The SPAB RESEARCH REPORT 2

The SPAB Building Performance Survey

Final Report

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Acknowledgements

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EXECUTIVE SUMMARY

In 2011, the Society for the Protection of Ancient Buildings embarked on a long-term research project to assess the effects of energy efficiency refurbishment in a variety of traditional buildings. The project measured several metrics in seven buildings prior to changes made in the name of improving energy efficiency. This ‘base case’ performance data included: wall U-values; interstitial and internal surface wall moisture; room conditions, including air quality, air permeability, and a thermographic survey. Following refurbishment these measurements were repeated, some over six years, with the project focussing, in particular, on the performance of moisture within insulated wall fabric. Findings have, to date, been presented in the form of seven detailed interim reports. This final report acts to collate and summarise the research work. It is inevitable that, given the scope of the project in a summary document such as this, some of the detail which might help substantiate certain observations may be absent. For this reason, we would urge readers to consult the earlier interim reports if further information is required.

We recognise that the study of a small number of solid-walled buildings is not sufficient as a basis for definitive statements on the performance of all traditional buildings or solid walls. Alternatively, this case study approach relies on gathering large amounts of data over a long time period and subjecting this to detailed analysis. This in-depth, systematic approach over several years allows for the development of an understanding of the different factors that drive performance within the individual walls, including the influences of internal and external environment. Armed with an appreciation of the structure under scrutiny and the ways its particular characteristics respond to competing influences within the environment, it may be possible to extrapolate from this study and use this information to infer or deduce aspects of likely performance in other similar walls/buildings.

The research finds that responses to refurbishment are highly conditioned by the individual circumstances of the buildings and their fabric. This includes the new materials introduced to save energy as well as, in one instance, the techniques used to install these. The buildings under study were quite different and responses were consequently quite diverse. Specifically, the three walls which formed the core of the wall fabric study present three quite different stories. Two of these walls have been insulated internally and now benefit from reduced heat loss. However, while the addition of insulation appears to be unproblematic in one wall, the other shows a trend of increasing moisture deep within its fabric, in the central part of the wall. The third building has been externally insulated and this shows how the work of refurbishment itself can unintentionally introduce moisture into building fabric. In all three walls we find different examples of how water enters building fabric and how it can, or might, exit again. Understanding this is one of the keys to the successful refurbishment of older buildings.

Thus, the value of this project lies not in proving or disproving certain methods purported to reduce the energy consumption of buildings. Instead it aims to learn about the ways walls, materials and buildings can behave to allow refurbishment work to be undertaken more effectively while minimising the risks posed to fabric and habitants.

1.1 Introduction

The SPAB Building Performance Survey (SPAB BPS 2011 to 2017) looked at various aspects of building performance in older, traditionally constructed properties before and after refurbishment for better efficiency. The houses were all solid wall properties constructed of various materials and refurbishment was carried out under the direction of their owners and/or agents. The survey began in 2011 and measured fabric heat loss, air leakage, wall moisture behaviour, indoor air quality and room conditions in seven houses. In subsequent years, measurements were repeated in four of the properties that had undergone refurbishment and each year findings were published in the form of SPAB research reports. In 2014, the Building Performance Survey was extended in three of the properties in order to focus on the performance of moisture in insulated solid walls. Measurements of temperature and relative humidity (RH) through, and either side of, an insulated wall section, referred to as interstitial hygrothermal gradient monitoring, had been made continuously since 2012. The extended Building Performance Survey expanded on this monitoring to include measurements of moisture content (MC) within the wall materials.

The purpose of the research was to consider a range of factors that may affect the energy performance and environment of traditionally built dwellings. The study attempts to quantify changes that have taken place within the buildings as a result of interventions made in the name of energy efficiency. These interventions may have had a positive impact with regard to energy performance, though determining this lay outside the scope of the study. Instead, various fabric and room condition quantities were measured both 'before' and 'after' refurbishment in order to map the effects of this work, as a means to determine some of the possible benefits and risks involved with the refurbishment of traditional buildings.

This report is intended to act as a summary of the SPAB BPS, with a principal focus on wall moisture behaviour. Information regarding the other factors under scrutiny - fabric heat loss, air leakage and interior conditions - is also provided, some in the form of Appendices to this report. If more detail is required we would refer readers to the original interim reports, which are available as free downloads via the SPAB website at: https://www.spab.org.uk/advice/research/findings/.

1.2 Methodology

Over the winter of 2011, seven houses that were due to have various forms of alteration, including work to improve energy efficiency, were visited. A room within each of these properties was singled out as providing a suitable location for the measurement of certain conditions: indoor temperature, RH and air quality, with an adjacent wall instrumented for measurements of fabric heat loss (*in situ* U-values) and interstitial hygrothermal gradient monitoring (IHGM). Over the same winter, an air pressure test accompanied by a thermographic survey was undertaken to measure and identify quantities and locations of air leakage within the building as a whole. The findings of this pre-refurbishment 'base case' work were presented as ***The SPAB Building Performance Survey 2011 Interim Report***.

During the following winters of 2012 and 2013, four of these buildings were re-visited and measurements repeated, with IHGM equipment being semi-permanently installed within the walls for longer-term measurements. The four buildings concerned were constructed principally of brick (Shrewsbury), cob (Riddlecombe) and stone (Drewsteignton and Skipton). The buildings in Shrewsbury, Riddlecombe and Drewsteignton then went on to become the focus for the extended moisture study in the second part of the research starting in 2014.

In 2011, there was little, if any, precedent for a study of this kind and the scope of the project evolved in response to findings over the seven years. Much of the measurement equipment, protocols, installation and analysis techniques used in the research were, by choice and necessity, bespoke. This allowed for a high degree of detail, control and understanding of the quantities under examination. Below descriptions are given of the principal methodologies employed in the measurement and analysis of moisture within the monitored walls.

Interstitial Hygrothermal Gradient Monitoring (IHGM)

The measurement of water vapour in air is used to provide an indication of the moisture performance of the wall fabric. The use of air as a proxy medium for moisture measurements has several advantages. Unlike measurements of moisture via electrical resistivity, it is unaffected by salt contamination or the presence of metals. As a quantity %RH is commonly used within fabric risk indices. Hence measurements of %RH may provide an immediate indication of risk without the need for interpretation based on the properties of individual materials - which are often unknown. However, the technique relies on high-quality equipment and a thorough and careful method of installation that ensures the sites of measurement are isolated to provide confidence in the findings.

Four sensor nodes containing precision temperature and RH sensors are embedded at varying depths through a wall section. Sensor specifications are as follows:

RH
Accuracy ±3%
Repeatability ±0.1%
Resolution (typical) 0.05%
Long-term drift < 0.5% per year

T
Accuracy ±0.4˚C
Repeatability ±0.1˚C
Resolution (typical) 0.01˚C
Long-term drift < 0.04˚C per year

Four separate 32 mm holes are dry core-drilled from the interior side with the aim of distributing the sensors evenly through the wall thickness, with sensor 1 closest to internal conditions, sensor 4 towards the external side of the wall and sensors 2 and 3 evenly spaced through the remaining material. If an air layer or material interface is present in the wall build-up, a sensor will be located in that position. Great care is taken to isolate the sensors and ensure that they are only able to measure conditions within the immediate point in front of the node. Additional sensors are placed on the external wall face in parallel with the embedded wall sensors to measure surface temperature, incident solar radiation, air temperature and RH. Measurements are also made internally of wall surface temperature, room air temperature and RH. Data from all these sensors (fifteen values in total) is logged at five-minute intervals by a dedicated ArchiMetrics datalogger.

Material Moisture Monitoring

A single 32 mm hole is dry core-drilled from the interior side of the wall. This hole is typically drilled to a depth of 100 mm from the external surface with three to four measurement ‘nodes’ evenly distributed through this core. Bespoke 100 mm-long gypsum sensor nodes measure electrical resistance and temperature via dedicated electronics developed by ArchiMetrics specifically for this task (the calibration of these sensors is explained below in section 1.3). Importantly, the nodes are carefully coupled to the wall material using a fine lime mortar to ensure the proxy measurement material is properly integrated into wall itself. Electrical resistance and temperature data from these sensor nodes are logged at ten-minute intervals by a dedicated ArchiMetrics' datalogger mounted in close proximity to the sensor array.

1.3 Definitions and Analyses

Due to the innovative nature of the BPS, the means by which data was presented was subject to development over the course of the study. The data generated by the two different moisture measurement techniques was examined via graphic analyses of a variety of different moisture quantities as described below.

Absolute Humidity (AH) and Relative Humidity (RH)

Absolute humidity (AH) is a measure of the mass of vapour in a given volume of air - g/m^3. In this case, it is derived from measurements of RH and temperature. It provides an indication of the quantity of vapour present at a particular location at a particular point in time allowing a way of identifying vapour trends within building fabric. However, whether this vapour presents a risk to fabric is usually determined in relation to vapour saturation and expressed as relative humidity (RH).

Relative humidity is a measure of the vapour saturation of air at a particular temperature. It is the ratio, as a percentage, of the actual water vapour pressure and the maximum water vapour pressure air could sustain at the same temperature, ie at 100% RH (dewpoint) the air has become saturated and water vapour may begin to condense. High RH (75%+) is one of the conditions required for mould fungus formation, which potentially leads to decay and rot within buildings.[1]

RH is a relational concept used to describe the water vapour content of air expressed as percentage of total capacity. Capacity varies with temperature. During the first part of the BPS up to 2014, RH was capped at 100%, the upper limit of the concept of 'dewpoint'. However, due to the method by which measurements of RH are typically derived by electronic sensors, it is possible to record RH values over 100%. The electrical capacitance of the surrounding air is measured, and this value is translated, using temperature, into an RH value. Above 100% RH we might start to get a film of liquid water forming on, or in proximity to, the sensing surface which would measure as additional capacitance and, therefore, show as a RH percentage greater than 100%. Prior to 2014, RH values above 100% were discarded at the point of capture to conform strictly with the concept of RH. However, as research progressed, the value of collecting this additional information was realised and from 2014 onwards we recorded RH measurements that exceeded 100%. The value of recording +100% RH is that we can observe the extent of overshoot and direction of travel for the RH beyond saturation.

Most of the analyses contained in this summary report use data from the full six years post-refurbishment of the BPS. Relative and absolute humidity behaviour is presented over time for the three walls and later in this report AH is analysed as a series of sectional annual averages, one for each of the six years post-refurbishment, plotted per measurement node. For the over-time analyses, each property is provided with a graphical analysis based on monthly aggregated data. In 'over time' analyses the difference between capped and uncapped RH quantities is visually evident in the form of a flat line at 100% RH (and at 0˚C in the saturation margin analysis – see below). The effect is most evident in the Riddlecombe analysis where RH at node 4 was high throughout the six years of monitoring; this results in an artificial 'increase' in RH which takes place in June 2014 when the sampling method was changed. For the other two properties under examination,

[1] 'The lowest humidity level for mould growth is around RH 75–80 % and for decay development above RH 95-98%': Ojanen, Viitanen and Peuhkuri, 2007, p1

Shrewsbury and Drewsteignton, the effect is less significant and overall this change does not impinge upon the conclusions drawn in this report.

Dewpoint and Saturation Margins

Dewpoint or saturation temperature (100% RH) is the temperature at which air reaches vapour saturation. The difference between the measured temperature and dewpoint temperature we term the 'saturation margin' and this represents the temperature drop required for condensation to begin at the measured locations within the wall. An illustration of the relationship between %RH, temperature and the 'saturation margin' is provided in Figure 1. In early reports we used the term 'dewpoint margin' as a means by which to quantify the risk of interstitial condensation. We now prefer the term 'saturation margin' as this shifts the emphasis of this concept to include the condition of wall material as well as the possibility of condensation. A narrow saturation margin is an indication that the air within the wall material is close to saturation, 100% RH. We may measure high RH values due to wetting from wind-driven rain, vaporisation from wet materials as a result of built-in construction moisture, the failure of rainwater goods and/or vapour control layers or just the inability, over time, for a wall to evaporate its moisture load. The term 'saturation margin' moves us away from the dewpoint/condensation risk paradigm which sees only internal water vapour moved by diffusion and condensed by cold temperatures as the sole moisture risk to buildings. 'Saturation' in this context refers to the state of air, but it also hints at the condition of surrounding fabric which may well be wet as a result of influences other than those of internally driven vapour diffusion and condensation. Nevertheless, due to cycles of condensation and evaporation, this wet material can contribute to the wetting and drying of the building fabric. Some moisture may be expected within the building fabric, particularly towards the outside of the building envelope in proximity to cold external conditions during winter months. It is generally considered that this is acceptable if interstitial moisture can dry out and not accumulate over longer periods of time.

For the three walls under study, post-refurbishment saturation margins are shown over time as monthly aggregated plots for each individual wall sensor over six years. These margins are also shown as sections through the walls, plotted per measurement node on an annual average basis and for the full six years.

Moisture Content

Moisture content can be expressed gravimetrically as the difference between the dry and wet mass of a material over its dry mass and is given as a percentage. Moisture content can be measured by gauging electrical resistivity between two metal pins. These pins are best embedded in a 'known' material, that is to say a material where the relationship between the resistivity measured from that material at particular moisture contents has been predetermined under controlled conditions. As measurements of electrical resistivity in different materials will vary widely, wood is often used as this 'known' material and acts as a proxy in much building monitoring for materials found within a wall. Although resistivity will still vary between timber species, plentiful tables of resistance values in relation to moisture content are available for a variety of wood types. Therefore, if the species is known, it is possible to deduce a reasonable idea of the moisture content of the timber and by extension materials that are in contact with it, assuming that they are in moisture equilibrium with the timber measurement medium. However, it is also possible to use other proxy materials as the basis for resistivity measurements, materials that may have characteristics more akin to the masonry materials under investigation. ArchiMetrics have developed and use a mineral-based resistivity sensor where the electrical probes are embedded in a gypsum medium and moisture content profiles have been produced for this specific material. It is hoped that these sensors, together with careful installation that allows for good coupling between the sensor and the wall material, can provide an accurate picture of moisture content within the wall over time.

Material moisture monitoring equipment was installed in 2014 as the second phase of the BPS. The analysis of this monitoring is presented as over-time plots using monthly aggregated data for each of the measurement nodes for the three-and-a-half years to the end of the project. Resistance measurements used to provide the material moisture analyses in earlier reports had been temperature-adjusted to take account of the thermal variation of the calibration of the sensors. However, this has proved to be unreliable and unnecessary. In this report, temperature compensation has been removed from the algorithm that underlies the analysis, resulting in a change to %MC values and plots from those previously published and greater confidence in results.

Data Holes and Date Series

The SPAB Building Performance Survey aims to record a continuous dataset within real-world conditions. However, there are, occasionally, during the course of this work periods of time when data is lost. This can be for a number of reasons including power outages and equipment malfunction. Where data is missing from an analysis values are shown as unchanging and where this impinges on the written commentary or interpretation this is noted within the text.

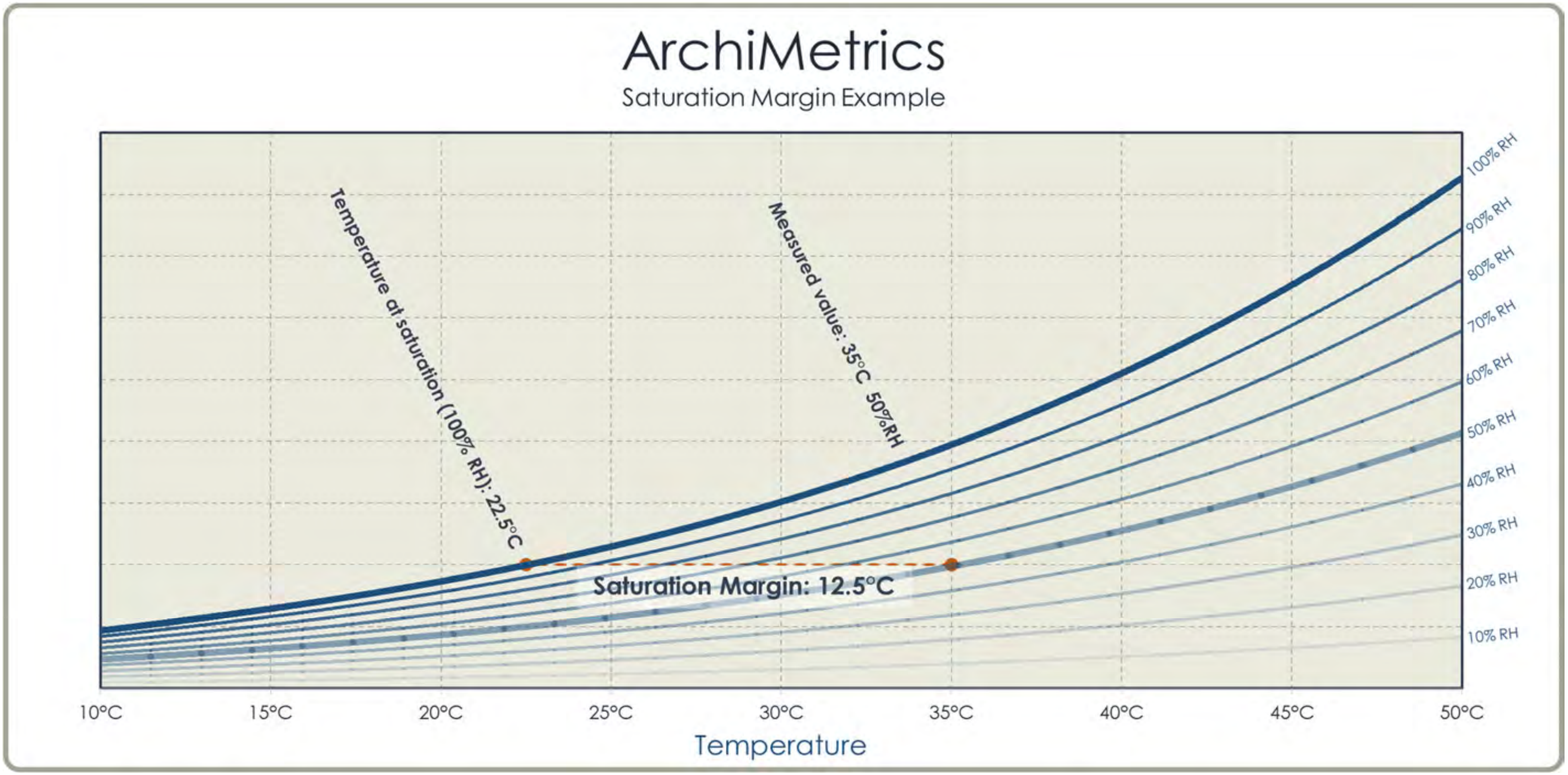

Figure 1. Illustration of saturation margin principle

2.1 Moisture in Walls

Energy efficient refurbishment practices are predicated, principally, on reducing heat losses that take place through fabric or via uncontrolled infiltration. However, it has been recognised for some time now that some materials and methods that reduce these heat losses may also cause moisture to accumulate, either within the spaces inside a building or within building elements themselves. This research has examined changes to the air permeability of buildings before and after refurbishment as well as indoor air quality and these findings are presented with the Appendices of this report. However, a key focus of the research has been to look at a more hidden aspect, to see in detail what occurs inside solid walls and the changes that may be occurring to moisture profiles as a result of refurbishment (insulation) work.

2.2 The Walls: Shrewsbury, Drewsteignton and Riddlecombe

The brick wall monitored in the study is found in a late Georgian building (1820s) located on Abbeyforegate, in the town of Shrewsbury. All the monitored walls are at ground floor level and floor plans showing monitoring locations are provided in Appendix A. The wall at Shrewsbury is south-facing and made of low-fired, relatively soft, porous and permeable brick bedded in lime mortar. It is a brick-and-a-half thick, ≈14”/350 mm, with some areas of pointing in poor condition. As part of the refurbishment of the house in 2012, the wall was internally insulated with 40 mm of woodfibre insulation board with a thermal conductivity (λ) value of 0.039 W/(m K) and finished with lime plaster and silcate paint. Table 1 provides details of the depths of combined RH and temperature monitoring sensors within the wall and the wall build-up post-refurbishment. The positions of the measurement sensors, (red for temperature and RH sensors and blue for gypsum) along with the build-up of the wall are illustrated in the section in Figure 2 below.

Build-up - internal - external	**Thickness of material**	**RH & T sensor No**	**Height from finished floor level**	**Depth of sensor from internal surface**
Lime plaster finish	8 mm	1	1875 mm	8 mm
Woodfibre insulation	40 mm	2	1725 mm	48 mm
Lime plaster	12 mm			
Brick	345 mm	3	1575 mm	195 mm
		4	1425 mm	355 mm
Overall	405mm			

Table 1. Interstitial hygrothermal gradient sensor positions for Abbeyforegate, Shrewsbury.

Figure 2. Interstitial hygrothermal gradient and material moisture monitoring, Abbeyforegate, Shrewsbury 2014.

The two other walls that were the focus of the extended wall moisture study were based in Devon: a granite stone wall in Drewsteignton and a cob wall in the village of Riddlecombe. The granite wall is north-west facing and as with many stone walls is quite thick, measuring approximately 600 mm. The quality of the granite is quite variable; with some blocks being harder than others, some with a dense, compact matrix and others with larger individual pieces of feldspar visible. Granite stone is considered relatively non-porous and not permeable although this can be quite variable, for example, where feldspar has been washed out, and the stone can contain fissures and fractures by which moisture might migrate. The stones are also bedded in lime mortar which is both porous and permeable. For the purposes of this research, in 2012 a floor-to-ceiling section of this wall was internally insulated with 100 mm of polyisocyanurate (PIR) insulation with a thermal conductivity (λ) value of 0.022 W/(m K) and dry-lined (Figure 3). The dimensions of the complete build-up are given in Table 2, the position and depth of the 25 mm air gap being as per the insulation manufacturer's recommendations at the time of installation.

Table 2. Interstitial hygrothermal gradient sensor positions for Mill House, Drewsteignton.

Build-up - internal - external	**Thickness of material**	**RH & T sensor No**	**Height from finished floor level**	**Depth of sensor from internal surface**
Gypsum skim	3 mm			
Plasterboard	12.5 mm			
Air gap	25 mm	1	1730 mm	30 mm
PIR Board	100 mm	2	1580 mm	140 mm
Tanking & gypsum	1 mm			
Lime Plaster	20 mm			
Granite	580 mm	3	1430 mm	340 mm
		4	1280 mm	610 mm
Total	**742 mm**			

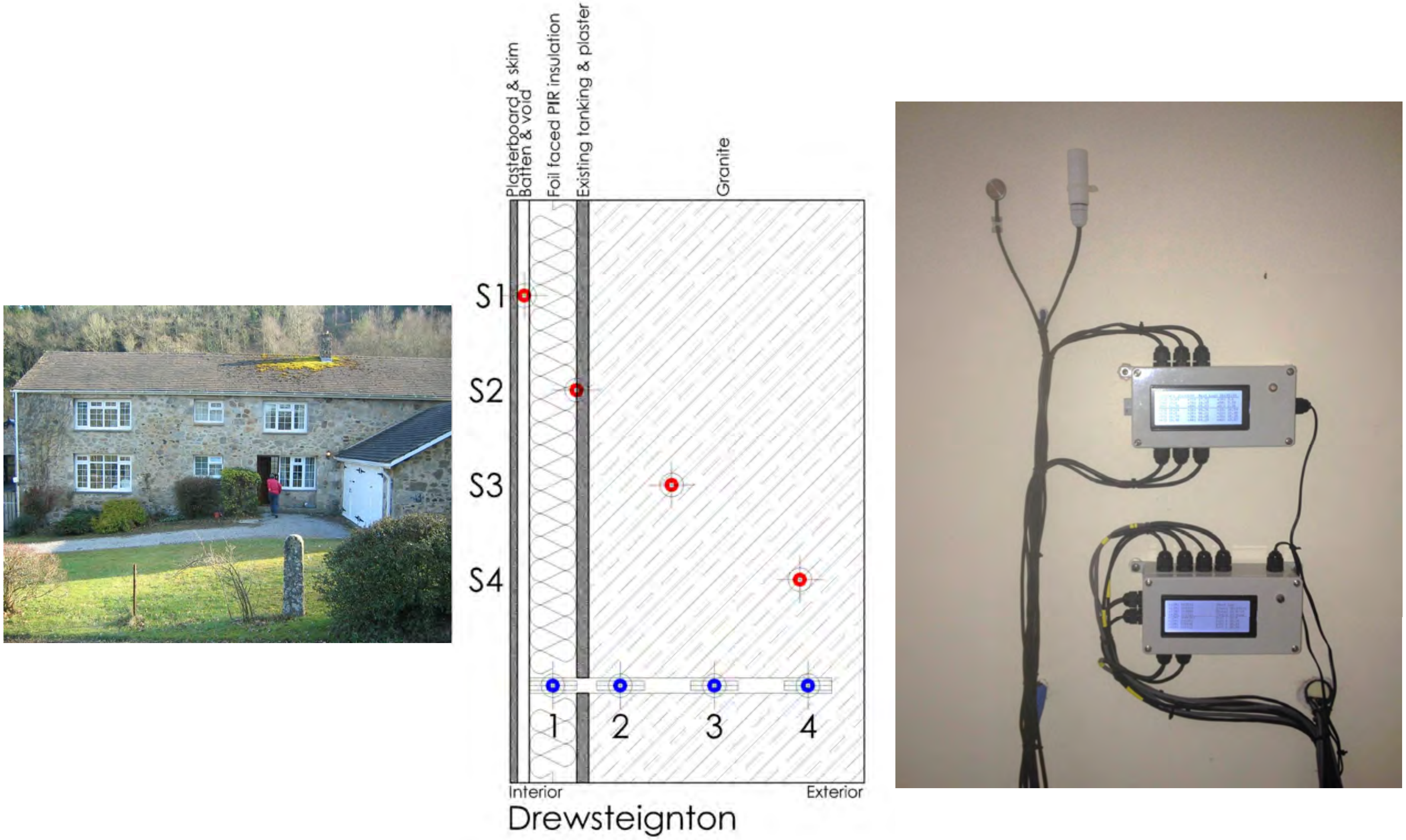

Figure 3. Interstitial hygrothermal gradient and material moisture monitoring, Drewsteignton, 2014.

The third building under study is somewhat different not being a masonry construction; it is built of cob (monolithic unbaked earth) and located in the village of Riddlecombe in north Devon. The wall is south-facing and, once again, as is usual for this material, is quite thick, around 550 mm. At the site of monitoring it had been historically reinforced or repaired with a layer of stone facing. Cob, made of clayey sub-soil sometimes containing aggregates and mixed with straw, is both eminently porous and permeable. Prior to refurbishment, the wall had an exterior cement render which was in poor condition and cracked. As part of refurbishment this was removed in 2012 and replaced with 60 mm of an insulating lime render incorporating perlite, with a thermal conductivity (λ) value of 0.066 W/(m K) (Table 3 and Figure 4).

Table 3. Interstitial hygrothermal gradient sensor positions and wall build up for The Firs, Riddlecombe.

Build-up - internal - external	**Thickness of material**	**RH & T sensor No**	**Height from finished floor level**	**Depth of sensor from internal surface**
Lime plaster	20 mm			
Cob	545 mm	1	1800 mm	60 mm
		2	1600 mm	225 mm
		3	1400 mm	395 mm
		4	1200 mm	575 mm
Masonry	90 mm			
Lime render scath coat	5 mm			
Insulating lime render	50 mm			
Lime render finish skim	5 mm			
Overall	**715 mm**			

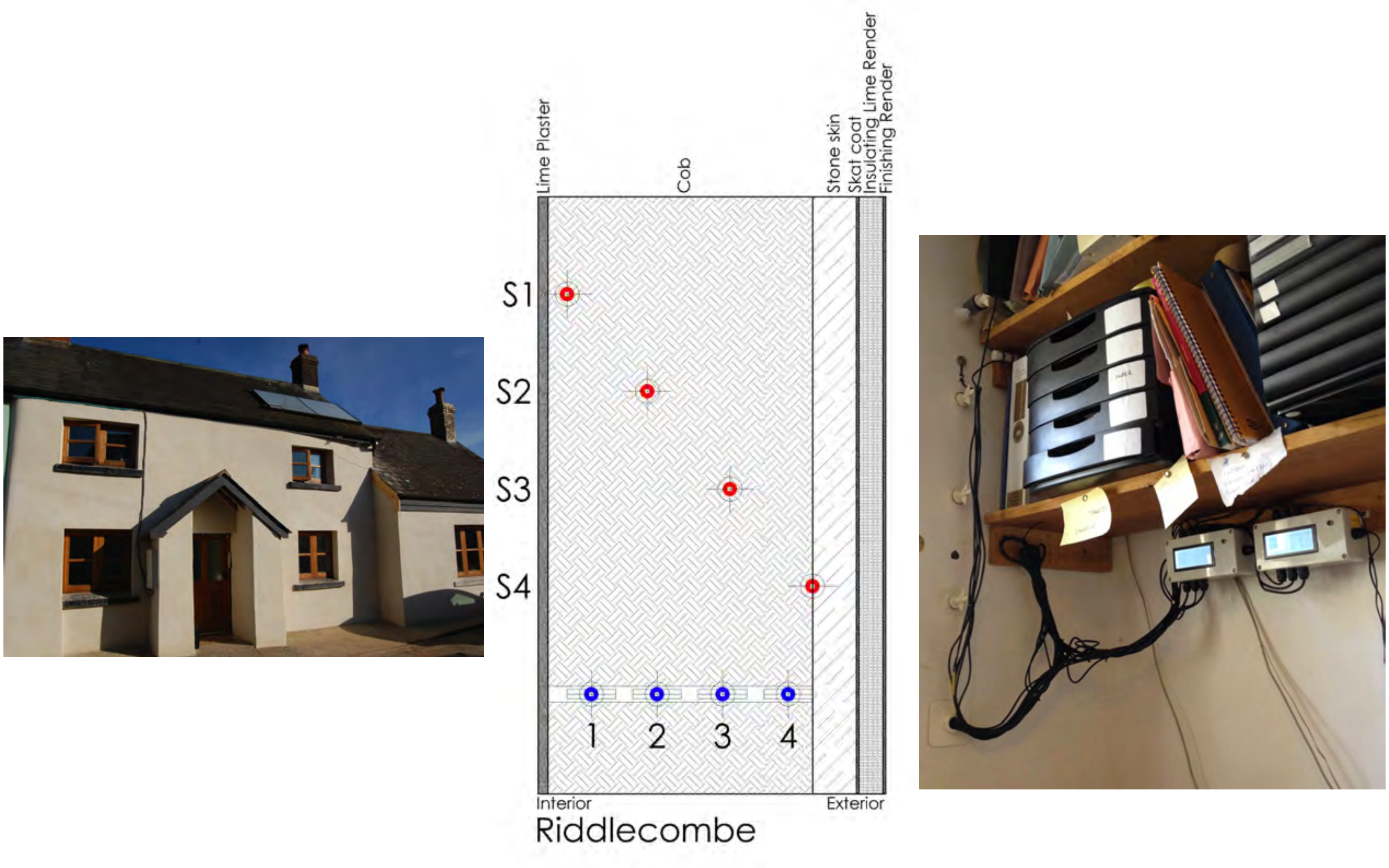

Figure 4. Interstitial hygrothermal gradient and material moisture monitoring, Riddlecombe.

2.3 Pre-refurbishment Wall Performance

Assessments of the performance of the walls (as well as the whole building) were carried out pre-refurbishment over the winter of 2011. They were, by necessity, undertaken over quite a short time frame of three to four weeks (ideally IHGM measurements through the wall section would have been carried out for a full year but project timescales did not allow this). Specifically, in relation to the walls, several *in situ* U-values were measured and IHGM monitoring equipment (measuring temperature and RH through, and either side of, the wall) was temporarily installed. U-values of relevance to the three walls under study along with their calculated equivalents are given in Table 4. (A table of all U-values for the project, measured and calculated, pre- and post-refurbishment, including details of wall build-ups, is provided in Appendix B.) The short-term IHGM data was subject to limited analysis in the form of hygrothermal sections which plotted average measured temperature and dewpoint temperature, based on averaged RH measurements, through the wall sections (Figures 5 to 7). Animations using the data recorded at five-minute logging intervals were also produced allowing observation of the responses within the walls over time.

Table 4. Measured and calculated U-values pre-refurbishment walls from the SPAB Building Performance Survey.

Location	Shrewsbury	Drewsteignton	Riddlecombe
Measured			
2011 Uninsulated	1.48 W/m²K	1.24 W/m²K	0.76 W/m²K
Calculated			
2011 Uninsulated	1.52 W/m²K	2.45 W/m²K	0.95 W/m²K

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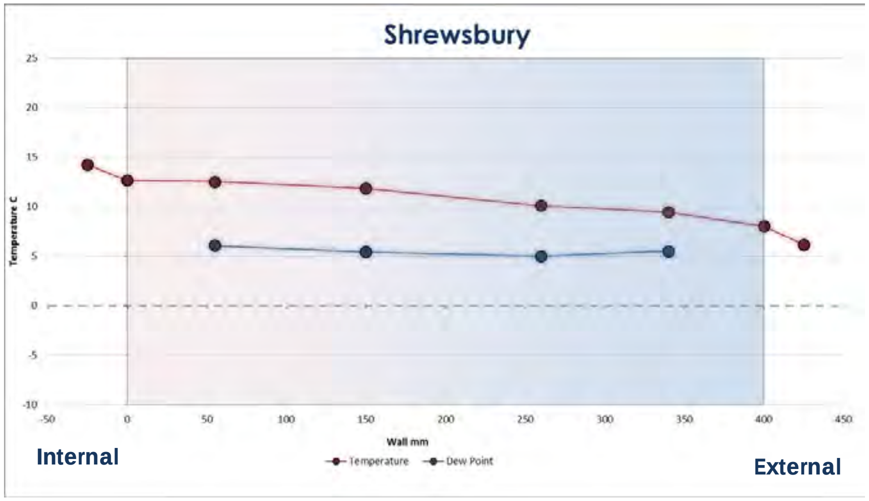


Figure 5. Temperature and dewpoint gradients for Abbeyforegate, Shrewsbury, 2011.

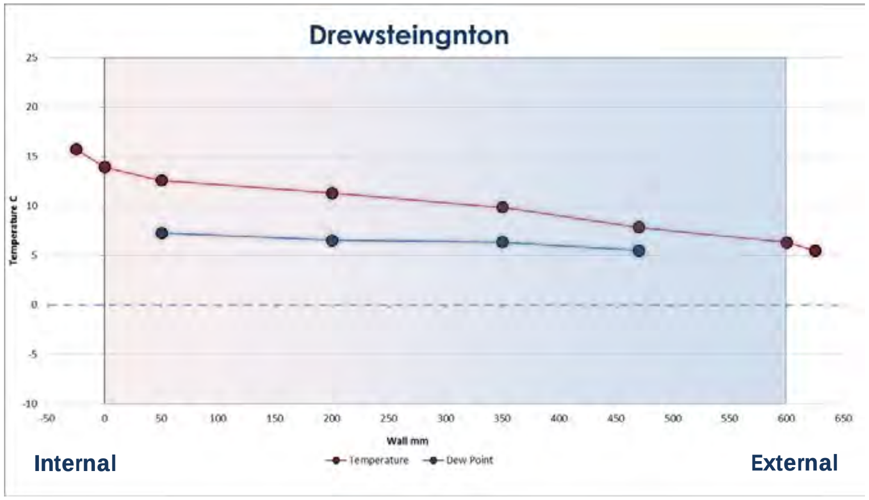


Figure 6. Temperature and dewpoint gradient for Mill House, Drewsteignton, 2011.

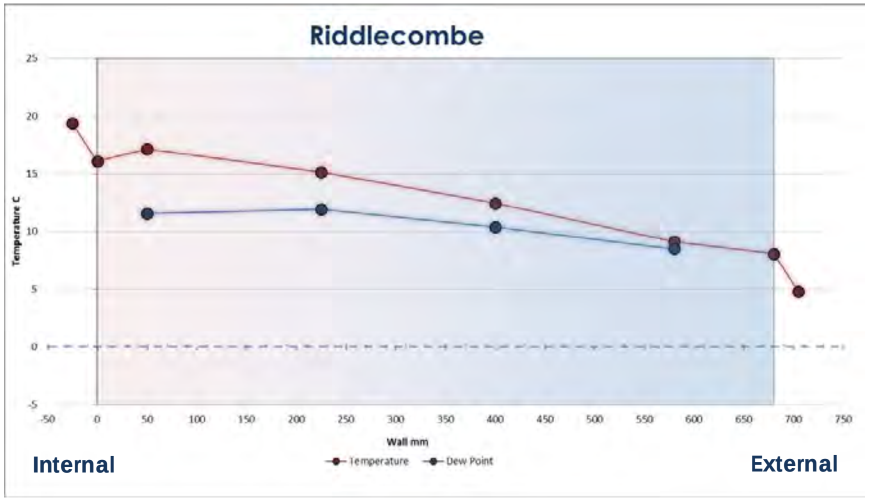


Figure 7. Temperature and dewpoint gradient for The Firs, Riddlecombe, 2011.

Based on these measurements, as well as information derived from the core-drilling of wall fabric to install measurement sensors, a number of observations were made about the character of the walls pre-refurbishment.

Shrewsbury was found to have good correlation between its measured and calculated U-value; giving some certainty to a U-value of around 1.50 W/m²K for the wall. The temperature gradient plotted through the wall shows on average only a 4˚C difference internally and externally and the report notes that internal heat input was quite low during the monitoring. The difference in the gradients between measurement nodes indicates a less homogenous thermal transfer response through the section. Heat loss towards the external side of the wall is increased due, perhaps, to the effects of air movement and/or wet materials. As measurements were taken in winter, during the coldest part of the year, some convergence towards the outside is expected between the plots of measured temperature and dewpoint temperature; the wall is cooler towards the external side resulting in the air within the wall being closer to saturation (dewpoint). Whilst there is some convergence seen at Shrewsbury it is more pronounced for the walls at Drewsteignton and Riddlecombe. This suggested that, during the period of measurements, the air towards the external wall face at Shrewsbury was of lower RH resulting in a higher margin of difference between actual temperature and dewpoint temperatures (on average calculated to be 5.49˚C). It had been observed during the core-drilling of the wall that there was a noticeable amount of air movement within the body of the wall. This effect was, probably, in part, due to air admitted by areas of missing pointing as well as the porous nature of the bricks themselves and the lack of an external render. It was thought that this, depending on external conditions, will have a drying effect. Also noticed in the hygrothermal animation were periods of reverse heat flow, which occurred on sunny days when solar gain had a dramatic effect on the south-facing wall quickly transferring heat into the body of the wall, something that would also promote drying.

There is considerable difference between the U-value measured from the granite wall at Drewsteignton, 1.24 W/m²K, and its calculated equivalent, 2.45 W/m²K. The reasons for this difference, common for stone walls, are discussed in detail in the ***SPAB U-value Report*** and stem from the difficulty of providing an accurate description, for calculation purposes, of all the factors which determine thermal transmissivity through a random rubble stone wall. For this reason, of the two quantifications of heat loss, the measured U-value might be the more representative. This wall, nearly twice as thick as that of Shrewsbury, measured on average an 8˚C internal/external surface temperature difference during the monitoring period and despite being constructed of random stone blocks the gradient between measurement nodes is quite consistent representing a homogenous thermal response. Indeed, when this wall was drilled no rubble core was evident and the construction was compact with few voids or loose rubble. Neither was air movement within the structure a noticeable feature of this wall. A more 'normal' convergence between temperature and dewpoint gradients towards the external side of the wall is found from the hygrothermal monitoring. The animation revealed the heavyweight nature of the construction with slow and muted temperature fluctuations measured inside the fabric in response to changes in internal and external conditions.

The U-value measured at Riddlecombe, 0.76 W/m^2K, compared with its calculated equivalent, 0.95 W/m^2K, is another example, like Drewsteignton, of the difficulty of providing a reliable U-value calculation for a non-standard construction. Cob, like natural stone, is an extremely variable material, its properties determined by local geology and construction methods and difficult to know. So, whilst this wall in theory had the advantage of being made of a single material, identifying an accurate thermal conductivity value for 'Riddlecombe cob' for the purposes of calculation is problematic. In addition, the measurement method is able to take account of reverse heat flow (the steady state calculation only allows for heat to flow from inside to outside) and thus accounts for the beneficial influence of solar gain on the south-facing wall as well as the wall's ability to retain heat due to considerable thermal mass. So, again, more faith may be placed in a measured U-value of 0.76 W/m^2K for this wall.

As with the other thick wall in the study, Drewsteignton, there was on average an 8˚C internal/external surface-to-surface temperature difference for this wall during the monitoring period and the consistency of the gradients between sensing nodes shows a very homogenous thermal response. Indeed, during drilling the cob material was found to be very uniform and seem to include very little aggregate. Of the three walls pre-refurbishment, the hygrothermal section for Riddlecombe showed the greatest convergence of temperature and dewpoint gradients and the saturation margin at node 4, towards the external side of the wall, was found to be on average only 0.6˚C pointing to the possibility of wet or damp conditions. As has been previously noted, this wall was finished with a cracked cement render and it was surmised that this was likely to be admitting water which was then unable to evaporate, leading to damp conditions within the cob in proximity to the external wall face.

2.4 Post-refurbishment Wall Performance

The measurement techniques used in the project were innovative as was much of the analysis of data. Therefore, as might be expected with such an approach, methods of interpretation evolved over the extended post-refurbishment timescale and were informed by what was observed. Most of the post-refurbishment analyses for the walls, except for material moisture, cover almost a full six-year time period and examine measured data in detail over a much broader base than that used for the pre-refurbishment analysis. The long-term monitoring of buildings allows for an appreciation and deeper understanding of the factors which impinge on their performance. Building on information gleaned from the 'base case' monitoring, it is possible to see to what extent temperature and moisture behaviour within the walls are determined by immediate, shorter-term influences, such as the weather, but also how these responses are affected over the longer term by the characteristics of the materials and structures themselves.

2.4.1 Shrewsbury – post-refurbishment wall performance

The external walls of the house in Shrewsbury were insulated internally with 40 mm of wood fibre board and in the winter of 2012, another set of U-values were measured and IHGM monitoring installed. Table 5 shows the post-refurbishment U-values, both measured and calculated, along with the pre-refurbishment values and percentage heat loss reduction figures for comparative purposes.

Table 5. Wall U-values pre- and post-refurbishment, Shrewsbury.

Shrewsbury	Uninsulated 2011	Insulated 2012	% reduction
Measured	1.48 W/m^{2}K	0.48 W/m^{2}K	68%
Calculated	1.52 W/m^{2}K	0.59 W/m^{2}K	61%

Pre-refurbishment there was good correlation between the measured and calculated U-values for this wall. Post-refurbishment the correlation has decreased, and the calculated U-value now lies outside of the ±10% error range deemed acceptable for a measured U-value. The difference can perhaps be explained by the contribution made by solar gain to this south-facing wall. As was seen in the pre-refurbishment monitoring, on sunny days this leads to reverse heat flows through the wall which overall will reduce the heat lost through the fabric. However, this, as well as the thermal capacity of materials, is not something that is accounted for within a calculated U-value. If during the time of the post-refurbishment measurements there were a number of clear sunny days this might account for the difference between the measured and calculated U-values, where measurements made from the wall show lower heat loss. In both instances, as would be expected, a reduction in heat loss following insulation is found of 61% based on calculated U-values, or 68% from measurements.

IHGM measurements made at five-minute intervals over six years between 19th February 2012 and 1st October 2017, have been used as the basis for assessments of post-refurbishment hygrothermal wall performance. Measurements of RH made either side and through the walls are plotted as monthly aggregated data over time, Figure 8. The RH-over-time analysis reveals much about the character and behaviour of moisture as a vapour within this wall. RH traces from the brick wall at Shrewsbury are perhaps the most distinctly different of the three walls. RH through the section occupies a broad range of quantities over a year and volatile responses are seen particularly at n4, the sensor closest to external conditions. Over most winters, bar that of 2016/17, RH reaches around 100% at n4 for a time before plunging back down to show some of the lowest levels of RH through the wall section during the summer months, between 50–60%. It can also be seen that the node towards the centre of the wall, n3, does not exhibit the same degree of volatility except for the year 2014. In this year n3 shows a sustained RH peak close to 100% with a trace that the echoes that of n4, albeit with roughly a five-month delay. The volatile RH response seen towards the external side of this wall occurs in direct response to the weather. Peaks in RH at n4 occur over the winter months where the porous and permeable brick is impacted by rain, particularly when the wind blows and drives rain deeper into the substrate. Over 2013-14 this response is noticeable at both n4 and n3, where high RH is recorded deeper within the wall fabric through the winter and summer months. Meteorological Office records show that after post-refurbishment monitoring commenced, the UK has experienced two of its wettest years since 1910, in 2012 and 2014. Both winters saw widespread flooding but a feature of the 2013/14 winter was the number of major storms, twelve in total, with high wind speeds. It is the combination of rain and wind which leads to the extreme response seen at n3 over 2014 where rain has been driven further into the fabric of the wall, leaving a legacy of higher RH which only reduces towards the end of the summer. Just how exceptional this is, is demonstrated in the AH over time record for the wall, Figure 9, where two detached peaks in absolute humidity are seen in 2014, first for n4 and then later at the end of summer at n3. In contrast, over the winter of 2016/17 RH traces from n4 and n3 show much lower records of RH measured. This was an unusually dry winter in comparison with previous years, where rainfall (measured annually September– August) was 32% lower in 2016-17 (334 mm) in comparison to 489 mm, for example, the previous 2015-16 year.

However, just as the wall shows it is capable of rapid increases in RH as a result of external conditions, it also experiences rapid decreases for the same reason. Because the wall is south-facing, quite thin and made of soft, dark red, low-fired brick and therefore is both porous and permeable, as soon as temperatures increase drying commences, driven by a combination of heat from solar gain and air movement within the fabric. At first, perhaps counterintuitively, this is seen as increases in RH within the fabric as damp materials release their moisture as vapour, drying by evaporation. However, after a period of time, which is determined by external conditions and the quantity of moisture held as a liquid with the materials, a tipping point is reached when the fabric has released enough residual moisture that the vapour load within the air is reduced and thereafter RH is seen to fall. For the wall at Shrewsbury, on an annual basis the tipping point at n4 is reached around April, this being the month sharp falls in RH commence. Normally this is followed shortly after by similar, although less pronounced, RH reductions at n3, although for reasons previously detailed, 2014 is an exception. Just as there has been a delay to the wetting of fabric deeper within the wall at n3, there is also delay to drying here as the effects of solar gain in 2014 and increased temperatures are slower to have an effect deeper within the wall. Indeed, a sustained peak of RH at n3 occurs over the summer months because of the vapour production taking place within the fabric. This is something also illustrated in the AH-over-time analysis where, following the end of the winter storms, weights of vapour continue to increase reaching a peak in September 2014, marking the cessation of drying - the tipping point for vapour measurements in this part of the wall in this year - followed by rapid reductions in AH/RH.

Just as wind and rain are seen to have a direct impact on the vapour picture towards the external side of the wall face at Shrewsbury, so is air movement and heat from the sun. These effects are the reason why n4, in the summer, sometimes records the lowest RH of all measurements through the wall section. Indeed, external conditions are the dominant influence on vapour behaviour in this part of the wall and overall result in a dynamic RH picture.

Another aspect of note regarding, in particular, the RH-over-time analysis for Shrewsbury, is RH behaviour at n2, the sensor at the interface between the masonry wall and the wood fibre insulation. This is sometimes referred to as the critical interface as it is thought that when a wall has been internally insulated this point, immediately behind the insulating layer, represents the greatest risk for interstitial condensation. At Shrewsbury, over six years we can see that, despite the volatility observed towards the external side of the wall at n2, RH stays within a relatively narrow range and over six years averages 72%. There are only two occasions in the monthly aggregated data when levels are seen to exceed that of 80%; early on in the post-refurbishment monitoring, as a result of the wet materials used on the internal side of the wall (lime plaster) as part of the refurbishment. (It is also possible to see a decrease in RH at n1 and n2 as these materials dry to a dynamic equilibrium by June 2012.) Then again in May–June 2014, in response to the exceptional wetting that has taken place that year due to winter storms. We have surmised that the relatively stable RH response plotted at n2 is a result of the hygroscopic properties of the wood fibre insulation in close proximity to it. This ‘buffers’ vapour in the air resulting in a more even, less extreme, RH response.

Based on measurements of RH, we have also looked at moisture vapour behaviour within the wall in Shrewsbury in terms of risk in the form of ‘saturation margins’. These quantify the risk of the air within the wall becoming saturated. A saturation margin is the difference between measured temperature and dewpoint temperature and thus indicates, in ˚C, how close the air at a particular location is to 100% RH. Whilst this does not relate directly to predictions of mould fungus formation, it is, nevertheless, indicative of a particular state within the fabric, suggesting high concentrations of vapour and the possibility of condensation and the deposition of water within fabric. In Figure 10, periods of the year where the wall reaches 100% RH (mostly only at n4) inevitably correspond with saturation margins of 0˚C. But, as with the RH record, these margins quickly improve as residual winter moisture is dried from the fabric. So whilst parts of this wall do exhibit high vapour records for part of the year, this vapour also reduces annually and the average saturation margins calculated overall for six years for the wall; n1, 6.34˚C, n2, 5.05˚C n3, 4.01 and n4, 3.89˚C are much wider than those found for the other two walls in the study.

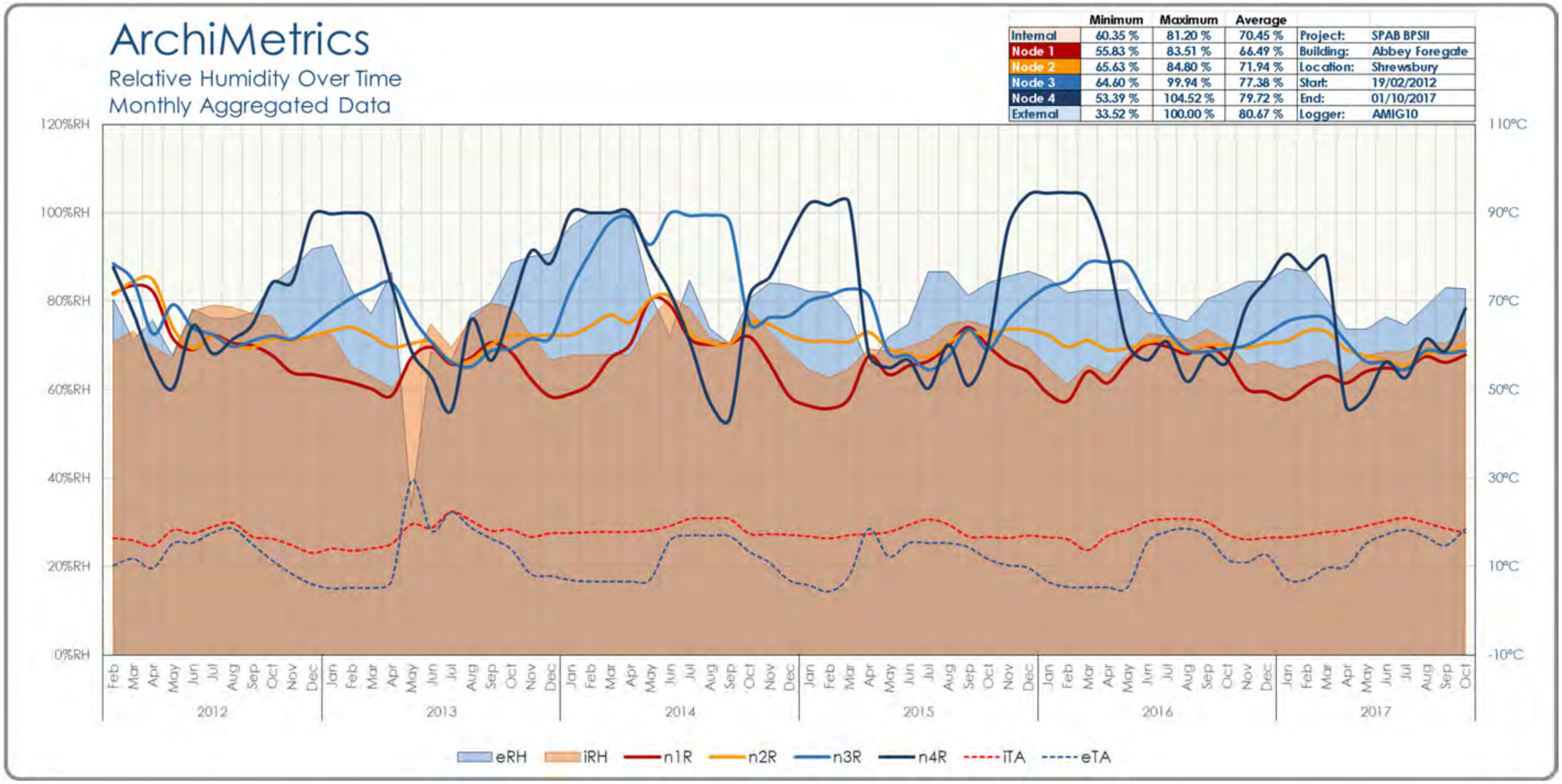


Figure 8. Relative humidity over time – post-refurbishment, Shrewsbury 2012–2017.[2]

[2] Definitions for abbreviations given in the key include: eRH – external RH; iRH – internal RH; iTA – internal air temperature; eTA – external air temperature.

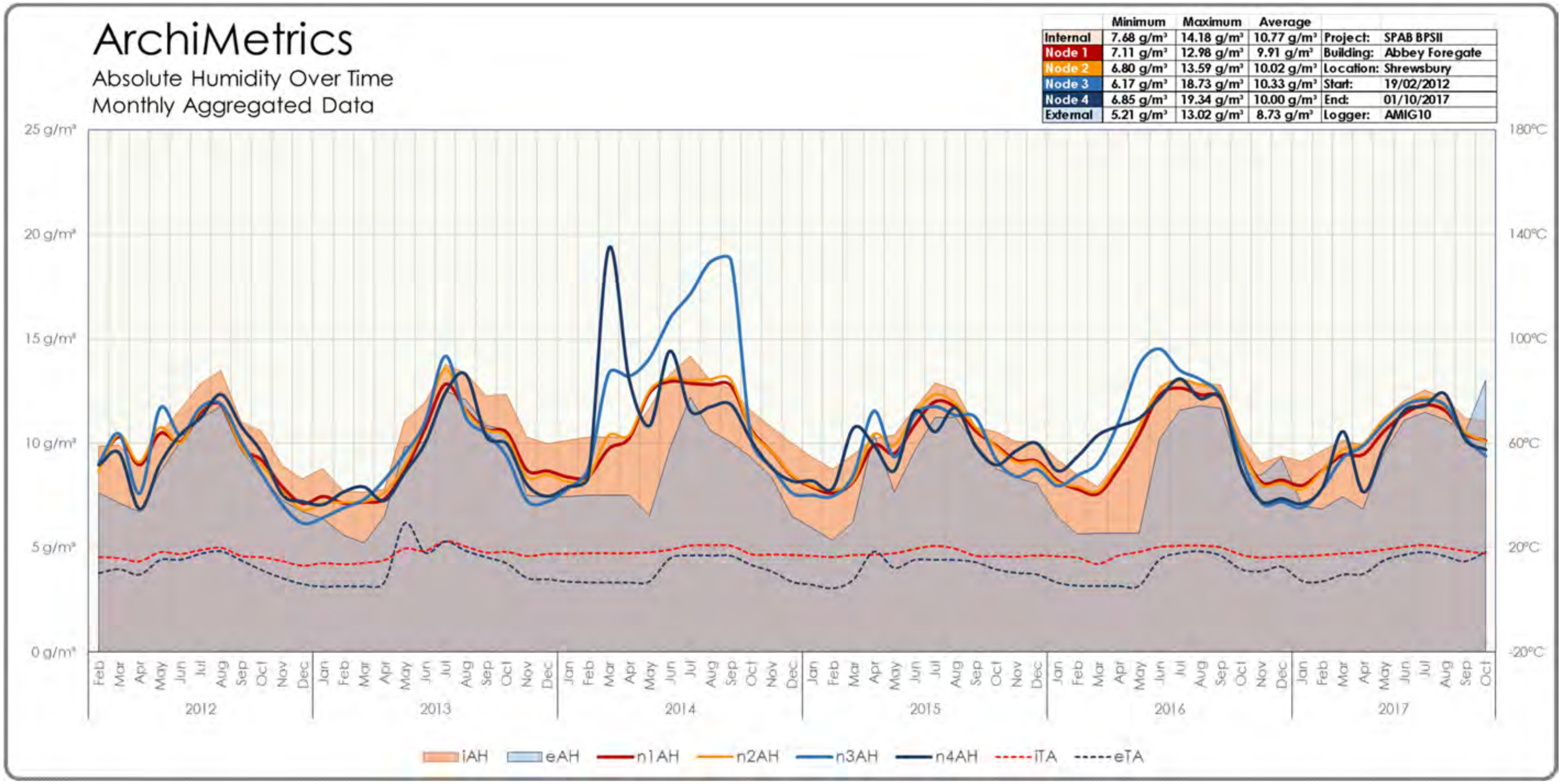


Figure 9. Absolute humidity over time – post-refurbishment, Shrewsbury 2012–2017.

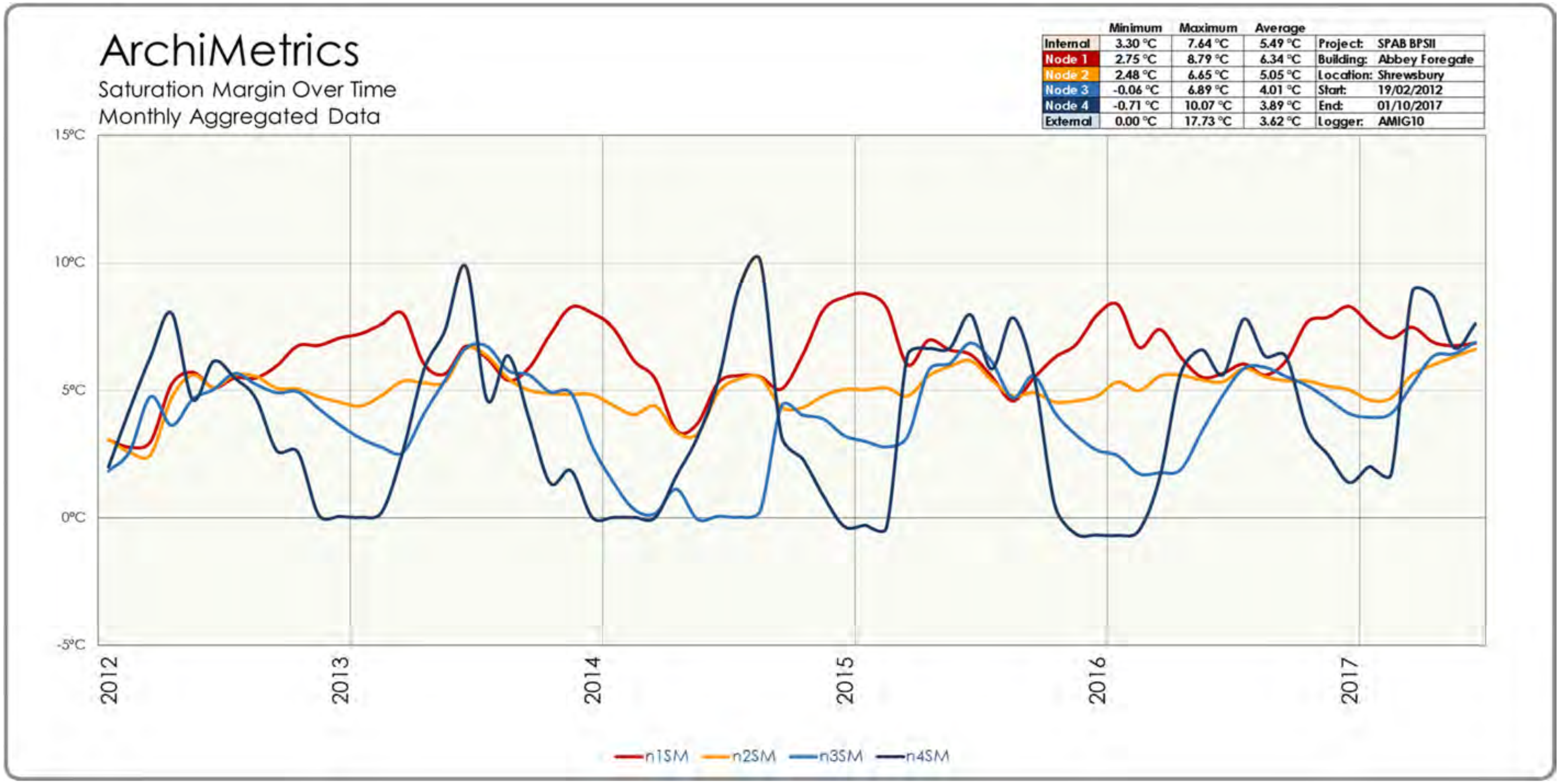


Figure 10. Saturation margin over time – post-refurbishment, Shrewsbury 2012–2017.

Thus far, our analysis has looked at moisture recorded as vapour within the wall. From July 2014 onwards, material moisture (%MC) monitoring was installed in Shrewsbury, Figure 11. This shows that overall the brick wall measures low %MC through its section. The start of the analysis, July 2014, shows higher but reducing %MC at MC2. This signature is an indication of the moisture introduced into the wall via the lime mortar, which is used to embed and couple the gypsum sensors to the fabric, drying and being dispersed. It is likely that this effect is only seen at MC2 as it is positioned in the centre of the wall further away from an evaporative surface. 'Drying' processes occurred more rapidly at MC1 and MC3 in proximity to internal and external surfaces and have already taken place prior to the analysis commencing in July 2014. Thereafter, throughout the remaining three-and-a-half-year period, slight temporary increases in %MC are observed annually over the winter but %MC is not seen to rise above 1%. Interestingly, for two of these winters, 2014/15 and 2016/17, these increases are measured only at MC1 and MC2, the two sensors located toward the centre and internal side of the wall face. The impact of colder, wet and windy weather is most pronounced in the vapour record at n4, near the external wall face, yet measurable increases in %MC in these years occur deeper within the fabric. As has already been mentioned, the winter of 2016/17 was quite dry with an annual (September–August) rainfall total for Shrewsbury of 334 mm. This total is not dissimilar to that of the year 2014/15, with a total rainfall of 352 mm, whereas the winter of 2015/16 was wetter and total rainfall that year is considerably higher, 489 mm. Over that winter, an increase in %MC is measured at MC3, closest to external conditions, as well as MC2. During the other monitored winters, 2014/15 and 2016/17, the wall was subject to less wetting overall and on sunny winter days enough evaporation took place towards the external side of the wall face, around n4, to ensure that residual moisture (measured as %MC) did not increase towards the external side and increases only show deeper within the fabric. This difference is not something that would show in the RH (vapour) record as RH would remain high during these winter periods and would only register as lower RH record once residual moisture has been reduced (something that occurs later in the year, around April or May). Therefore evaporation, as well as wet weather, is part of the high RH picture over winter at this location.

Overall, however, as with the vapour records, the wall is clearly able to recover from the impact of winter weather as it returns to a lower baseline %MC during the summer months. And throughout the three-and-a-half years of monitoring, as has been previously stated, %MC quantities are low. No doubt, once again, the qualities of this wall, including its aspect, thinness and porous and permeable materials, ensure that the drying of excess moisture takes place over an annual cycle.

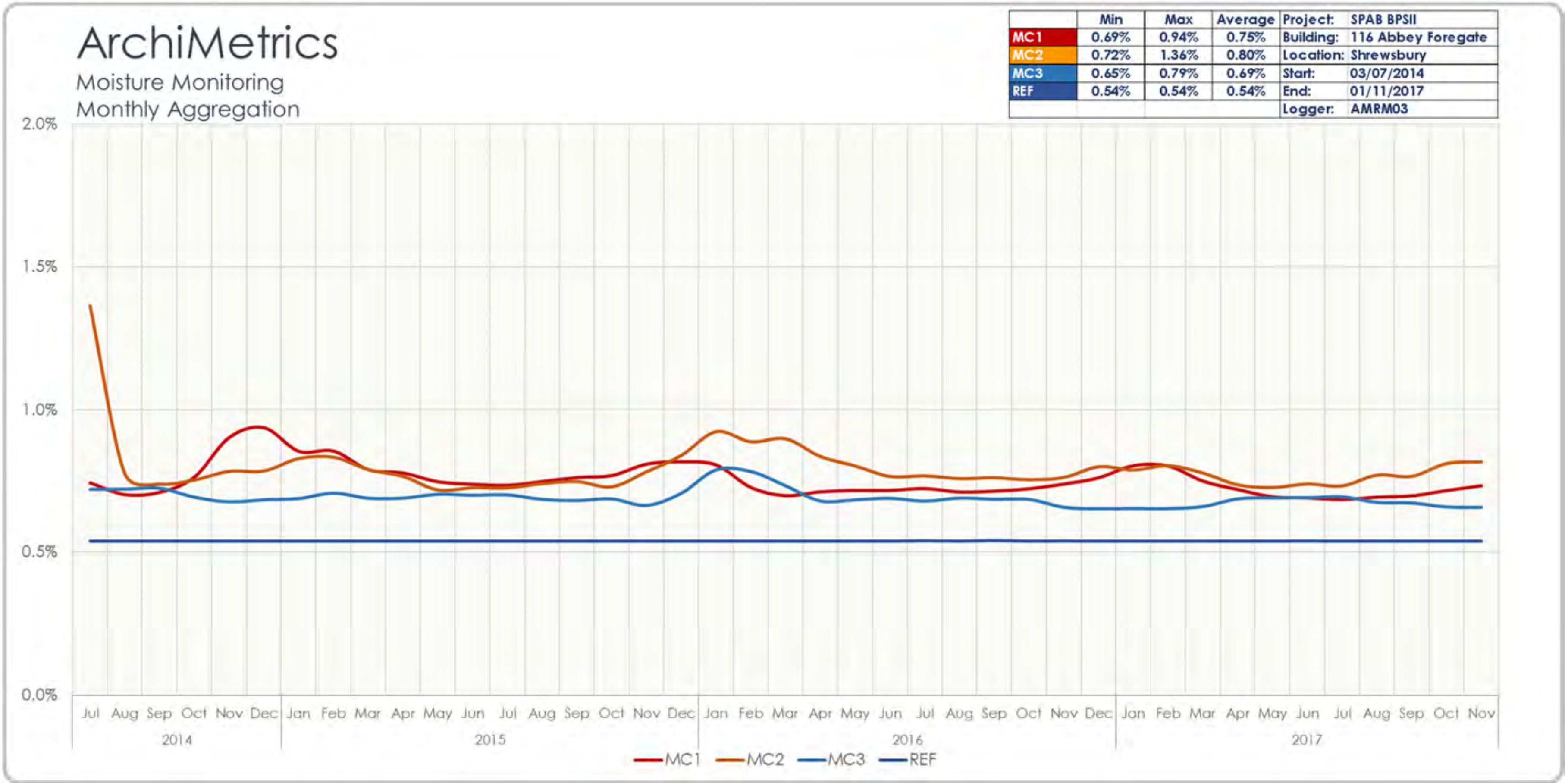


Figure 11. Material moisture over time – post-refurbishment, Shrewsbury 2014–2017.

2.4.2 Drewsteignton – post-refurbishment wall performance

A 5.5 m^2 section of wall at the house in Drewsteignton was insulated internally with 100 mm of PIR board and in the winter of 2012 another set of U-values were measured and IHGM monitoring installed. Table 6 shows the post-refurbishment U-values, both measured and calculated, along with the pre-refurbishment U-values and percentage heat loss reduction figures for comparative purposes.

Table 6. Wall U-values pre- and post-refurbishment, Drewsteignton.

Drewsteignton	Uninsulated 2011	Insulated 2012	% reduction
Measured	1.20 W/m^2K	0.16 W/m^2K	87%
Calculated	2.45 W/m^2K	0.19 W/m^2K	93%

There is far greater correspondence between the measured and calculated U-value for the wall at Drewsteignton post-refurbishment in comparison with the two U-values found for the wall before the addition of internal wall insulation. The improved alignment between the two methods of quantifying heat loss occurs because the calculation process relies on known quantities of materials with defined thermal conductivity (something that has been previous noted as problematic for existing walls made of historic, variable, potentially unknown and untested materials). The large quantity of insulation material added to the wall at Drewsteignton becomes the dominant factor in determining the wall's thermal resistance, because the properties of this particular element of the wall build-up are well-known, the effect that it has on the overall heat loss of the wall can be calculated with some accuracy. As with the previous example of Shrewsbury, the good correlation between measured and calculated U-values leads to additional confidence for both the post-insulation U-values. A comparison of these two shows that there has been a reduction in heat loss from the wall of between 87–93% - the 87% figure being perhaps the more reliable as this is based on measurement, which, for the wall prior to refurbishment, is likely to have quantified heat loss more accurately and therefore the 87% figure will provide a more realistic estimate of the overall change that has taken place regarding heat loss for this wall.

The RH-over-time analysis for Drewsteignton (Figure 12) looks very different to that of Shrewsbury (Figure 8). For most of the six years (07/02/11-13/11/17) the RH range for the three sensors embedded in the masonry section of the wall, n2 – n4, is quite narrow and high, between ≈85–100% and responses are more muted or less volatile. N1, however, exhibits quite different RH behaviour from that measured by the other sensors. It occupies a wider range, 48–84% RH and responses are more dynamic. This node is positioned within the air gap behind the plasterboard finish of the wall and as such is decoupled from the rest of the wall assembly; it is not encapsulated within a material and 'looks at' a larger and more changeable air mass. It is clear through the matching profiles of n1 and that of the room interior (iRH) that RH conditions behind the plasterboard are very similar to those measured within the interior space, albeit, with slightly elevated %RH behind the plasterboard. It seems that there is a good deal of vapour exchange between these two spaces and that the 3–4 %RH increase measured from within the air gap is likely to be the result of reduced infiltration/renewal of air in this closed, narrow space.

The sensors in the masonry part of the wall all show high RH throughout an annual cycle. It is interesting to track the annual peaks in RH measured at each of the three sensors. Across most years, RH peaks at n4 are measured in or around the month of April, while those at n3, like n3 at Shrewsbury, lag behind, peaking approximately three months later in June. Peaks in the n2 trace are harder to discern but tend to arise in November and are sometimes accompanied by an additional, lesser peak at the end of the winter in February. Between the three sensor nodes, the narrowest range of RH through the masonry section is found through autumn and winter, with spring and summer seeing a more diverse spread of measured RH. For sensor positions n3 and n4, in the centre and towards the external side of the wall, the RH picture recorded at Drewsteignton is predominantly determined by evaporation. Moisture that has built up in materials during the colder, wetter, winter months evaporates due to warmer, external, springtime temperatures resulting in RH peaks in April. This effect is delayed deeper within the wall at n3 as evaporation can only take effect here once a certain quantity of residual moisture (resulting in lower vapour pressure) has been lost towards the outside of the wall at n4. As the year progresses, more intense solar radiation provides longer periods of increased warmth which aids evaporation deeper within the structure. This is the reason for the later peaks, measured at n3 in June (Figure 13). The evaporative activity provoked by warmer atmospheric temperatures is also the reason that the greatest RH range is measured in spring and summer for this wall.

It is perhaps not surprising that RH behaviour at n2 is somewhat detached from the obvious influences of the external environment buried, as it is, deep within the wall fabric at the ‘critical’ masonry/insulation interface. However, even here perhaps the picture is also determined by external conditions. Annual measurements show less defined peaks which most often (although not always) take place over the winter months, between November and February. It would seem likely that these are caused not by wetting, as the location is well away from the external surface and the peaks occur at the start of the winter, but are a result of cooler temperatures through the section increasing the vapour saturation of the air over the winter. Therefore, while some evaporation may take place over an annual basis at n2, peaks in RH here are probably not a result of evaporation but lower ambient temperatures.

Therefore, RH behaviour tracked through the wall at Drewsteignton is somewhat different from that of Shrewsbury and the reasons for this stem from the differences between the two walls. Whereas Shrewsbury is a thin, south-facing wall made of quite porous and permeable brick, the wall at Drewsteignton faces north-west, is much thicker and constructed of dense, heavyweight stone. Granite is an igneous rock formed by the crystallisation of magma. As such, it lacks an interconnected pore structure, has limited permeability and low water-carrying capacity. However, as Figures 12 and 13 make clear, there is some vapour movement within the structure and it is likely that this occurs predominantly via permeable lime mortar bedding joints and micro-fissures within the stones. Thus, the more muted RH signature reflects the combination of these materials and the wall’s more massive and heavyweight construction, with less solar influence or air infiltration. Thus vapour and temperature responses are less extreme and take place over an elongated timescale in this wall.

As is to be expected, the saturation margin over-time analysis for Drewsteignton (Figure 14) is less volatile than that of Shrewsbury and shows a clear distinction between the plot for n1, in the air gap, where conditions have been seen to be coupled to the room interior, and those of the sensors embedded within the masonry wall. As a result of the persistently high RH measured from the masonry section, saturation margins for nodes 2, 3 and 4 are much narrower than those found for the wall at Shrewsbury; the six-year averages being, n2, 1.17˚C, n3, 0.88 ˚C and n4, 0.47˚C. This indicates that air, particularly in proximity to n3 and n4, is quite close to saturation, especially during spring (n4) and summer (n3) when evaporative drying creates peaks in RH as previously observed. Figure 14 shows one extended period of negative margins, at n4 in 2016. (Negative margins may have also occurred in the years prior to 2014 but RH measurements capped at 100% mean it is not possible to identify these.) Looking at autumn and winter rainfall for the south-west, Table 7 (September–February), we find that, of the years monitored post-insulation, the winter of 2015/16 saw higher rainfall (731 mm) than that of the winters 2014/15 (593 mm) and 2016/17 (505 mm). Overall, if annual (twelve-month) average rainfall for all monitored years is calculated with a year end of August (which takes account of the possibilities of spring and summer drying having occurred within the fabric following the impact of colder and wetter autumn and winter weather), the years 2014/15 and 2016/17 have the lowest rainfall averages of all the six post-insulation years, 1017 mm and 954 mm respectively. Thus it seems that the negative margin found at n4 in 2016 (and not for years either side) may well be a result of increased wetting of the fabric over the winter 2016/16 due to higher rainfall. In general, the saturation margin trace for n4 has a greater range than that of either n3 or n2, the deeper wall sensors, and vapour conditions measured at n4 are in closer contact and seem to be more immediately influenced by external conditions.

Table 7. South-west England and Wales regional precipitation 2011–2017 sourced from Meteorological Office Hadley Centre observations datasets: HadUKP. Alexander, LV and Jones, PD (2001) Updated precipitation series for the UK and discussion of recent extremes*, Atmospheric Science Letters doi:10.1006/asle.2001.0025.*

Year	**Sept. Oct. Nov.**	**Dec. Jan. Feb.**	**Winter Total mm**	**March April May**	**June July August**	**Annual total mm**
2011/12	227	265.6	492.6	236.2	394.3	1123.1
2012/13	415.4	416.5	831.9	204.4	146	1182.3
2013/14	352.2	609.9	962.1	236.3	210.5	1408.9
2014/15	297.1	295.8	592.9	165.8	257.9	1016.6
2015/16	276.6	454.5	731.1	233.6	203	1167.7
2016/17	280.3	224.6	504.9	185.1	263.9	953.9

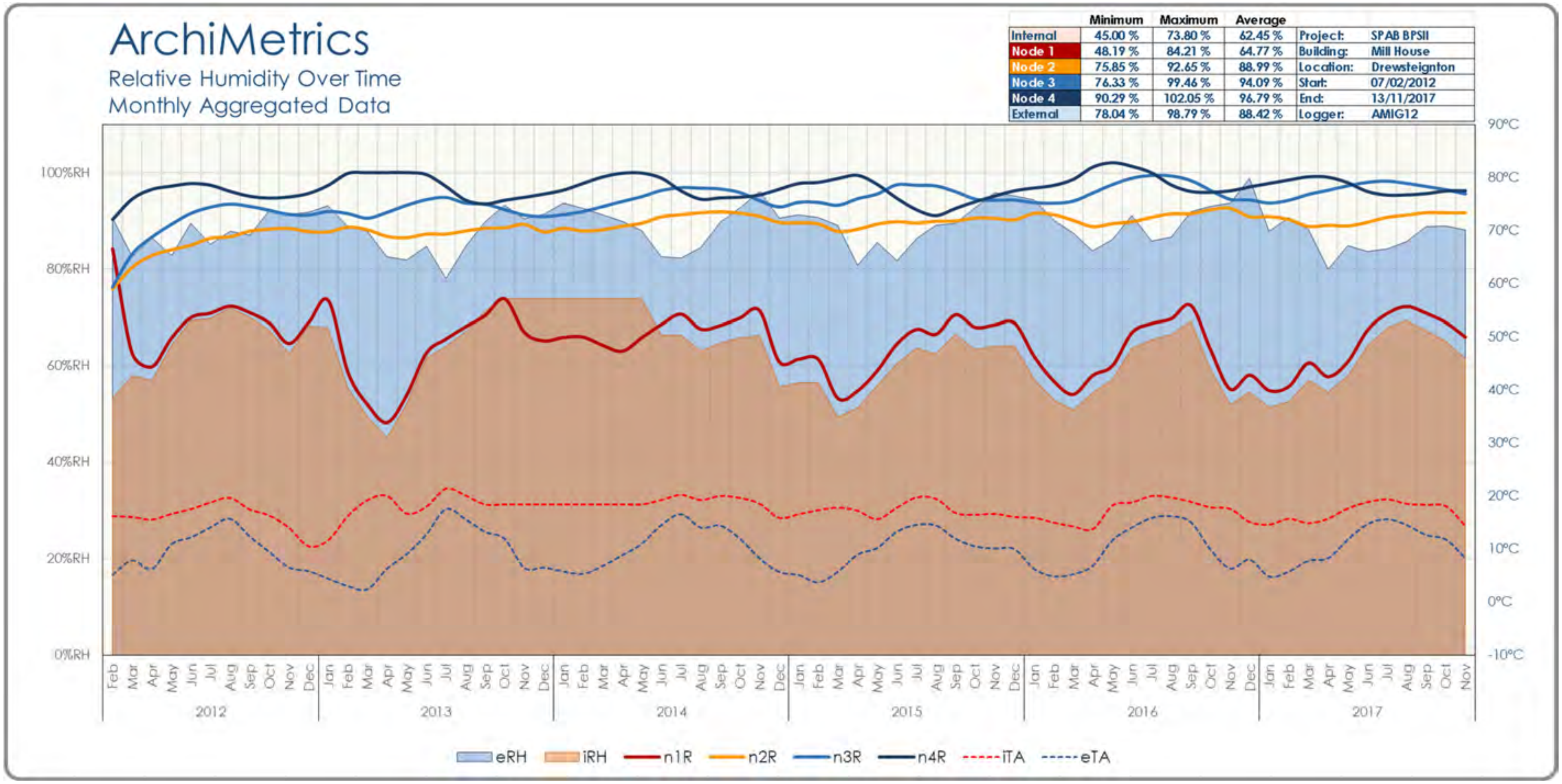


Figure 12. Relative humidity over time – post-refurbishment, Drewsteignton 2012–2017.

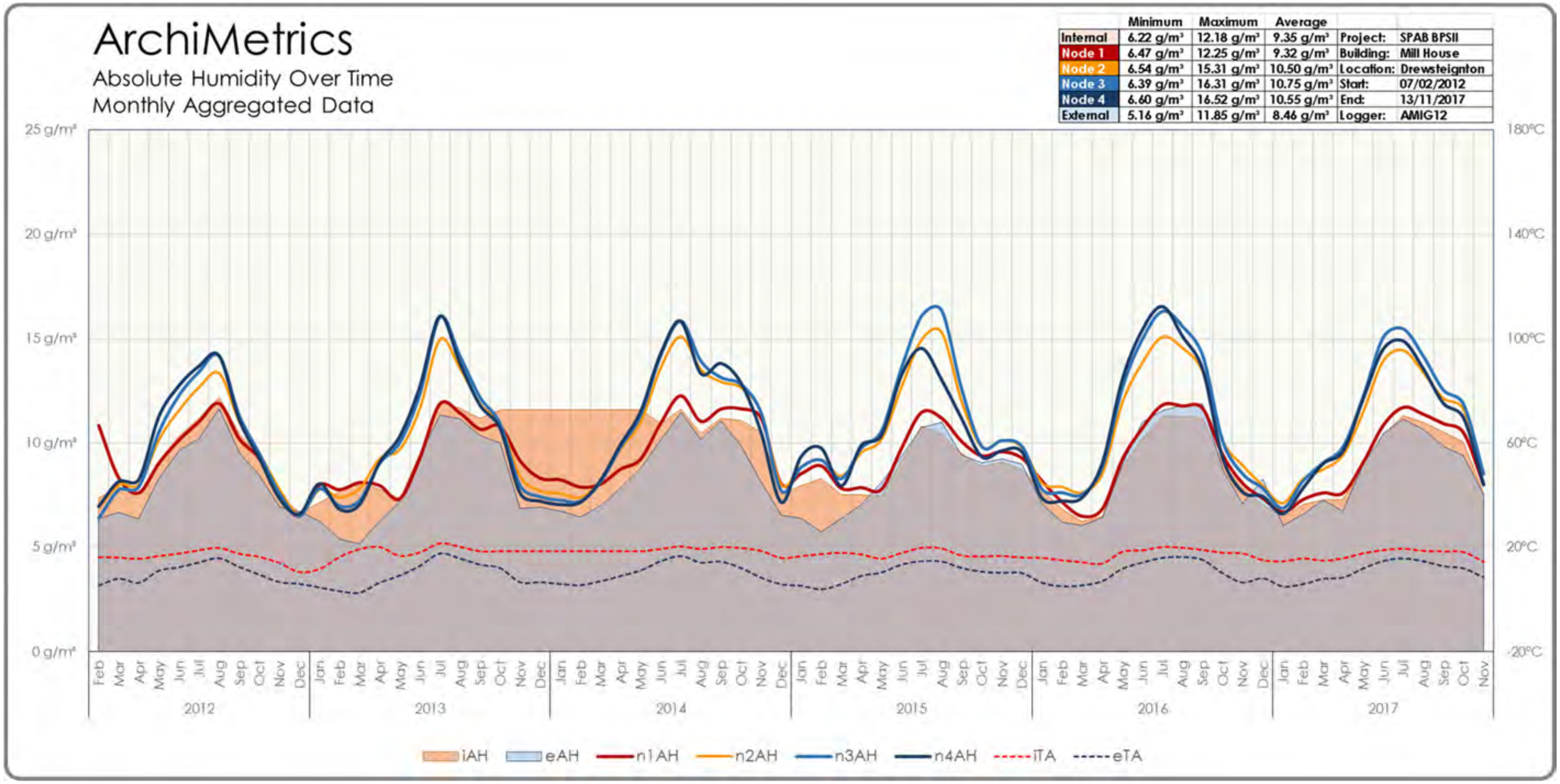


Figure 13. Absolute humidity over time – post-refurbishment, Drewsteignton 2012–2017.

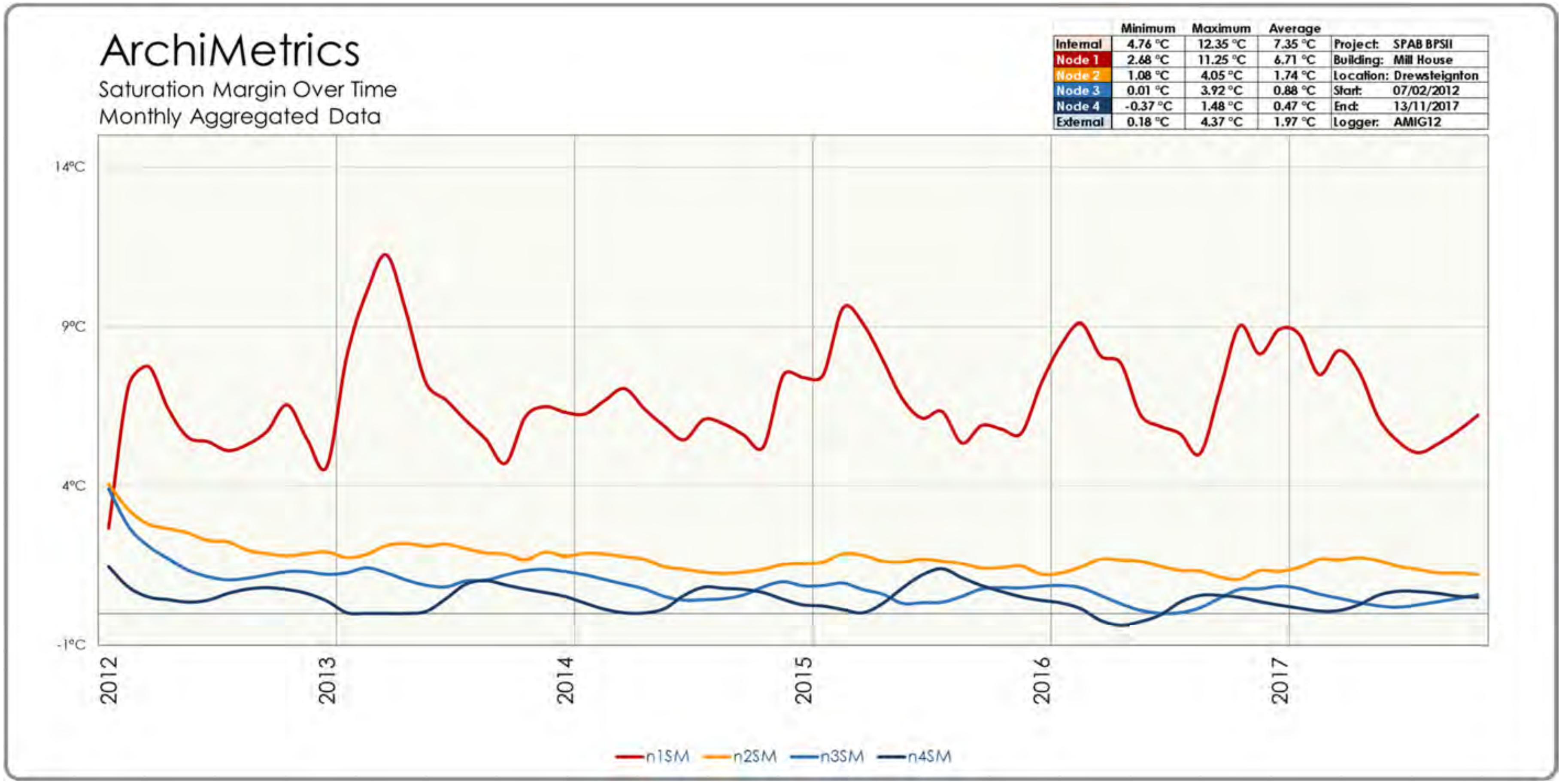


Figure 14. Saturation margin over time – post-refurbishment, Drewsteignton 2012–2017.

The %MC analysis for Drewsteignton, Figure 15, clearly shows 'drying' taking place following the introduction of wet lime mortar used in the installation of moisture monitoring sensors. This response is measured over an extended period, some parts of the wall, MC2 and MC4, only seeming to reach equilibrium around the middle of 2015, a year after sensors were embedded. The prolonged 'drying' seen at the start of the monitoring indicates a qualitative difference between the way this wall deals with moisture in comparison with that of Shrewsbury, where a less extreme and faster 'drying' response was measured following installation of moisture monitoring sensors.

Figure 15 indicates that the lowest rates of %MC occur towards the internal and external sides of the wall. This could be expected as proximity to these surfaces allows for greater evaporation from surrounding materials, causing %MC within the fabric to be lower than that found towards the centre of the wall. This is likely to be the explanation for the lower %MC recorded at MC4, but the lowest rates of %MC are measured at MC1 towards the internal wall surface. This sensor is positioned within the PIR material which insulates the wall. This material is a hydrophobic, closed-cell foam, encased in a foil vapour barrier. Therefore, in this instance, it is the 'dry' nature of the material itself, rather than its proximity to an (internal) wall surface, which is the cause of the low %MC in this layer of the wall.

The centre of the wall at Drewsteignton, MC2 and MC3, exhibits higher %MC and this is particularly evident from October 2016 onward. Prior to this the signature at MC2, following a downward 'drying' trajectory, has suggested material moisture quantities akin to those measured at MC1 and MC4. In September 2016, however, there is a sudden and extreme increase in %MC measured at MC2, the speed of which seems out of character for this wall. This change coincided with a service visit to the property, where measurement equipment was tested using a resistance meter which seems to have altered the state of the sensor (a similar, although less dramatic and temporary, change can also be seen at MC1 at this time). We think that the change in %MC quantities seen around September/October 2016 is reflective of a recovery in moisture measurements, rather than a change in moisture conditions within the wall, and from this time onward the measurements made at MC2 may be a more accurate indication of material moisture quantities in this part of the wall than those made previously. This is supported, in part, because, thereafter, from November 2016 the trace from MC2 follows a pattern not dissimilar to that found for the other 'central' wall node, MC3, albeit showing slightly lower %MC.

The moisture behaviour revealed by the %MC monitoring at Drewsteignton shows both similarities and differences with that of vapour measurements. As with the %RH records, %MC values are high in this wall when looked at in comparison with those of Shrewsbury. However, there is a difference between where peak RH quantities are measured within the wall section in comparison with %MC. %RH is found to be highest at n4, towards the external wall face but %MC is highest at MC3 in the centre of the wall. This is because peak measurements of %RH are determined principally by the evaporation of moisture bound within wall materials. Within the wall fabric at both Shrewsbury and to a lesser extent at Drewsteignton, this evaporative process occurs primarily in response to external conditions; warmer atmospheric temperatures including heat from solar gain and air movement, resulting in increases in moisture vapour which also dry the fabric, reducing the moisture load within materials. This results in high RH at n4 (particularly during spring) but lower %MC at MC4 in proximity to these evaporative influences/external conditions. The %MC measurements show the central part of the wall, MC2 and MC3, to have higher moisture content because more moisture remains bound within materials at this location where less evaporation takes place deeper within the wall, further away from the conditions that encourage drying.

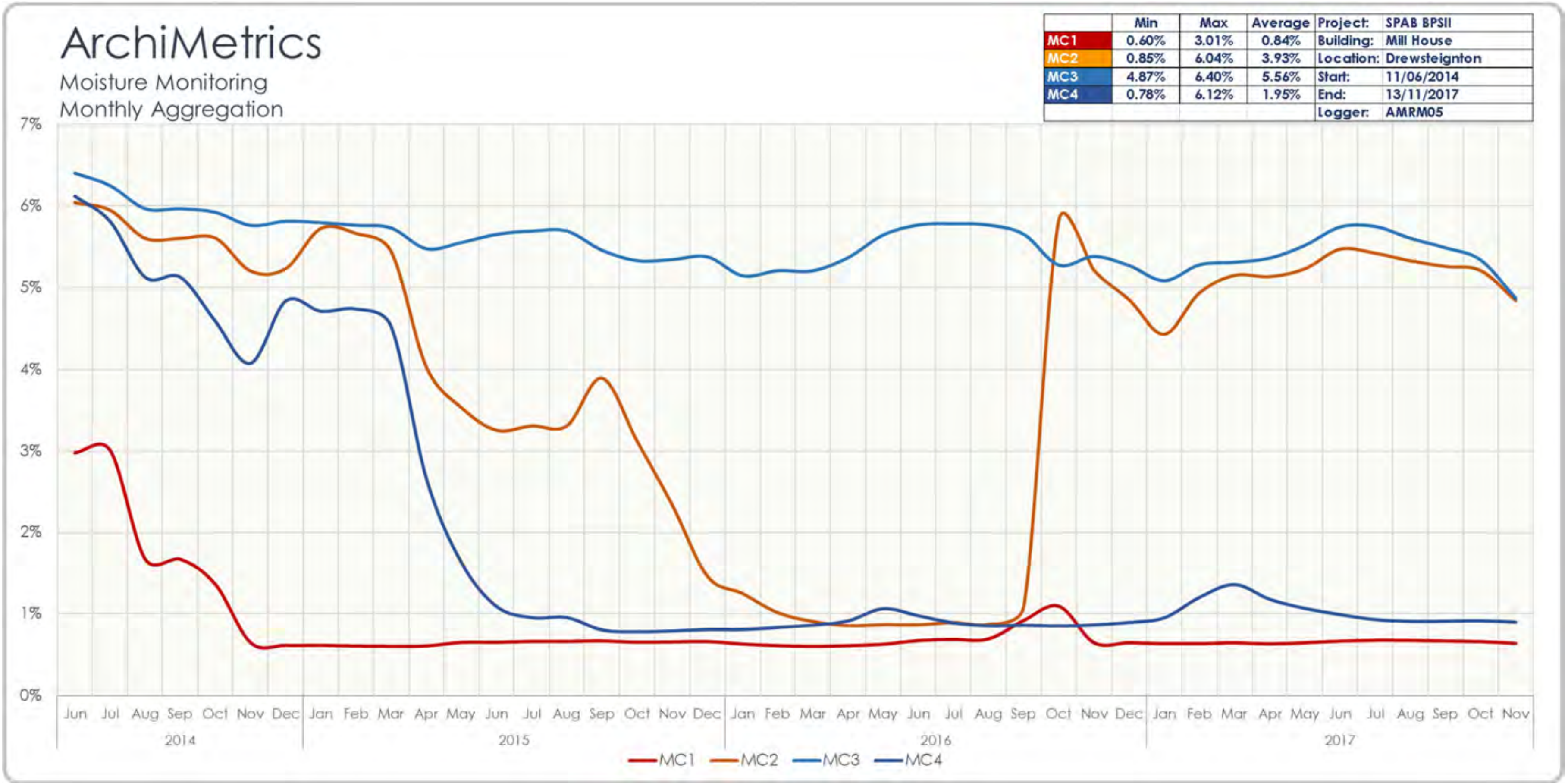


Figure 15. Material moisture over time – post-refurbishment, Drewsteignton 2014 – 2017.

2.4.3 Riddlecombe – post-refurbishment wall performance

The wall at Riddlecombe differs in a number of ways from those of Shrewsbury and Drewsteignton. It is primarily constructed from unbaked earth - cob - and has been externally insulated with 60 mm of insulating lime render. Table 8 provides details of before and after refurbishment of U-values measured and calculated for the wall.

Table 8. Wall U-values pre- and post-refurbishment, Riddlecombe.

Riddlecombe	**Uninsulated 2011**	**Insulated 2012**	**% reduction**
Measured	0.76 W/m^2K	0.72 W/m^2K	4%
Calculated[3]	0.95 W/m^2K	0.56 W/m^2K	41%

The difference between the pre- and post-insulation calculated U-values for the wall suggests that a reduction in heat loss of 41% has taken place. However, the percentage reduction shown by a comparison of the measured U-value figures is significantly less, being 4%. The calculated figures show a large reduction, in part, because of the overestimation of heat loss by the pre-refurbishment U-value for reasons explained in Section 2.3, p16. It is known that there is considerable uncertainty pertaining to calculated U-values for historic walls, particularly for walls constructed of site-specific materials with variable and untested thermal properties, such as that of Riddlecombe. In these circumstances, as previously stated, more validity can be given to a measured U-value, providing the measurement is carried out according to the appropriate standard.[4] Pre-insulation, the measured U-value indicated lower heat loss for the wall when compared with its calculated equivalent as is the norm when comparing measured and calculated U-values for traditionally-built walls.[5] However, post-insulation this relationship is inverted and greater heat loss is shown by the measured U-value, resulting in little difference between the pre- and post-insulation U-values. It was noted in the pre-refurbishment account of interstitial hygrothermal behaviour that this wall had narrow saturation margins (high RH), suggesting the possibility of damp material, particularly towards the external side of the wall face. This, it was surmised, may have been caused by rainwater penetrating the wall through cracks in the old cement render which also then restricted evaporation, causing the wall to accumulate moisture. During the installation of post-refurbishment IHGM equipment, mineral wool that had been used to temporarily plug the cores was found to be wet when retrieved from the wall. It was subsequently understood that, following the removal of the old render, the application of the new render had been preceded by the use of a hose to thoroughly wet down the cob substrate. Therefore, it is possible that both the pre- and post-insulation measured U-values may reflect higher heat loss as a result of damp substrate and, in particular, the post-insulation U-value is compromised by the quantity of water added to the cob during the refurbishment process. This would also go some way to explaining the lower U-value calculated for this wall in comparison with the measurement, post-refurbishment, where normally one might expect to see better correlation between measured and calculated U-values due to the 'known' effect of the insulation layer.

The wall at Riddlecombe is externally insulated. However, the RH traces plotted over time for this wall, Figure 16, bear some similarities with the other 'thick' wall at Drewsteignton which is internally insulated. The analysis shows none of the volatility of RH response found at Shrewsbury and largely consists of gently undulating annual peaks

[3] Calculated wall U-values of 0.93 W/m^2K uninsulated and 0.60 W/m^2K insulated were first published in Annual Interim Report 2012. These were subsequently revised in 2013 following clarifications regarding the constitution and thickness of the wall build-up.

[4] Building Research Establishment, 2014.

[5] See Rye and Scott, 2012 and Baker, 2011.

which at Riddlecombe mostly occur over the summer months, lagging slightly behind peaks in external temperatures (eTA). Unlike the RH picture at Shrewsbury, where RH peaks in the external 'half' of the wall (n3 and n4) mostly occur over winter and into spring (from November to April, or May for n3), the Riddlecombe wall more resembles that of Drewsteignton. Annually, at Drewsteignton, RH peaks at n4 mostly in April or May and later in the year, in June, deeper within the wall at n3. For Riddlecombe, peaks at n3 are delayed even further and tend to be seen around August or September, with those at n2 and n1 either occurring in sync with those of n3, or manifesting a month or so later, in October or November. Over a number of annual interim reports, we have provided detailed analysis to explain this phenomenon as, like the behaviour seen deeper within the wall at Drewsteignton, it runs counter to conventional ideas concerning RH which, externally at least, is higher over winter when ambient temperatures are lower. However, as has been previously discussed, vapour measurements inevitably reflect periods of evaporation which can be at their most intense within wall materials following winter wetting, hence RH peaks at n4 in April/May for the south-facing wall at Shrewsbury and slightly later in the thicker, slower-to-respond, north-west facing wall at Drewsteignton. Like Shrewsbury, the Riddlecombe wall is also south-facing but RH responses here are very delayed, occurring at the end of summer and into autumn.

Winter wetting is not likely to be such a factor for the wall at Riddlecombe, protected as it is by 60 mm of external render. However, the RH analysis makes it clear that evaporation is taking place in this wall and that this reaches a peak of %RH at the end of the summer. The AH over time record, Figure 17, shows that weights of vapour peak in this wall mid-summer, in June or July, along with external temperatures, suggesting that peak evaporation activity is taking place at this time of year. Thereafter, temperatures begin to fall which, coupled with this release of vapour, results in an increasing saturation ratio for the air in the various locations within the wall. The peaks in RH seen at the end of the summer can be attributed to this solar-driven evaporation followed by declining temperatures but they are also indicative of very slow vapour movement within the substrate. Following peak evaporation, levels of vapour remain quite high within the wall for some months and are the reason that RH peaks are seen a month or two after peak weights of vapour are recorded. Cob is eminently permeable and porous and thus the movement of vapour by diffusion can be assumed. It is also, as compacted, unbaked earth, quite air tight and the lag seen in the RH record, in comparison with peaks at Shrewsbury and Drewsteignton, can be, in part, explained by the absence of air movement within the wall, meaning vapour is predominantly dispersed by diffusion, a much slower mechanism.

The rounded peaks of RH responses at Riddlecombe are found only for n1, n2 and n3. The trace at n4 shows very high RH throughout the six years, post-insulation, with very little variation and measurements from March 2012 to June 2014 appear unchanging due to measurements of RH capped at 100%. After June 2014, slight variations are seen in measured quantities which, from January 2015, are at, or exceed, 110%. As before, these measurements suggest that materials found towards the external side of the wall, in proximity to n4, may be wet (as may those, perhaps to a lesser extent, measured at n3 where RH is also sometimes close to 100%). During refurbishment, when the cement render was removed from the wall, it was discovered that the monitored part of the wall included a thin external stone buttress built at some point to repair the cob. This was rendered over as it had been previously but it was now known that sensor position n4 was located close behind this single layer of stone. The presence of this stone, coupled with the now thicker external render layer, may in part explain why responses in this section of the wall appear different and unchanging in comparison with those measured elsewhere within the cob. As before, we believe the moisture content of the material may be high, particularly towards the external side of the wall, largely due to water added during refurbishment. (The wall should now be well-protected from rain as a result of the new render.) It can also be seen elsewhere within the wall that evaporation of this construction moisture takes place over the summer. Dispersal of this moisture as a vapour occurs slowly, probably predominantly through diffusion (as well as the airtight cob material, the render and new internal plaster having also sealed air pathways and reduced air exchange through the wall). The wall is south-facing so receives plenty of solar radiation. However, the render is of a light colour so the quantity of heat energy absorbed into the body of the wall will be less than, say, the darker south-facing brick wall at Shrewsbury. Therefore, it is possible that the evaporation and dispersal of vapour is also slow in this wall due to multiple factors: the quantity of moisture added to the wall; reduced energy input during the summer; a less permeable stone layer towards the external wall face; as well as the thick external render itself which, despite being lime-based, is likely to be less vapour open than the cob. This would account for the high RH measured through the wall section and, in particular, at n4 where vapour release is somewhat impeded.

Because of the persistently high levels of RH measured from the wall in Riddlecombe from 2012 onwards, this wall is the only one in the study to exhibit an average negative saturation margin at n4, -0.94˚C (Figure 18). This suggests that materials in proximity to n4 may be damp or even wet. One period of negative margins is also shown for n3, over the summer and autumn of 2014 after the 100% RH cap was removed from measurements. (It is possible that negative margins would have been seen prior to June 2014 for the wall at Riddlecombe but the 100% cap prevents this.) However, a negative margin is not seen in the following years at n3. We believe that the wall is, in theory, well-protected from rain due to the render coating and we know that RH peaks occur later in this wall, towards the end of summer, as a result of evaporation of moisture from materials and it's slow dispersal via diffusion. Therefore, moisture vapour behaviour factored as RH in this wall seems to be less immediately affected by external conditions and more driven by its internal moisture load (a legacy of wetting due to the cracks in the old render followed and greatly increased by the addition of water across the whole substrate during the re-rendering process in the belief this would aid adhesion) and seasonal solar-derived heat input. That negative margins are seen at n3 in 2014 but not again may suggest that the moisture load within the centre of the wall is diminishing slightly year-on-year through cycles of summertime evaporation, resulting in lower annual RH peaks and widening saturation margins.

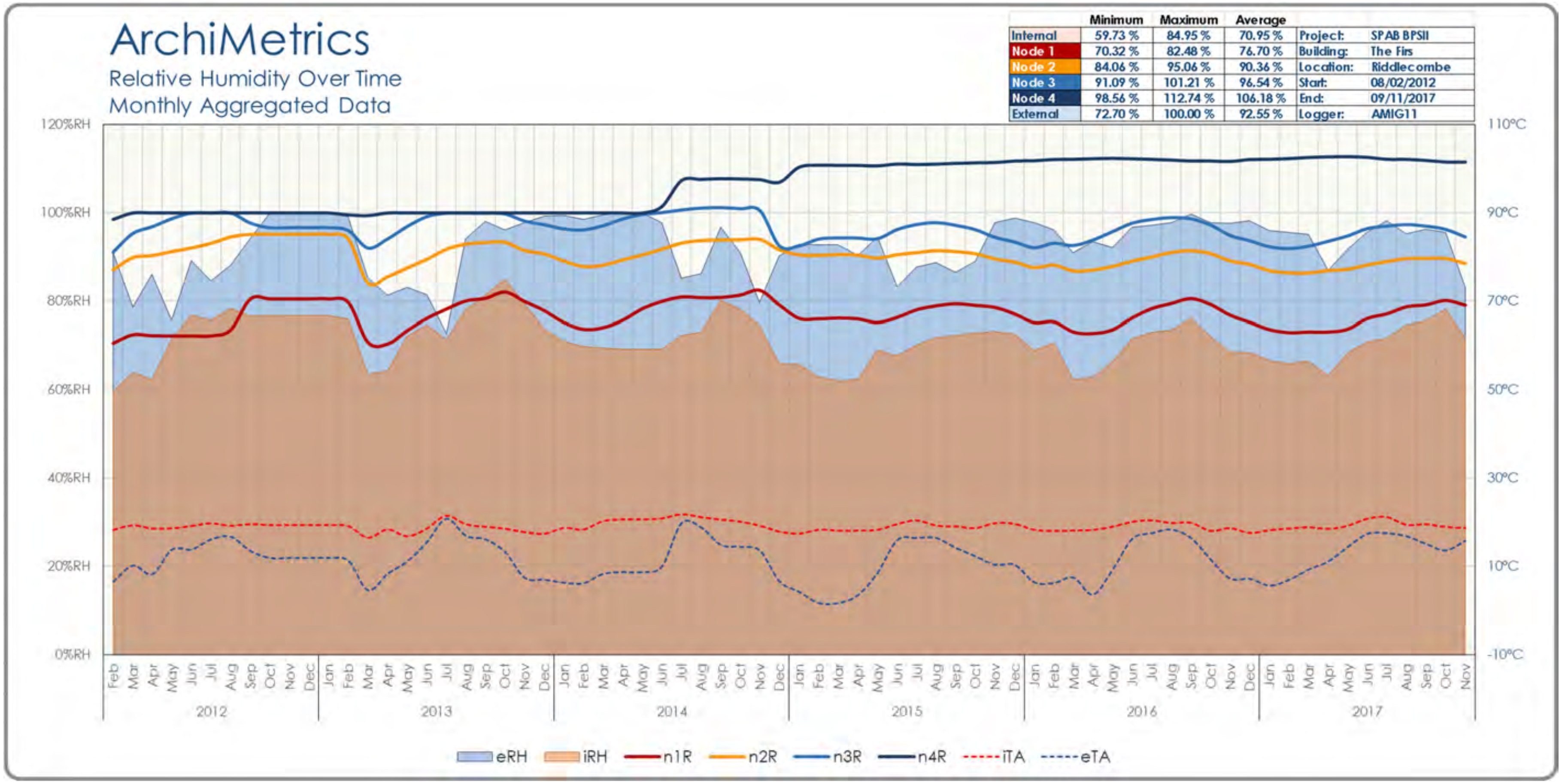


Figure 16. Relative humidity over time – post-refurbishment, Riddlecombe 2012–2017.[6]

[6] There is a flat line for all measured quantities, October 2012–January 2013, as a result of data loss over this period. The same is visible in all the over-time analyses graphs for Riddlecombe.

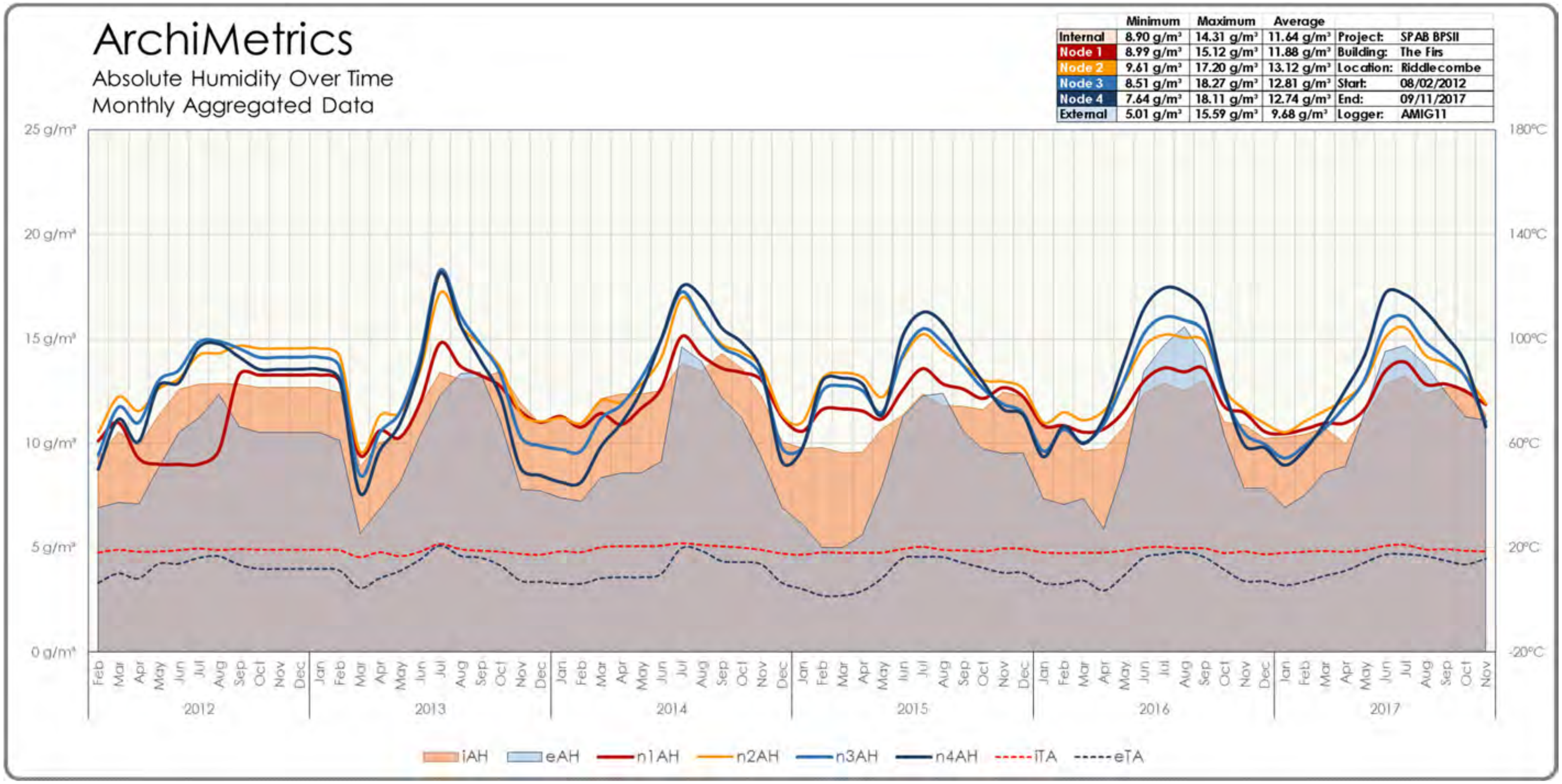


Figure 17. Absolute humidity over time – post-refurbishment, Riddlecombe 2012–2017.

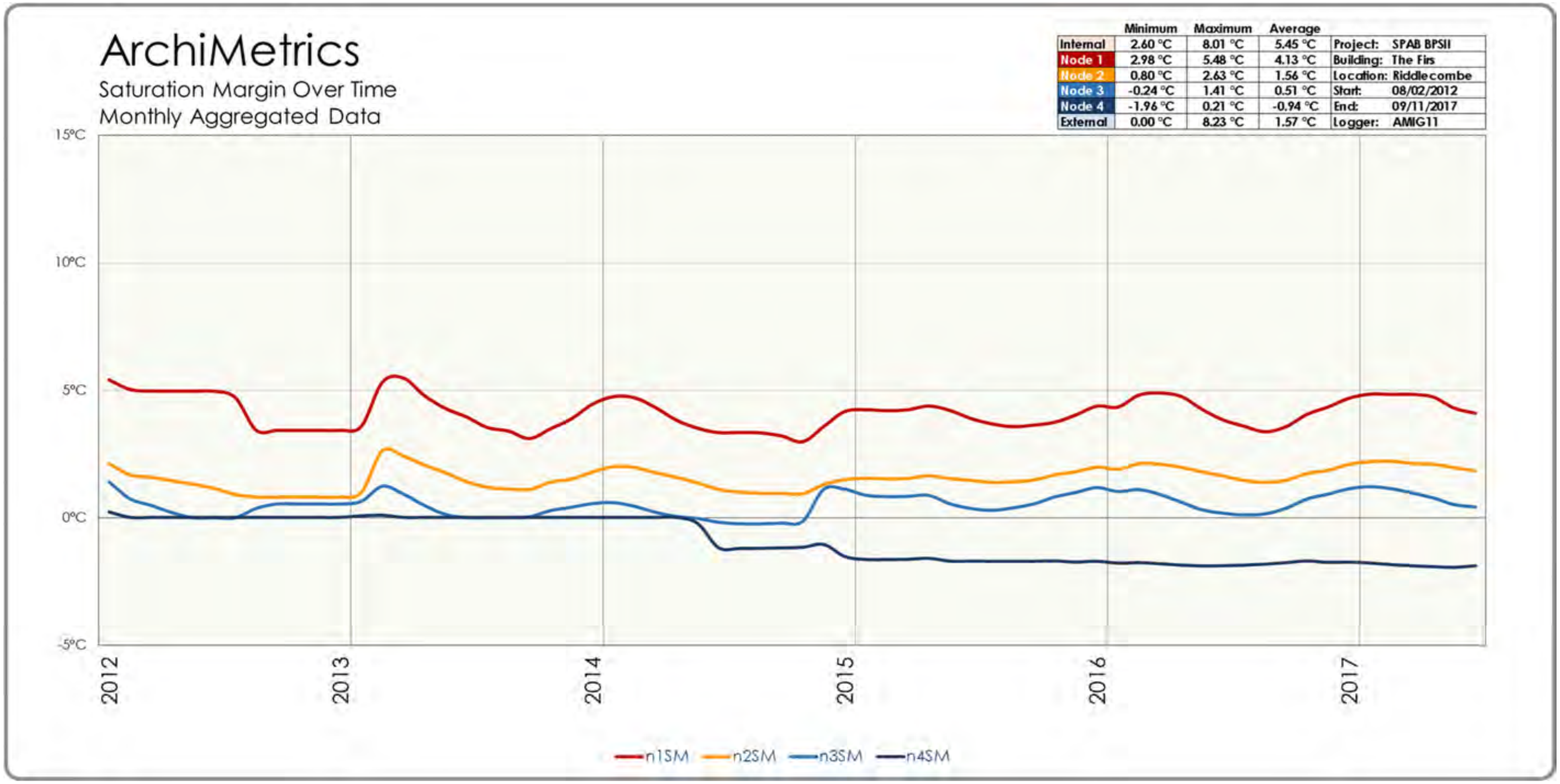


Figure 18. Saturation margin over time – post-refurbishment, Riddlecombe 2012–2017.

The wall at Riddlecombe initially shows higher %MC than that of the other two walls under study. It also shows that, overall, %MC is decreasing in the wall at all but one of its sensor positions, MC1 (Figure 19). Reductions in %MC are seen at all four nodes at the commencement of measurements, June 2014, indicating the 'drying' of lime mortar used to bond the sensors to the substrate. There is a hiatus in this downward drying curve from September–November; over this time %MC increases at MC1, MC2 and MC3 and flatlines at MC4. Reductions in %MC recommence in November and fall sharply at MC1, MC2 and MC3 but more gradually at MC4. It is likely that the difference between %MC behaviour seen at MC4, where reductions in %MC take place over a longer period, are the result of the presence of the stone buttress in proximity to this location, whereas the other three measurement sensors are surrounded by cob material. The sensors in the central part of the wall, MC2 and MC3, share a similar drying curve and, after a separate spike in quantities measured at MC3 over the summer of 2015, thereafter record similar and comparatively low %MC. The trace for MC1, towards the internal side of the wall face, includes a few temporary increases in %MC with reducing peaks indicating overall a trend of %MC reduction until conditions here become similar to those measured at MC2 and MC3, with low %MC measured January–March 2016. Unlike the two central wall sensors, however, after this time %MC starts to increase again at MC1 and is still on a rising trajectory at the cessation of measurements in November 2017. As previously mentioned, moisture behaviour at MC4 towards the external side of the wall seems retarded in comparison to that of the other interstitial node locations. %MC has been reducing slowly here up to November 2015 but then increases again, starting a pattern which sees winter/spring increases in %MC and summer/autumn decreases. (This is not present for the 2014 year due to the injection of moisture into the wall at the time of sensor placement and subsequent drying of this.) This pattern is the opposite of that measured for RH further back in the wall where RH peaks in the summer/autumn. However, like that of RH behaviour, this pattern is likely to be driven by the input of heat and specifically direct solar radiation on the external surface of the wall, causing moisture held in materials to evaporate, resulting in an increase in water vapour in the air within the wall whilst simultaneously lowering the moisture content of materials. For the last two years of the survey it can be seen that these evaporative processes seem to gradually be reducing %MC overall within the wall at MC4; the 2017 %MC peak is lower than that of 2016 and 2016's winter low is lower than that of 2015 (measurements ended in November 2017 and quantities are possibly lower this month than those found for the two previous years). Given this pattern, it is possible that, like MC2 and MC3, the gradient at MC4 resolved to a near flat line of < 1 %MC sometime at the end of the following year 2018 (after measurements had ceased).

As with Drewsteignton, the vapour and material moisture records for Riddlecombe share similarities and differences. RH is highest towards the external side of the wall at n4 and n3, %MC is also relatively high at MC4 (albeit reducing) but it has been relatively low since December 2015 at MC3. The highest overall average weights of vapour (AH) are found in the centre of the wall, n2 and n3, but the highest average overall %MC is measured at the internal and external sides of the wall, MC1 and MC4. The differences between the vapour and %MC records through the wall section are a result of the materials used in the wall's construction, sources of moisture and the extent and immediacy of the influence of external conditions. Cob, as well as being highly permeable and porous, is also highly hygroscopic, with a high moisture capacity because of its ability to adsorb and desorb moisture from the air. This ability to hold (buffer) moisture as a vapour might explain why it is simultaneously possible for the wall to exhibit high vapour and low %MC in its central section. Vapour produced as a result of summer evaporation is held and only slowly diffused whilst this same evaporation also ensures that the moisture content of earth materials is reduced. %MC continues to be recorded as higher at the two edges of the wall as vapour from the centre moves slowly towards the larger evaporative surfaces of the internal and external sides of the wall.

Towards the external side of the wall progress is slowed perhaps by the presence of the less permeable stone buttress but also the thick lime render, resulting in higher RH at this location and overall less opportunity for evaporation from materials and hence higher %MC. Toward the internal side of the wall a similar sequence might be in process complicated by the influences of the internal environment. The internal side of the wall is coated with a thinner layer of more permeable lime plaster although traces of the previous gypsum plaster may remain, and the house also measures low rates of air permeability/infiltration (Appendix C) Riddlecombe has lower room volume, high occupancy and the highest internal room (70%+) RH in comparison with the other properties surveyed (see Appendix D). On average, measured over the six-year post-refurbishment period, Riddlecombe has the highest rates of internal AH and RH, 11.64 g/m^3 and 71% RH respectively. Internally generated vapour is of greater quantity within the room and may be dispersed less easily and this could inhibit and retard evaporation from the internal wall surface resulting in higher %MC in proximity to the internal side of the wall.

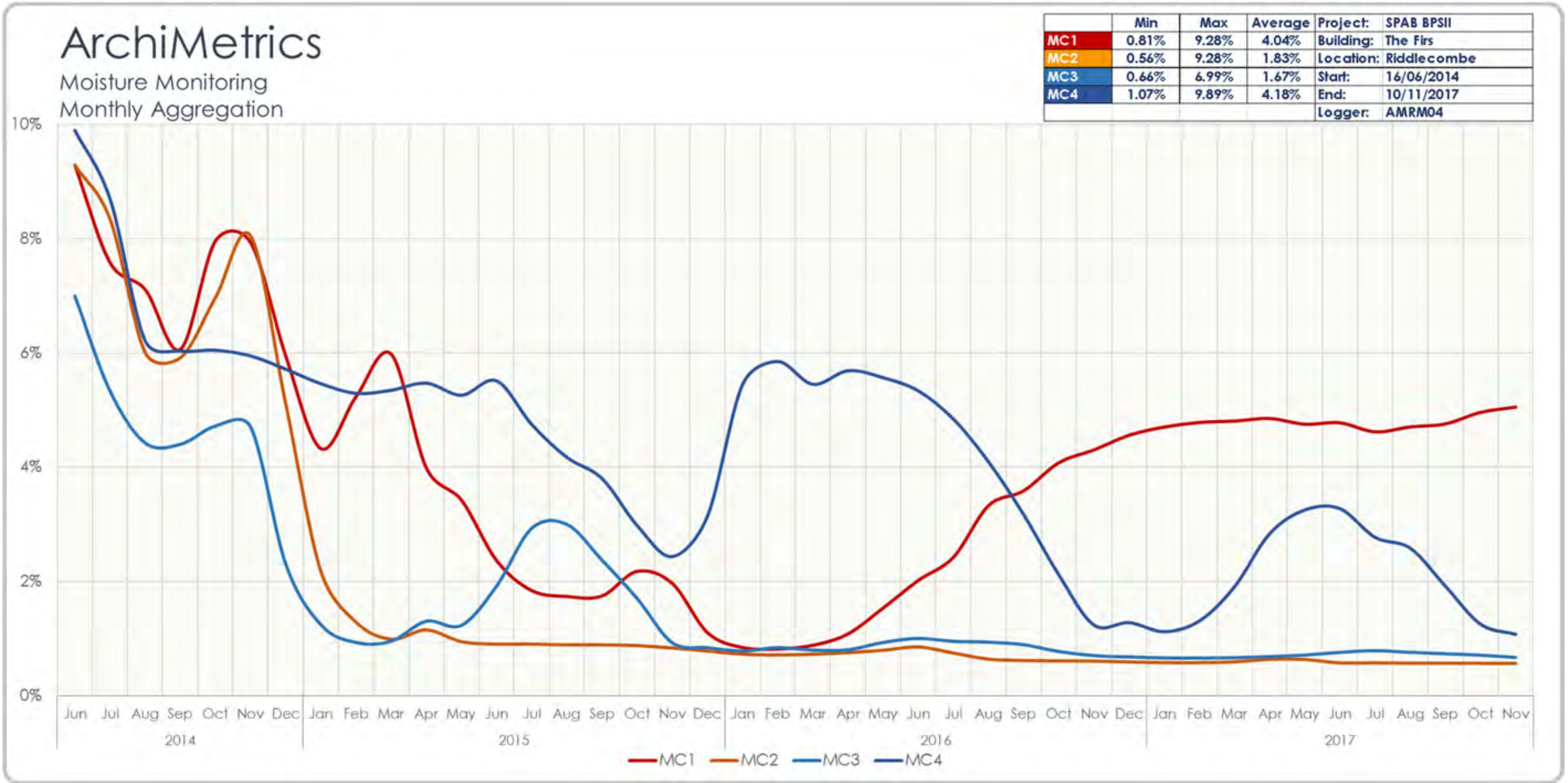


Figure 19. Material moisture over time – post-refurbishment, Riddlecombe 2014–2017.

2.4.4 Summary – post refurbishment wall performance.

Hygrothermal responses within the walls are determined by numerous factors but principally, we find, it is aspect and the materials that the wall is constructed from that are of greatest significance. The characteristics of their materials with regard to moisture are especially important; including their ability to hold, carry and move moisture through the substrate in the form of either liquid or vapour.

In the thin, dark, south-facing, porous and permeable brick wall at Shrewsbury, extreme winter wetting followed by rapid, solar-driven, drying over springtime predominantly drive moisture responses. These same influences can also be seen at play at n4 towards the external side of the north-west facing wall at Drewsteignton. However, in general, responses in this wall are more sluggish and muted as a result of the thick, heavyweight granite blocks, a material with limited permeability and negligible porosity. Effective evaporative drying (as well as wetting) is more likely to occur in the wall at Drewsteignton via the more porous and permeable lime mortar used to bed the stones (as well as micro-fissures in the stones themselves). As a result, drying in this wall takes place more slowly and the consequences of this can be seen particularly deeper within the wall at Drewsteignton at n2 and n3, where responses are more detached from external conditions, delayed and isolated.

After refurbishment, the externally insulated cob wall at Riddlecombe is physically isolated from the rain by a new render but contains its own microclimate due to past wetting and construction moisture added as part of the re-rendering work. Cob can hold high quantities of moisture as a liquid and vapour which is activated within the wall as a result of solar-driven processes of evaporation in the south-facing wall resulting in measurements of high quantities of vapour. Although cob is both porous and permeable, it is also quite airtight and so drying in this material relies to a great extent on vapour moving through diffusion in order to access an evaporative surface. This is another slow process that may also be inhibited by the conditions and finishing materials found on, and in proximity to, the internal and external wall surfaces.

3 Comparisons and Consequences

The previous section has looked at the three walls, more or less in isolation, in order to identify details of the conditions and properties that determine moisture responses within the walls post- insulation. With the knowledge that the three walls under study are very different, the following section will look across the sample to draw out points of similarity and difference that may extend our understanding and look, in particular, at the consequences of moisture responses over the longer term.

3.1 Absolute Humidity (AH)

AH is a measurement of the weight of water vapour in air regardless of temperature and is one of the ways we have sought to analyse the wall's performance with regard to moisture. The 'over-time' AH analyses (Figures 9, 13 and 17) show some interesting differences between the three walls and changes taking place over the six years of post-refurbishment monitoring. AH traces at both Drewsteignton and Riddlecombe look broadly similar with usually a pronounced single peak shared across all four wall nodes. These peaks also show higher weights of vapour (≈ + 5 g/m^3) than those measured from the immediate internal and external environments either side of the wall. This is of interest because in some senses the two walls are quite different: one is constructed of cob and the other hard, dense stone. They have been insulated in fundamentally different ways, internally with a large quantity of impermeable foam insulation at Drewsteignton and externally with a thick but porous and permeable insulating lime render. Yet, despite these differences, the character of vapour production appears to be quite similar in both walls, albeit the cob wall at Riddlecombe, on average, measures higher weights of vapour, as this material has a higher moisture capacity (the ability to hold water hygroscopically). The AH over time analysis for Shrewsbury looks very different. The weights of vapour measured at Shrewsbury are lower than those found at Drewsteignton and Riddlecombe. Peaks are not unified across the fours sensors and often occur in different months through each year. In addition, most often, AH peaks lie between the AH quantities measured from the internal and external environments (just as the wall itself sits physically between these two environments). The few occasions where wall AH quantities exceed those of the internal and external environment, most notably in 2014, correspond with years where there was increased wetting of the substrate due to winter storms and particularly wind-driven rain (also signalled, in this particular wall, by more extreme RH responses).

Despite their differences, the walls at Drewsteignton and Riddlecombe share some similarities which differentiate them from the wall in Shrewsbury and may explain the AH behaviour seen within the walls. Both properties are located in the south-west, in Devon; Drewsteignton in the south and Riddlecombe in the north of the county. The south-west region has a wetter climate than that of the West Midlands and Shropshire where Shrewsbury is located. There is more rain and more moisture within the atmosphere in general in the south-west, which may go some way to explaining the higher weights of vapour found in the Devon walls. But this alone does not account for higher peak weights of vapour which exceed those of summertime atmospheric peaks in these walls. The walls in the south-west have different aspects and are made of materials with very different moisture-carrying capacities, but both walls are much thicker than the wall in Shrewsbury and have much slower vapour responses. The mass of these walls also results in slower responses to changes in temperature difference through the fabric. In addition, both walls are noted to be more airtight than the wall at Shrewsbury, and both these factors, heat and air movement, allow for evaporative drying. The Drewsteignton and Riddlecombe walls can, and do, hold quantities of water that mean that when evaporation occurs within the fabric higher amounts of vapour are produced than those found in the surrounding atmosphere and internal environment. The same effect is not seen at Shrewsbury because, although this wall becomes at times quite wet during the winter months, the thinner wall coupled with its south-facing aspect and more open, porous and permeable nature means that excess moisture evaporates and leaves the fabric quite rapidly when atmospheric conditions allow. This means that the fabric rarely contains quantities of residual moisture that result in higher than atmospheric levels of AH.

A wall's ability to evaporate moisture has consequences for the long-term performance of the fabric. Figures 20, 21 and 22 plot average AH at each measurement node for each year of the BPS post-refurbishment as another means by which to look at changes in responses over time. The Shrewsbury analysis, Figure 20, shows similar average weights of vapour measured through the entire wall section, with the lowest weights found in the first two years of monitoring, 2012 and 2013. The year 2014 results in an exceptionally high response, particularly in the centre of the wall and, as with the AH and RH over-time analyses, this is explained by drying following extreme winter wetting during this year.

At Drewsteignton, vapour quantities are found to be higher towards the centre of the wall and like those of Shrewsbury these are at their lowest average quantities in 2012 and 2013. The year 2014 produces a higher trace, this being the wettest year of the series. But the highest average AH measured through the masonry section at Drewsteignton is found in the last year of the study, 2017, which was the driest of the series, Table 7, p28.

The wall with the highest average AH is, not surprisingly, measured from the material best able to hold vapour, the cob wall at Riddlecombe. Here, we find the ranking of average quantities, highest to lowest, switching between nodes within a single year. For the first year of measurements, 2012, weights of vapour are at their lowest at n1 but highest at n2 and n3. Thereafter, average AH falls in the centre of the wall and decreases before increasing at n4 towards the external wall face, and increases then decreases at n1, indicating a shifting picture of weights of vapour through different parts of the wall section in different years.

Overall, these analyses suggest a fairly consistent annual picture of AH quantities for the wall at Shrewsbury (disregarding the aberrant 2014 year) whereas at Drewsteignton it seems that AH increases through the section in the later years of the study, being at its highest in the final year. At Riddlecombe, average AH decreases over time in the centre of the wall but increases at n4, towards the external side.

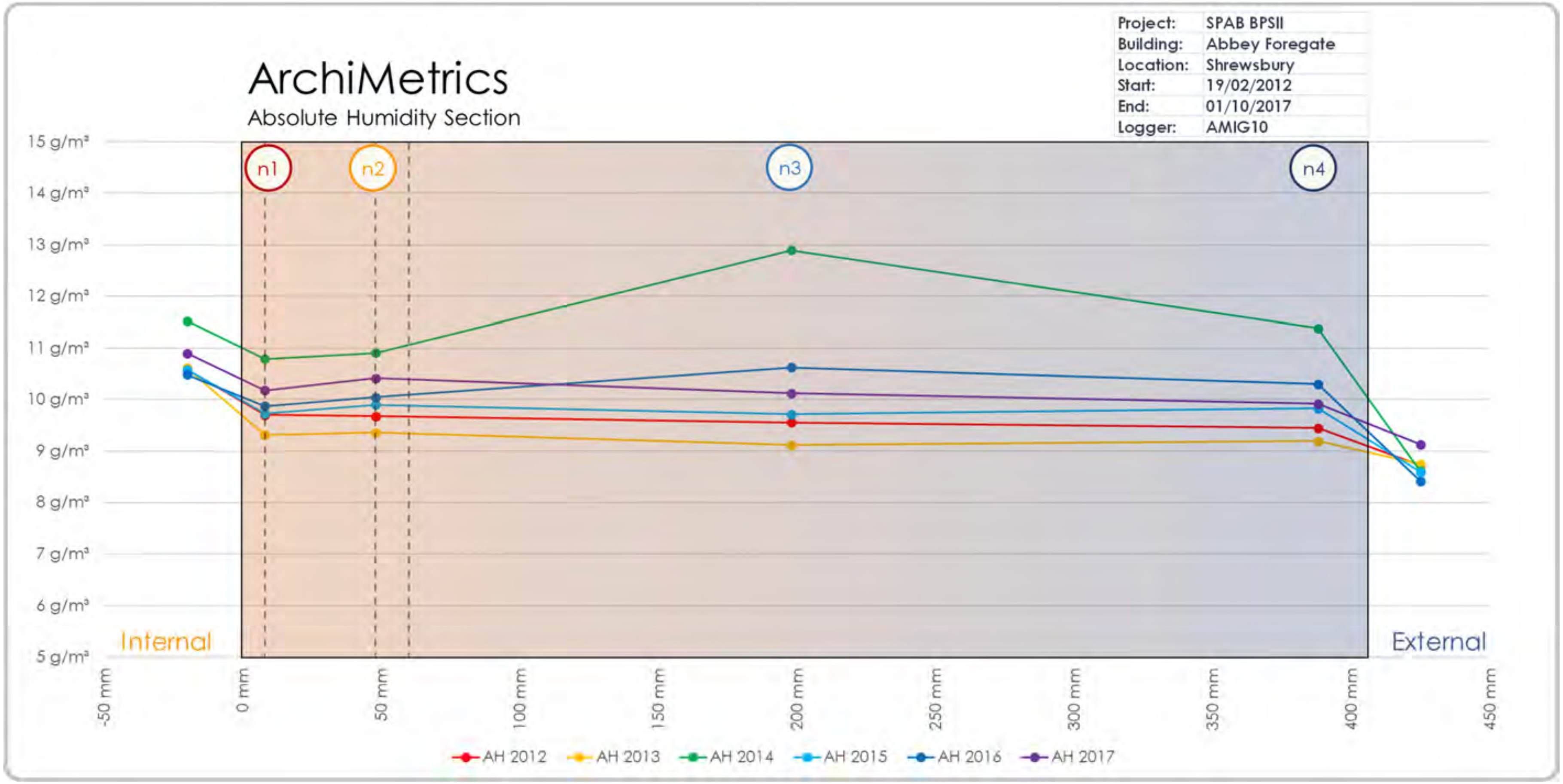


Figure 20. Annual average AH section – post-refurbishment, Shrewsbury 2012–2017.

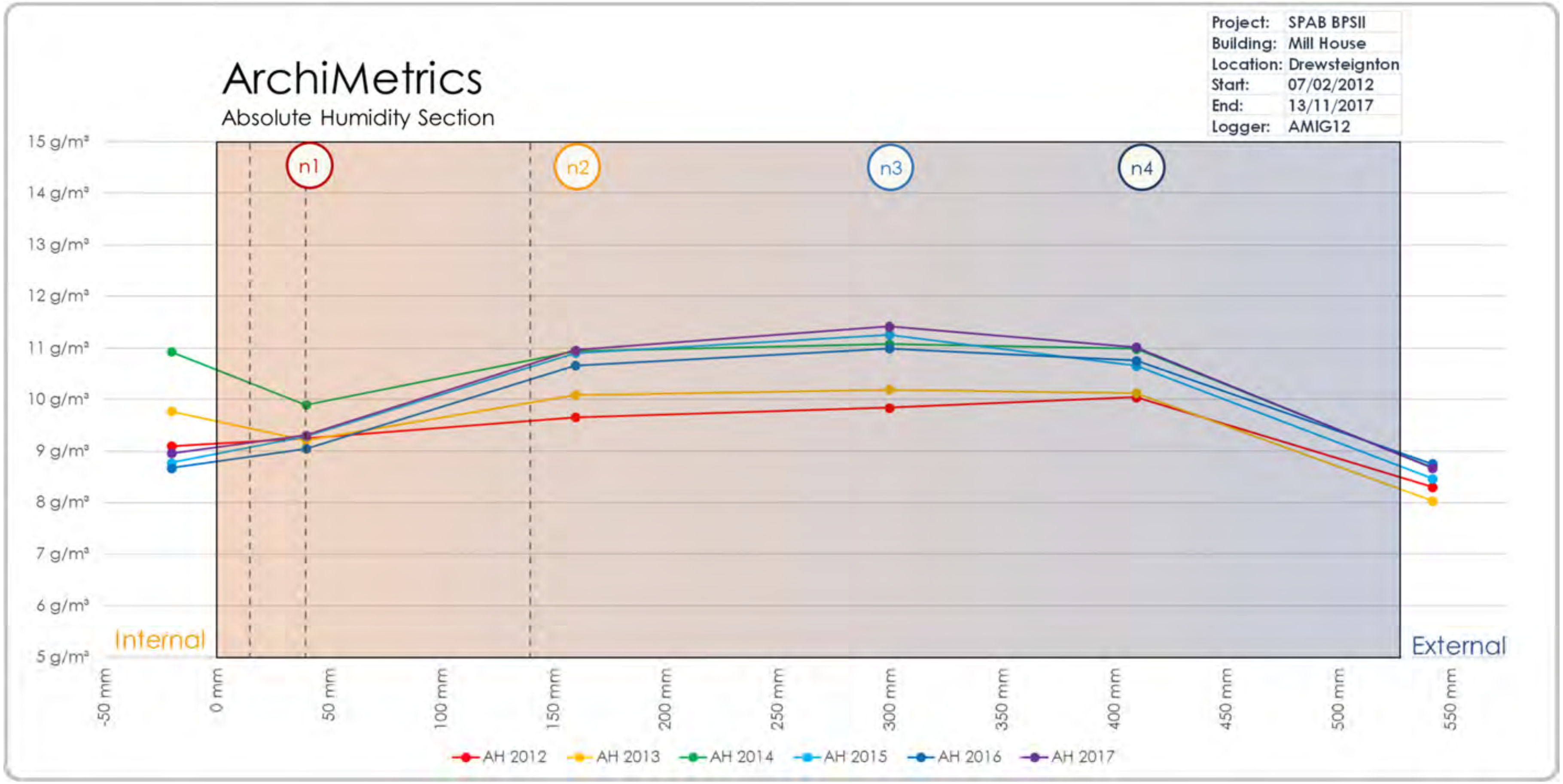


Figure 21. Annual average AH section – post-refurbishment, Drewsteignton 2012–2017.

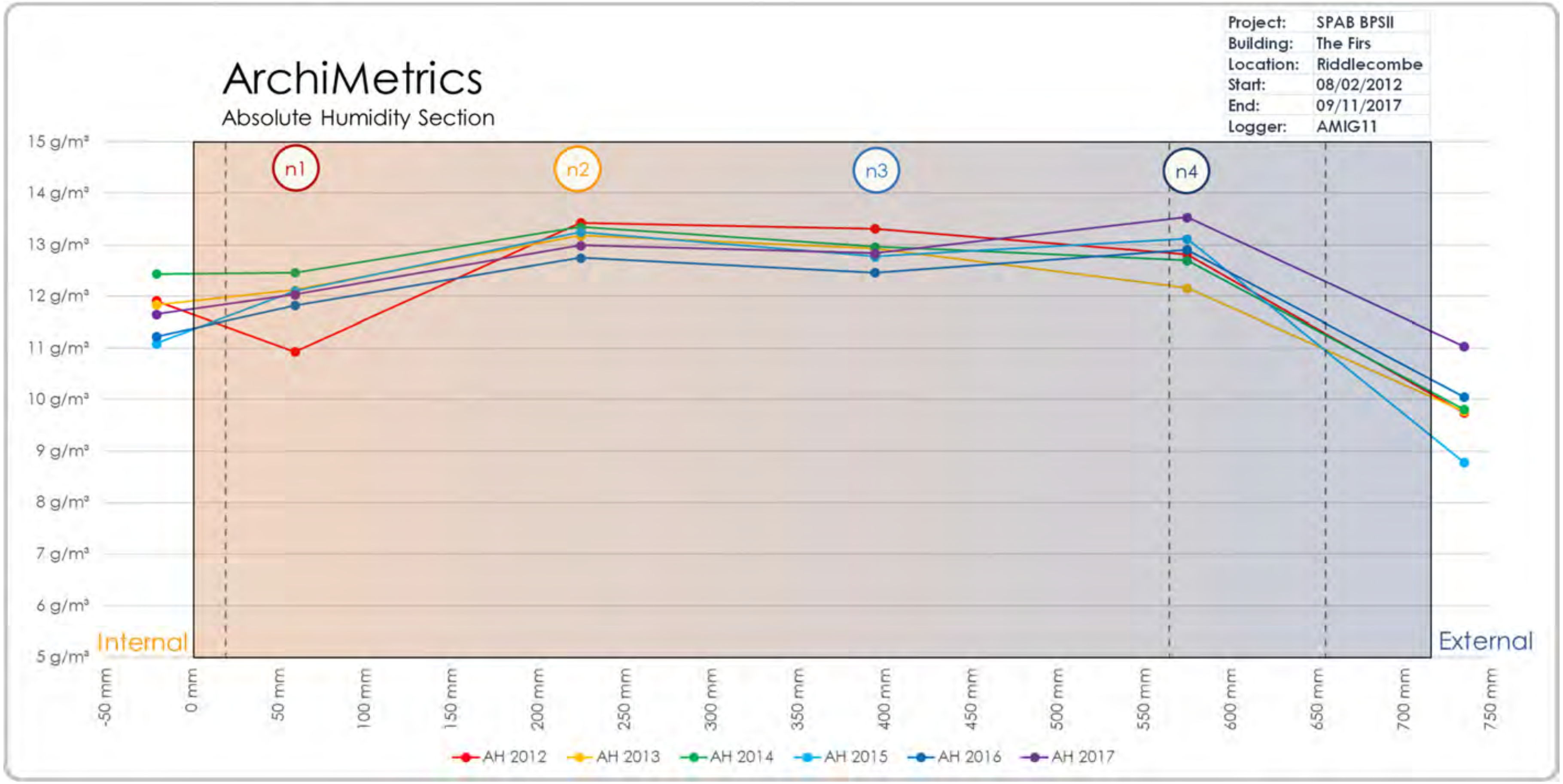
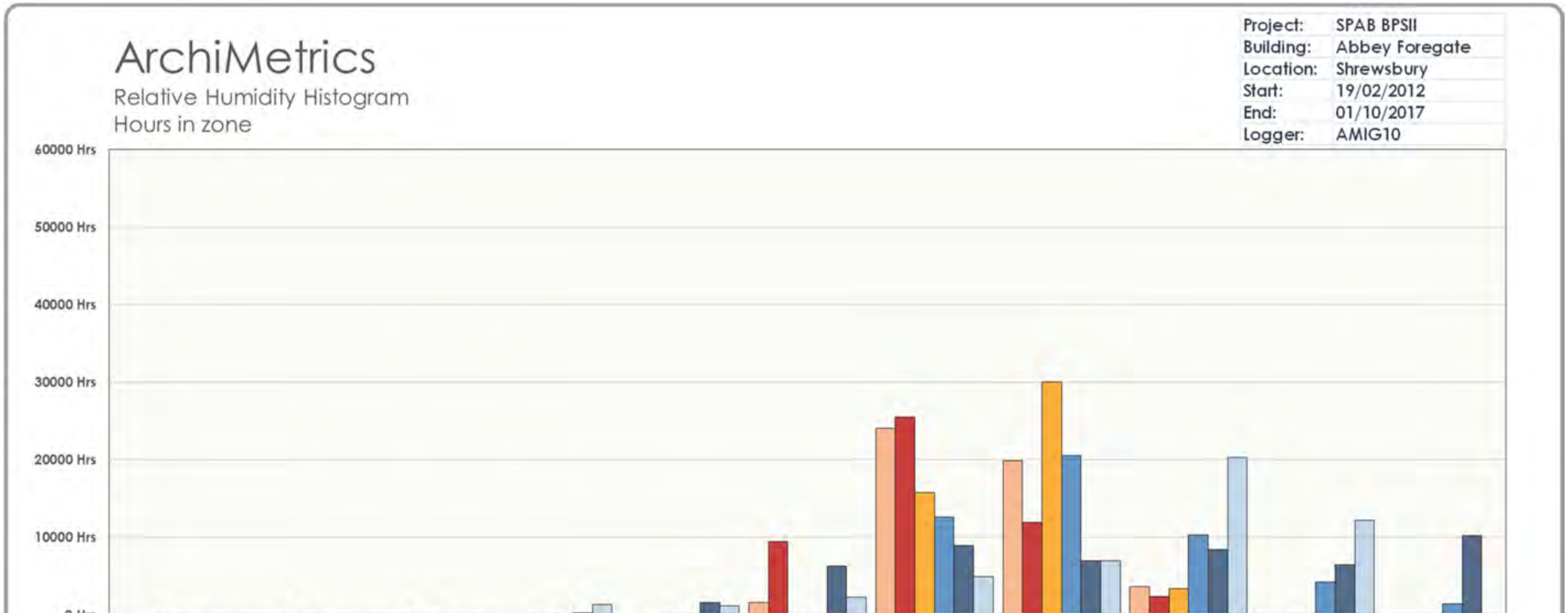


Figure 22. Annual average AH section – post-refurbishment, Riddlecombe 2012–2017.

3.2 Relative Humidity (RH)

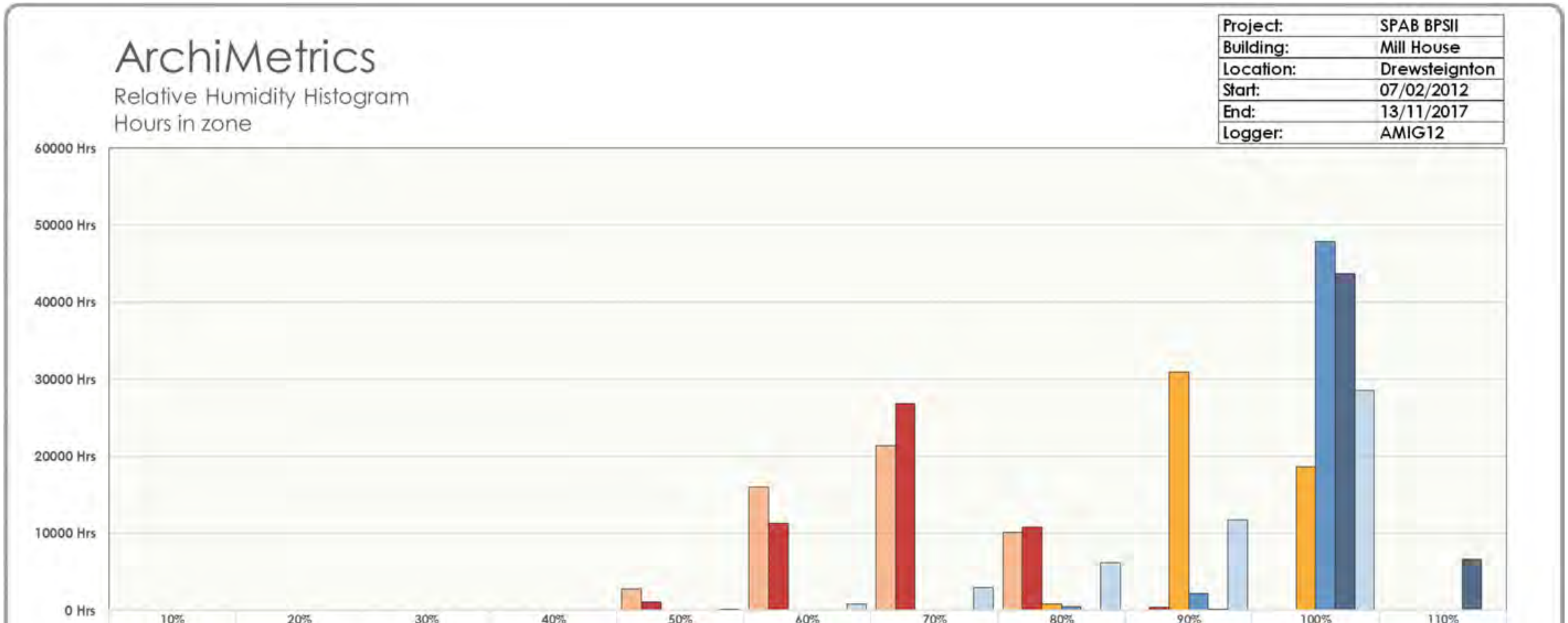
So far, we have compared moisture measured as AH in the three walls but in order to have some understanding of whether this humidity might represent a risk, ie when the air within the walls comes close to saturation, it is necessary to also look at RH behaviour through the wall sections.

Three histograms have been produced which identify the total number of hours for RH quantities in 10% RH brackets for each of the measurement locations through the wall section for the six years of study (Figures 23, 24 and 25). These show the predominant RH condition of the walls. Shrewsbury has the broadest spread of RH with the lowest quantities. Here n2 shows the highest number of hours of all four measurement nodes, indicating the greatest consistency/least change over the six years is at the interface between the wood fibre insulation and brick masonry; 30,002 hours between 71–80% RH. The wall at Drewsteignton has higher RH and at n2, the insulation/masonry interface, records 30,986 hours at 81–90% RH. However, a greater number of hours is found at n3 and n4: 47,862 hours and 43,695 hours respectively, with a higher measurement of RH, 91–100%; with n3 showing the greatest number of hours overall for the wall in this higher RH bracket. The cob wall at Riddlecombe (best able to hold vapour) has the highest RH of all three walls. RH is high at n3, 91–100% for 40,549 hours, but, of all the walls, is highest for longest at n4 behind the stone buttress, close to the interface between the original wall and the new insulated external render with 49,736 hours at 101–110%.



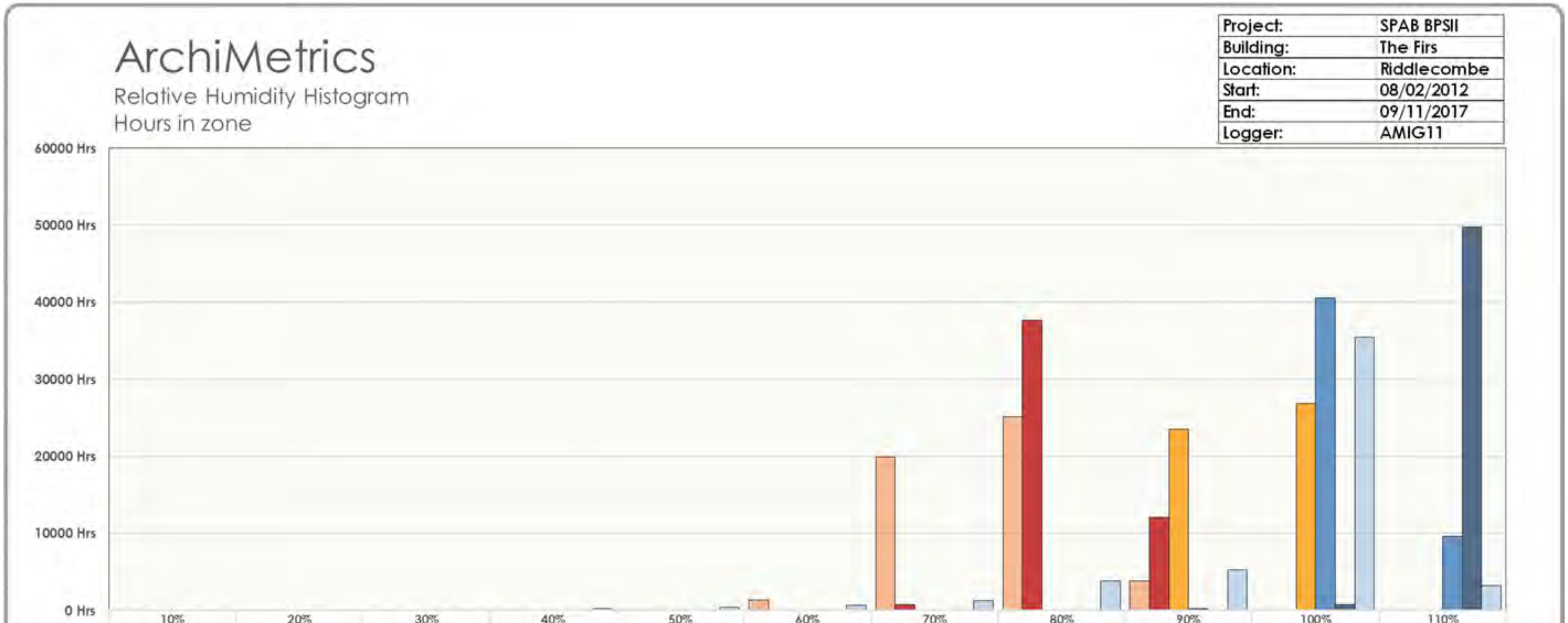
	0-10%	10-20%	20-30%	30-40%	40-50%	50-60%	60-70%	70-80%	80-90%	90-100%	100-110%
iRH	0	0	0	0	2	1609	24034	19911	3642	35	3
n1R	0	0	0	0	13	9424	25492	11958	2348	0	0
n2R	0	0	0	0	0	16	15808	30002	3397	13	0
n3R	0	0	0	0	0	50	12579	20528	10331	4282	1464
n4R	0	0	3	215	1641	6317	8965	6977	8448	6467	10206
eRH	0	6	94	1309	1183	2286	4919	6958	20257	12224	0

Figure 23. Relative humidity histogram – post-refurbishment, Shrewsbury 2012–2017.



	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%	110%
iRH	0	0	0	106	2799	16040	21424	10107	65	0	0
n1R	0	0	0	0	1052	11350	26845	10859	382	51	0
n2R	0	0	0	0	0	0	60	802	30986	18693	0
n3R	0	0	0	0	0	0	0	474	2204	47862	1
n4R	0	0	0	0	0	0	0	0	184	43695	6661
eRH	0	0	3	21	182	840	2971	6186	11737	28602	0

Figure 24. Relative humidity histogram – post-refurbishment, Drewsteignton 2012–2017.



	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%	110%
iRH	0	0	0	1	45	1383	19951	25124	3851	92	2
n1R	0	0	0	0	0	0	776	37587	12085	0	0
n2R	0	0	0	0	0	0	0	15	23557	26876	0
n3R	0	0	0	0	0	0	0	0	253	40549	9645
n4R	0	0	0	0	0	0	0	0	0	713	49736
eRH	0	3	67	228	392	641	1253	3831	5312	35514	3210

Figure 25. Relative humidity histogram – post-refurbishment, Riddlecombe 2012–2017.

Whilst the histogram analyses indicate the predominate state of the walls with regard to RH, they are unable to tell us about the trends of RH behaviour within the walls over time. Figures 26, 27 and 28 use monthly aggregated data to plot 'over-time' analyses, with the addition of dashed trend lines to map RH developments over the timescale of the post-refurbishment monitoring. An additional solid purple line shows the trend of external RH over this same time period.

The practice of capping RH measurements at 100% in the first two-and-a-half years of the project, seen at n4 at Shrewsbury and Drewsteignton and n3 and n4 at Riddlecombe, could lead to misleading plots of RH trends towards the external side of the walls. However, at Shrewsbury, despite the potential under-representation of RH early on, the predominant trend at n4 over six years is still shown as reducing. At Drewsteignton, the capping of RH was only effective between February–June 2013, which is unlikely to have significantly altered the more or less flat trend line at n4 plotted for the full six years of the project. High (100%) RH was measured for several months in the first two years of the project at n3 at Riddlecombe and nearly continuously at n4. At n3, RH has been reducing over six years and, therefore, like Shrewsbury, the trend line indicates the predominant direction of change regardless of the capping of RH quantities at 100% early on. However, the trend line for n4, where RH has been very high throughout, is undoubtedly exaggerated by capping early in the post-refurbishment monitoring and for this reason is faded within Figure 28 and should be discounted. Beyond these caveats regarding the trend lines for n4, more confidence can be given to an examination of trends towards the centre of the walls; at n2 and n3, as well as n1, locations where high, 100%+ RH is rarely recorded.

In Shrewsbury, over the six years of monitoring external RH shows a trend of increasing slightly from just below to above 80% RH. During this same time period, RH trends at n1, n2 and n3 have fallen and average RH is below 80% at these three nodes (and 80% at n4 bearing in mind this might be slightly higher if uncapped RH had been measured throughout). At Drewsteignton, mindful of earlier comments regarding climate in the south-west, external RH is higher and also has a slightly rising trend, being around 89% by the end of 2017. RH in the wall at n2 and n3 also has a rising trend, steeper than the one plotted for external conditions, ending the monitoring period above 90% at n2 and near 100% at n3. (At Drewsteignton, n1 is not coupled to moisture influences within the bulk of the wall as it sits within the air gap between the foil-face of the PIR insulation and the plasterboard finish, in a separate microclimate influenced primarily by room conditions. Therefore, this trend is not so much an indication of moisture behaviour within the wall but rather that of the room.) Riddlecombe also has a high, +90% and rising, trend of external RH throughout, but within the centre of the wall RH is falling over time. The trends seen within the walls, not surprisingly, correspond with those seen in the AH record. But the RH trend analysis shows that in terms of the risk within the centre of the walls, n2 and n3, at Shrewsbury and Riddlecombe, conditions are moving away from the likelihood of the air being saturated, whereas this possibility is increasing at Drewsteignton.

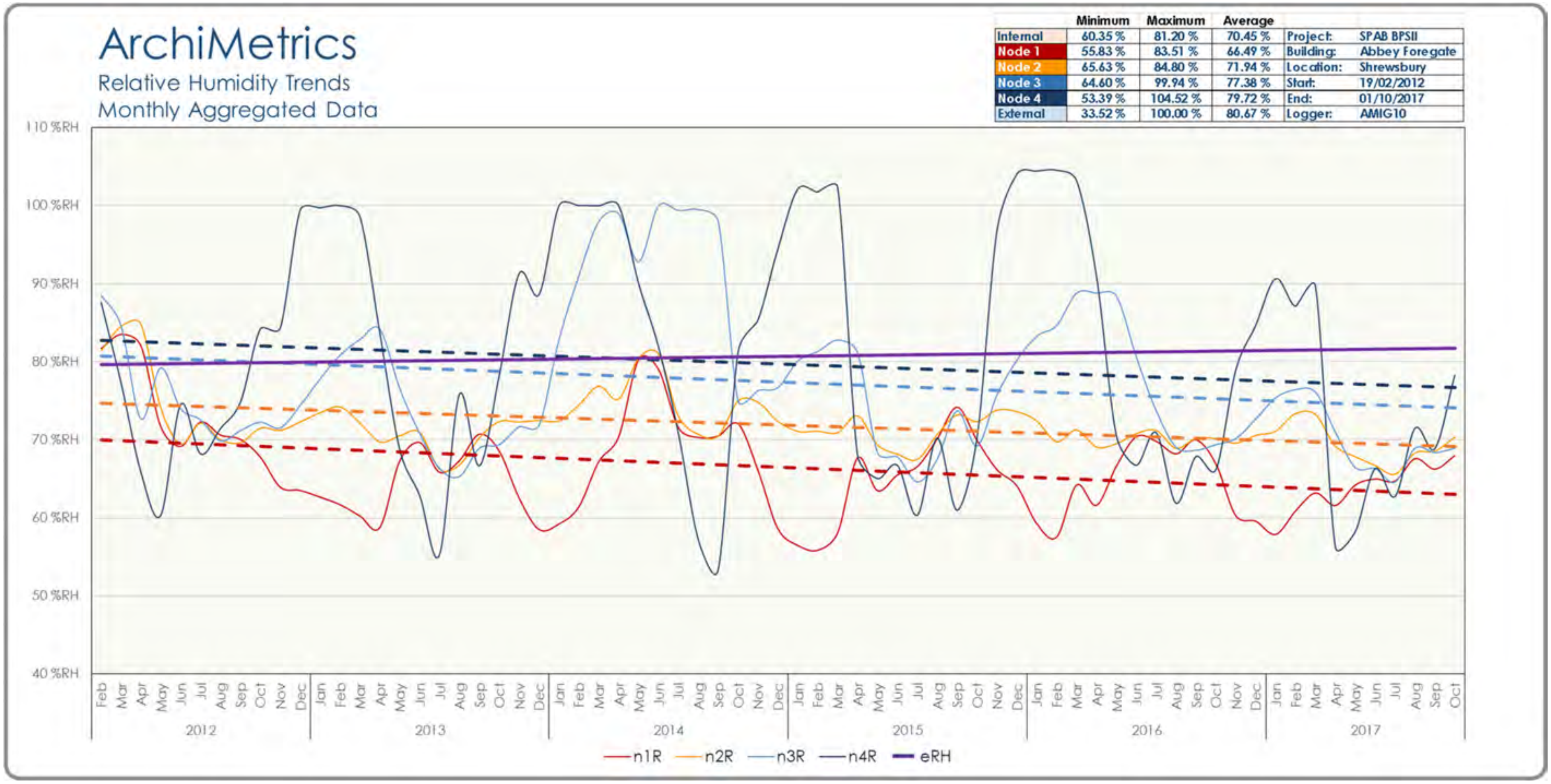


Figure 1 - Post-refurbishment, Shrewsbury 2012–2017.

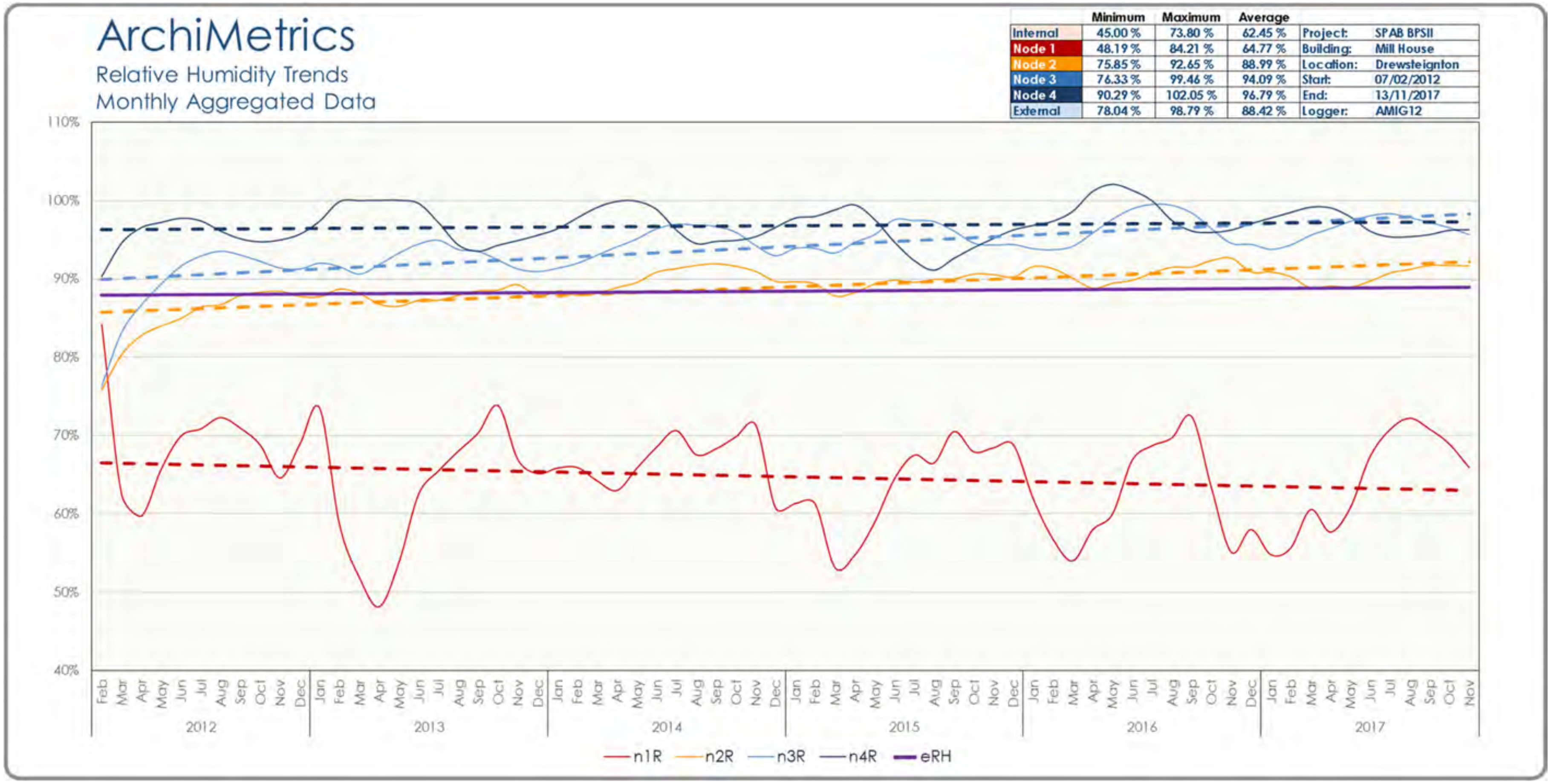


Figure 27. Relative humidity trends - post-refurbishment, Drewsteignton 2012–2017.

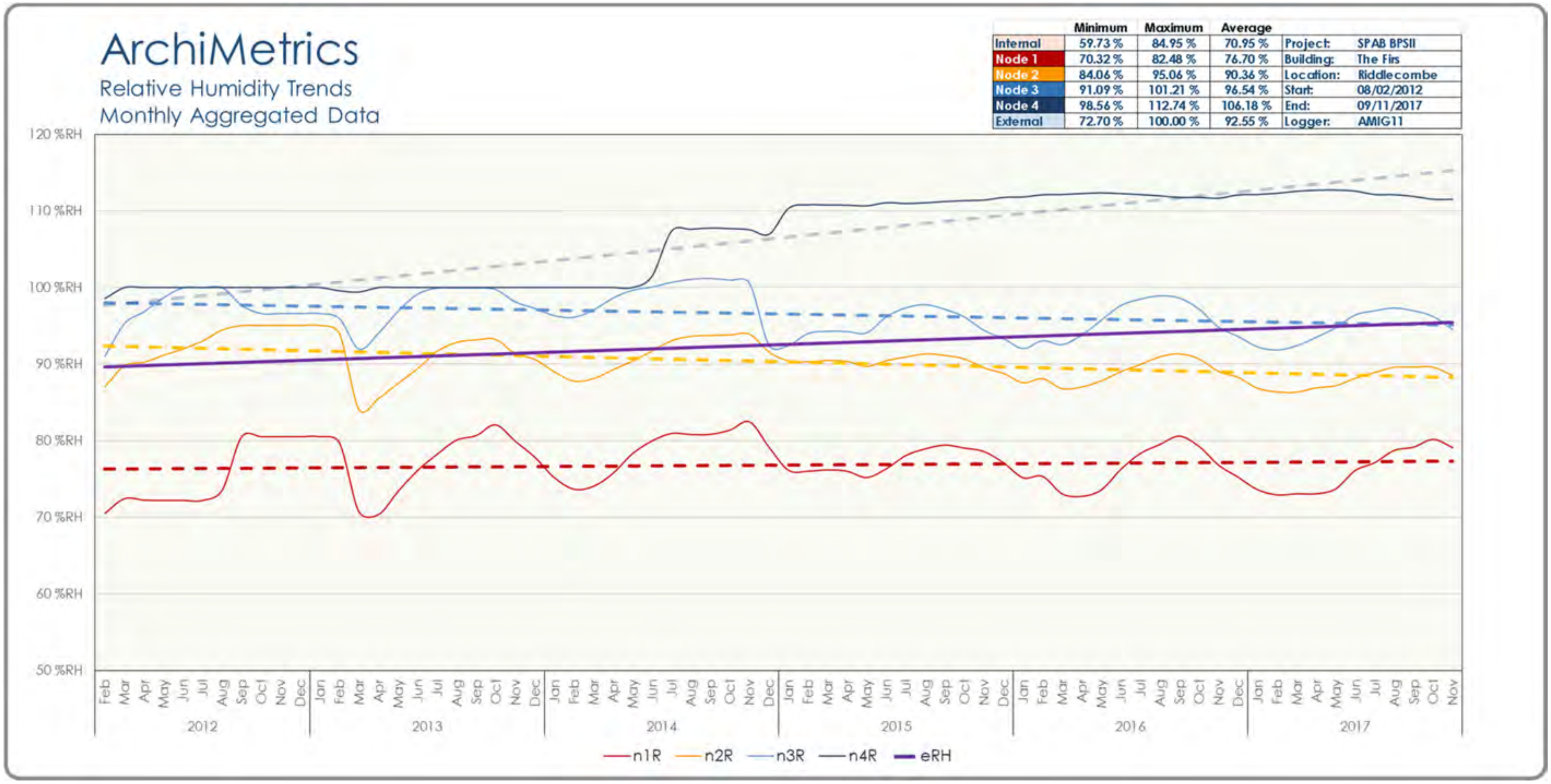


Figure 28. Relative humidity trends - post-refurbishment, Shrewsbury 2012–2017.

3.3 Saturation Margins

Saturation margins are the other means we have used to identify the risk of dewpoint/the saturation of air in these walls. As with AH, gradients based on annual averaged saturation margins for each measurement node have been produced to show a saturation margin through the wall sections for the six years post-refurbishment (Figures 29, 30 and 31). Measured vapour is now factored in relation to temperature. Plotting the risk of saturation posed by average quantities of vapour leads to a clearer picture of how the walls are changing over time.

In comparison with the other properties, saturation margins at Shrewsbury throughout the section over most years are comparatively high, with, as before, 2014 showing as an aberration. As is hinted at by the RH trend analyses, the most recent year, 2017, is found to have the widest margins (lowest RH, lowest occurrence of saturation). At Drewsteignton, there is a big difference between margins found in the air gap at n1, which are similar to those measured with the room, and those within the masonry of the wall. Margins in the wall are much narrower, and, in particular, it is possible to see a year-on-year reduction in these margins taking place at n2 and n3. (Just as RH is increasing in this part of the wall, this inevitably leads to ever-narrowing saturation margins.) The picture is less clear at n4 because RH/saturation conditions here are more directly influenced by external climate. The 2017 margins should benefit from this being the driest year in the measured series, although these only result in margins that are slightly wider than those of the previous year, 2016. Overall, at n2, n3 and n4, the years 2016 and 2017 have the narrowest margins of all the six measured years.

Riddlecombe starts with the narrowest margins of all three measured walls but shows improving, that is to say widening, margins which increase year-on-year in the centre of the wall at n2 and n3. By 2017, these margins, which to begin with were narrower than those found at Drewsteignton, are now wider than those of Drewsteignton as this part of the wall moves away from the possibility of saturation and the centre of the wall at Drewsteignton moves closer towards it. The opposite is found, however, at n4 in Riddlecombe and is more like Drewsteignton in that margins have worsened over the years, being on average close to -2˚C in the year 2017.

The reasons for the contrasting vapour behaviour seen at Riddlecombe are related to its materials, the form of its construction and the primary source of moisture within the fabric, which is water added during refurbishment. This is lodged deep within the cob due to this water being applied under pressure from a hose and the ability of unbaked earth to absorb large quantities of water. Overall, the only way the wall can reduce its moisture load is through evaporation into the surrounding environment. Peaks of RH in this wall are found to relate to evaporative activity over the spring and summer months, where water within the cob material becomes a vapour and then moves slowly through the wall by diffusion. Vapour is reducing in the centre of the wall indicating, overall, some excess moisture may be exiting the structure. However, the saturation margin analysis suggests this is mostly occurring at the internal wall face. Saturation margins here are wider as are AH and RH measurements. Towards the external side of the wall, at n4, this process seems to be slower, leading to an accumulation of vapour resulting in negative saturation margins at this side of the wall. As has been previously suggested, the stone of the buttress, as well as the thickness of the render itself, may be retarding the progress of water vapour moving by diffusion, and be the reason for this stasis. However, something that the average annual section analyses for Riddlecombe are unable to show is hinted at in the RH over-time analysis (Figure 16) towards the end of the monitoring programme. In Figure 16, RH is seen to reduce very slightly over the final months of the project, which may imply that this position in the wall had passed its ‘peak’ RH condition and that reductions in vapour and moisture from surrounding materials were beginning to be reflected through lower RH measurements. However, as measurements have now ended in this wall, it cannot be known whether this was a short-term seasonal response or part of a more significant change of trend.

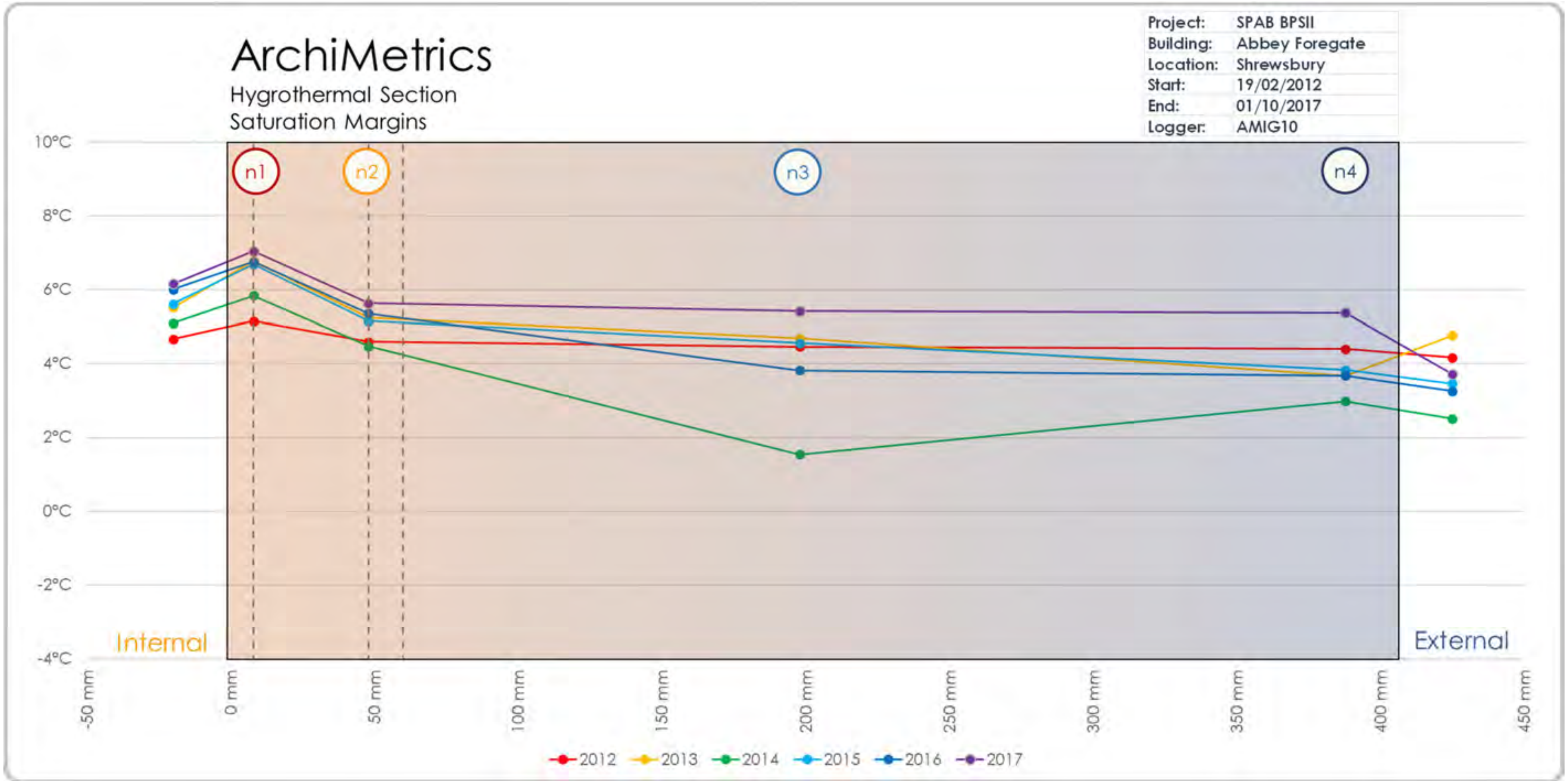


Figure 29. Saturation margins annual sections – post-refurbishment, Shrewsbury, 2012–2017.

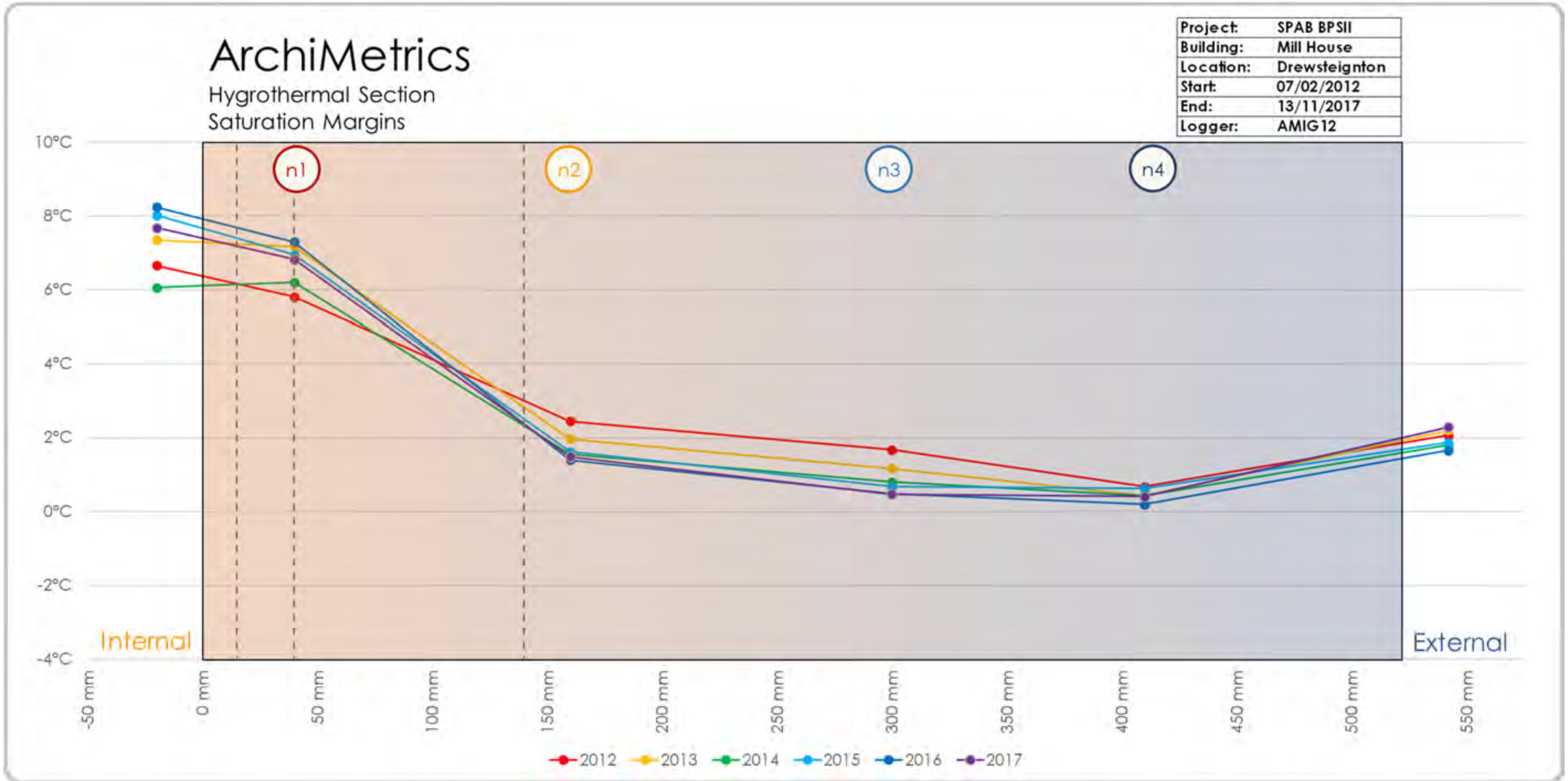


Figure 30. Saturation margins annual sections – post-refurbishment, Drewsteignton, 2012–2017.

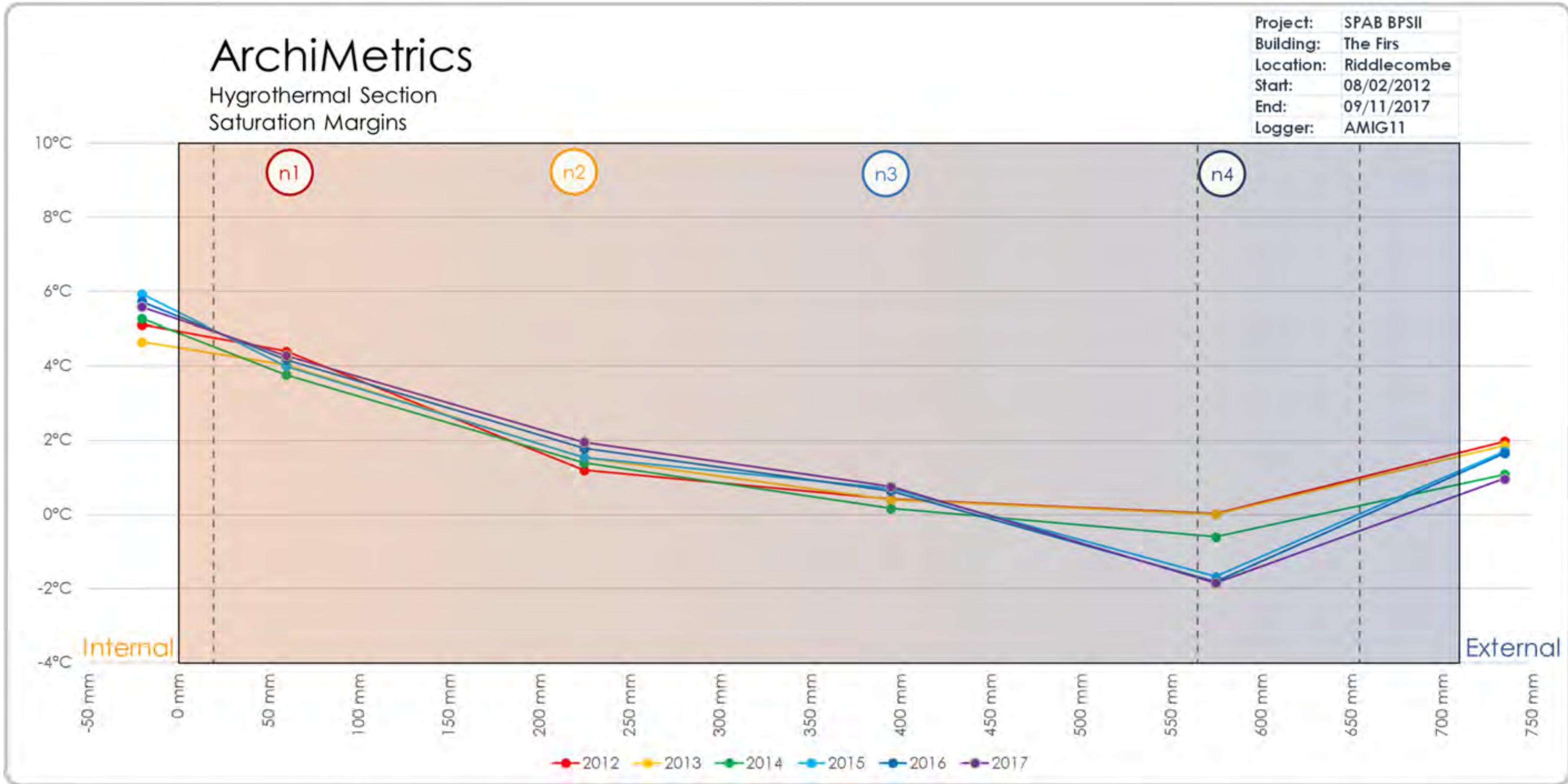


Figure 31. Saturation margins annual sections – post-refurbishment, Riddlecombe 2012–2017.

4 Summary and Conclusions

We have looked in detail at moisture responses within the three walls studied in the BPS and find, overall, three different stories.

The wall at Shrewsbury seems to operate within 'safe' limits with regard to moisture. Whilst there are periods each year when RH spikes to around 100% (dewpoint), over an annual cycle the wall recovers and measures lower RH. Measurements of %MC are also found to be low within the fabric, around 0.75%. This wall appears to be able to evaporate sufficient moisture over a twelve-month seasonal cycle to prevent moisture from accumulating or building up within its fabric. This is due to multiple factors, such as its relatively thin construction, the condition (which admits air), a southerly aspect and the materials which go to make up the wall, including the wood fibre insulation. The addition of a 40 mm layer of this material resulted in a 68% measured reduction in heat loss. Like that of the brick substrate, the wood fibre insulation is porous, permeable and capillary active. It is able to hold and move moisture as a liquid through its pores as well as hold moisture as a vapour, increasing opportunities for evaporation.

The picture for the other internally insulated wall, at Drewsteignton, is somewhat different. It has been noted that this wall is much slower in its vapour responses and, over time, we find a trend of increasing RH within the centre of this wall, where it is consistently above 90% at n2 and n3 in the final two years of the project. We also find higher %MC in this wall, +5% within the centre and at the masonry/insulation interface in the final year. This wall is much thicker than the wall at Shrewsbury, more tightly constructed, north-west facing and located in a damper climate. The material it is principally constructed from, granite, is relatively non-porous and impermeable and lacks capillaries. In addition, the insulation used on this wall is of an impermeable, closed-cell structure, bound with a metallised foil sheet which acts as a moisture barrier at the internal face of the masonry. The larger quantity of this more thermally resistive PIR insulation resulted in an 87% measured reduction in heat loss for the wall. Despite impermeable elements, the monitoring shows that the wall is able to contain, and accumulate, moisture. This is probably largely within the lime mortar used to bed the stones as well as micro-fissures and cracks within some stone blocks. The geographical location, aspect and form of its construction mean evaporative opportunities for this wall are already, prior to insulation, more restricted. This is then compounded by the use of an insulating material that limits the movement of moisture, as well as drastically lowering the U-value of the wall. A tighter wall construction results in less adventitious air movement through the structure. Thermal transfer through the wall as a result of direct and indirect solar radiation is slower and more limited too, due to the north-west aspect of the wall and its thickness. The higher density of granite also results in greater thermal mass for the wall requiring a higher input to raise its temperature. Heat input into the wall from heating in the internal space is compromised as well, by the quantity of insulating material applied to the internal wall face. All these factors - restricted moisture movement, lack of air movement and lower fabric temperatures - conspire to reduce the ability of the wall to evaporate moisture. As a result, it appears that moisture measured as a vapour is increasing year-on-year in the central part of the wall at Drewsteignton, where measurements of %MC are also high.

The wall at Riddlecombe is somewhat different from those of Shrewsbury and Drewsteignton. It is a thick, south-facing, externally insulated wall principally made of earth - cob, a material of high moisture capacity and mobility. The origin of much of the moisture monitored in this wall is not directly linked to the external environment in the form of rainfall but is a result of water added to the cob substrate during re-rendering (refurbishment). RH and %MC are both high but this might be expected due to the hydrophilic nature of the cob. Over time, we see vapour, which has been highest in the central part of this wall, reducing and %MC increasing towards the internal and external sides of the wall. We propose this is the result of processes of evaporation and diffusion which occur during the warmer months of the year driven by solar heating of the substrate. As well as being able to absorb and contain large quantities of water, the cob material is eminently porous and permeable, meaning when temperatures increase through the south-facing wall excess water is converted to a vapour and migrates by diffusion (the cob is extremely airtight so there is little or no displacement due to air movement occurring within the wall). As this vapour load moves, air towards the internal and external sides of the wall increasingly experiences saturation conditions (100% - dewpoint) leading to moisture deposition and increased wetting of the substrate in proximity to the internal and external surfaces. Whilst the centre of the wall thus seems able to slowly purge itself of excess moisture added during refurbishment, there remains a slight question mark as to conditions, particularly towards the external side of the wall where RH is continually high (+110%). By the end of the project in November 2017, %MC monitoring showed the lowest rates of moisture measured here, at MC4, over the past six years, suggesting an improving situation. Whilst moisture quantities may be reducing in general through the wall, RH continues to be high, particularly towards the external wall face. This is partly as a result of the hygroscopic qualities of cob material but also as quantities of moisture in the materials at this location, whilst they may be reducing, have not yet reached a tipping point at which a reduction in RH will also be measured. Indeed, a slight dip in RH is seen in measurements made in the final few months of the project and it may be that, had these measurements continued, a trend of reducing RH as seen elsewhere within the wall would have emerged for this location.

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APPENDIX A

Monitoring Location Floor Plans.

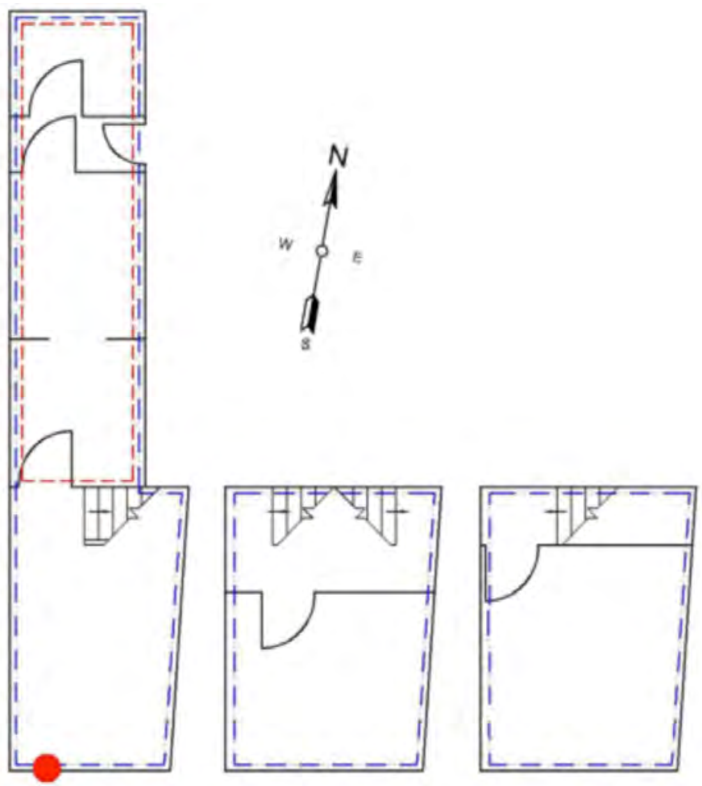

Figure 32. Plan of 116 Abbeyforegate, Shrewsbury (ground floor on left hand side). The red dot indicates the location of monitoring equipment.

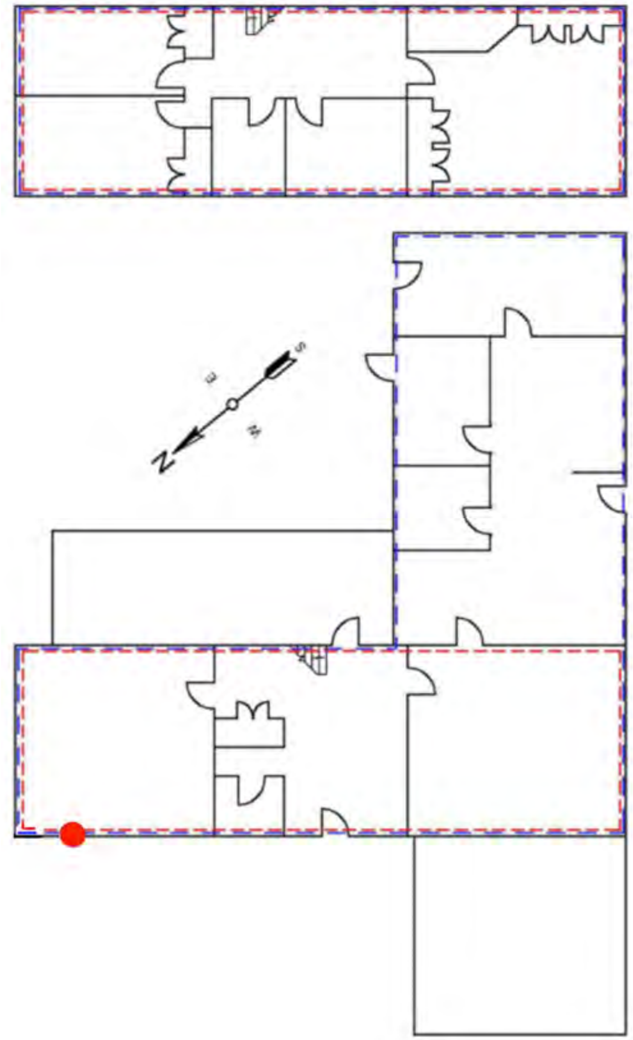

Figure 33. Plan of Mill House, Drewsteignton (ground floor in lower part of plan). The red dot indicates the location of the monitoring equipment.

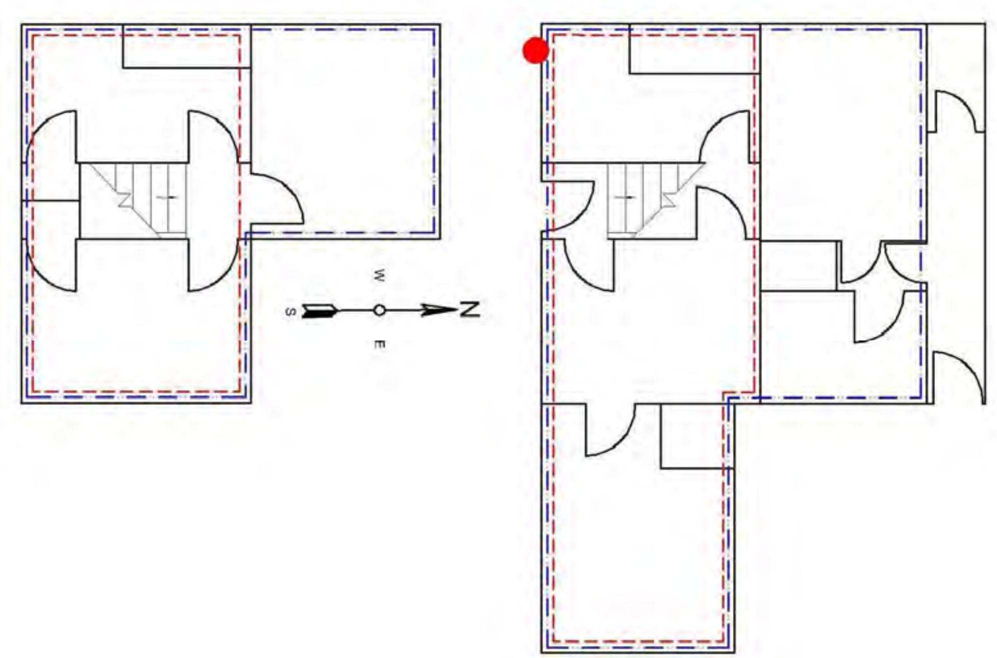

Figure 34. Plan of The Firs, Riddlecombe (ground floor on right-hand side). The red dot indicates the location of monitoring equipment.

APPENDIX B

Table 9. Measured and Calculated U-values including, where relevant, % reductions from all SPAB Building Performance Study properties.

Location	**2011 Measured uninsulated W/m^2K**	**2012/13 Measured insulated W/m^2K**	**% reduction**	**2011 Calculated uninsulated W/m^2K**	**2012/13 Calculated insulated W/m^2K**	**% reduction**
Shrewsbury South, grd floor 1200 mm above FFL	1.48	0.48	68%	1.52	0.59	61%
Shrewsbury West, grd floor 1200 mm above FFL	2.06	0.63	70%	1.71	0.62	64%
Drewsteignton North-west, grd floor 1200 mm above FFL	1.24	0.16	87%	2.45	0.19	93%
Riddlecombe South, grd floor 1200 mm above FFL	0.76	0.72	4%	0.95	0.56	41%
Skipton South, 1st floor 1200 mm below FFL	1.63	0.97	40%	2.31	1.72	26%
Skipton South, 1st floor 1200 mm above FFL	1.62	1.04	36%	2.31	1.72	26%
Lower Brailes North, grd floor 1200 mm below FFL	1.39			2.03		
Lower Brailes North, grd floor 1200 mm above FFL	1.49			2.03		
Ashburton East, grd floor 1200 mm below FFL	1.33			1.79		
Ashburton East, grd floor 1200 mm above FFL	1.04			1.79		
Ashburton East, 1st floor 1200 mm below FFL	0.46			0.43		
Ashburton East, 1st floor 1200 mm above FFL	0.35			0.43		

APPENDIX C

*Table 10. Summary of Air Permeability results for all SPAB BPS Properties taken from **The SPAB Building Performance Survey 2011 Interim Report**, p14.*

	Units	Shrewsbury	Drewsteignton	Riddlecombe	Skipton	Lower Brailes	Ashburton	Devon Consuls
Whole dwelling								
Internal floor area	m^2	60	325	86	190 ~	113	332	161
Habitable building volume	m^3	134	759	189	458 ~	263	817	379
Dwelling envelope area	m^2	185	708	245	401 ~	285	690	380
Measured air flow	m^3h^{-1}@50Pa	2106	6139	1355	6789 ~	2478	15615*	7615
Air permeability test result @ 50Pa	$m^3h^{-1}m^{-2}$@50Pa	11.4	8.7	5.5	16.9 ~	8.7	22.6*	20.0
Air changes per hour @ 50 Pa	ach @ 50 Pa	15.7	8.1	7.2	14.8 ~	9.4	19.1*	20.1
Estimated ach through infiltration at ambient pressure	ach	0.8	0.4	0.4	0.7 ~ #	0.5	1.0*	1.0
Part of dwelling								
Description		Extension	Barn Conversion	Original Cottage		Original Cottage	Original house plus old extension	
Internal floor area	m^2	17		54		96	240	
Habitable building volume	m^3	41		124		224	643	
Envelope area	m^2	81		184		230	514	
Measured air flow	m^3h^{-1}@50Pa	520		927		2152	11494	
Air permeability test result @ 50 Pa	$m^3h^{-1}m^{-2}$@50Pa	6.4		5.0		9.4	22.4	
Air changes per hour @ 50 Pa	ach @ 50 Pa	12.8		7.5		9.6	17.9	

*Ashburton whole house figures likely to be inaccurate due to error; ~ Skipton – not full dwelling area; # Skipton – using 1/20 approximation – see 2011 Report for further information.

*Table 11. Comparison of air permeability results for Shrewsbury, Riddlecombe and Skipton before and after refurbishment taken from **The SPAB Building Performance Survey 2012 Interim Report**, p9.*

	Units	**Shrewsbury**		**Riddlecombe**		**Skipton**	
		2011 pre-refurbishment	**2012 post-refurbishment**	2011 pre-refurbishment	**2012 post-refurbishment**	2011 pre-refurbishment	**2012 post-refurbishment**
Whole dwelling							
Internal floor area	m^2	60	**60**	86	**86**	190 ~	**298**
Habitable building volume	m^3	134	**134**	189	**189**	458 ~	**718**
Dwelling envelope area	m^2	185	**185**	245	**245**	401 ~	**567**
Measured air flow	m^3h^{-1}@50Pa	2106	**1570**	1355	**1308**	6789 ~	**6181**
Air permeability test result @ 50Pa	$m^3h^{-1}m^{-2}$@50Pa	11.4	**8.5**	5.5	**5.4**	16.9 ~	**10.9**
Air changes per hour @ 50 Pa	ach @ 50 Pa	15.7	**11.7**	7.2	**6.9**	14.8 ~	**8.6**
Estimated ach through infiltration at ambient pressure	ach	0.8	**0.6**	0.4	**0.3**	0.7 ~ #	**0.4**
Part of dwelling							
Description		Extension		Original Cottage			
Internal floor area	m^2	17	**17**	54	**54**		
Habitable building volume	m^3	41	**41**	124	**124**		
Envelope area	m^2	81	**81**	184	**184**		
Measured air flow	m^3h^{-1}@50Pa	520	**459**	927	**924**		
Air permeability test result @ 50 Pa	$m^3h^{-1}m^{-2}$@50Pa	6.4	**5.6**	5.0	**5.0**		
Air changes per hour @ 50 Pa	ach @ 50 Pa	12.8	**11.3**	7.5	**7.5**		

~/# The 2011 pre-refurbishment test on Skipton was not carried out on the full area of the dwelling.

APPENDIX D

Room Conditions.

The main body of this report deals at length with conditions inside the three insulated walls in the SPAB Building Performance Survey. However, as part of the wider study, measurements were also made within the rooms adjacent to the wall monitoring within three of the properties. This means it is also possible to produce an analysis of internal room conditions both before and after the walls and properties were refurbished. Temperature and RH were measured at five-minute intervals and plotted against two polygons representing ‘ideal’ and ‘acceptable’ temperature and RH conditions for ‘comfortable’ habitation. The analysis also includes three temperature and RH curves showing ‘limiting isopleths for mould growth’ for different materials: LIM 0 – ideal growth medium; LIM 1 – biodegradable materials; and LIM 2 – porous materials. These are based on the work of Sedlbauer and indicate the risk of the possibility of mould growth.[7] Conditions within rooms will be determined by, amongst other things: room aspect, volume, levels of occupation, heating regimes, glazing to wall ratios, construction fabric, decorative fabric, and the degree of ventilation and infiltration within the room, as well as the property as a whole. Part of the survey included air permeability tests which quantified air leakage rates for the properties before and after refurbishment and are provided in Appendix C. Thermographic surveys were also carried out which pinpoint specific areas of potential heat loss pre- and post-refurbishment. Details of these are given in the 2011, 2012 and 2013 Interim Research Reports.

As with other monitoring, pre-refurbishment room temperature and RH data was gathered over a short time period, in a matter of weeks over winter 2011, to provide a ‘snapshot’ of room conditions. These are shown without the inclusion of external conditions data in Figures 35, 36 and 37. These short surveys show that conditions in the monitored rooms, a living room in Shrewsbury and a study in Drewsteignton (see Appendix A for plans), were during the time of monitoring mostly outside of the ‘ideal’ range as well as the ‘acceptable’ comfort range. Rooms were cold, with only a few measurements of above 20˚C and some measurements at Shrewsbury were below 10˚C. These low temperatures are perhaps not unexpected given that these houses had been identified by their owners as requiring refurbishment, presumably in part not only to improve energy efficiency but also comfort levels. Perhaps as a result of these low temperatures, Shrewsbury also records some RH values which bisect LIM 0 and LIM 1, but there was no evidence of mould growth on any surfaces in the room so it is thought that this risk was not significant. The room at Riddlecombe shows a better alignment of temperature and RH measurements with the ‘ideal’ comfort criteria, as well as a trace where temperatures decrease for a time and most likely as a result RH is raised above LIM 0. It is thought that this occurred due to lack of heating over a period of time while the occupants were not in residence.

[7] Sedlbauer, 2001.
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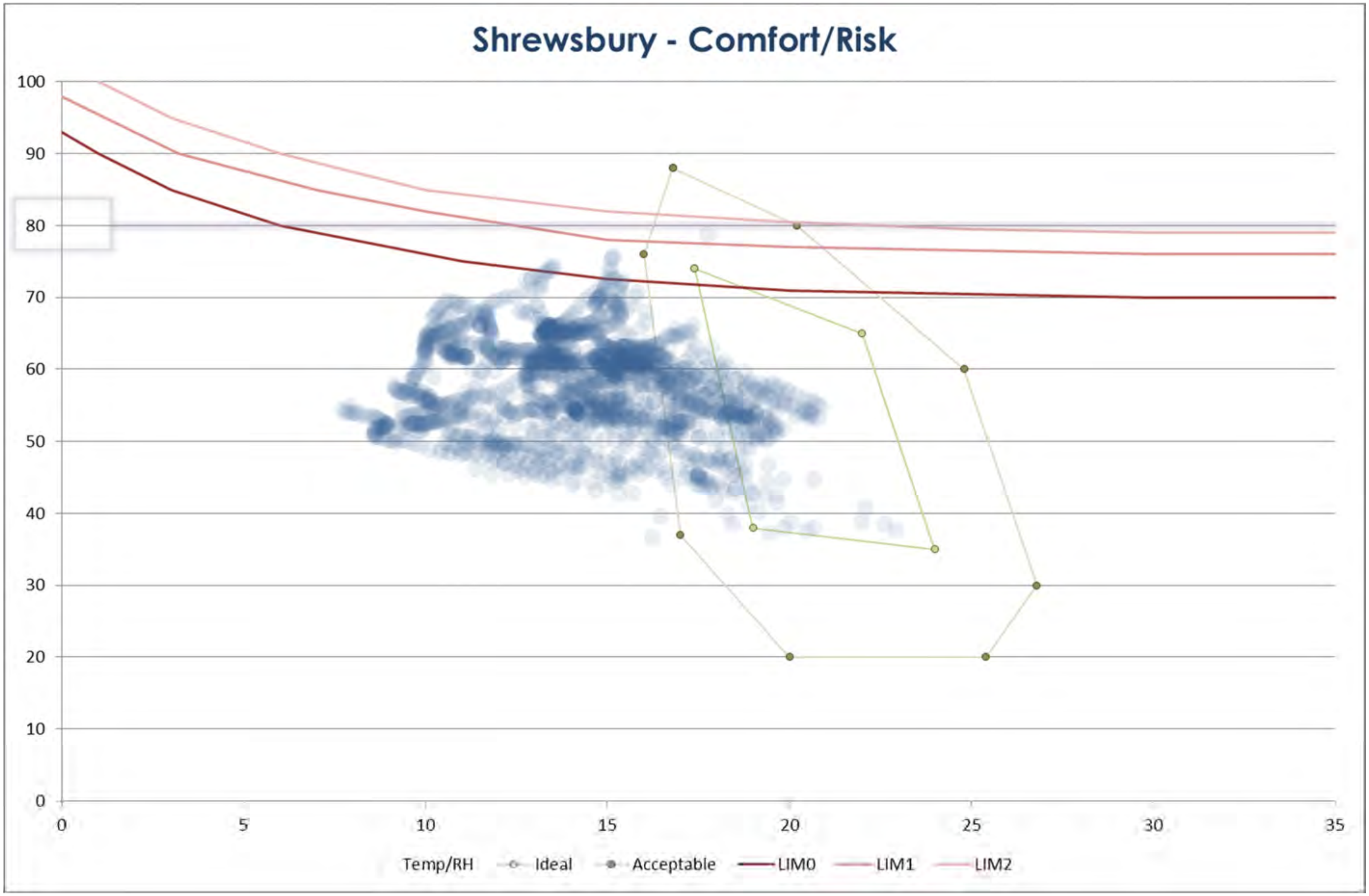

Figure 35. Comfort/risk analysis, Shrewsbury, 2011 – pre-refurbishment.

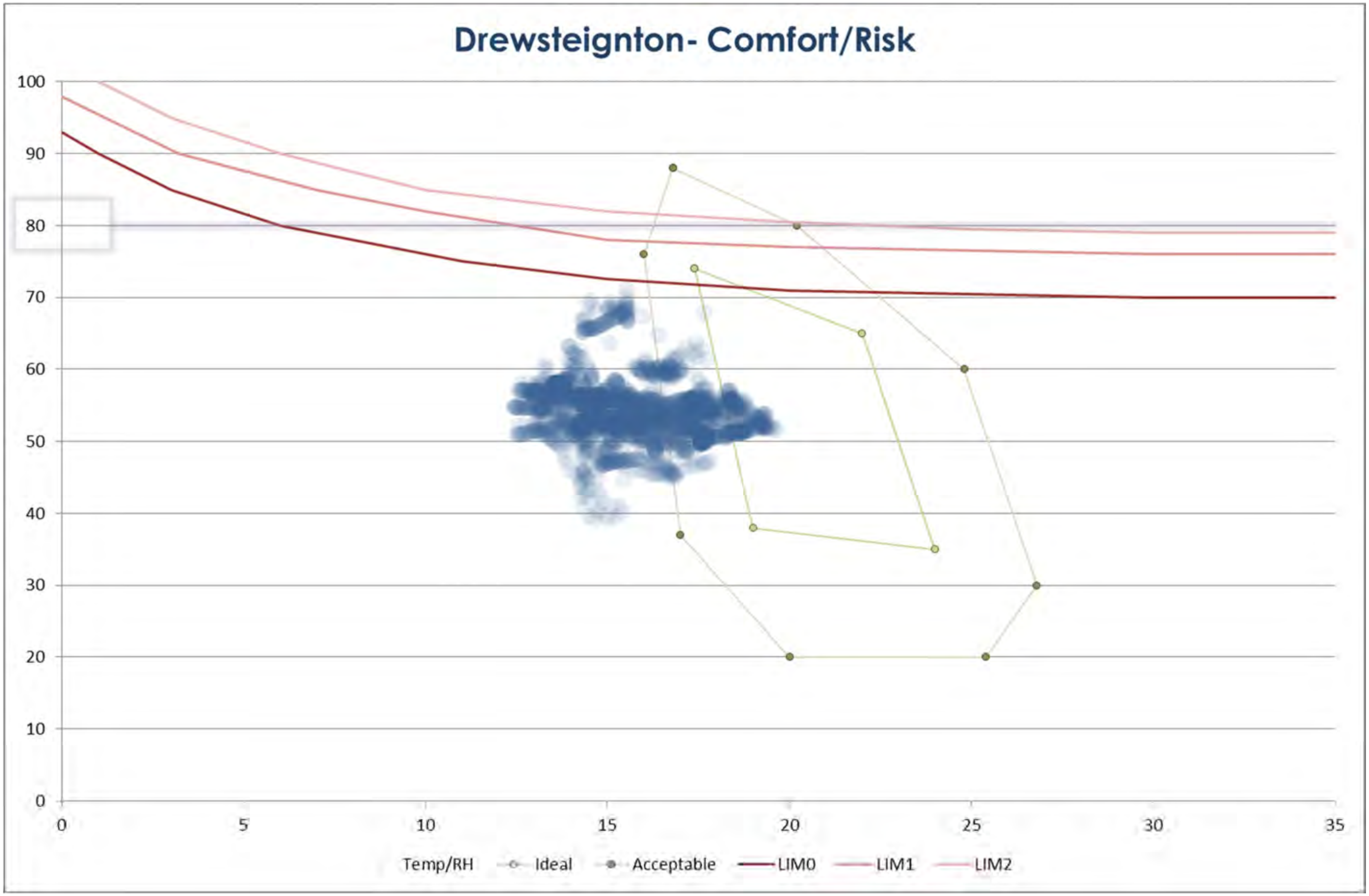

Figure 36. Comfort/risk analysis, Drewsteignton, 2011 – pre-refurbishment.

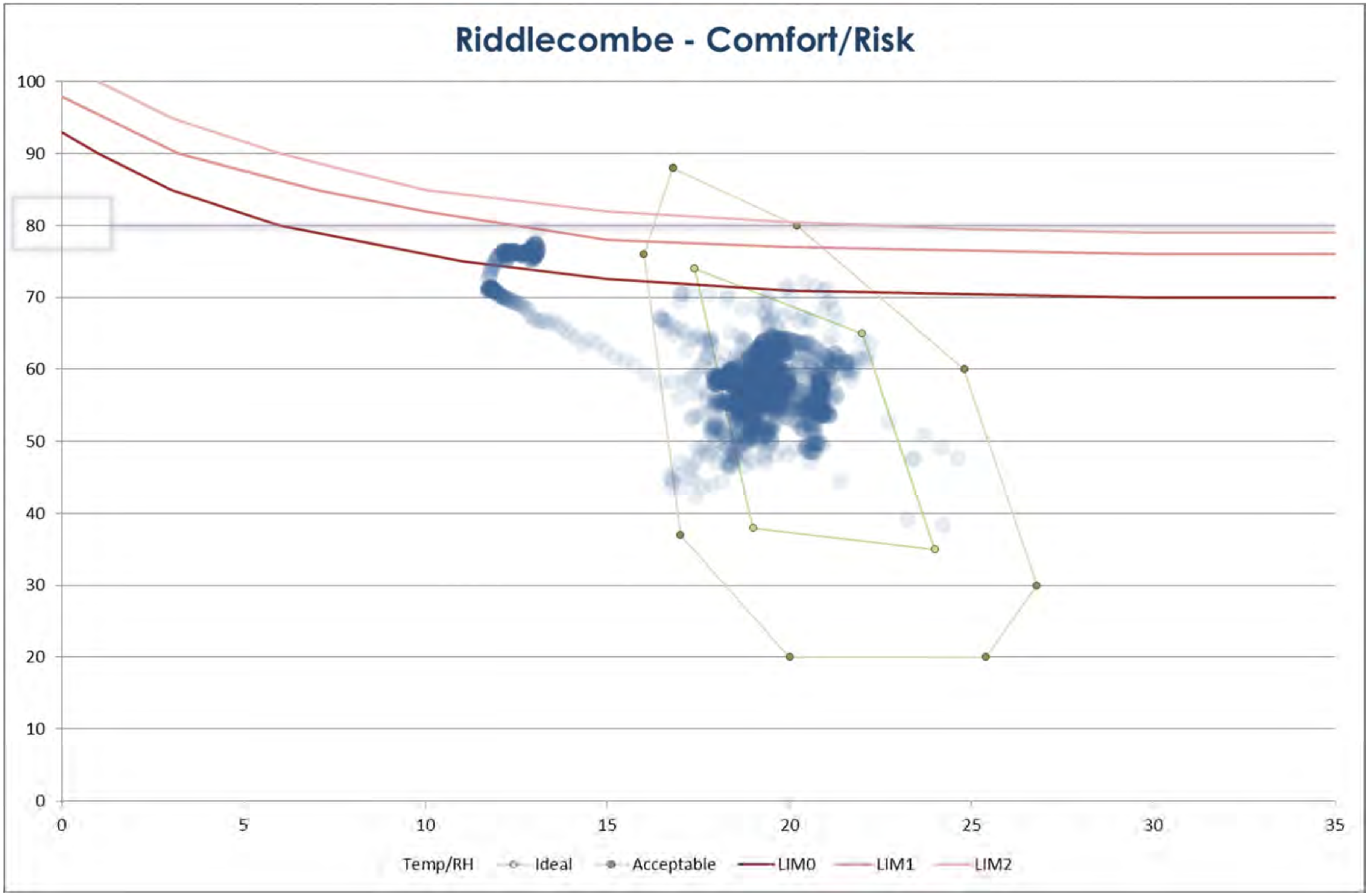

Figure 37. Comfort/risk analysis, Riddlecombe, 2011 – pre-refurbishment.

The post refurbishment analyses for the rooms, Figures 38, 39 and 40, use nearly a full six years of measured temperature and RH data to map conditions within the rooms. These analyses also include external conditions and details of hours spent above and below 17–25˚C and 40–70% RH for the three rooms and the commonly given 80% threshold for mould growth on surfaces is marked in red.

Perhaps unsurprisingly, as the analyses now encompass full years and thus includes warmer seasons, the majority of the temperature measurements have moved into the ‘acceptable’ comfort polygon plotted for the living room at Shrewsbury. They are, however, towards the lower end of the comfort scale with the average room temperature post-refurbishment found to be 17.8˚C. Average room RH is 70% but the room was only measured between the brackets of 40–70% for 52% of the time post-refurbishment, with a total of 23,590 hours being above 70% with peaks up to 100%. However, as before, there is no visible evidence of mould growth on surfaces within the room at Shrewsbury.

The study at Drewsteignton has a larger volume than both the measured rooms at Shrewsbury and Riddlecombe and RH is notably lower in this room, mostly below the 80% threshold. Average internal room RH over the six years post-refurbishment is 63% with an average temperature very similar to that of Shrewsbury 17.4˚C. As with Shrewsbury, a proportion of measured temperatures are low and lie outside of the ‘acceptable’ comfort polygon. Some of these may coincide with holiday periods and lack of occupation when heating was set back.

Riddlecombe seems to have the best fit between measured conditions and comfort criteria, although higher humidity means a proportion of measurements exceed the ‘ideal’ polygon. Some exceed 80% and all LIM thresholds but, like Shrewsbury, there is no evidence of mould growth on surfaces within the room. The improved fit is in part due to higher average temperatures, 19˚C with average room RH being similar to that found for Shrewsbury, 71%. The improved temperatures mean that the room was within the temperature bracket 17–25˚C for 94% of the time it was monitored, although due to higher RH, the room was maintained between 40-70% for less than half the time it was monitored, 43%.

Because of the very different time series for the pre- and post-refurbishment room condition monitoring, it is not really possible to state whether the changes seen post-refurbishment are the result of improvements made to the fabric or just reflect warmer overall conditions. RH measured in all three rooms has increased but again this could just be a reflection of a much larger data set. However, temperatures have improved and there is no sign of mould growth in the two rooms of smaller volume where RH exceeds 80%.

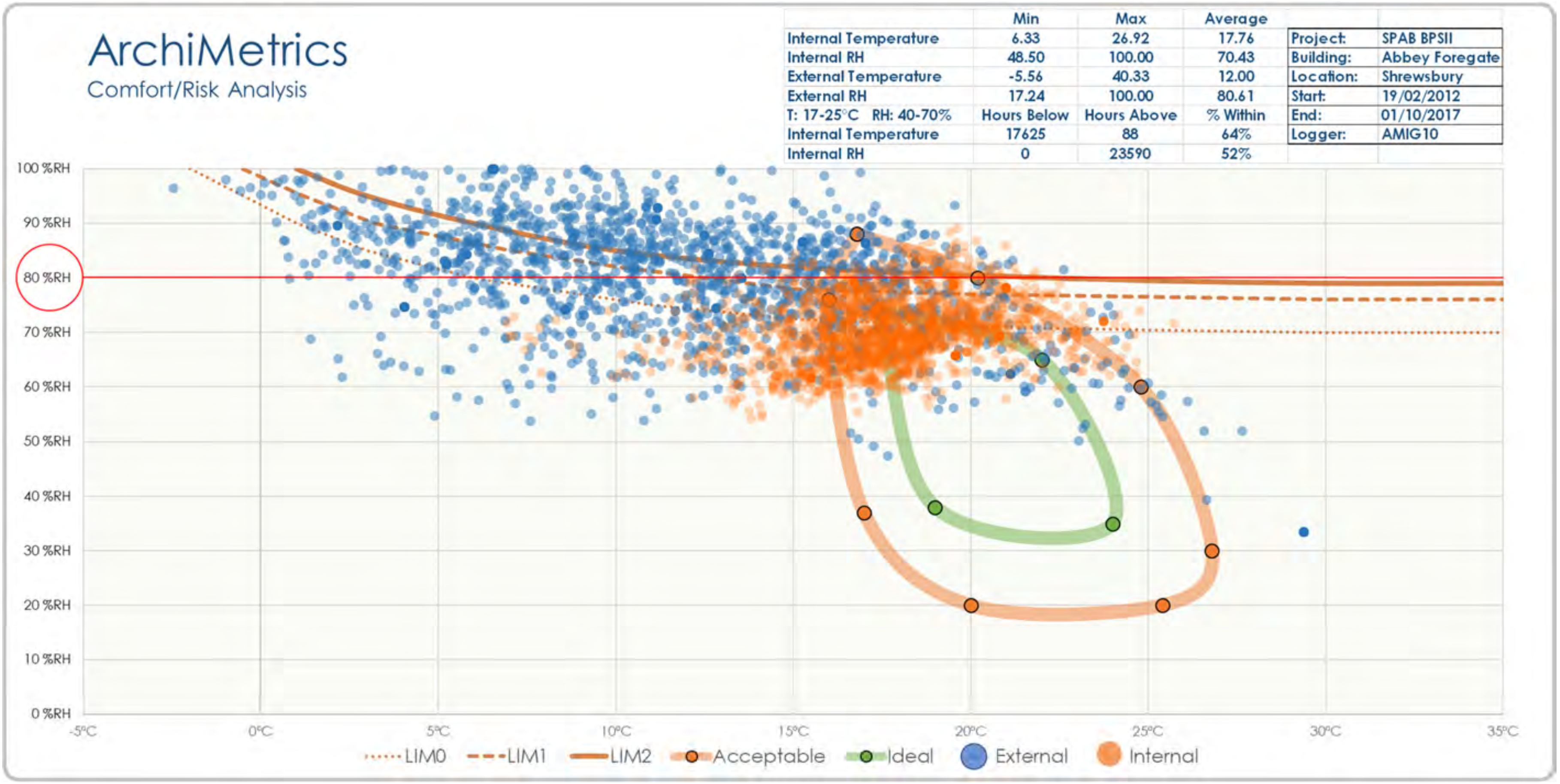

Figure 38. Comfort/risk analysis, Shrewsbury, 2012–2017 post-refurbishment.

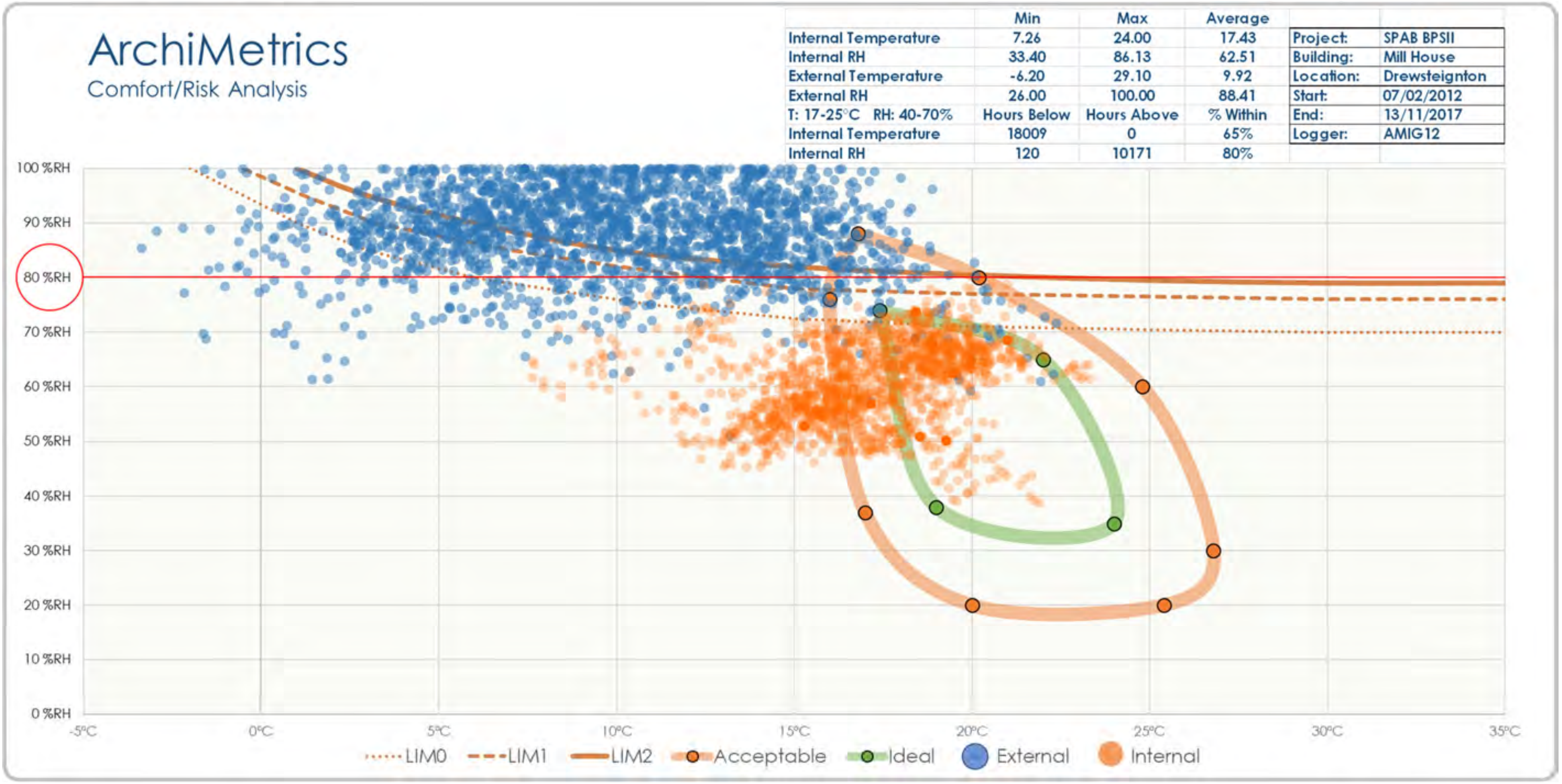

Figure 39. Comfort/risk analysis, Drewsteignton, 2012–2017 post-refurbishment.

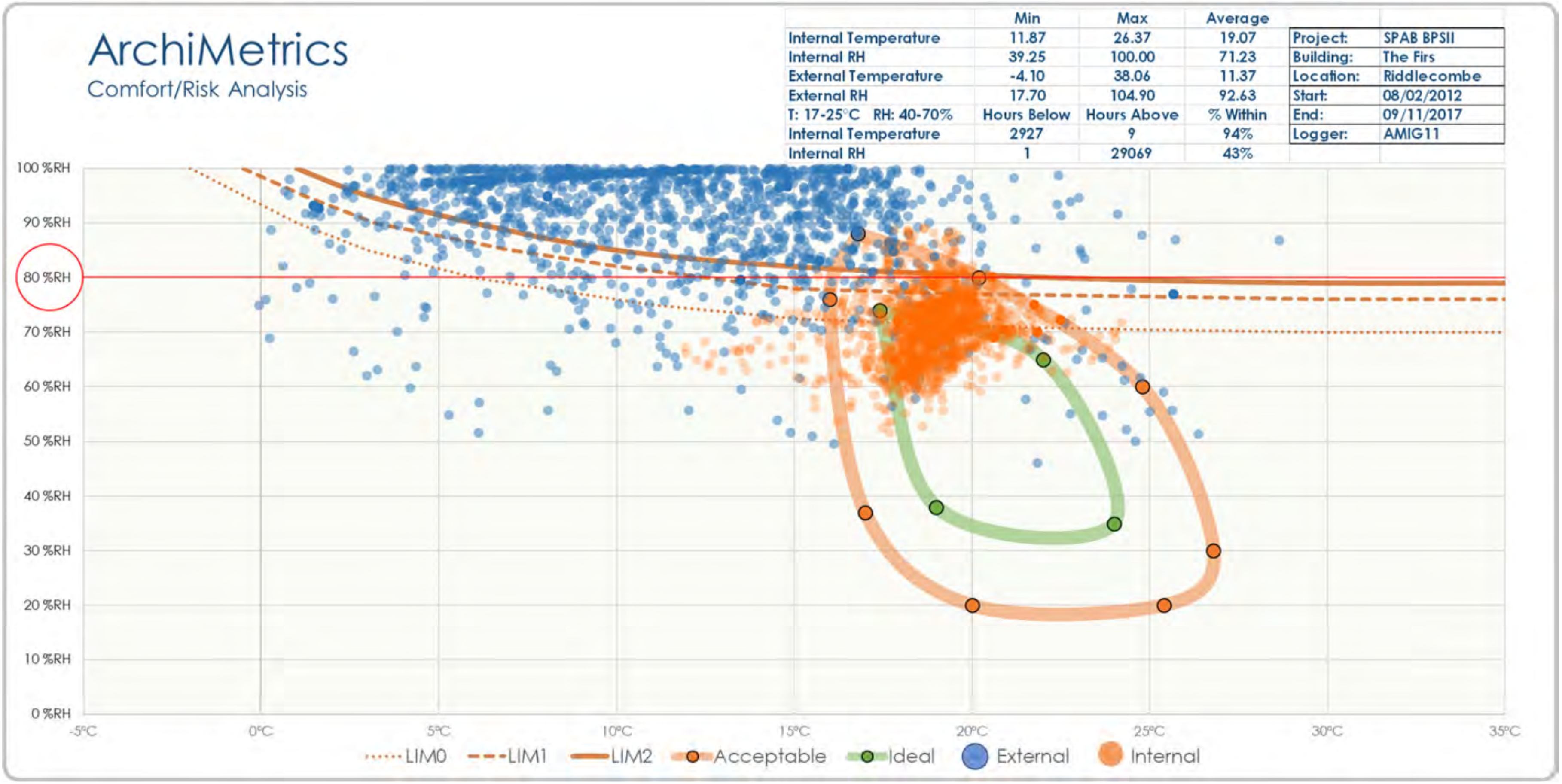

Figure 40. Comfort/risk analysis, Riddlecombe, 2012–2017 post-refurbishment.