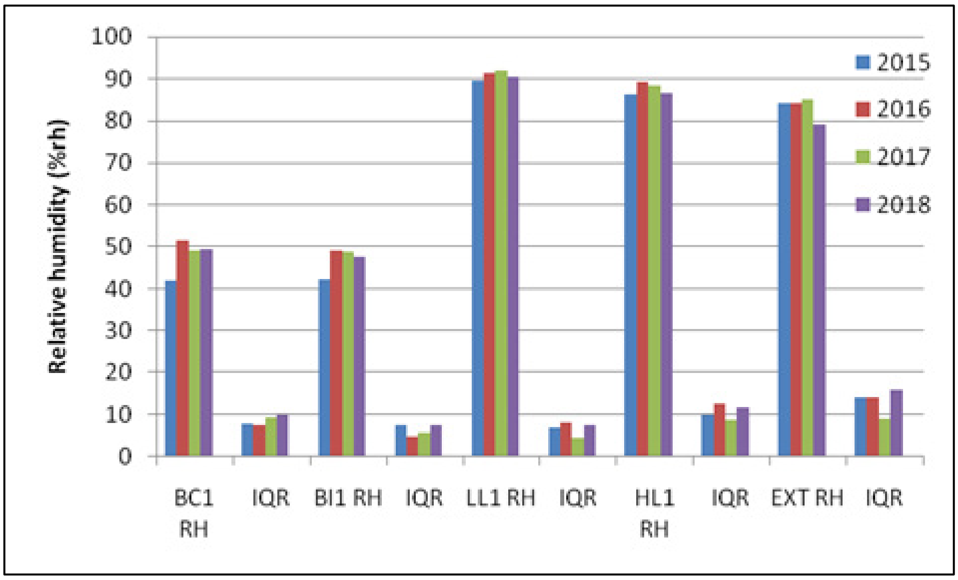


Fig 93: Median relative humidities (%) and their interquartile ranges (IQR) in the room (BC), below insulation (BI), low level (LL), high level (HL) and the exterior (Ext) for 2015 to 2018

Median temperatures and relative humidities below ceiling and below insulation do not vary by much for January/February over the four years. The interquartile ranges are also rather small. Roof space temperatures are much lower and the variation, as demonstrated by the interquartile range, is greater and more like the exterior. Relative humidities are, consequently, much higher in the roof. There are still no indications that increasing the thickness of the insulation affected the roof environment, but this may be because the lack of a roofing underlay enhances air exchange with the exterior.

Figure 94 presents interquartile temperature data from below ceiling to the underside of the tiles for January/February 2016, when there was only 100mm of insulation between the ceiling joists. Figure 95 provides similar data for 2017, when the insulation had been increased to 300mm.

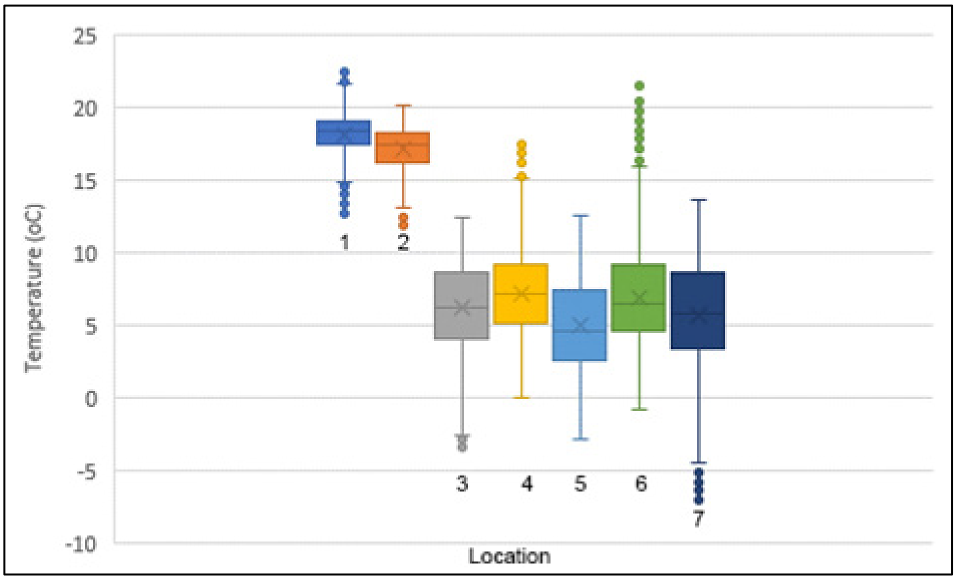


Fig 94: Interquartile temperature ranges (°C) from below the ceiling (BC) to the exterior for January/February 2016, when there was 100mm of glass fibre insulation

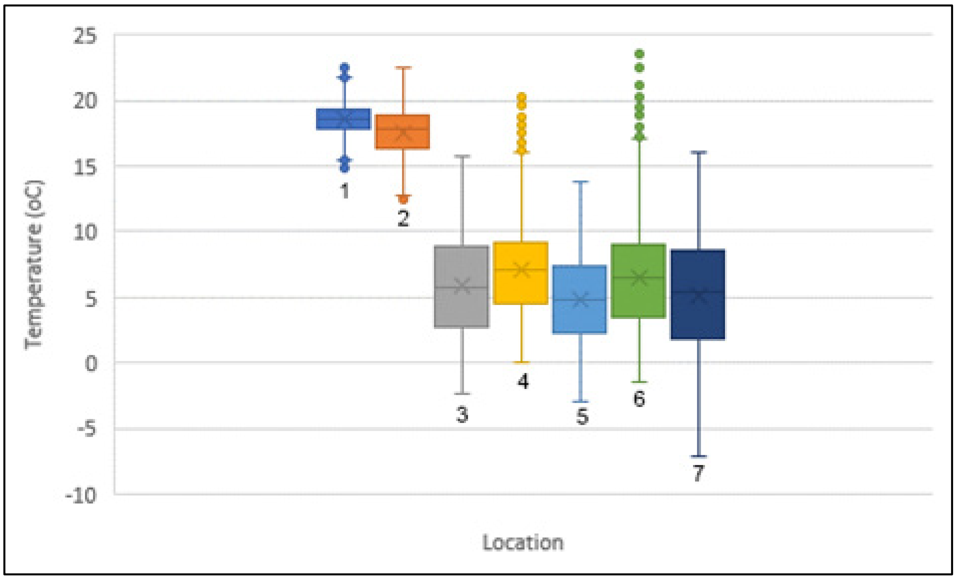


Fig 95: Interquartile temperature ranges (°C) from below the ceiling (BC) to the exterior for January/February 2017, when there was 300mm of glass fibre insulation

Key to Figures 94 and 95
1 = below ceiling (BC1)
2 = below insulation (BI2)
3 = low level (LL1)
4 = high level (HL1)
5 = between tiles and underlay (BTU1)
6 = dew point (HL1 DPT)
7 = surface temperature under tiles (STUT1)

Similar data are presented for relative humidity in Figures 96 and 97.

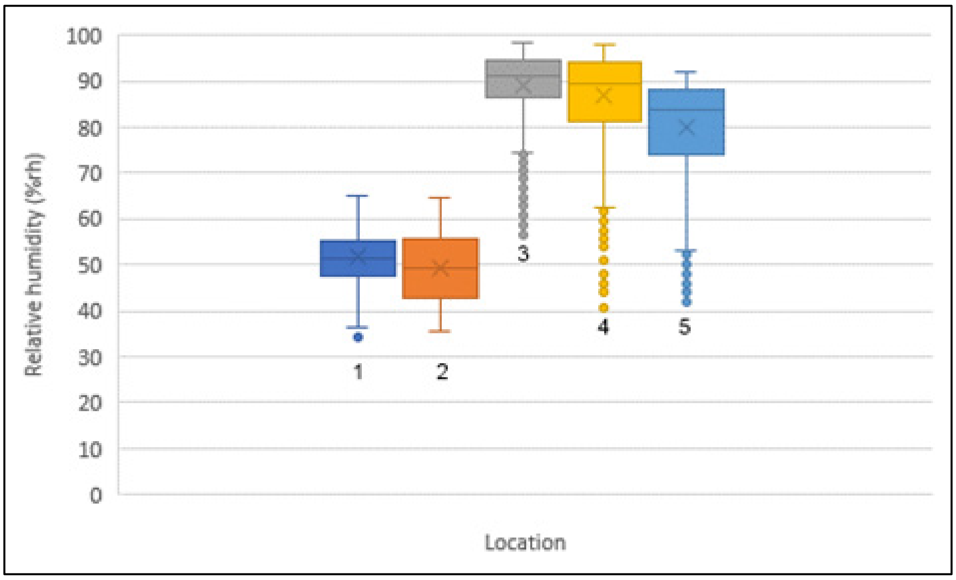


Fig 96: Interquartile relative humidity ranges (%) from below the ceiling (BC) to the exterior for January/February 2016, when there was 100mm of glass fibre insulation

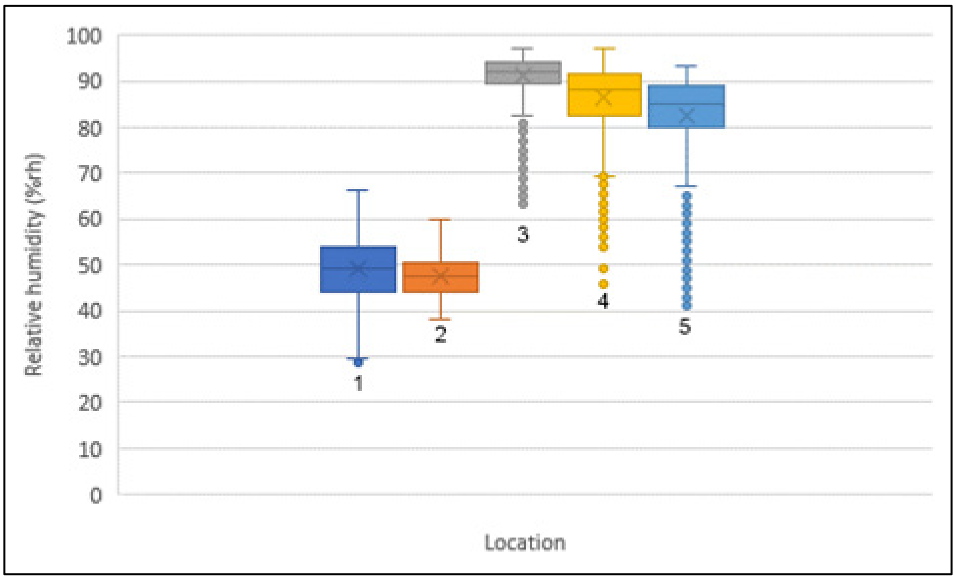


Fig 97: Interquartile relative humidity ranges (%) from below the ceiling (BC) to the exterior for January/February 2017, when there was 300mm of glass fibre insulation

Key to Figures 96 and 97
1 = below ceiling (BC1)
2 = below insulation (BI2)
3 = low level (LL4)
4 = high level (HL1)
5 = exterior (Ext)

None of these box plots suggest any significant environmental consequences resulting from deepening the insulation.

Figures 98 and 99 show that deepening the insulation did not affect the air moisture gradient because glass fibre is non-hygroscopic.

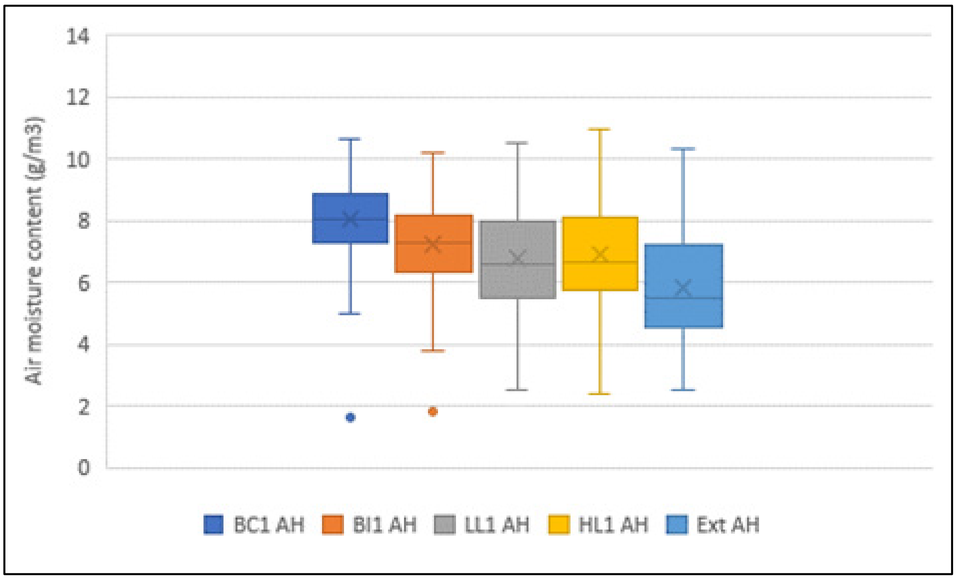


Fig 98: Interquartile air moisture content (g/m³) ranges from below the ceiling (BC) to the exterior (Ext) for January/February 2016, when there was 100mm of glass fibre insulation

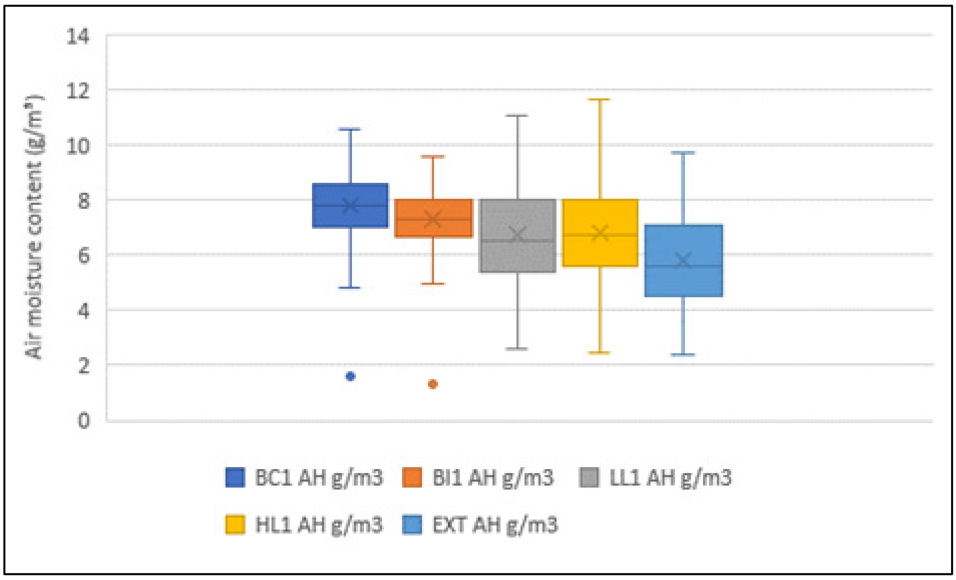


Fig 99: Interquartile air moisture content (g/m³) ranges from below the ceiling (BC) to the exterior (Ext) for January/February 2017, when there was 300mm of glass fibre insulation

4.4 Data analysis: Summer (July/August 2015–2018)

Table 19 compares statistics for the room, through the roof space to the exterior.

Table 19: July/August average temperature (°C) and relative humidity (%) in the roof at low level (LL) and high level (HL), below insulation (BI), in the room (BC), and the exterior (Ext) for 2015 to 2018

		2015 July/August	2016 July/August	2017 July/August	2018 July/August
HL1 T	Maximum	39	35.7	43.6	37.7
	Minimum	10.8	10.3	11.7	9.2
	Median	18,5	20.6	19.7	22.1
	IQR	5.5	7.8	7.2	7.4
HL2 T	Maximum	31.4	34.9	34.5	34.9
	Minimum	8.8	9.7	10.2	9.7
	Median	17.4	18.8	18.1	22.0
	IQR	4.4	6.1	5.5	6.6
LL1 T	Maximum	30.4	39.4	35.5	39.4
	Minimum	7.9	9.8	10.2	8.6
	Median	17.5	19.4	18.3	22.3
	IQR	5.1	7.9	5.2	7.5
LL2 T	Maximum	31.2	33.8	No data	No data
	Minimum	9.0	10.5	No data	No data
	Median	17.4	18.9	No data	No data
	IQR	4.4	5.7	No data	No data
LL3 T	Maximum	32.0	37.2	37.1	41.2
	Minimum	8.4	10.6	10.1	8.9
	Median	17.4	19.3	18.4	22.6
	IQR	4.7	6.5	6.0	8.4
LL4 T	Maximum	30.4	36	36.4	39.3
	Minimum	9.2	10.6	10.5	8.8
	Median	18.0	19.1	18.6	22.3
	IQR	4.2	6.3	5.8	7.6
BI1 T	Maximum	26.2	38.5	29	No data
	Minimum	16.2	10.7	17.6	No data
	Median	20	19.7	21.6	No data
	IQR	2.43	7.2	2.7	No data
BI2 T	Maximum	26.4	30.3	28.2	42
	Minimum	16.2	12	17	8.9
	Median	19.8	20.0	21.4	22.6
	IQR	2.4	4.6	2.6	8.6
BC1 T	Maximum	28	32.7	28.1	30.2
	Minimum	16.8	18.5	18	21.8
	Median	22.5	27.3	21.5	25.7
	IQR	3.0	2.7	2.3	3.2
Ext T	Maximum	29.1	32.6	31.2	33.6
	Minimum	4.1	8.1	6.9	6.2
	Median	16.0	17.3	16.7	18.4
	IQR	5.1	5.7	5.6	7.2

		2015 July/August	2016 July/August	2017 July/August	2018 July/August
HL1 RH	Maximum	96.4	95.6	95.7	92.1
	Minimum	21.7	20.9	21.3	23.4
	Median	68.9	64.2	66.4	59.4
	IQR	24.7	23.4	25.1	22.4
HL2 RH	Maximum	96.3	95	95.7	89.6
	Minimum	35.2	37.4	35	26.2
	Median	75.8	74.5	76.5	59.8
	IQR	19.6	18.2	19.6	20.6
LL1 RH	Maximum	95.2	93.4	94.4	93.9
	Minimum	34.3	35.2	34.7	20.1
	Median	74.4	70.9	74.7	59.4
	IQR	21.4	20.3	19.3	25
LL2 RH	Maximum	95.5	94.3	No data	No data
	Minimum	35.2	38.5	No data	No data
	Median	75.5	73.5	No data	No data
	IQR	20.4	16.8	No data	No data
LL3 RH	Maximum	96.4	92.9	95.8	93.5
	Minimum	34.5	36.2	31.3	20.3
	Median	75.6	70.9	74.0	56.8
	IQR	20.2	18.8	21.5	24.9
LL4 RH	Maximum	94.1	93.5	94	91.7
	Minimum	36.1	35	32.9	22.8
	Median	71.3	71.0	72.6	58.1
	IQR	18	18.5	19.1	23.0
BI1 RH	Maximum	77.1	88.5	68.9	No data
	Minimum	48.4	28.9	51.4	No data
	Median	61.5	67.2	60.9	No data
	IQR	9.3	18.7	5.6	No data
BI2 RH	Maximum	82.6	82.9	69.1	92.2
	Minimum	46.8	50.7	49.1	49.1
	Median	61.7	66.3	60.3	54.4
	IQR	11.9	10.5	6.4	9.6
BC1 RH	Maximum	72.6	73.5	84.3	67.7
	Minimum	36.2	39.3	42.4	38.5
	Median	55.3	60.8	61.6	49.3
	IQR	9.3	7.2	9.1	6.4
Ext RH	Maximum	93	91	92	91
	Minimum	32	26	28	20
	Median	82	75	76	67
	IQR	27	26	28	33

Figures 100 and 101 show that HL1 is a little warmer and, therefore, less humid than HL2. Generally, median high and low level temperatures with their interquartile ranges only differ from each other by less than 3°C each year. Summer 2018 has a higher median temperature than the other years.

Fig 100: July/August median high level (HL) and low level (LL) temperature (°C) compared with exterior (Ext) for 2015 to 2018

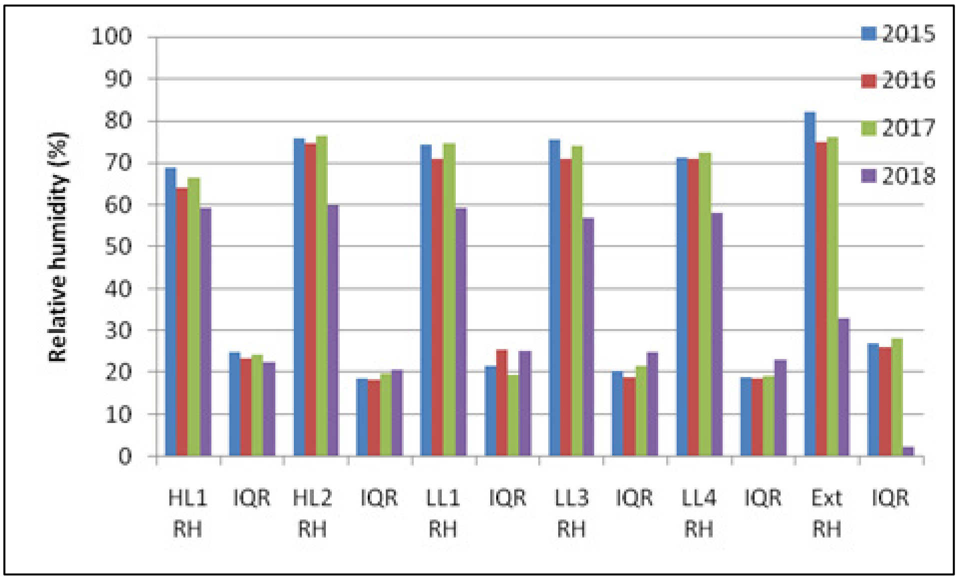


Fig 101: July/August average high level (HL) and low level (LL) relative humidity (%) compared with exterior (Ext) for 2015 to 2018

Figures 102 and 103 compare data for 2016 with 2017. Both demonstrate that the roof temperature closely follows the exterior temperature, with the addition of spikes attributable to solar gain, particularly in 2016.

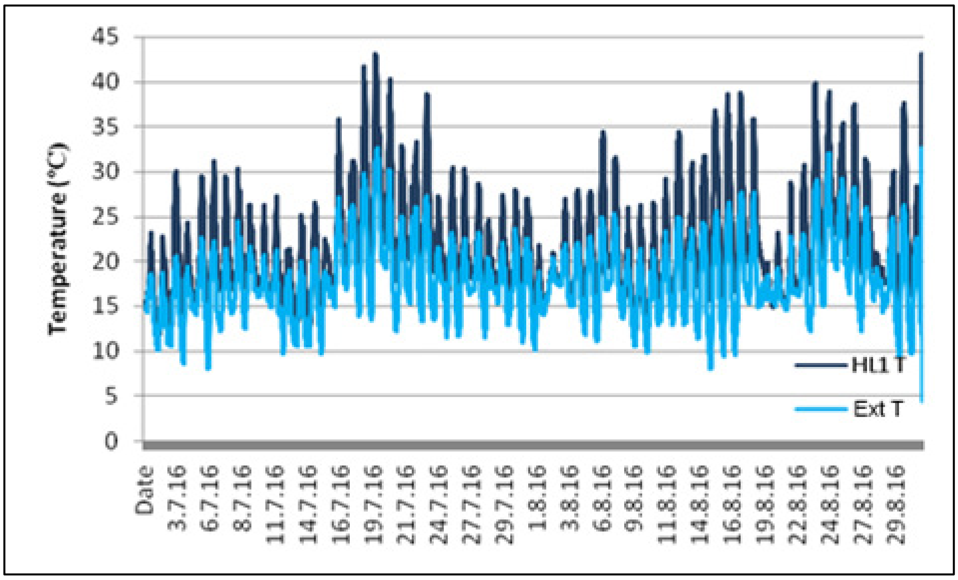


Fig 102: July/August 2016 high level (HL) temperatures compared with exterior (Ext)

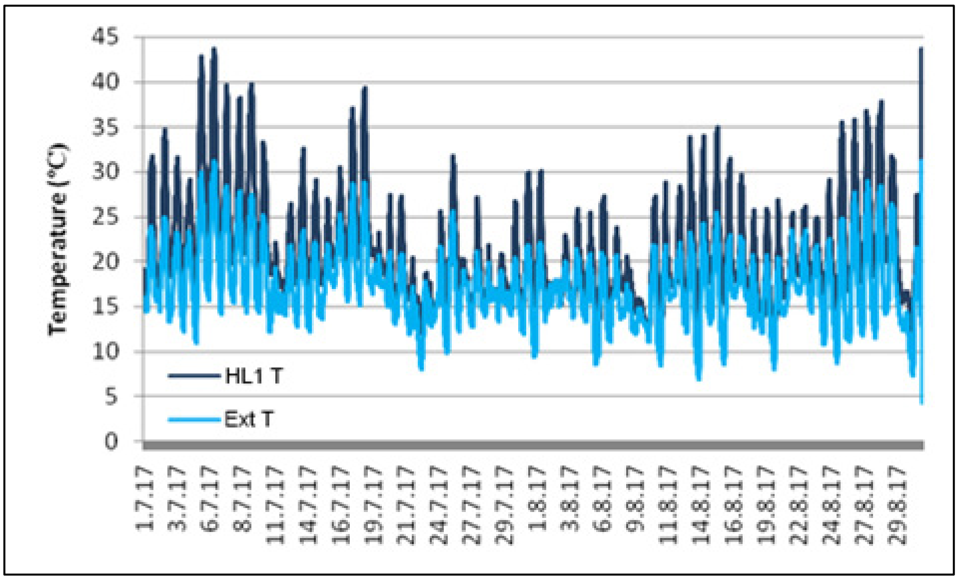


Fig 103: July/August 2017 high level (HL) temperatures compared with exterior (Ext)

Room and below insulation temperature statistics are added in Figure 104 and relative humidity in Figure 105. The room environment tends to be a little warmer than the roof environment, and more stable. Temperature and relative humidity medians and interquartile ranges for 2016 are provided as box plots in Figures 106 and 107.

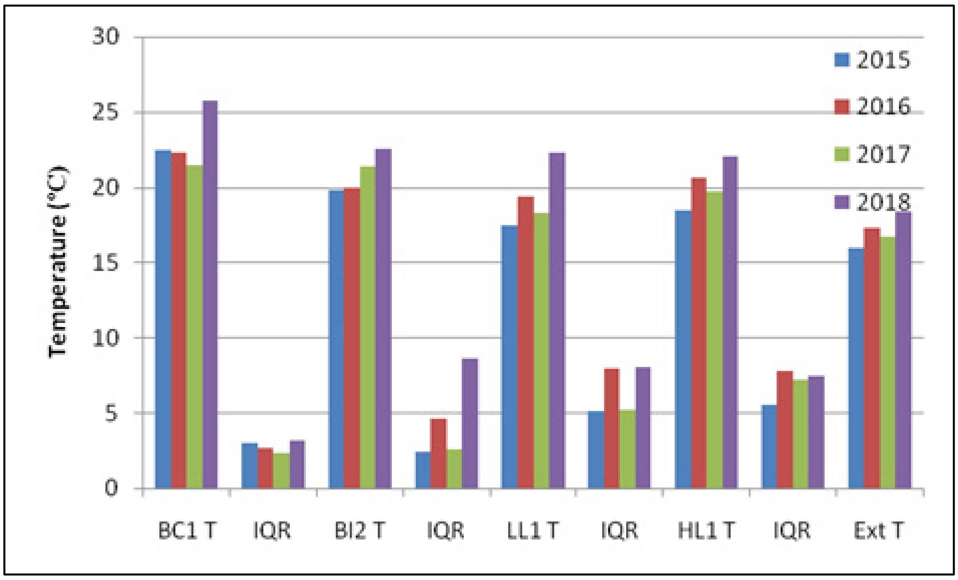


Fig 104: July/August average temperatures (°C) in the room (BC), below insulation (BI), high level (HL), low level (LL) and the exterior (Ext) for 2015 to 2018

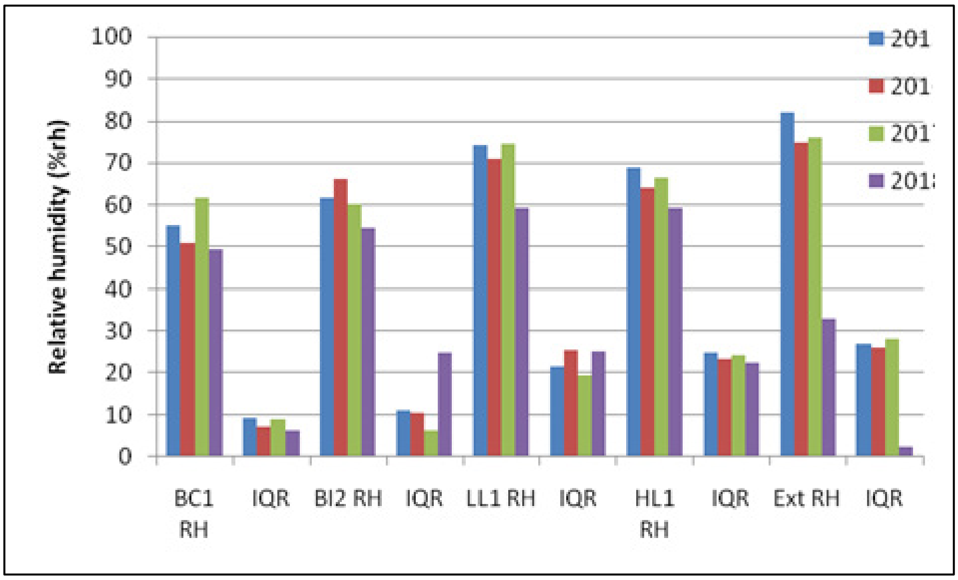


Fig 105: July/August average relative humidities (%) in the room (BC), below insulation (BI), high level (HL), low level (LL) and the exterior (Ext) for 2015 to 2018

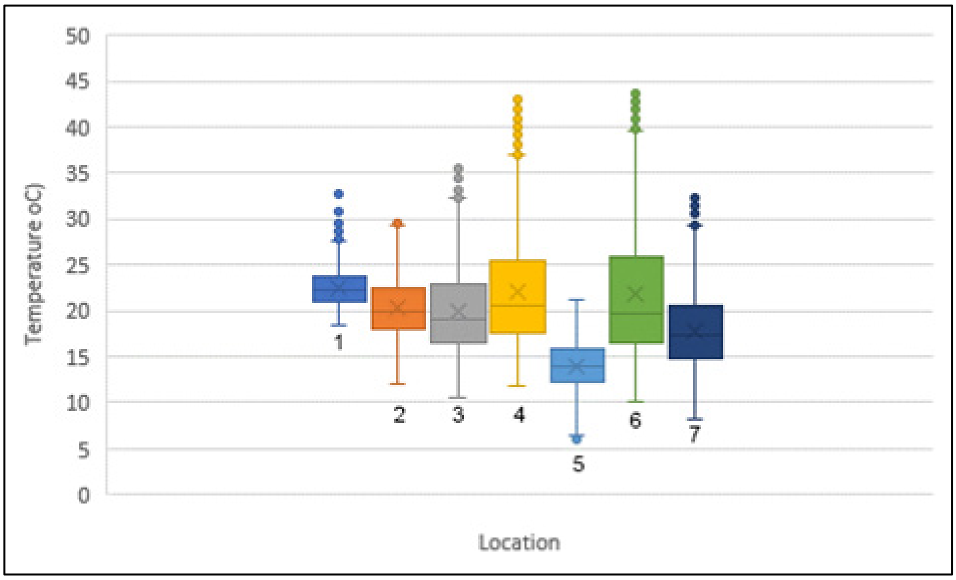


Fig 106: Median and interquartile temperatures (°C) for July/August 2016 from the room, through the roof space to the exterior

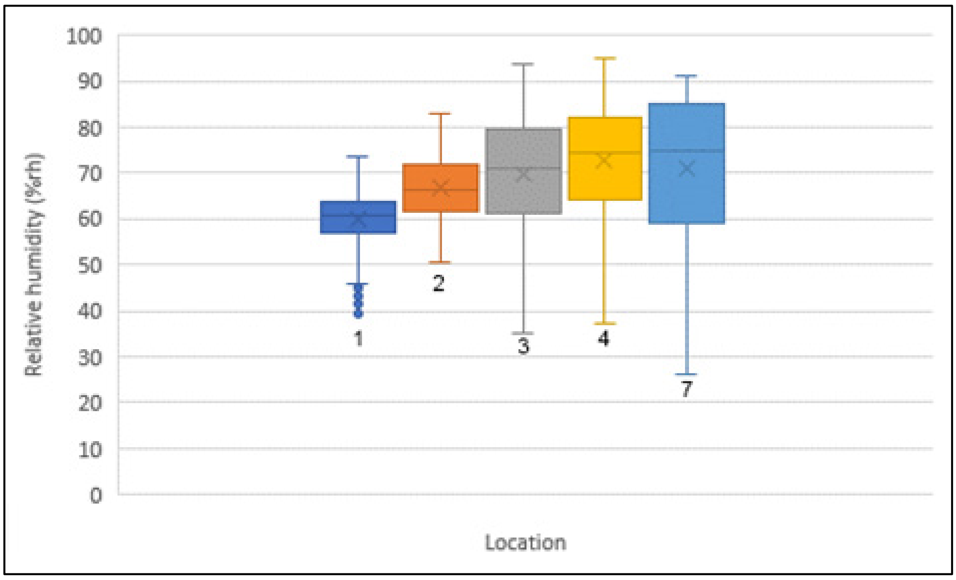


Fig 107: Median and interquartile relative humidities (%) for July/August 2016 from the room, through the roof space to the exterior

Key to Figures 106 and 107
1 = below ceiling (BC1)
2 = below insulation (BI2)
3 = low level (LL4)
4 = high level (HL1)
5 = dew point (HL1 DPT)
6 = surface temperature under tiles (STUT1)
7 = exterior (Ext)

The greatest temperature ranges are shown by the underside of the tiles and the surrounding air. Solar gain, as demonstrated by the outliers and the off-centre median, makes the roof space generally warmer than the exterior. The median from the air below the insulation is generally similar to low level and high level, but with a more limited interquartile range. The median for the room data is slightly higher, but only by about 2°C. Figure 108 shows that the pattern of room and roof temperature change replicates the exterior. The interquartile boxes for relative humidity (Fig 107) increase from below the ceiling to the exterior.

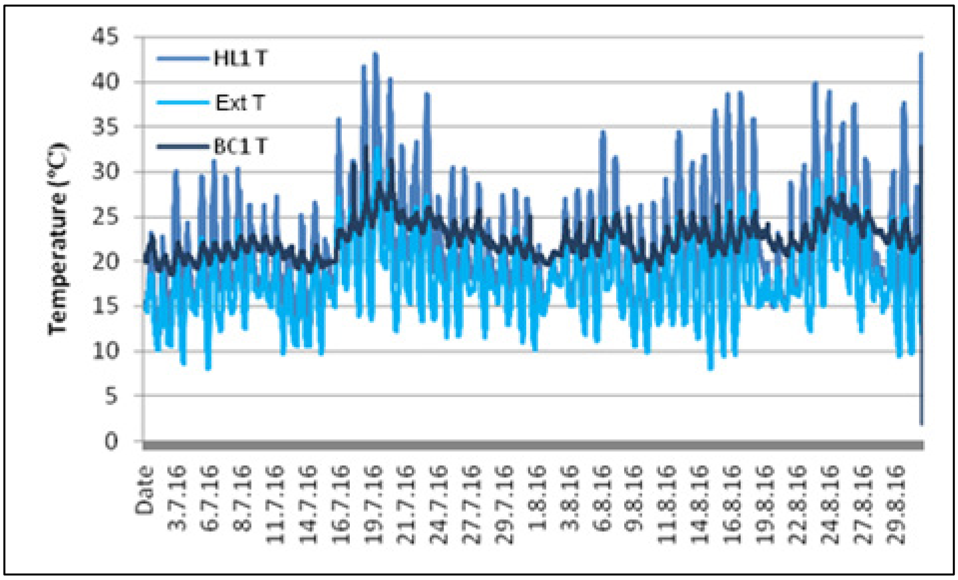


Fig 108: Room (BC1), roof (HL1) and exterior (Ext) temperatures compared for July/August 2016

Surface temperatures under tiles are compared in Table 20. All medians vary by less than 5°C.

Table 20: July/August comparison of surface temperatures (°C) under tiles at high (HL) and low (LL) levels for the years 2015 to 2018

		2015 July/August	2016 July/August	2017 July/August	2018 July/August
STUT1 HL NW slope	Maximum	36.9	41.3	42.5	41
	Minimum	9.4	10.1	10.4	8.6
	Median	17.9	19.8	19	22.5
	IQR	5.9	8.1	7.5	8.2
STUT2 HL SE slope	Maximum	41.6	43.6	39.8	40.5
	Minimum	9.6	10.1	10.8	8.6
	Median	17.8	19.7	18.9	22.2
	IQR	6.3	9.3	6.6	8.2
STUT3 HL SW slope	Maximum	42.5	45.1	45.9	42.7
	Minimum	9.8	11	10.7	9.3
	Median	18.4	20.6	19.6	22.8
	IQR	6.1	8.4	8.0	8.4
STUT1 LL NW slope	Maximum	33.3	38.1	40.4	37.6
	Minimum	6.4	9.7	8.6	9.2
	Median	17.1	18.7	18	22.3
	IQR	6.2	8	7.3	7.5
STUT2 LL SE slope	Maximum	43.6	47.1	48	42.7
	Minimum	6.6	9.6	8.6	9.3
	Median	17.5	20.1	18.9	22.7
	IQR	7.4	10.5	9.4	8.2
STUT3 LL SW slope	Maximum	40.9	44.9	37.1	37.7
	Minimum	8.6	9.7	10.1	9.2
	Median	17.3	18.9	18.2	22
	IQR	5.8	8.1	7.5	7.4

4.5 Building 3 'Woodbury' – Summary

Glass fibre insulation between the joists was increased from 100mm to 300mm thickness halfway through the four-year monitoring period. However, there are no indications from the monitoring data that this had any impact upon the roof environment. This may be because the absence of a roofing underlay means that there is good air exchange with the exterior. However, sensitive air velocity sensors did not record air flow in this roof or in any of the others. Nevertheless, the householder intended to install an underlay because tree pollen was deposited on stored items, indicating some amount of air movement. There certainly would have been a vapour pressure gradient from the inside of the roof to the exterior over the large surface areas of the roof slopes.

Figure 109 plots high level temperature and dew point for 2016. Condensation would seem to be likely during the winter months, with the chance of a rare occurrence during the warmer months. It is possible that increasing the thickness of the insulation might have lowered the temperature in the roof during winter if there had been an underlay beneath the tiles. However, it is difficult to see from Figure 103 why this would have exacerbated the risk from condensation.

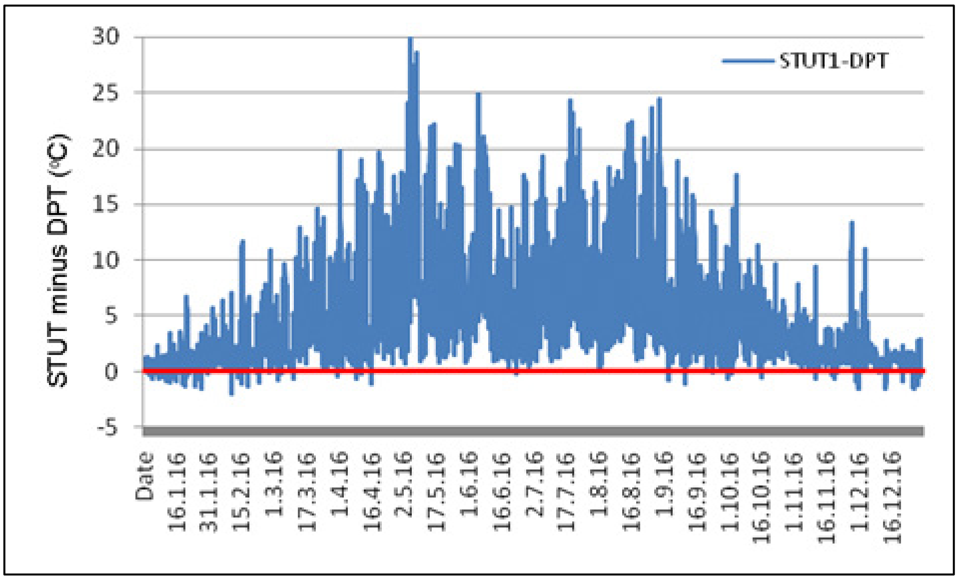


Fig 109: Condensation risk (below red line) for 2016 obtained by subtracting dew point (DPT) from surface temperature (STUT). This demonstrates the risk of condensation or moisture absorption during the winter months

5.0 BUILDING 4 'LONG COMPTON' (WORCESTERSHIRE)

5.1 Roof construction

Building 4 'Long Compton' is a terraced house built in the 1970s. The roof incorporates an impermeable BS747 Type 1F bituminous felt underlay below single lap concrete tiles. There is an eaves board that restricts ventilation. The construction is shown in Figures 110 and 111.

The attic was used for storing household items. In 2014, it was noticed that the original 100mm of glass fibre insulation between the ceiling joists was dirty and compacted. A further 200mm of glass fibre insulation was, therefore, added, covering the ceiling joists and extending into the eaves (Fig 111). A particle board floor was also installed.

Fig 110: Loft construction with an impermeable BS747 Type 1F underlay and a boarded floor

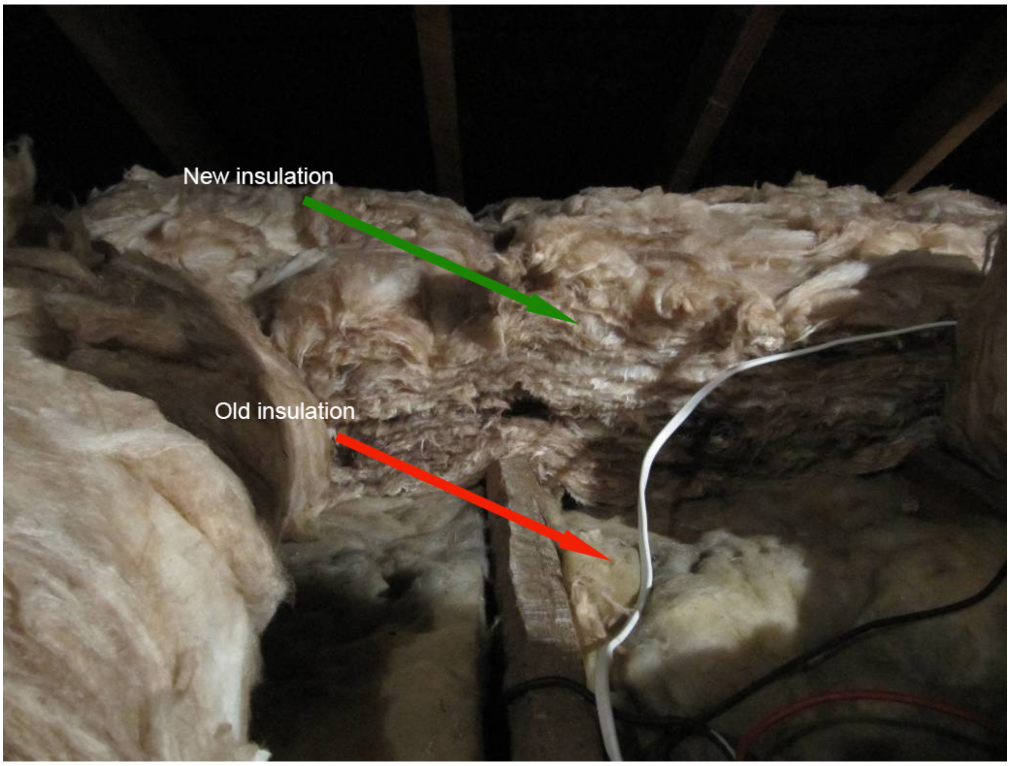


Fig 111: Showing 100mm of glass fibre insulation, increased to 300mm in 2014

5.2 Sensor type and location

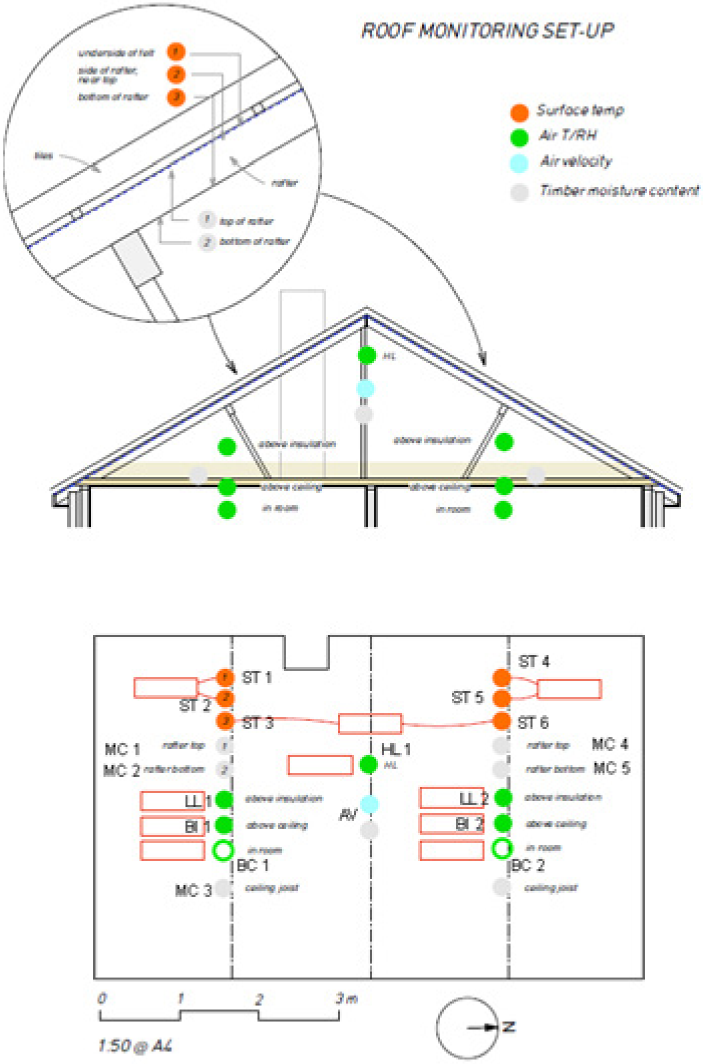


Fig 112: Sensor types and locations

Key for Figure 112
ST = surface temperature (1 and 4 under felt, 2 and 5 side of rafter, 3 and 6 underside of rafter)
HL = high level temperature/relative humidity
LL = low level temperature/relative humidity
BI = below insulation temperature/relative humidity
BC = below ceiling temperature/relative humidity
AV = air velocity
MC = wood moisture content

5.3 Induced condensation

A visit to the attic in November 2015 revealed that the addition of the extra insulation had apparently caused extensive condensation. A leather suitcase was coated in mould, there were drip lines on the floor boarding and water was dripping from the impermeable roof underlay (Fig 113). The additional insulation would seem to have destabilised the roof environment after 30 years of use as dry storage.

Fig 113: A mouldy suitcase, drip marks on the floor boarding and condensation on the impermeable BS747 Type 1F underlay

5.4 Data analysis: Winter (January/February 2018–2019)

5.4.1 Roof slope orientation and sensor position

There are only January/February data for 2018 and 2019. A weather station was installed in 2018, together with sensors between the tiles and the underlay and five wood moisture content sensors. Temperature (T) and relative humidity (RH) medians and interquartile ranges are compared in Table 21 and Figure 114.

Table 21: January/February median temperature (°C) and relative humidity (%) at high level (HL), low level (LL), between the tiles and underlay (BTU) and the exterior (Ext) for 2018 and 2019

		2018 Jan/Feb	2019 Jan/Feb
HL1 T Ridge	Maximum	14	25.8
	Minimum	2.2	1.2
	Median	7.5	8.6
	IQR	2.7	3.6
LL1 T N slope	Maximum	13.2	22.3
	Minimum	2	1.0
	Median	7.4	8.6
	IQR	2.7	3.6
LL2 T S slope	Maximum	12.9	19.8
	Minimum	2.3	1.2
	Median	7.4	8.7
	IQR	2.6	3.6
BTU1 T S slope	Maximum	No data	35.1
	Minimum	No data	-2.1
	Median	No data	7.3
	IQR	No data	4.6
BTU2 T N slope	Maximum	No data	18.6
	Minimum	No data	-2.9
	Median	No data	7.0
	IQR	No data	2.1
Ext T	Maximum	No data	18.6
	Minimum	No data	-6.5
	Median	No data	5.1
	IQR	No data	5.9

		2018 Jan/Feb	2019 Jan/Feb
HL1 RH Ridge	Maximum	94	92.8
	Minimum	73.2	41
	Median	88.7	85.4
	IQR	3.9	6.8
LL1 RH N slope	Maximum	94.6	94.2
	Minimum	73.6	56.8
	Median	89.1	86.4
	IQR	4.9	7.3
LL2 RH S slope	Maximum	95.3	93.5
	Minimum	77	61.8
	Median	90.7	86.9
	IQR	3.7	6.3
BTU1 RH S slope	Maximum	No data	100
	Minimum	No data	15.6
	Median	No data	93.1
	IQR	No data	13.5
BTU2 RH N slope	Maximum	No data	100
	Minimum	No data	69.5
	Median	No data	92.4
	IQR	No data	8.7
Ext RH	Maximum	No data	94
	Minimum	No data	32
	Median	No data	84.0
	IQR	No data	13.5

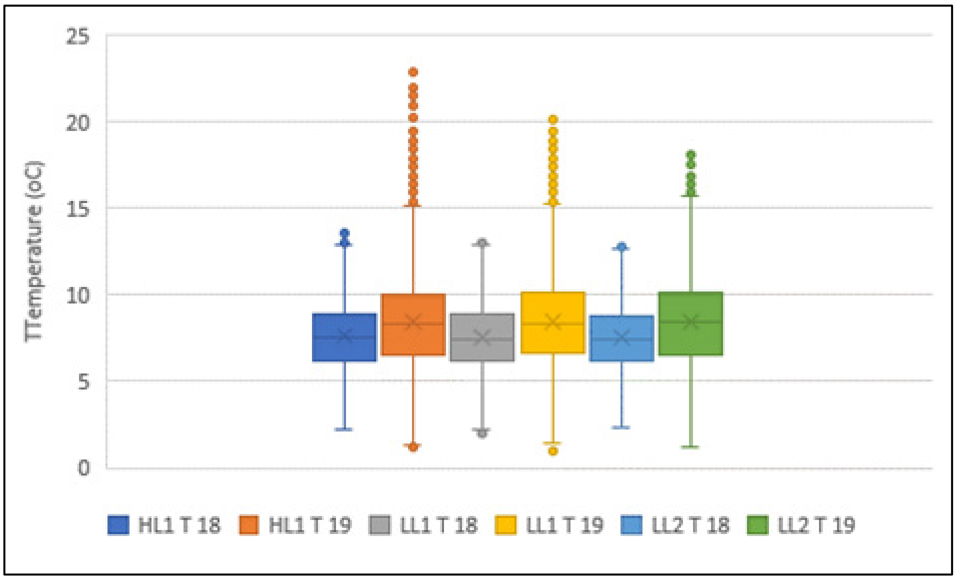


Fig 114: A comparison of high (HL) and low level (LL) temperatures for January/February 2018 and 2019

Interquartile blocks for high and low level are similar within each year. However, 2019 was warmer and there are extensive outliers under the south slope of the roof caused by solar gain. Plots for relative humidity are provided in Figure 115.

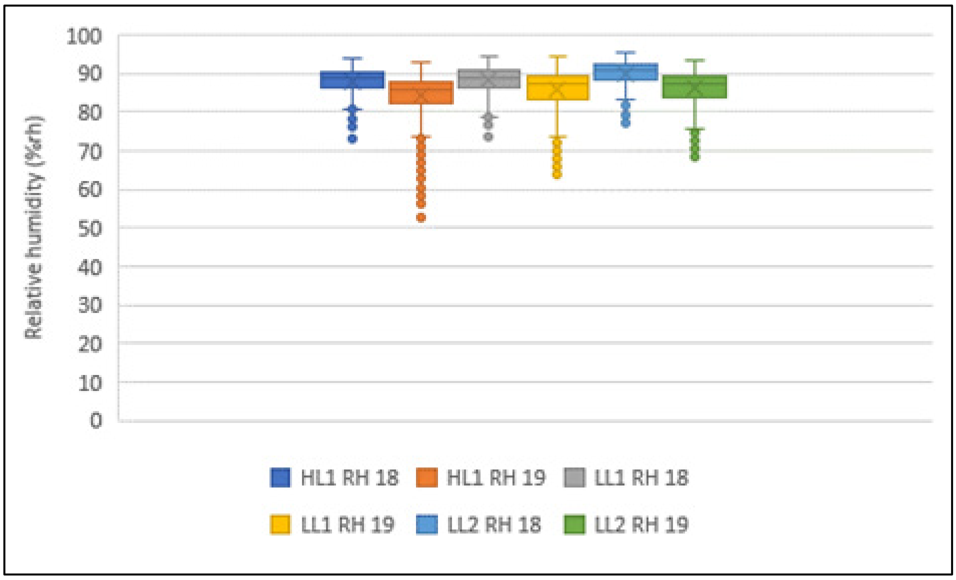


Fig 115: A comparison of high (HL) and low level (LL) relative humidity (%) for January/February 2018 and 2019

The 2019 temperature fluctuations and their consequences for relative humidity are shown in Figures 116.

The roof is very humid when temperatures are low, but the humidity drops considerably (particularly at high level) when the temperature rises at the end of February (Fig 116).

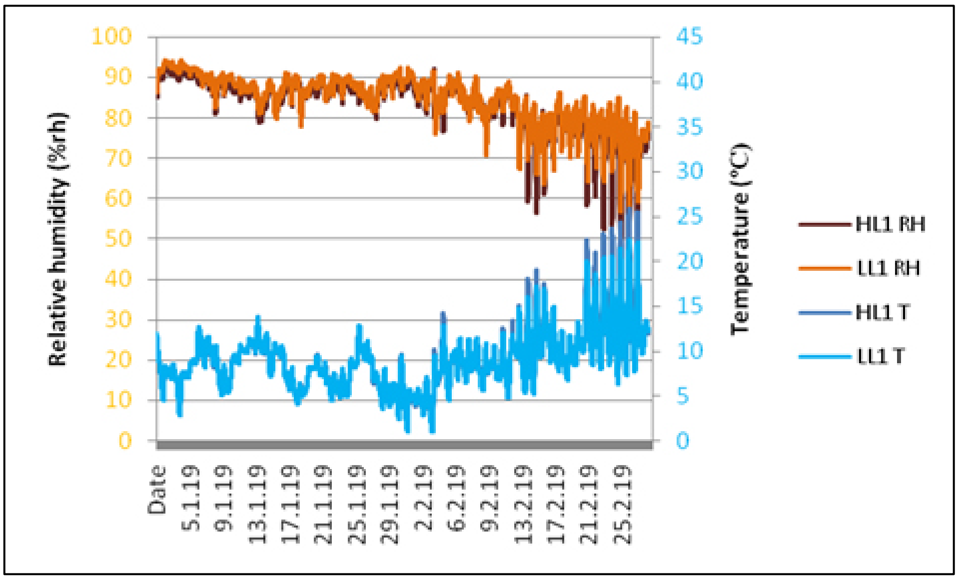


Fig 116: January/February 2019 temperature (°C) and relative humidity (%) comparisons between high (HL) and low level (LL) within the roof space

5.4.2 Roof covering temperature and condensation

Surface temperatures were measured on the underside of the underlay and not on the underside of the tiles. Box plots are provided in Figure 117. There are no data for the south slope (ST1) for 2018.

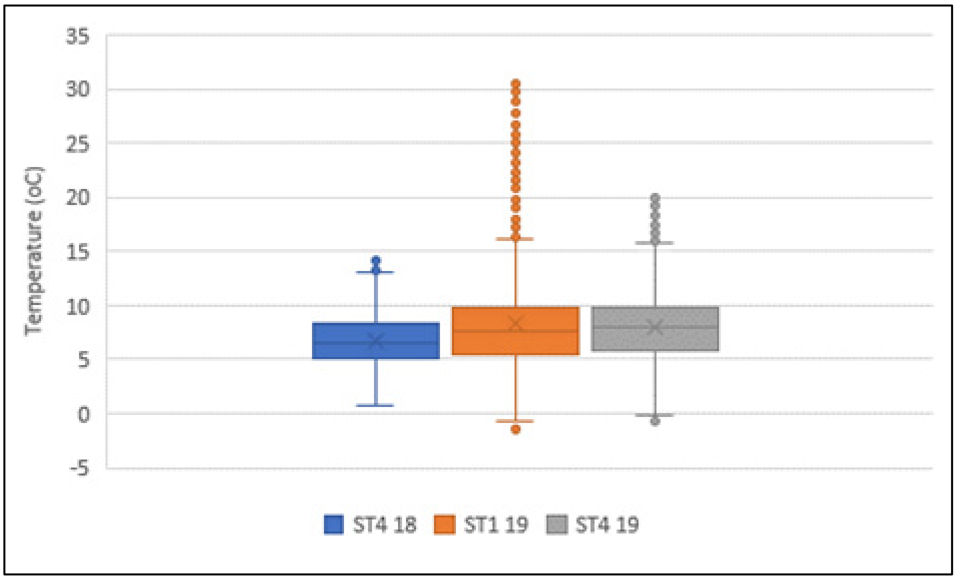


Fig 117: Surface temperature (°C) under felt data for 2018 and 2019

Figure 117 shows that the surface temperatures on the underside of the underlay are similar for the north (ST4) and south (ST1) slopes, but solar gain has a strong effect on the south side. If the data are plotted, this is particularly noticeable towards the end of February (Fig 118).

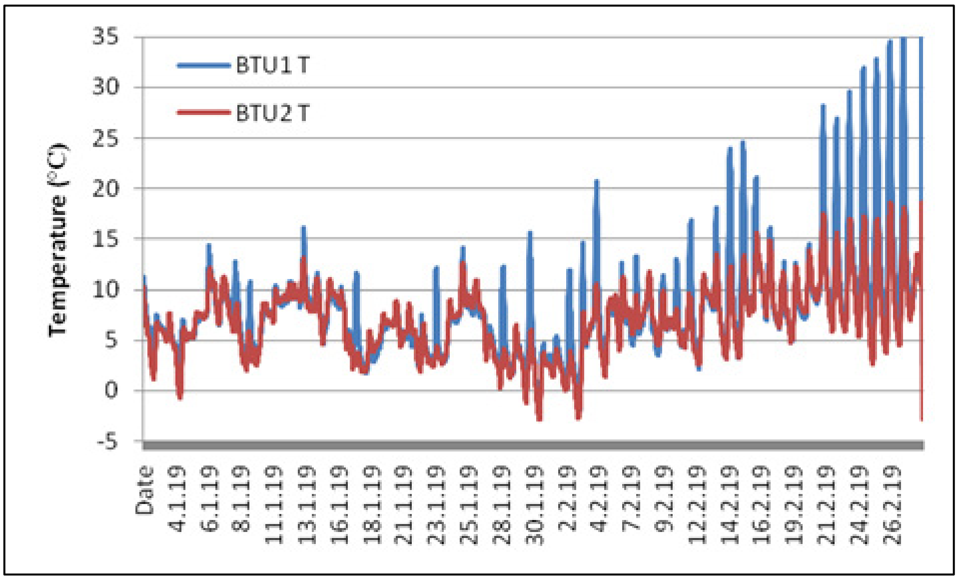


Fig 118: A comparison of January/February 2019 daytime solar gain between the south slope (BTU1) and the north slope (BTU2)

This additional heat gain warms the roof environment in comparison with the exterior (Fig 119).

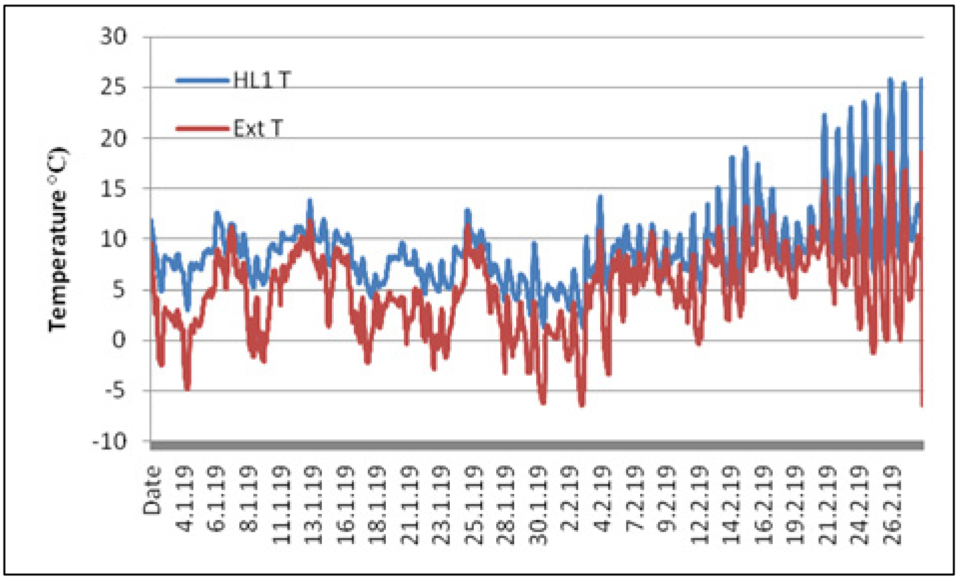


Fig 119: In January/February 2019, the roof environment (HL1) is warmer than the exterior (Ext) because of solar gain

The temperature spikes shown in Figure 119 lower relative humidity. However, they still recycle some moisture from the structure so there are also spikes in air moisture content (Fig 120).

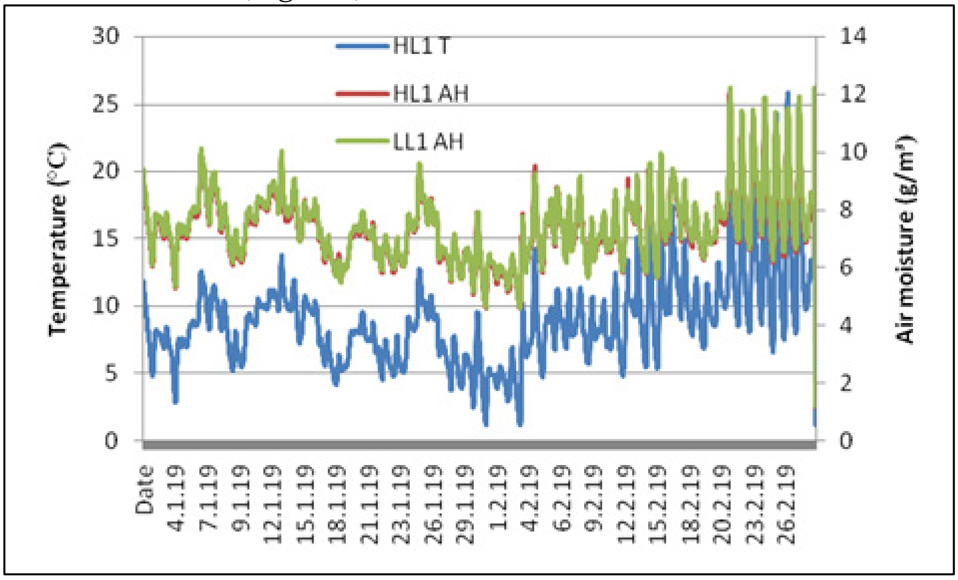


Fig 120: January/February 2019 air moisture contents (g/m³) rise with temperature (°C) increases, particularly at low level (LL1)

Figure 121 shows the condensation events on the north side of the roof in 2018 (no data from south side), when the dew point at high level is subtracted from the surface temperature under the felt. Figures 122 and 123 plot surface temperature on the underside of the underlay minus dew point and show similar data for both slopes during January and February 2019.

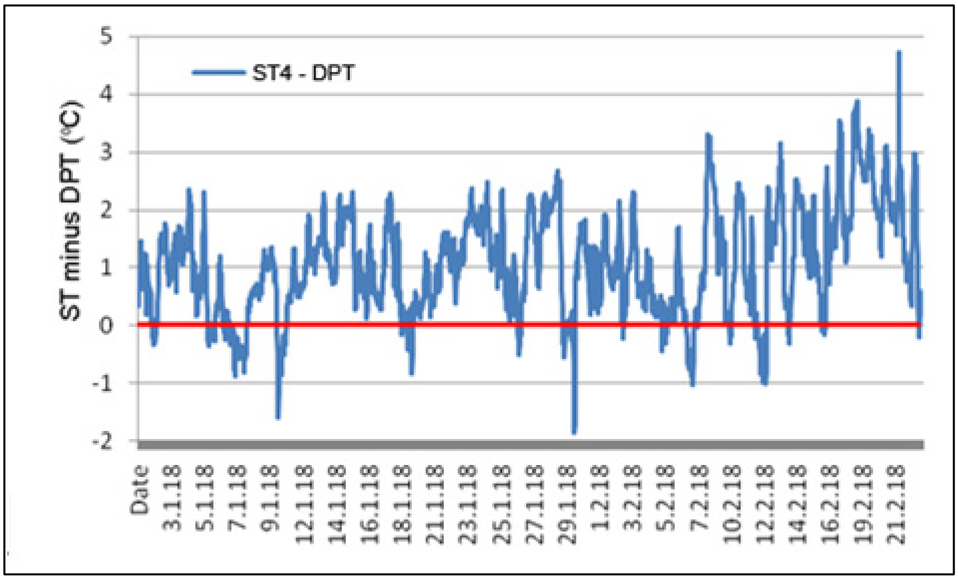


Fig 121: January/February 2018 condensation events (below red line) for the north slope of the roof

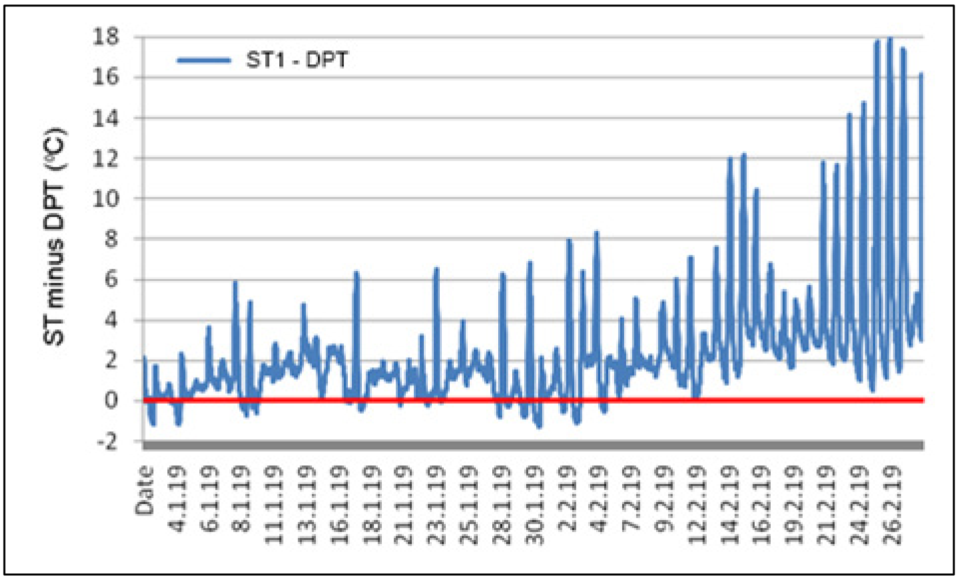


Fig 122: January/February 2019 condensation events (below red line) for the south slope of the roof

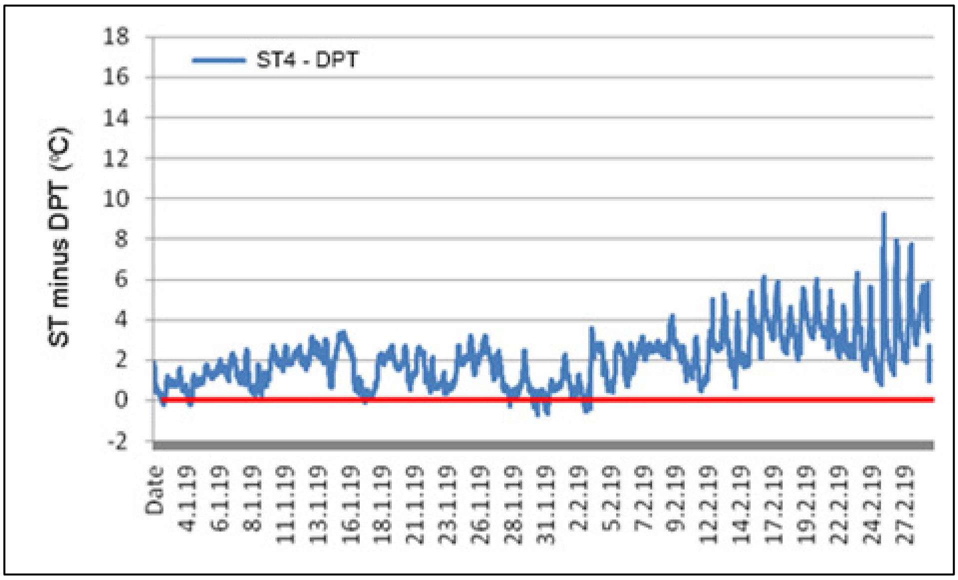


Fig 123: January/February 2019 condensation risk (under red line) for the north slope of the roof

Figure 121 shows that condensation events, sometimes lasting more than 24 hours, were not uncommon in 2018. Figures 122 and 123 for 2019 (both on the same temperature scale) show that the south slope tended to be warmer than the north, and condensation events were a little more severe.

The roof space was visited to store some items on 13 November 2017, when a severe condensation event was found to be occurring. This is illustrated in Figure 113 and the temperature drop is shown by an arrow in Figure 124. This condensate accumulated over a two-day period.

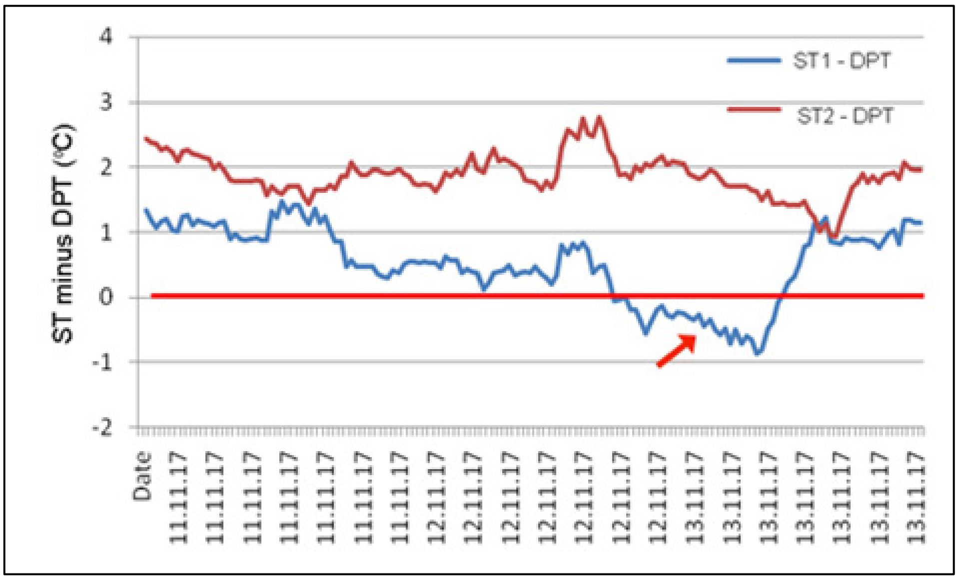


Fig 124: A severe condensation event (below red line) commenced on the night of 12 November 2017 and was observed on 13 November 2017. This is the event photographed in Figure 113

Figure 125 incorporates temperature data from the rafters by comparing condensation risk (ST minus DPT) during November and December 2017 on the underside of the felt (ST1) and on the rafter sides (ST2). Condensation is an unlikely event on the wood, which remains warmer than the underlay.

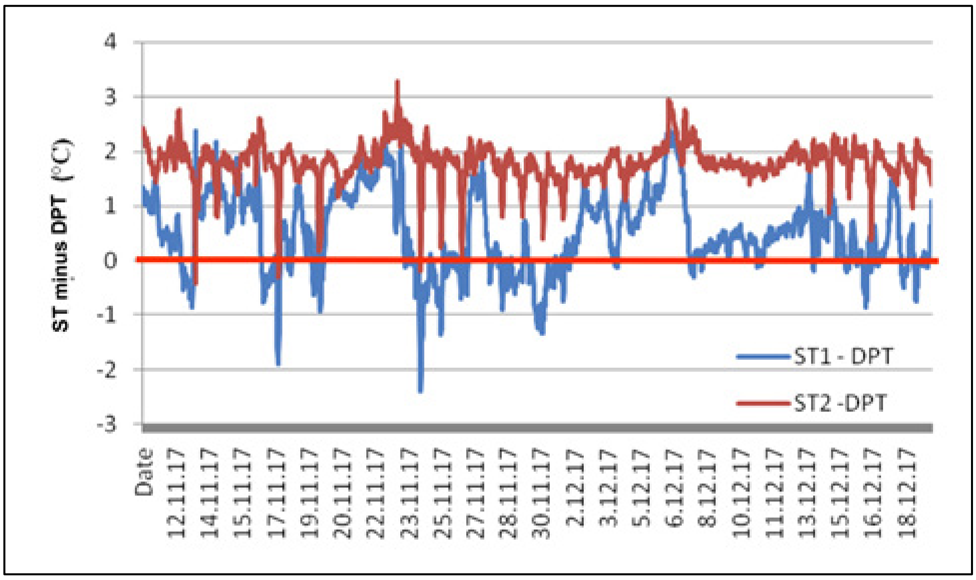


Fig 125: November/December 2017 condensation risk (below red line) for the south slope of the roof

Temperature statistics for the underside of underlay and the rafters are shown in Table 22.

Table 22: January/February comparisons between surface temperatures (ST), high level (HL) and exterior (Ext) temperatures for 2018 and 2019

UF = underside of felt; SR = side of rafter; UR = underside of rafter

		2018 Jan/Feb	2019 Jan/Feb
ST1 UF	Maximum	No data	30.7
	Minimum	No data	-1.4
	Median	No data	7.7
	IQR	No data	4.3
ST2 SR	Maximum	No data	29.9
	Minimum	No data	-1.3
	Median	No data	7.7
	IQR	No data	4.1
ST3 UR	Maximum	13.5	23.8
	Minimum	2.2	1.4
	Median	7.6	8.8
	IQR	2.8	3.5
ST4 UF	Maximum	14.2	20.4
	Minimum	0.8	-0.7
	Median	6.6	8.0
	IQR	3.2	4.0
ST5 SR	Maximum	13.4	20.3
	Minimum	1.4	0
	Median	6.0	8.3
	IQR	2.9	4.1
ST6 UR	Maximum	13.1	21.9
	Minimum	2.8	2
	Median	8.0	9.2
	IQR	2.5	3.5
HL1 T	Maximum	14	25.8
	Minimum	2.2	1.2
	Median	7.5	8.8
	IQR	2.7	3.6
Ext T	Maximum	No data	18.6
	Minimum	No data	-6.5
	Median	No data	5.1
	IQR	No data	5.9

The underside of the felt has a lower minimum temperature than the rafter, although the medians and interquartile ranges are similar. The temperature of the underside of the rafter is closer to high level air temperature.

5.4.3. Occupancy and insulation

The below ceiling environment was monitored in two rooms. BC1, on the south side of the house was in a spare bedroom that was never used. BC2, on the north side of the house, was in the bathroom. Figures 126 to 129 compare the temperature and air moisture gradients from room to roof for 2018 and 2019.

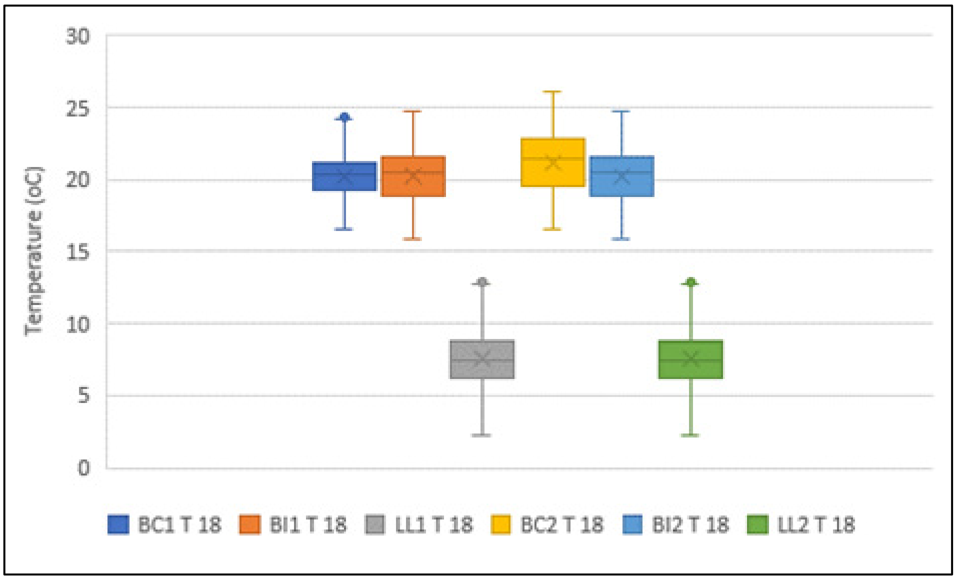


Fig 126: Temperature gradients (°C) from below ceiling (BC) to low level (LL) in the roof for January/February 2018. BC1 is in a spare unused bedroom; BC2 is in the bathroom

The bathroom is warmer than the spare bedroom (both median and interquartile range), but low level temperatures remain the same.

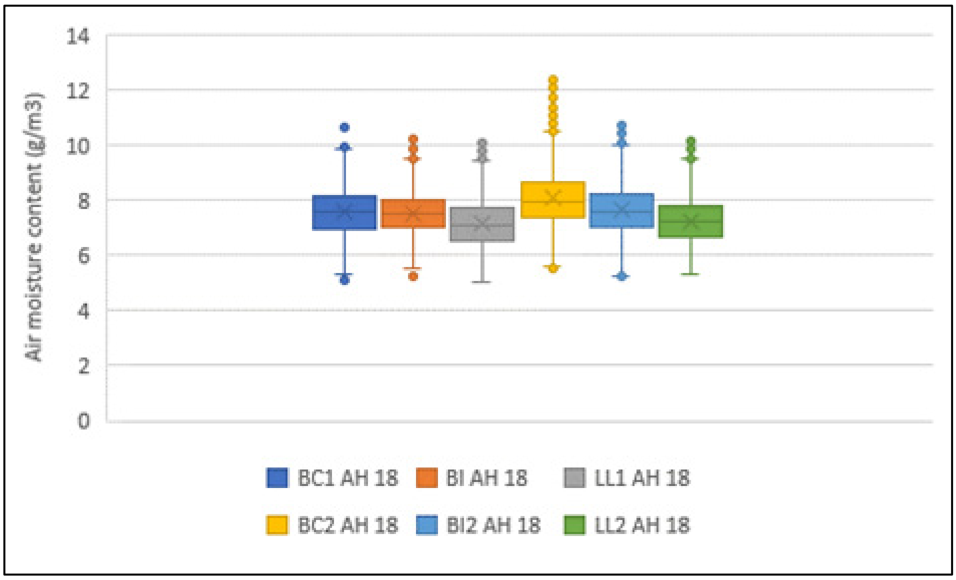


Fig 127: Air moisture content gradients (g/m³) from below ceiling (BC) to low level (LL) in the roof for January/February 2018. BC1 is in a spare unused bedroom; BC2 is in the bathroom

The air moisture content is higher and more variable in the bathroom, but there is no significant change in the air moisture content at low level within the roof.

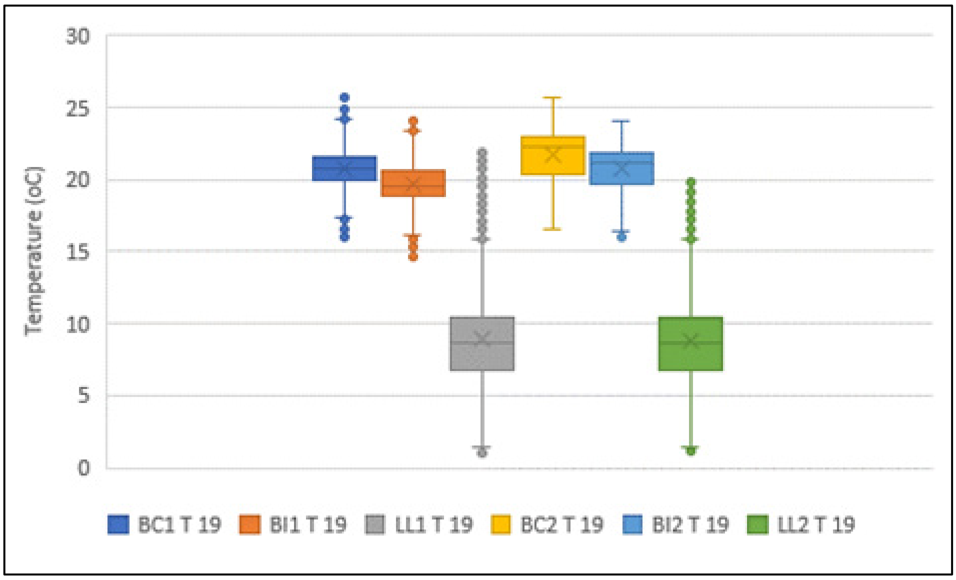


Fig 128: Temperature gradients (°C) from below ceiling (BC) to low level (LL) in the roof for January/February 2019. BC1 is in a spare unused bedroom; BC2 is in the bathroom

The temperature within the roof has many outliers caused by solar gain, as shown in Figure 118. However, the medians and interquartile ranges are the same above both rooms at low level. The insulation is an effective temperature barrier.

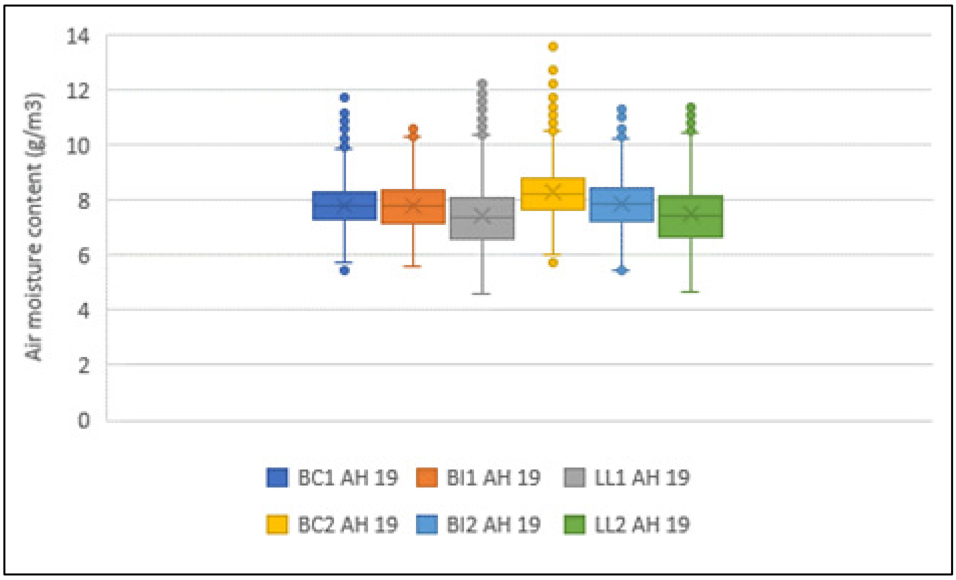


Fig 129: Air moisture content gradients (g/m³) from below ceiling (BC) to low level (LL) in the roof for January/February 2019. BC1 is in a spare unused bedroom; BC2 is in the bathroom

Elevated bathroom moisture content has no obvious effect upon roof space air moisture, but if medians from the rooms and beneath the insulation are compared then it may be discernible (Table 23).

Table 23: A comparison of median air moisture contents (g/m³) from below and above the ceiling in the bedroom (BC1 AH and BI1 AH) and the bathroom (BC2 AH and BI2 AH)

	BC1 AH	BI1 AH	BC2 AH	BI2 AH
2018	7.56	7.52	7.98	7.59
2019	7.78	7.79	8.20	7.85

However, the differences are small. This may be because the rooms are opposite one another across a small landing, and a single occupant may not necessarily close the bathroom door when it is in use. Nevertheless, some moisture from domestic activities must percolate up into the attic because there is no AVCL below the insulation.

Figures 130 and 131 consider the temperature and relative humidity profiles with dew point and the risk from condensation under the north slope for 2019.

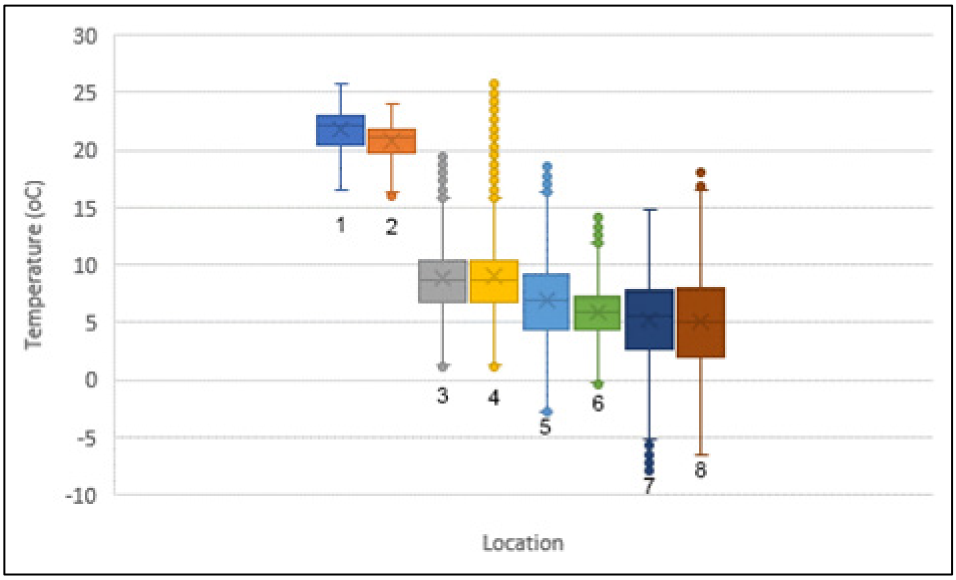


Fig 130: Temperature profile from room to exterior for January/February 2019

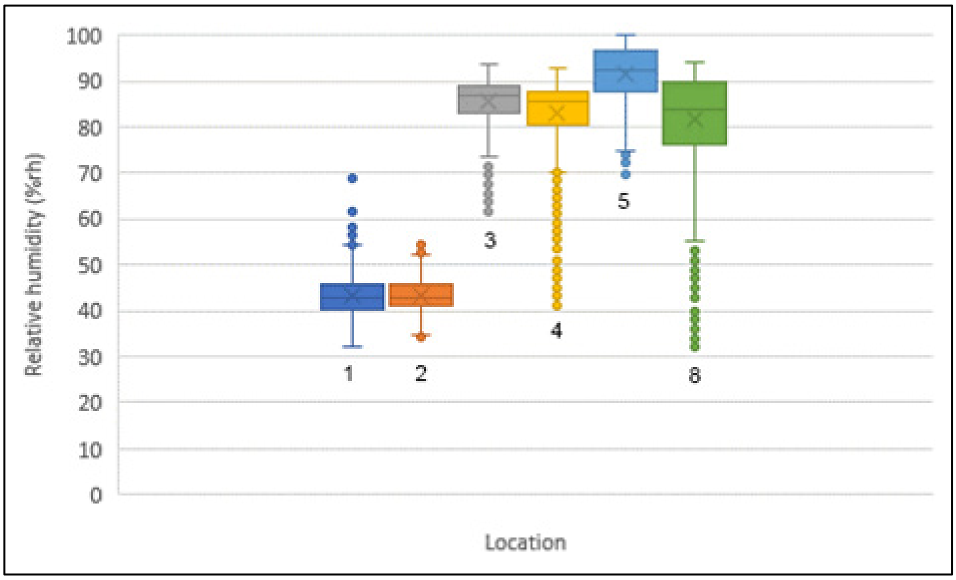


Fig 131: Relative humidity profile from room to exterior for January/February 2019

Key for Figures 130 and 131
1 = below ceiling (BC2)
2 = below insulation (BI2)
3 = low level (LL2)
4 = high level (HL2)
5 = between tiles and underlay (BTU2)
6 = high level dew point
7 = between tiles and underlay dew point
8 = exterior

Low level and high level temperatures are similar (Fig 130), and their medians are several degrees higher than the median for dew point. The interquartile range boxes for low level and high level barely overlap with high level dew point. The interquartile range box for between tiles and underlay air overlaps high level and high level dew point boxes. It is also largely within the between tiles and underlay dew point range .

Low and high level relative humidities (Fig 131) do not reach dew point at the positions of the sensors, but BTU (5) does.

The insulation would seem to be effective (Fig 132).

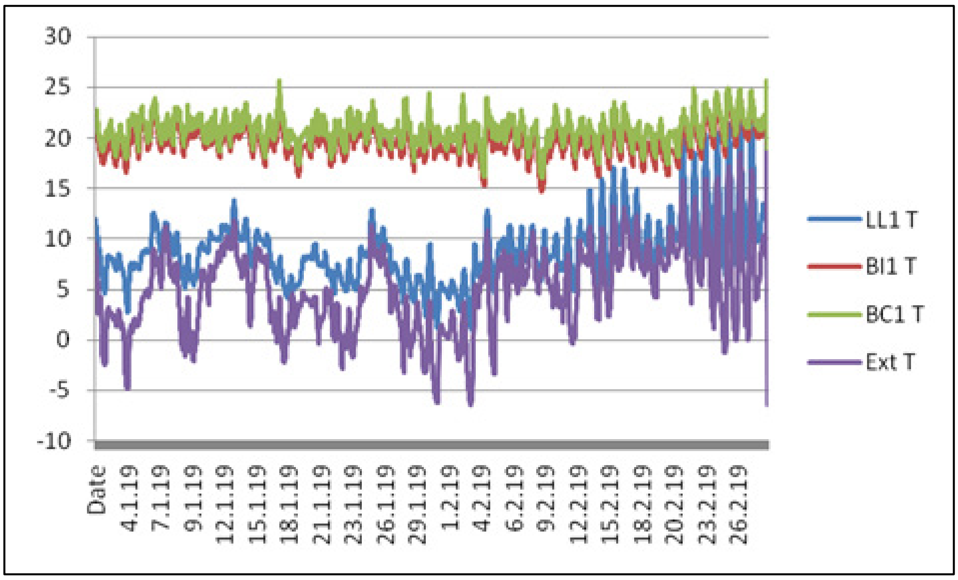


Fig 132: The room (BC) and below insulation (BI) environments remain much warmer than the roof above the insulation (LL) and the exterior (Ext). There is no indication that occupancy during January and February warms the roof space

5.5 Data analysis: Summer (July/August 2017–2019)

Temperature and relative humidity statistics are compared in Table 24.

Table 24: July/August average temperatures (°C) and relative humidities (%) in the roof at high level (HL) and low level (LL), below insulation (BI), in the room (BC), and the exterior (Ext) for 2017 to 2019

		2017 July/August	2018 July/August	2019 July/August
BTU1 T (South)	Maximum	No data	No data	54.4
	Minimum	No data	No data	10.3
	Median	No data	No data	21.0
	IQR	No data	No data	11.0
BTU2 T (North)	Maximum	No data	No data	48.6
	Minimum	No data	No data	9.3
	Median	No data	No data	20.8
	IQR	No data	No data	10.4
HL1 T (South)	Maximum	47	47.6	48.4
	Minimum	10.8	8.8	12.2
	Median	20.5	23.6	21.9
	IQR	7.9	10.6	9.0
LL1 T (South)	Maximum	43.5	43.8	44.3
	Minimum	10.6	8.7	12.1
	Median	20.2	23.0	21.6
	IQR	7.2	9.9	8.1
LL2 T (North)	Maximum	41.8	41.3	41.6
	Minimum	10.2	8.6	11.8
	Median	19.7	22.1	20.9
	IQR	6.5	8.7	7.5
BI1 T (South)	Maximum	28.2	29.1	30.7
	Minimum	18.6	18.6	18.4
	Median	21.3	21.3	22.2
	IQR	2.2	22.2	2.4
BI2 T (North)	Maximum	27.4	28.4	29.5
	Minimum	17.9	18.8	18.6
	Median	21.4	23.6	18.6
	IQR	1.9	3.2	2.2
BC1 T (South)	Maximum	28.1	29.2	31
	Minimum	19.1	19	18.8
	Median	21.7	24.4	22.6
	IQR	2.0	3.5	2.3
BC2 T (North)	Maximum	27.9	28.8	30.2
	Minimum	16.8	19.2	19
	Median	21.9	24.0	22.6
	IQR	2.0	3.1	2.3
Ext T (North)	Maximum	No data	No data	35
	Minimum	No data	No data	6.7
	Median	No data	No data	16.8
	IQR	No data	No data	5.2

		2017 July/August	2018 July/August	2019 July/August
BTU1 RH (South)	Maximum	No data	No data	100
	Minimum	No data	No data	14.5
	Median	No data	No data	56.0
	IQR	No data	No data	32.5
BTU2 RH (North)	Maximum	No data	No data	93.7
	Minimum	No data	No data	18.7
	Median	No data	No data	59.7
	IQR	No data	No data	29.9
HL1 RH (South)	Maximum	85.7	87.7	89.6
	Minimum	22.3	16.3	23
	Median	61.8	48.9	57.1
	IQR	20.2	26.3	20.2
LL1 RH (South)	Maximum	85.2	88.4	89
	Minimum	27.4	21.1	27.9
	Median	63.3	52.7	60.2
	IQR	18.0	25.3	18.4
LL2 RH (North)	Maximum	85.2	88.3	85.9
	Minimum	25.1	20.1	26.2
	Median	64.9	55.4	62.8
	IQR	17.1	23.2	17.4
BI1 RH (South)	Maximum	73.9	70.2	72.3
	Minimum	48.7	40.4	48.1
	Median	60.3	60.3	61.2
	IQR	6.3	6.3	5.6
BI2 RH (North)	Maximum	70.8	70.5	73.6
	Minimum	47.4	39.5	48.2
	Median	60.9	54.2	61.2
	IQR	4.8	13.3	5.6
BC1 RH (South)	Maximum	77	78.3	79.1
	Minimum	43.9	36.6	43.7
	Median	60.6	53.4	60.3
	IQR	5.3	14.5	6.2
BC2 RH (North)	Maximum	84.4	78.9	84.4
	Minimum	44.3	29.1	48.7
	Median	62.0	56.4	62.5
	IQR	5.1	12.4	5.7
Ext RH (North)	Maximum	No data	No data	93
	Minimum	No data	No data	27
	Median	No data	No data	75.0
	IQR	No data	No data	5.0

Maximum temperatures are compared in Figure 133 to illustrate the effects of solar gain. The south side is warmer than the north side.

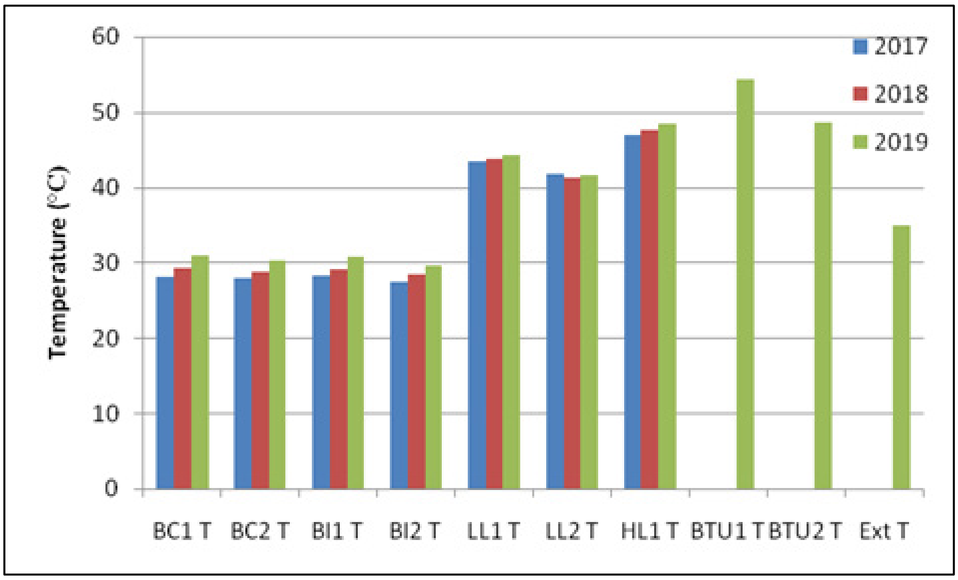


Fig 133: July/August maximum temperatures (°C) recorded in the rooms (BC), beneath insulation (BI), low level (LL), high level (HL), between tiles and underlay (BTU) and exterior (Ext) during 2017 to 2019. LL1 and BTU1 are on the south side; LL2 and BTU2 are on the north side; HL1 is below the ridge

A box plot for the ceiling to exterior temperature profile (2019) is provided in Figure 134 and a profile for relative humidity (2019) in Figure 135.

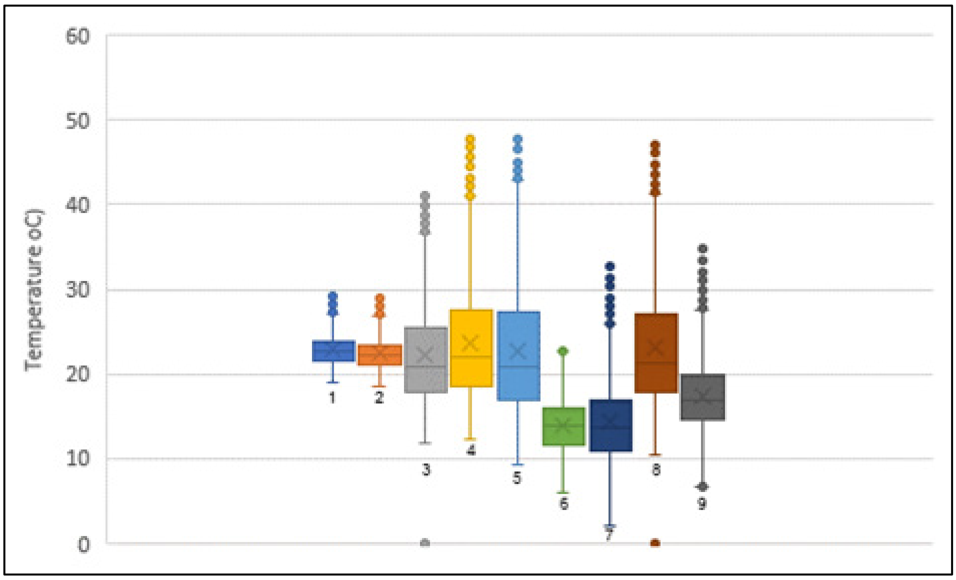


Fig 134: Median and interquartile temperatures (°C) for July/August 2019 from the room, through the roof space to the exterior

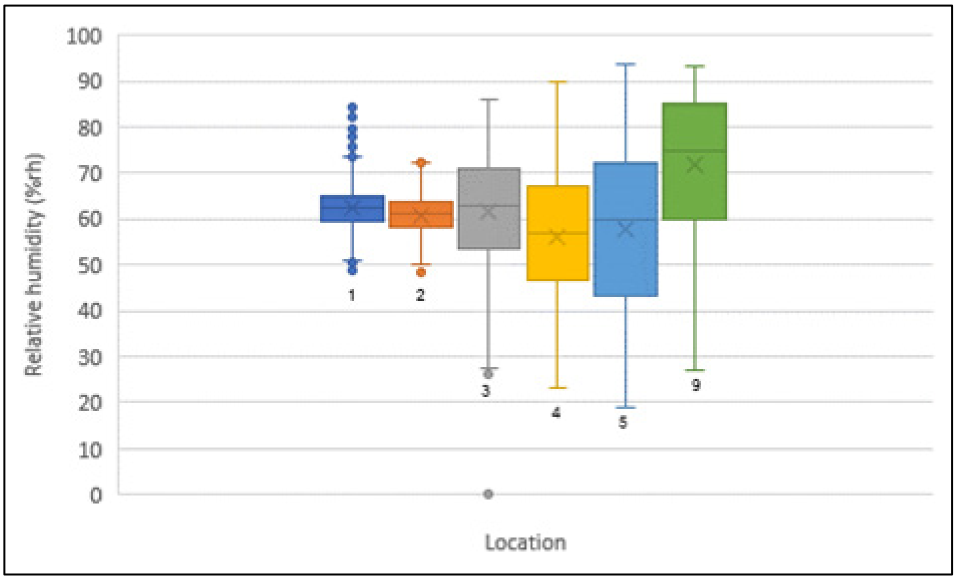


Fig 135: Median and interquartile relative humidities (°C) for July/August 2019 from the room, through the roof space to the exterior

Key for Figures 134 and 135
1 = below ceiling (BC2)
2 = below insulation (BI2)
3 = low level (LL2);
4 = high level (HL2)
5 = between tiles and underlay (BTU2)
6 = high level dew point
7 = between tiles and underlay dew point
8 = surface temperature under felt (ST4)
9 = exterior

5.6 Building 4 'Long Compton' – Summary

The construction of the attic floor and ceiling below was uniform throughout the roof space. There was a small elevated air moisture content (g/m^3) under the insulation above the bathroom compared with above the spare bedroom. This suggested that some moisture percolated through the ceiling.

The risk from condensation during 2016 is illustrated in Figure 136. Condensation might easily occur during the winter months, but would be an unlikely event in the summer. The winter risk does not seem greater than in any of the other roofs monitored, and while it is easy to see why an impermeable underlay would allow condensation to accumulate until it formed droplets, it is difficult to see why this should have become more of a problem when extra insulation was added. No air movement was detected by the sensors, but perhaps the extra insulation restricted air exchange and, consequently, the vapour pressure gradient at the eaves.

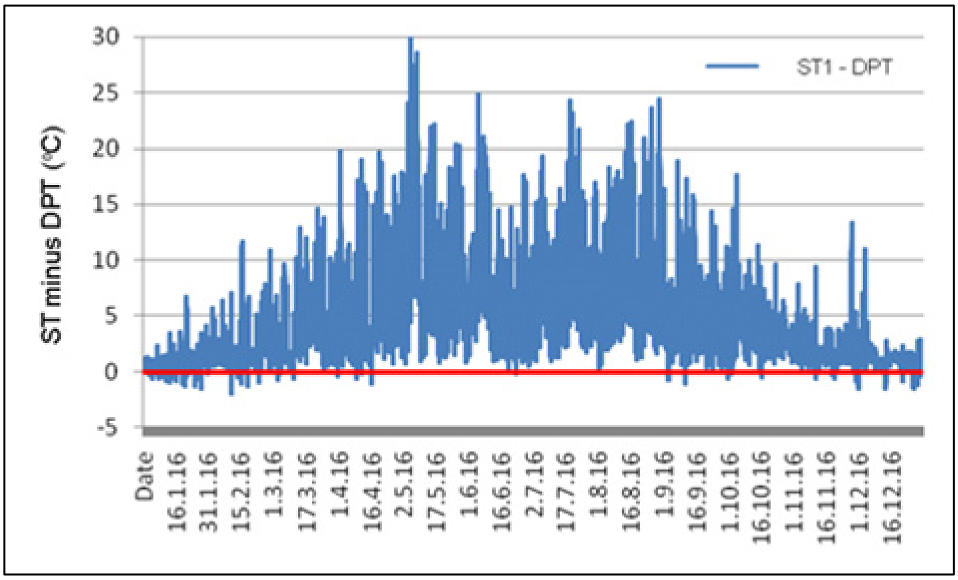


Fig 136: Condensation risk (below red line) for 2016, obtained by subtracting dew point temperature (DPT) from surface temperature under felt (ST1), showing seasonal trends

6.0 WOOD MOISTURE CONTENTS

Conventional wisdom still has it that timber decay is inevitable when wood moisture content (as measured with some form of moisture meter) remains above 20%. However, there is an important difference between equilibrium moisture content and moisture from some other source. The equilibrium moisture content of wood depends on ambient relative humidity (Fig 137), and high humidities commonly occurred in the roofs monitored. However, while high humidities might support mould growth, they will not usually be enough to raise the moisture content of timber to a level that would allow decay fungi to develop. To germinate, spores of decay fungi require a moisture content around the fibre saturation point of the wood. This is the point at which all the sites on the cellulose molecules to which water molecules can attach are occupied and free water starts to accumulate in the wood. Decay commonly occurs when wood equilibrium moisture content reaches 30% (at 100% relative humidity). Then the source of moisture must be sustained, otherwise the fungus will desiccate and die.

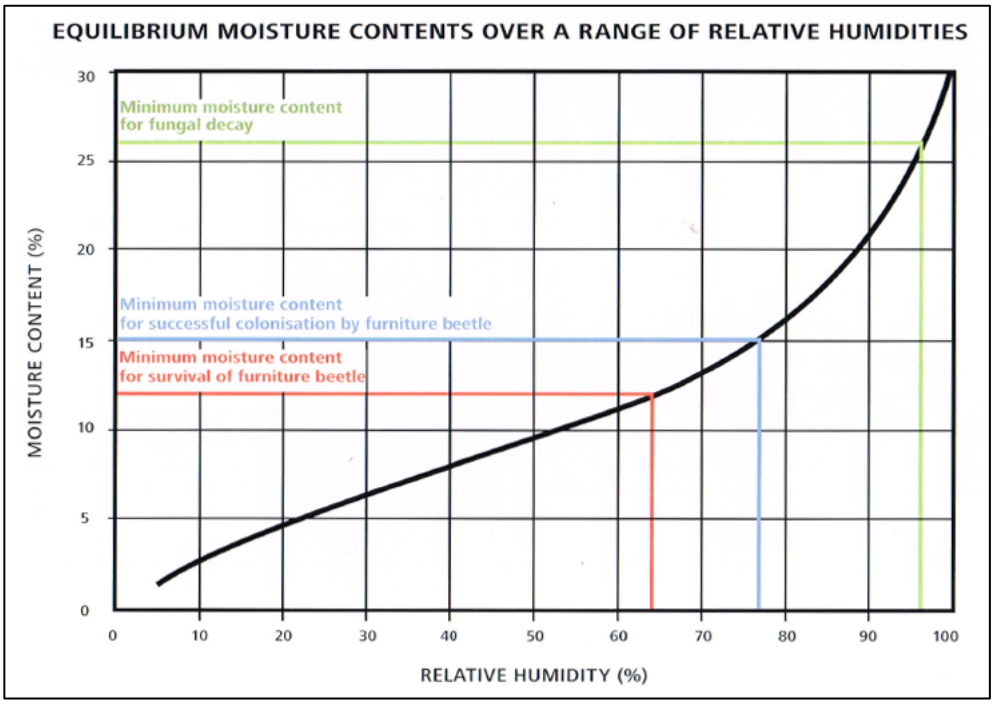


Fig 137: Equilibrium moisture contents (%) of wood at different relative humidities (%)

Temperature has only a small effect on equilibrium moisture content. For example, a relative humidity of 90% at 21°C will induce an equilibrium moisture content in wood of 20.5%. This rises to 20.9% at 10°C and 21% at -1°C. These figures are relevant because the average relative humidity in the roof at Building 1 'Addison' ranged from 88.8% to 92.5% during the four January/February periods monitored (*see* Table 3).

Temperature does, however, have an effect upon the electrical resistance of timber and, therefore, upon resistance moisture meter readings. Resistance moisture meters are generally calibrated at 20°C and the average discrepancy will be about 0.15% away from this value. This discrepancy will produce erroneous readings if resistance moisture meters are used over a period that includes very hot or very cold weather. Serial data must, therefore, be temperature corrected if seasons are to be compared, and this may be accomplished using the modified Pfaff-Garrahan equation (Equation 1).

$$u_k = \frac{u + 0.567 - 0.0260x + 0.000051x^2}{0.881\,(1.0056)^x}$$

u_k = temperature corrected % moisture content
u = moisture meter reading
x = surface temperature + 2.8°C

Equation 1: The Pfaff-Garrahan equation for temperature correcting resistance meter moisture readings

Five moisture sensors (MC1 to MC5) recording electrical resistance between steel pins were installed at Building 4 'Long Compton' in positions shown in Figure 112. Unfortunately, the system proved to be temperamental, but some sequences of useful data were obtained. The positions of MC1 and MC2 are shown in Figure 138. MC3 was in a ceiling joist.

Figure 139 compares corrected and uncorrected data for January/February 2020. Figure 140 shows corrected data from sensors MC1 to MC3 for December 2019 to the beginning of February 2020, and Figure 141 shows corrected summer data for 2019.

Fig 138: Wood moisture content sensors MC1 (upper nearest underlay) and MC2 (lower)

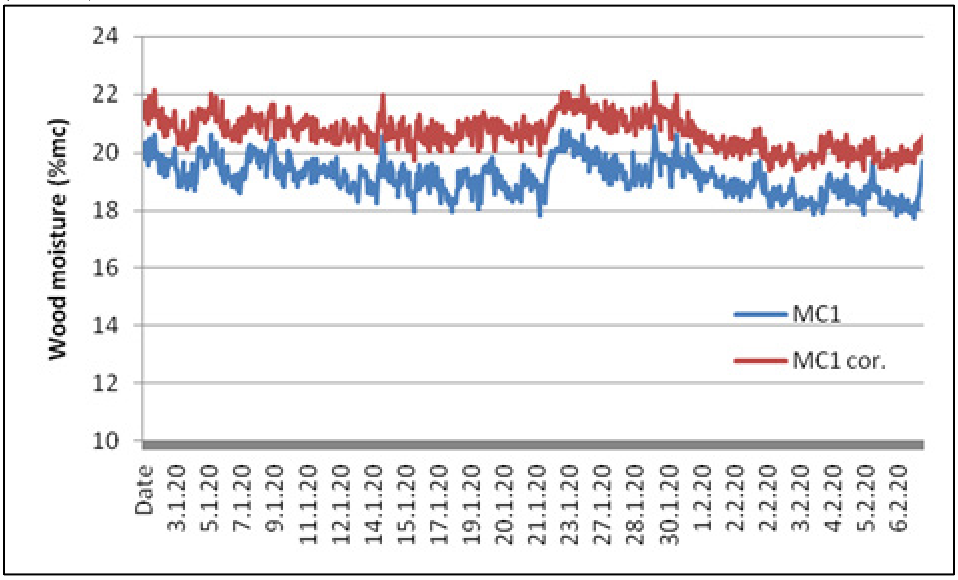


Fig 139: January/February 2020 corrected and measured moisture content data (calculated from resistance). The corrected readings are higher because the surface temperature of the wood is low

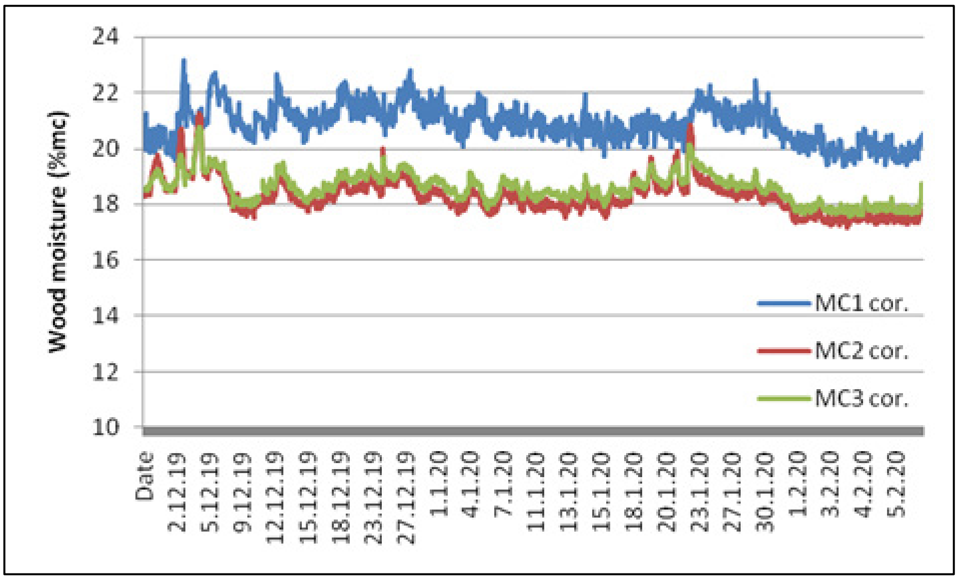


Fig 140: Temperature corrected data from December 2019 to the beginning of February 2020. The underside of the rafter (MC2) and the joist (MC3) have very similar moisture contents, whereas just under the felt (MC1) is much damper

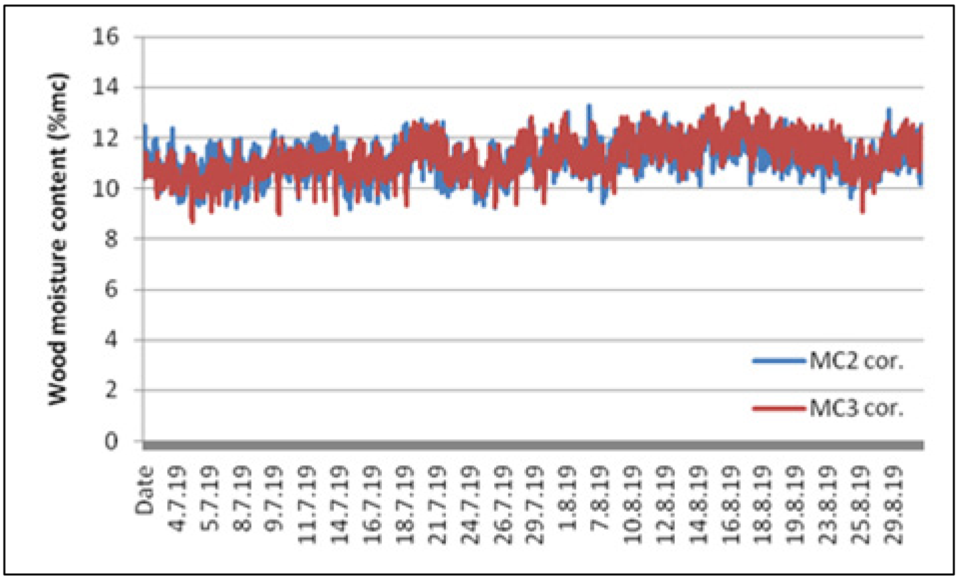


Fig 141: July/August 2019 temperature corrected equilibrium moisture contents remained low (MC1 provided spurious readings and is not included)

A surveyor with a moisture meter might conclude that there was a damp problem in the roof in winter because the rafter moisture content exceeded 20% (Fig 140). If, however, the survey was undertaken in summer, the conclusion would be that the roof structure was safely dry (Fig 141).

7.0 ROOF ENVIRONMENTS COMPARED

Comparing the environments in buildings is always problematic because the parameters used are confused by other differences. Thus, the monitored effects of hygroscopic insulation at Building 1 'Addison' and Building 2 'Rectory' may be confounded by the difference in vapour permeability of the AVCL beneath the insulation. Similarly, both Building 3 'Woodbury' and Building 4 'Long Compton' have glass fibre insulation, but the latter has an impermeable underlay whereas the former has none.

These differences are somewhat ameliorated by the seasonal consistency from year to year of the data collected for each roof. This means that data from short periods can be considered as acceptably representative of the environment within that roof at that time of year. The following comparisons are based on median data from the first seven days of January 2017.

7.1 Building 1 'Addison' and Building 2 'Rectory'

Figure 142 shows the effects of the insulation upon temperature. Medians and interquartile ranges are provided in Table 25.

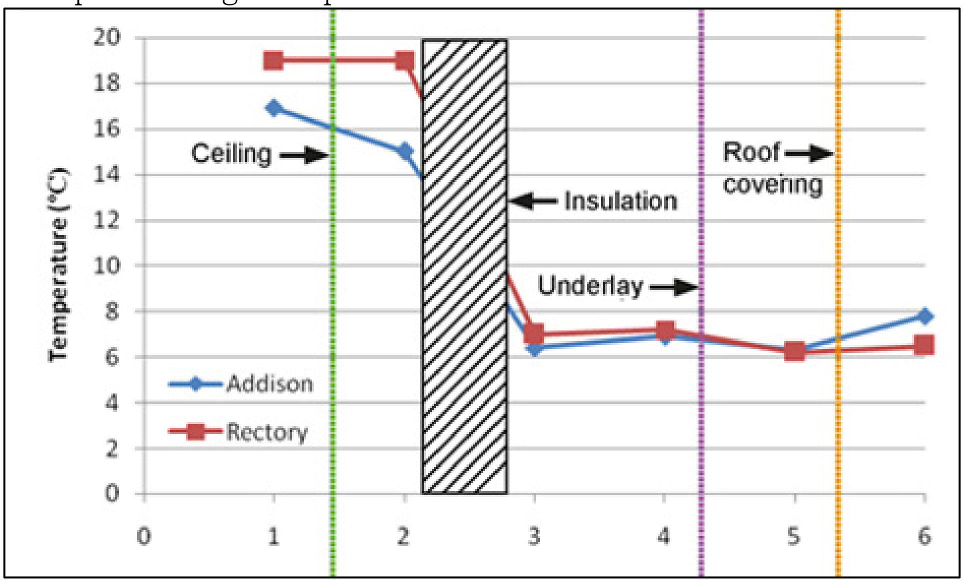


Fig 142: The median temperature gradients across the roof from the room (1) to the exterior (6) during the first week of January 2017

Key to Figures 142, 143 and 144
1 = below ceiling (BC)
2 = below insulation (BI)
3 = low level (LL)
4 = high level (HL)
5 = between tiles and underlay (BTU)
6 = exterior (Ext)

The temperature drops through the ceiling at 'Addison' and then declines rapidly through the insulation for both roofs. Within roof temperatures are similar. The greater temperature drop through the ceiling at 'Addison' will be a consequence of the complex ceiling construction (*see* Fig 3) and the reflective Tyvek membrane.

The drop in temperature causes a rise in relative humidity and this is compared for the two roofs in Figure 143.

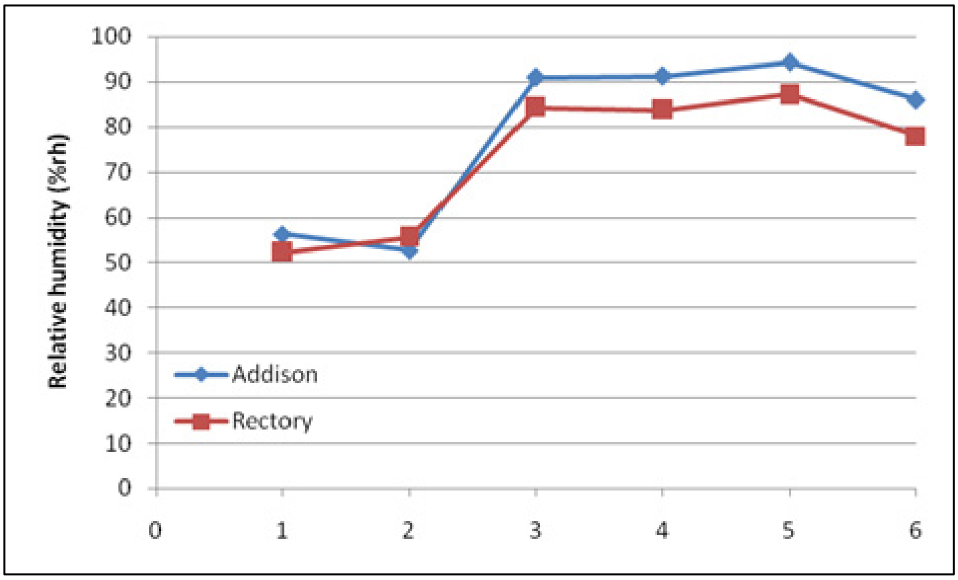


Fig 143: The average relative humidity gradients across the roof from the room (1) to the exterior (6) during the first week of January 2017

The relative humidity within the roof at 'Addison' is higher than at 'Rectory', but median temperatures are similar. If temperatures are nearly the same but relative humidity at 'Addison' is higher, then there must be a difference in air moisture contents (Fig 144).

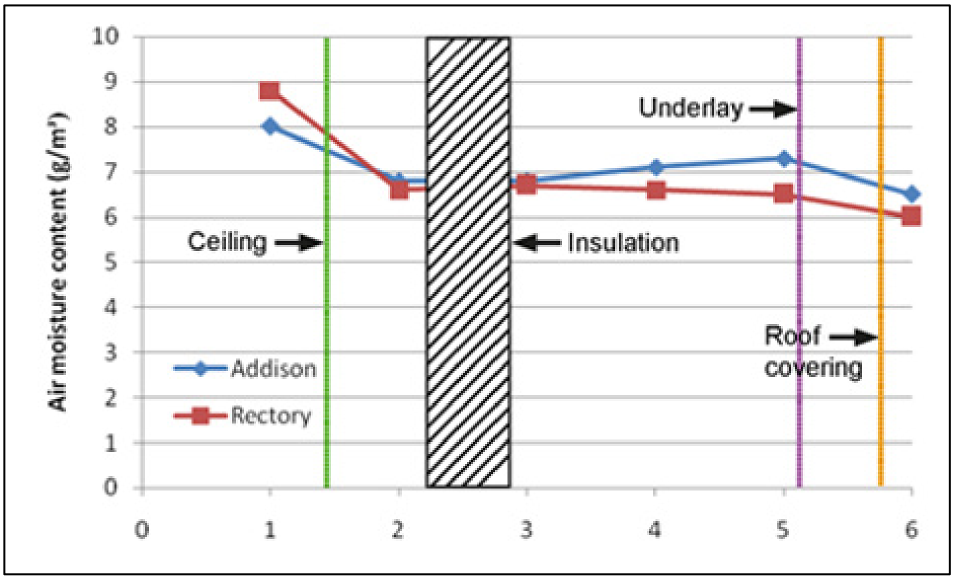


Fig 144: The average air moisture content gradients across the roof from the room (1) to the exterior (6) during the first week of January 2017

Air moisture content drops through the ceiling construction and this is attributable to the vapour barriers incorporated into the construction.

Low level median moisture contents are similar, but air moisture content lines increase towards the roof coverings and then converge again to the exterior. It would seem that the extra moisture is released from the structure and insulation by afternoon solar gain. This may be demonstrated by comparing high level and between the tiles and underlay temperature data as box plots (Fig 145). The median lines (that cross the boxes) are less than 2°C apart, but the total temperature range shown by the between the tiles and underlay plot (grey box) for 'Addison' is greater than the range for 'Rectory' (yellow box).

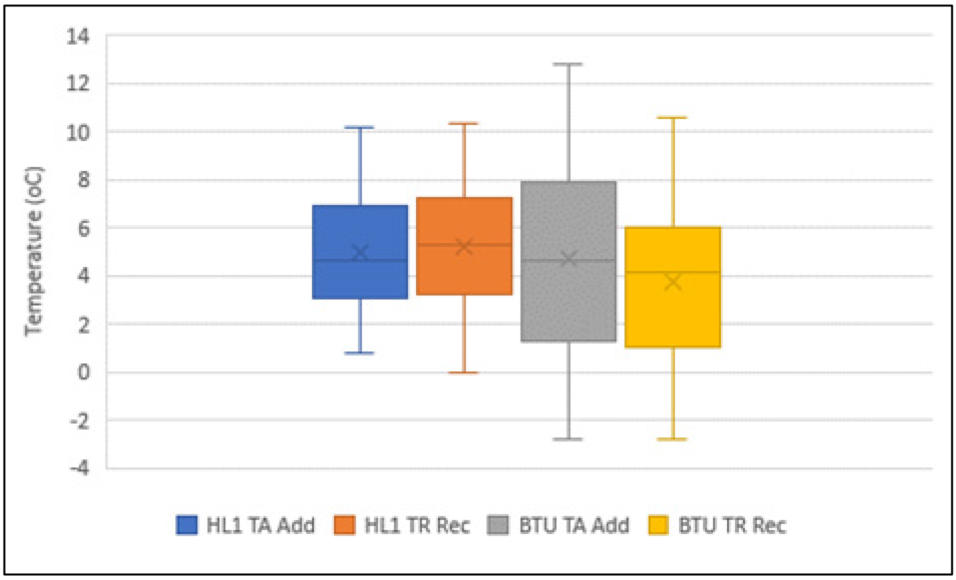


Fig 145: Box plot for high level (HL) and between tile and underlay (BTU) air temperatures for the first seven days of January 2017 at 'Addison' (A) and 'Rectory' (R)

This elevated temperature is reflected in an increased air moisture content range (Fig 146).

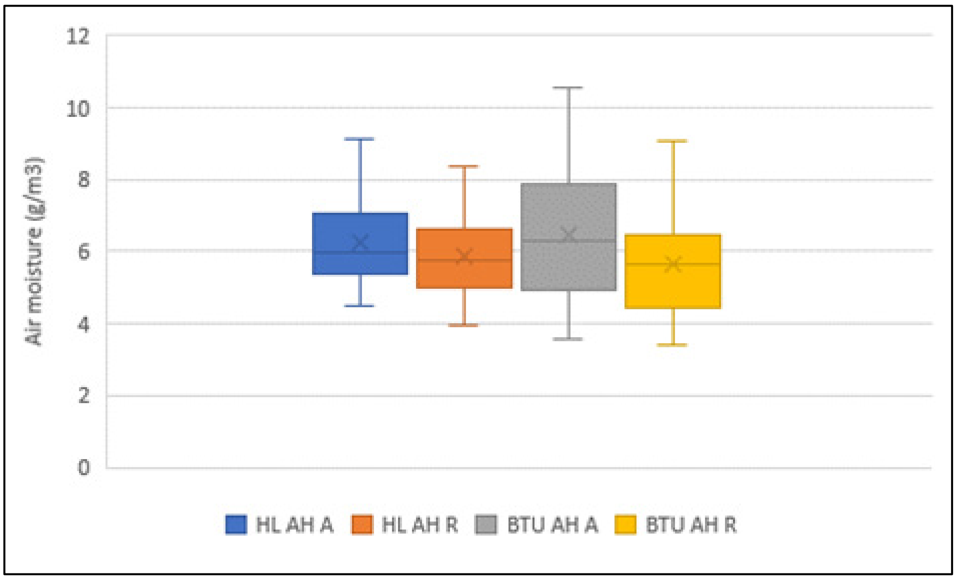


Fig 146: Box plot for high level (HL) and between tile and underlay (BTU) air moisture contents for the first seven days of January 2017 at 'Addison' (A) and 'Rectory' (R)

The apparent increase in potential condensation events at 'Addison' (*see* Fig 10) compared with 'Rectory' (*see* Fig 58) would seem to be caused by differential solar gains during the monitoring periods, rather than by extra moisture from domestic activities. The reflective underlay may also be contributing to the heating effect below the tiles.

Table 25: Seven-day January 2017 air moisture content (g/m³), relative humidity (%) and temperature (°C) medians and their interquartile ranges for 'Addison' and 'Rectory'

	BC1 AH	BI1 AH	BI2 AH	LL1 AH	HL1 AH	BTU1 AH	Ext AH
Addison	8.0	6.8	6.8	6.8	7.1	7.3	6.5
IQR	0.32	0.2	0.4	1.5	1.7	2.1	2.3
Rectory	8.8	9.0	6.6	6.7	6.6	6.5	6.0
IQR	0.6	0.5	0.6	1.5	1.6	1.0	1.6

	BC1 RH	BI1 RH	BI2 RH	LL1 RH	HL1 RH	BTU1 RH	Ext RH
Addison	61.8	62.9	52.3	91.2	91.5	97.7	90.0
IQR	3.8	0.5	1.3	1.6	1..8	1.6	9.0
Rectory	54.6	55.6	39.4	84.7	84.6	91.0	85.0
IQR	3.0	2.4	3.1	1.3	1.8	5.0	11.0

	BC1 T	BI1 T	BI2 T	LL1 T	HL1 T	BTU1 T	Ext T
Addison	16.9	12.4	15.0	6.4	6.9	6.3	7.8
IQR	1.6	0.4	0.7	3.6	3.8	4.8	8.3
Rectory	19.0	19.0	20.0	7.0	7.2	6.2	6.5
IQR	0.8	0.8	0.8	4.4	3.9	4.8	3.3

7.2 Building 3 'Woodbury' and Building 4 'Long Compton'

The roof at 'Woodbury' had the thickness of the insulation increased from 100mm (winter 2015 and 2016) to 300mm (winter 2017 and 2018). If this made any difference to the temperature flux into the roof, then the comparative temperature drop between below insulation and low level should increase. However, the four winter monitorings failed to show any consequential drop in the roof space temperature (*see* Fig 90).

Figure 147 compares the effects of the insulation on temperature drop and the roof environment for 'Woodbury' and 'Long Compton' during the first seven days of January 2018.

Medians and interquartile ranges are provided in Table 26.

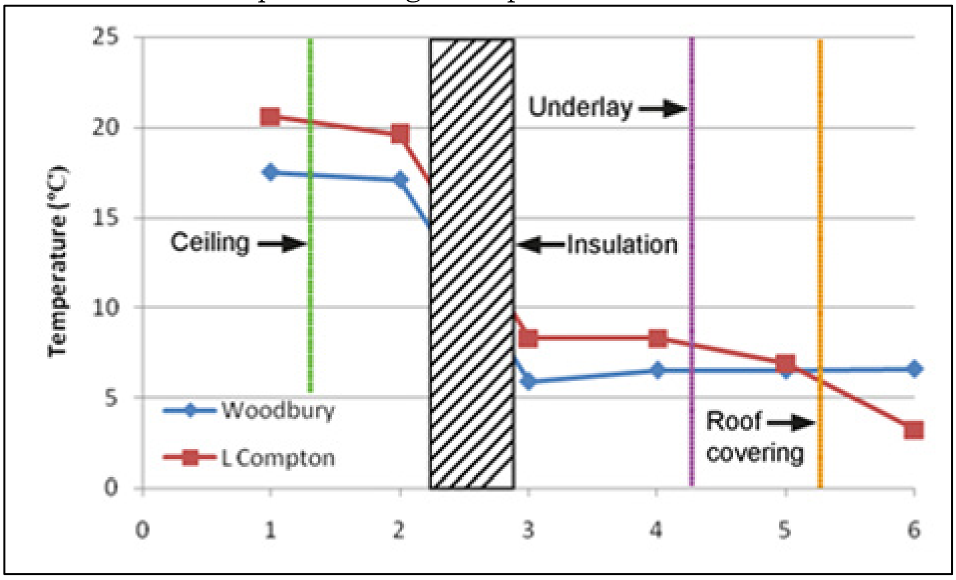


Fig 147: The average temperature gradients across the roof from the room (1) to the exterior (6) during the first week of January 2018 ('Woodbury') and the first week of January 2019 ('Long Compton'). 'Woodbury' does not have an underlay

Key to Figures 147, 148 and 149
1 = below ceiling (BC)
2 = below insulation (BI)
3 = low level (LL)
4 = high level (HL)
5 = between tiles and underlay (BTU)
6 = exterior (Ext)

There is no AVCL below the insulation in either roof, and the drop in temperature across the insulation is similar. 'Woodbury' is slightly warmer at high level than at low level, but the average internal temperature is the same as the exterior, presumably because there is no underlay to impede air exchange. The impermeable underlay at 'Long Compton' seems to impede cold air exchange so that high level and low level temperatures are similar, while the temperature under the tiles declines towards the exterior.

The consequences for relative humidity are shown in Figure 148.

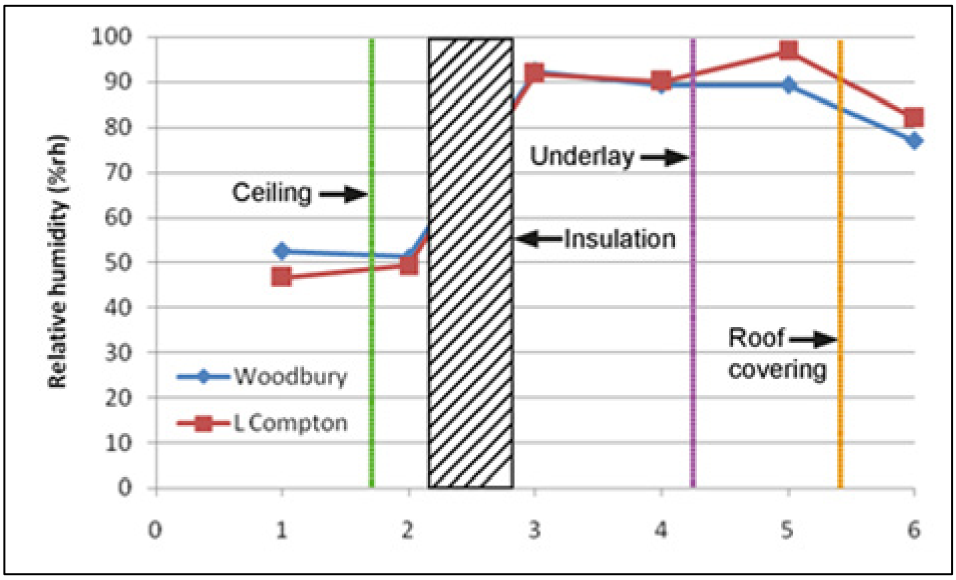


Fig 148: The average relative humidity gradients across the roof from the room (1) to the exterior (6) during the first week of January 2018 ('Woodbury') and the first week of January 2019 ('Long Compton'). 'Woodbury' does not have an underlay

The 300mm of glass fibre insulation causes an identical drop in temperature and rise in relative humidity in both roofs. Point 5 for 'Woodbury' is a repeat of point 4 and is speculative because 4 was close to the roof covering and there was no underlay behind which to put a sensor. Point 5 at 'Long Compton' is in the gap between the underlay and the tiles. This seems to be very humid.

The air moisture content is presented in Figure 149.

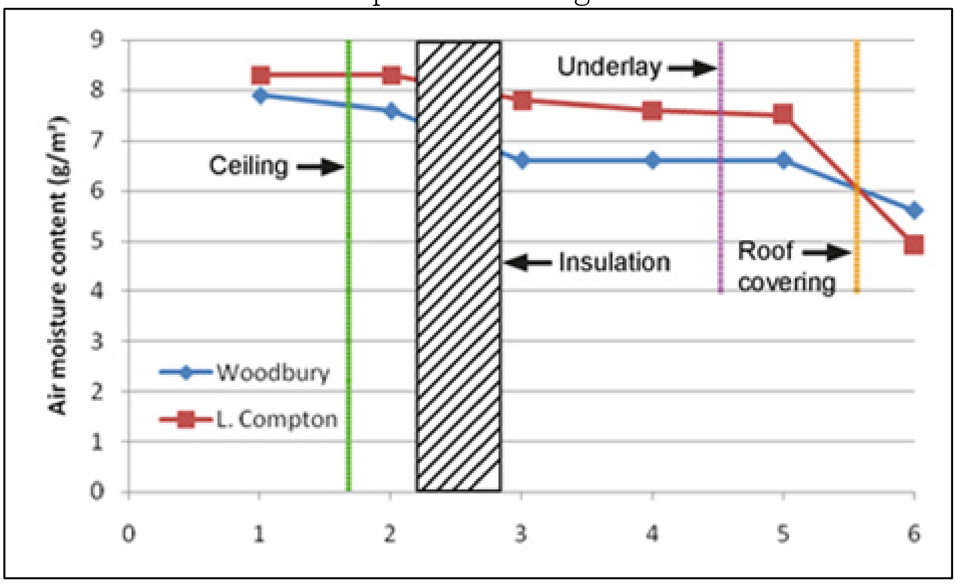


Fig 149: The average air moisture gradients across the roof from the room (1) to the exterior (6) during the first week of January 2018 ('Woodbury') and the first week of January 2019 ('Long Compton'). 'Woodbury' does not have an underlay

Glass fibre insulation is not hygroscopic, so the drop between below insulation and low level in both roofs must be caused by the moisture buffering effect of the joists and floorboards. The air moisture content across the roofs then remains rather uniform, dropping slightly at 'Long Compton'. The high relative humidity recorded under the tiles is not accompanied by a higher air moisture content and must, therefore, be a function of winter temperature and air exchange.

Medians and interquartile ranges are shown in Table 26.

Table 26: Seven-day January air moisture content (g/m³), relative humidity (%) and temperature (°C) medians and their interquartile ranges for 'Woodbury' (2018) and 'Long Compton' (2019)

	BC1 AH	BI1 AH	LL1 AH	HL1 AH	BTU1AH	Ext AH
Woodbury	7.9	7.6	6.6	6.6	No data	5.6
IQR	1.2	0.7	0,9	0.8	No data	0.9
Long Compton	8.3	8.3	7.8	7.6	7.5	4.9
IQR	0.9	0.8	0.9	0.9	1.3	1.6

	BC1 RH	BI1 RH	LL1 RH	HL1 RH	BTU1RH	Ext RH
Woodbury	52.5	51.3	92.3	89.3	No data	77.0
IQR	6.5	2.31	3.0	6.1	No data	13.0
Long Compton	46.7	49.3	91.9	90.1	96.8	82
IQR	5.7	4.1	1.9	1.6	2.9	10

	BC1 T	BI1 T	LL1 T	HL1 T	BTU1 T	Ext T
Woodbury	17.5	17.1	5.9	6.5	No data	6.6
IQR	1.2	2.4	2.5	2.4	No data	3.7
Long Compton	20.6	19.6	8.3	8.3	6.9	3.2
IQR	1.9	2.0	2.3	2.2	2.6	5.0

7.3 The consequences of attic floor construction

Figure 150 shows the differences between below ceiling and low level air moisture contents obtained from all four buildings at half-hourly intervals from 1 January to 23 February 2019. The data obtained by subtracting one parameter from the other demonstrate the air tightness and possibly also the buffering capacity of each attic floor construction.

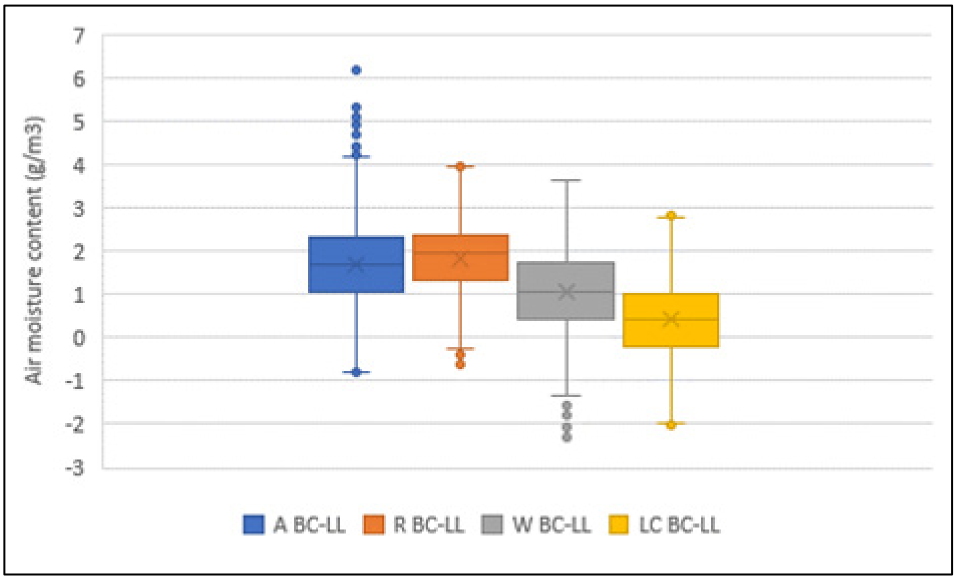


Fig 150: A comparison between the moisture buffering potentials of the four attic floor constructions from 1 January to 23 February 2019. Data obtained by subtracting low level (LL) air moisture content from below ceiling (BC) air moisture content

Figure 150 shows that the two more complex airtight attic floors at 'Addison' and 'Rectory' hold back more moisture from the building than 'Woodbury' and 'Long Compton', irrespective of the type of AVCL. The attic floor at 'Long Compton' – the roof where there is a visible condensation problem – is the least effective at moisture control.

Lowering the air temperature in the roof space will not change the dew point at the roof covering, but reducing the air moisture content will lower the temperature at which condensation occurs. Although this might not have much effect during severely cold weather, lowering the 100% saturation threshold could reduce the frequency and duration of condensation events, thereby mitigating the risk of dripping moisture. A steeper humidity gradient from the underside of the roof covering into the attic void will also enhance evaporation by lowering relative humidity in the evaporative zone.

Although the effect of moisture migration from the dwelling to the attic was rather small in the buildings monitored, it must be remembered that the level of occupancy was also low. The phenomenon may be far more significant in other domestic environments.

8.0 DISCUSSION AND CONCLUSIONS

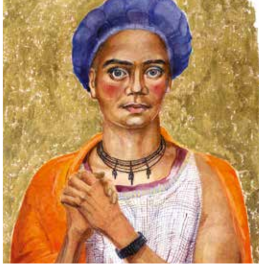
This investigation demonstrates that roof environments tend to be rather predictable, month by month and year by year.

In winter, the relative humidity of most ‘cold roofs’ will be high. This increases the moisture content of porous materials, and may result in condensation on impermeable surfaces. However, this is generally a transient superficial wetting that evaporates as the day progresses and the roof environment warms and moisture vapour re-joins the gases in the air. Condensation occurs on impermeable surfaces that form foci for nucleation above ‘saturated vapour pressure’ - the point at which condensation is balanced by evaporation (air does not ‘hold’ moisture). Daily evaporation of surface condensation requires a vapour pressure gradient away from the surface. During very cold weather, if the relative humidity within the roof space is high (>90%) there will be little or no gradient, so moisture will accumulate. As the rate of evaporation declines, condensate builds up from a film of moisture until it forms droplets. This is more likely to occur during prolonged periods of very cold weather. In some roofs this phenomenon may be exacerbated by adding additional insulation, especially if moist air from the building enters the attic and/or air exchange with the exterior is restricted. This appears to have been the case in Building 4.

However, adding extra insulation at Building 3 did not exacerbate condensation by further lowering the attic air temperature. This was probably due to the lack of a roofing underlay which allowed the environment in the roof interior to equilibrate readily with the external environment.

The differences between the insulation systems in the buildings monitored did not seem to have any significant impact on the risk of condensation. The environment beneath the tiles at Building 1 showed the greatest temperature variation and tendency towards dew point during the day, but this was caused by solar gain perhaps augmented by the reflective underlay. However, there were no reports of damp surfaces and the attic space remained apparently dry. It is probable that condensate was absorbed by the roof tiles

AVCLs and hygroscopic insulation materials may be useful in controlling and buffering moisture entering the attic from the building, particularly where domestic activity levels are high. Most of the buffered moisture will be released back into the air in the attic as roof coverings warm. In winter, attic relative humidities are generally so high that only a small drop in temperature will result in high equilibrium moisture contents and condensation. To avoid accumulation, moisture must be able to escape by diffusion through vapour-permeable roofing underlays or air exchange to the external environment where vapour pressures are generally lower.



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ISSN 2398-3841 (Print)
ISSN 2059-4453 (Online)