Historic England

SPAB Building Performance Survey 2012

Interim Report
October 2012

Dr Caroline Rye, Cameron Scott and Diane Hubbard
Society for the Protection of Ancient Buildings
Supported by Historic England

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THE SPAB RESEARCH REPORT 2

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Foreword

This report is the second in a series which details the interim findings of the SPAB's Building Performance Survey, a research project that looks at the performance of a number of traditional buildings both before and after refurbishment designed to improve energy efficiency. This report is the first to provide details of post-refurbishment performance in three of the buildings within the survey. The report is in two parts: The first part sets out the background to the project, provides an update of progress and is followed by a summary discussion of findings so far. The second part, called Appendix A, is formed of individual documents that report in detail from the three refurbished properties studied over the past year. Further background information, including details of the monitoring procedures and data processing used in the study can be found in the previous report, *SPAB Research Report 2: The SPAB Building Performance Survey 2011 Interim Report*.

The SPAB would like to thank all the owners of the seven properties used in the SPAB Building Performance Survey and particularly James Ayres, Jason Fitzsimmons and Sebastian Payne whose houses are the focus of this particular report. We are also grateful to Stephen Bull and Tim Ratcliffe from the SPAB Technical Panel for their assistance in preparing this document. In addition we would like to give a special thank you to Val Harrison and the Dartmoor National Park Authority for their continued support throughout this project via their Dartmoor Sustainable Development Fund and English Heritage for their support of the 2012 monitoring work and publication of this report, through their National Heritage Protection Commissions Programme.

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1. INTRODUCTION

In the winter of 2011 the SPAB embarked upon a research study to assess the performance of seven traditional buildings that were destined for various energy efficiency refurbishment schemes. This research looks at a range of factors that may affect the energy performance and environmental behaviour of traditionally built dwellings specifically;

- Fabric heat loss through the U-value measurement of wall elements both in the form of *in situ* and calculated U-values,
- Air infiltration through air permeability testing and thermographic survey,
- Moisture behaviour; room and wall moisture including wall surface, sub-surface and interstitial moisture via hygrothermal monitoring and
- Indoor air quality, comfort levels and fabric risk through the measurement of CO_2, interior temperature and relative humidity.

During a two week period between January and April 2011 measurements were taken of the seven properties whilst in an 'unimproved' condition. Following this pre-refurbishment assessment, in 2012, we returned to those properties that had completed their refurbishment work to repeat our measurements. The finding's of the 2012 post-refurbishment monitoring is the subject of this report alongside a comparison with the previous year's data for the properties concerned[1]. This work has been supported by a grant from the Dartmoor National Park Sustainable Development Fund and the 2012 post-refurbishment monitoring and reporting has been supported, in part, by a grant from English Heritage.

[1] Details of how this monitoring was carried out and the findings of this work can be found in the previous version of this report, *SPAB Research Report 2: The SPAB Building Performance Survey 2011 Interim Report.*

2. PROJECT BACKGROUND AND UPDATE

All the buildings included in the Building Performance Survey conform to the definition of a 'traditional building' provided by, amongst others, English Heritage[2] that is to say they are of pre-1919 origin and consist of solid walls built of permeable materials without the use of a damp-proof course or similar moisture breaks or barriers. The buildings span a variety of materials including brick, sandstone, limestone, granite, slate-stone and cob and are quite widely distributed within England, with a cluster concentrated within the south-west as a reflection of the funding provided by the Dartmoor National Park Authority (Fig. 1).

Figure 1. Map showing distribution of the SPAB Building Performance Survey Properties.

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[2] This definition is given in English Heritage's publication *Energy Efficiency and Historic Buildings* (p. 17) and can also be found in the Building Regulation's Approved Document Part L1B & L2B *Conservation of Fuel and Power 2010*, 3.8,c and the *Scottish Building Regulations Technical Handbooks.*

The properties were chosen as they were all intended to be refurbished within the timespan of the project and although this refurbishment work may not have been exclusively driven by the desire to improve energy performance and comfort levels, this was articulated as one of the primary motivating forces for the changes planned for the individual buildings. The refurbishment work planned for, or undertaken, on these properties has been the responsibility of their owners or agents, such as surveyors or architects, acting on behalf of the owners.

It would appear from this study that the refurbishment of solid wall properties can be an unexpectedly lengthy process. In the winter of 2011, whilst embarking on this study, most home-owners expected to have completed their refurbishment work within a 12 month period. However, by the following winter of 2012, only three of the seven buildings had reached some form of completion. After visits to these three buildings situated in Skipton, Shrewsbury and Riddlecombe it became apparent that only two were suitable for the full suite of post-refurbishment monitoring. The condition of the house at Skipton meant it was not possible to conduct a conclusive post-refurbishment air test and furthermore the finishes at this house, a hemp/lime insulating plaster, were still in the process of drying. Some monitoring equipment has been installed at Skipton and during the winter of 2013 we will conduct the remaining tests required to provide a full set of post-refurbishment data for this property. In addition to the houses at Shrewsbury and Riddlecombe the owners of the property at Drewsteignton allowed a small section of wall, at the site of the previous winter's measurements, to be insulated and monitored and data from this also forms part of the findings in this report.

3. RESULTS AND DISCUSSION

A summary of the results of the post-refurbishment monitoring at Shrewsbury, Riddlecombe and Drewsteignton, including comparisons between the three properties and with findings from the pre-refurbishment monitoring carried out in 2011, is provided below. Appendix A contains individual reports for each of the properties. These reports contain a detailed commentary on the separate findings at each property and further comparisons.

Fabric Heat Loss (U-values)

Following the refurbishment of the walls at the three properties in Shrewsbury, Riddlecombe and Drewsteignton reductions in heat loss, measured as a U-value have been noted at all three cases. Two of the properties have added internal wall insulation; Shrewsbury in the form of 40mm of woodfibre board and the other; the test wall at Drewsteignton, via the application of 100mm of polyisocyanurate (PIR) insulation. The cob wall at Riddlecombe has been externally insulated using 40mm of lime-based insulating render. The measured and calculated U-values for the walls, both pre and post-refurbishment, are given in Table 1.

Location	**2011 Measured Un-insulated W/m^2K**	**2012 Measured Insulated W/m^2K**	**2011 Calculated Un-insulated W/m^2K**	**2012 Calculated Insulated W/m^2K**
Shrewsbury South wall	1.48	0.48	1.52	0.59
Shrewsbury West wall	2.06	0.63	1.71	0.62
Drewsteignton	1.24	0.16	2.45	0.19
Riddlecombe	0.76	0.72	0.93	0.60

Table 1. Measured and calculated U-values of pre and post-refurbishment walls from the SPAB Building Performance Survey.

The results presented in Table 1 are from walls of different widths made of different materials and refurbished with different insulation products applied at different thicknesses, therefore no direct comparisons between these figures can be made. However, the percentage reduction in each case is of interest. Both the internally insulated walls at Shrewsbury and Drewsteignton have seen considerable reductions in heat loss, at Shrewsbury this reduction has been in the order of 68% and 70% respectively and at Drewsteignton, an 87% reduction in heat loss is recorded. The exception to this is the externally insulated wall at Riddlecombe which has measured only a 4% reduction in heat loss. The superior percentage reduction for the wall at Drewsteignton compared with that of the other internally insulated wall at Shrewsbury, is a result of the additional width of insulation material used at Drewsteignton, 100mm as opposed to 40mm and the lower conductivity of the PIR board, 0.022 W/mK in comparison with that of 0.039 W/mK for woodfibre board.

The fractional improvement in heat loss measured at Riddlecombe is not replicated in the calculated U-value estimates for this wall as here a 37% reduction is predicted following the application of insulating render to the cob wall. The percentage reduction predicted via a calculation of pre and post refurbishment U-values is partly a result of the pessimistic evaluation of heat loss made for this wall by the pre-refurbishment 2011 calculated U-value. This follows a common trend seen in the calculation of U-values for solid walls in general where there is a tendency for a calculated U-value to underestimate the thermal performance of the wall[3]. The possible overestimation of heat loss provided for the uninsulated wall then leads to a misapprehension as to the reduction in heat loss that can be achieved following the application of insulation to this wall. It is interesting to note that of the four sample walls the 2012 calculated U-value for the wall at Riddlecombe is the only occasion when a calculated U-value for an insulated wall exceeds that of the measured value for the same wall (that is to say it is of a lower number value). Once again the tendency, post refurbishment, is that the measured *in situ* U-value seems to be of a lower number value than its calculated equivalent, probably as a result of the heat loss, or inversely the thermal resistance of the original wall, not being fully appreciated within a calculated U-value for the wall prior to its insulation. However, in general, the discrepancy between the two sets of 2012 post-refurbishment measured and calculated U-values is quite small and

[3] See Rye, C. (2010). *The SPAB Research Report 1: The U-value Report*. Revised 2011. London: The Society for the Protection of Ancient Buildings and Baker, P. (2011). *Technical Paper 10 - U-values and Traditional Buildings*, Edinburgh: Historic Scotland

does not replicate anything like the 100% increase seen, for example, in the 2011 pre-refurbishment measured and calculated U-values for the wall at Drewsteignton. This is because the insulating addition to the wall is probably making the single most significant contribution to overall heat loss for that element and as a new addition it is likely to be of a known quantity accompanied by a specific thermal conductivity (lambda) value. These two factors, a known quantity of a material with precise conductivity data are required by the U-value calculating process and therefore if these quantities also relate to the most thermally resistive part of a wall build-up we can expect the calculation to produce a reasonably defined U-value. This, therefore, may be the reason why we see better correlation between calculated and measured U-values in walls after they have been subject to insulation. However, this is not the case for the wall at Riddlecombe where there has been very little change between the pre and post-refurbishment measured U-values. Unlike the other examples, the 2012 calculation for the insulated wall, post-refurbishment, improves upon the measured U-value for the same wall. There maybe a number of reasons why the performance of this wall has not really altered since the application of insulating render. As detailed in the previous Building Performance Survey Report (*SPAB Research Report 2: 2011*) this wall was noted to have a raised moisture content and monitoring carried out in 2012 has found that these conditions have persisted and indeed worsened within the measured section of wall (more details about this can be found in the Moisture section of this report). Therefore the thermal performance of the wall maybe compromised by the high moisture content of the cob material which will make the element more thermally conductive. In addition it could be that the thermal conductivity value attributed to the insulating render product may not reflect its performance *in situ*.

Air Permeability

Only two of the test properties had progressed sufficiently to have the post refurbishment air permeability testing and thermographic survey carried out in early 2012. These were 116 Abbeyforegate, Shrewsbury and The Firs, Riddlecombe.

	Units	Shrewsbury		Riddlecombe	
		2011 Pre-refurbishment	**2012 Post-refurbishment**	2011 Pre-refurbishment	**2012 Post-refurbishment**
Whole dwelling					
Internal floor area	m^2	60	**60**	86	**86**
Habitable building volume	m^3	134	**134**	189	**189**
Dwelling envelope area	m^2	185	**185**	245	**245**
Measured air flow	m^3h^{-1} @50 Pa	2106	**1570**	1355	**1308**
Air permeability test result @50Pa	$m^3h^{-1}m^{-2}$ @50 Pa	11.4	**8.5**	5.5	**5.4**
Air changes per hour @ 50Pa	ach @50 Pa	15.7	**11.7**	7.2	**6.9**
Estimated ach through infiltration at ambient pressure	ach	0.8	**0.6**	0.4	**0.3**
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} @50 Pa	520	**459**	927	**924**
Air permeability test result at 50Pa	$m^3h^{-1}m^{-2}$ @50 Pa	6.4	**5.6**	5.0	**5.0**
Air changes per hour @ 50Pa	ach @50 Pa	12.8	**11.3**	7.5	**7.5**

Table 1a. Comparison of air permeability results for Shrewsbury and Riddlecombe before and after refurbishment.

Air Infiltration

The results of the air permeability testing at Shrewsbury and Riddlecombe are summarized in Table 1a. The air permeability results for Shrewsbury and Riddlecombe from the 2012 testing are 8.5 $m^3h^{-1}m^2$ @ 50 Pa and 5.4 $m^3h^{-1}m^2$ @ 50 Pa respectively. Both results are below the limiting air permeability under Approved Document L1A 2010 for new build dwellings (10 $m^3h^{-1}m^2$ @ 50 Pa).

The air permeability of both properties has improved from the 2011 test to the 2012 post-refurbishment test. In the case of Shrewsbury, the change is significant (11.4 $m^3h^{-1}m^2$ @ 50 Pa to 8.5 $m^3h^{-1}m^2$ @ 50 Pa) reflecting the state of the building at the time of the 2011 test when the first floor room exterior wall was unplastered and prior to the inclusion of secondary glazing. . It should also be noted that items still awaiting completion at the time of the 2012 test will have affected the air permeability result. These include a ground floor area of wall requiring plastering, missing window sill and completion of the floor on the first floor. There is merit in considering a further test after these works have been completed. For Riddlecombe, the improvement in air permeability is less significant (5.5 $m^3h^{-1}m^2$ @ 50 Pa to 5.4 $m^3h^{-1}m^2$ @ 50 Pa) due to the building already being relatively airtight and the limited scope of the draught proofing measures applied between the 2011 and 2012 tests. It is understood that the homeowner has undertaken further work to the property since the 2012 test at Riddlecombe therefore, once again, an additional test to provide a definitive figure for this property could be considered. The secondary glazing fitted to two windows at Shrewsbury was of particular note. The secondary glazing was closed for the 2012 test. However, when it was opened, leaving the single glazed windows only, an increase in air flow through the property of 11% was noted

The air changes per hour at 50Pa for the whole dwellings is reduced at Shrewsbury from 15.7 ach @ 50 Pa to 11.7 ach @ 50 Pa and for

Riddlecombe from 7.2 ach @ 50 Pa to 6.9 ach @ 50 Pa. Translating these results to air changes per hour at ambient pressure, Shrewsbury has a figure of around 0.6 ach and Riddlecombe has a result of around 0.3 ach. It is generally viewed that occupants and their activities require a ventilation rate of 0.4-0.5 ach and, taking account of the high level of occupancy at Riddlecombe, the existing air change rate may present a problem without further means of ventilation in place.

Both Shrewsbury and Riddlecombe have at least one addition to the property and in both cases sections of the newer parts of the buildings were tested separately, with the provision that windows in the untested volume were not opened. In the case of Riddlecombe, the same air permeability result was achieved for the cob portion of the building in 2011 and 2012 (5.0 $m^3h^{-1}m^{-2}$ @50 Pa). The situation for Shrewsbury is not as clear. There was a reduction in air permeability despite there being no work carried out in this area of the dwelling (6.4 $m^3h^{-1}m^2$ @ 50 Pa to 5.6 $m^3h^{-1}m^2$ @ 50 Pa). One explanation may be the improved air tightness of the rest of the dwelling making a subsequent reduction in this area. This could be proved by testing with and without the windows being opened in the remainder of the house in a future test.

Though flues are excluded from the standard test procedure the flues in the test properties were also examined. There is a contrast between the flues in the two properties studied. In 2011, it was not possible to study the air flow in an open flue at Riddlecombe, due to stoves being fitted to both open flues. To permit the improvements to the floor, one of the stoves has been temporarily removed and a chimney balloon fitted. This allowed one flue to be measured during the 2012 test which, in comparison with similar measurements carried out by Hubbard presented a relatively low additional air flow under the test conditions (158 m^3h^{-1} @ 50 Pa)[4]. This represents an increase in air flow through the whole dwelling of 12% .The air flow measured at Shrewsbury

[4] Hubbard, D.C. 2012. *Chimney balloons – a solution for rural fuel poverty?* Commissioned by Sustainable and Energy Network, Staveley (SENS) through the Department of Energy and Climate Change Local Energy Assessment Fund (LEAF). Unpublished document.

from the living room fireplace was substantially higher than at Riddlecombe and provided an increase in airflow through the property as a whole under the test conditions of 56% (compared to 47% in 2011). This result highlights the fact that as the airtightness of a building improves, air flow relating to remaining flues becomes increasingly important. It should be noted the measured result under the test conditions will not relate directly to the air flows through chimneys, but offers a simple comparison. Evidence of the heat losses being incurred via the flue at Shrewsbury are shown in Figure 1a.

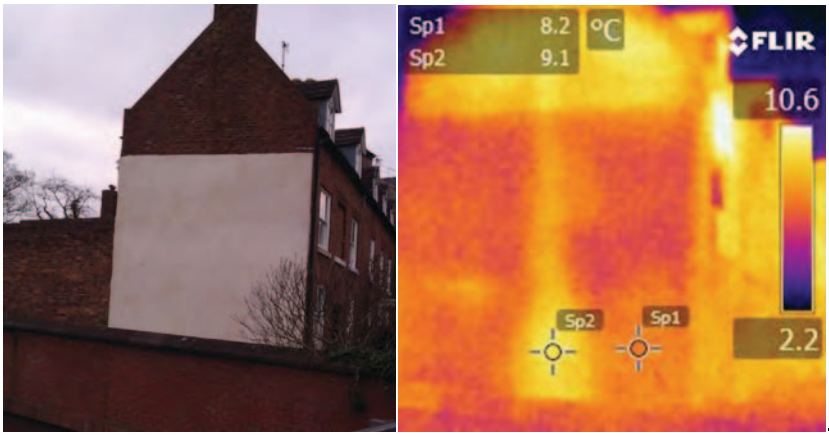


Figure 1a. 116 Abbeyforegate, Shrewsbury – West elevation.

<u>Thermographic survey</u>

With respect to the thermographic surveys, the weather conditions at both Riddlecombe and Shrewsbury permitted the thermal imaging of the exterior of both properties as well as examining their interior. One of the most interesting images obtained was the one above (figure Y1), but the location of thermal bridges and heating pipes and appliances was also identified. From inspection inside the dwellings, ingress around beams and loft hatches was common to parts of both properties, together with older windows at Shrewsbury showing ingress. At Riddlecombe, the position of the stone plinth at the base of the cob wall could be identified from images.

Surface and Sub-Surface Moisture

The following observations concern moisture readings taken at the interior surface and sub-surface of the walls at Shrewsbury, Drewsteignton and Riddlecombe. In general all three walls, post-refurbishment, have seen a decline in moisture readings at both surface and sub-surface levels. The two walls that have been subject to internal wall insulation, Shrewsbury and Drewsteignton, show similar patterns of behaviour. Previously, in 2011, the surfaces of these two walls appeared to be fairly stable and dry (there is a brief deflection mid-way up the plot for the wall in Shrewsbury which has been accounted for as the effect of water moving into the interior surface along a lintel). The 2011 plots for the sub-surfaces of these walls, about 40mm back, were a little more dynamic and indicated the influence of ground water at the base of the walls. The measurements taken in 2012 show both the plots of surface and sub-surface moisture occupying the 'dry' end of the nominal moisture scale (Fig. 16, p. 38 & Fig. 49, p. 82). This indicates something about the limitation of these methods of measurement as a means by which to assess moisture risk in internally insulated solid walls. The internal surface and sub-surface of the walls at Shrewsbury and Drewsteignton are drier as this is where a new insulating layer of material has been applied. The effect of this build-up to the internal face of the wall is to move the zone of moisture measurement away from the original masonry part of the wall. It is in the solid masonry part of these walls that we have previously seen fluctuating moisture readings indicating a dynamic environment influenced by external forces such as ground water and/or rain, therefore, whilst it is true to say that the internal leaves of these walls appear to be slightly drier this is not necessarily the case for the wall as a whole.

The graph for Riddlecombe, an externally insulated wall, is somewhat different but also shows the general declining trend for surface and sub-surface moisture (Fig. 34, p. 63). At this property the moisture permeability of both the internal and external finishes of the walls has, in theory, been increased by the application of lime-based finishes and both the moisture buffering and evaporation potential of these materials could account for the improvement in moisture readings taken here in 2012. This improvement is particularly pronounced for the lower part of the wall and it should be noted that the stone plinth (300mm) upon which the cob wall sits has received an additional coat of stabilising mortar to both its interior and exterior face which maybe benefitting moisture readings for this part of the wall. Also of note, however, is that above 1400mm readings for sub-surface moisture at Riddlecombe return to those previously recorded, pre-refurbishment, in 2011. This suggests that beyond the internal wall surface moisture conditions deeper within the wall have not really altered as a result of the refurbishment work. This may be of some concern given that high moisture levels within this wall have already been established as a potential problem in the previous 2011 report on this property[5].

Interstitial Hygrothermal Conditions

<u>Heat</u>

An examination of the hygrothermal comparison graphs for all three walls subject to survey in 2012 show raised temperatures for the majority of the wall section compared with those recorded pre-refurbishment in 2011 (Fig. 19, p. 42, Fig. 37, p. 67 & Fig. 52, p. 86). This is not as a result of the improved thermal performance of the walls but is a factor of the duration of the monitoring compared with that of the short period of winter monitoring of 2011. In 2012 the period of interstitial hygrothermal gradient monitoring been extended and will now take place for a full 12 months (or longer) therefore the period of time represented in the data now includes the warmer spring and summer parts of the year. The significant reductions in heat loss (measured as *in situ* U-values) for the two walls at Shrewsbury and Drewsteignton can be seen in the decline in temperature gradients through the insulated sections of

[5] Rye, C., Scott, C., Hubbard, D. (2011). *The SPAB Research Report 2: The Performance of Traditional Buildings - the SPAB Building Performance Survey 2011 Interim Findings*. London: The Society for the Protection of Ancient Buildings pp. 79 - 84.

both these walls. The decline is steeper at Drewsteignton reflecting the greater reduction in heat loss for this wall, however, following this, the temperature gradient through the original masonry parts of both these walls is flatter than previously recorded pre-refurbishment in 2011. This reflects perhaps both the influence of warmer external temperatures in the 2012 data but also the reduction of heat passing from the interior into the masonry as a result of the application of internal wall insulation which has de-coupled the wall from the internal environment. The gradient for the wall at Riddlecombe, which has been externally insulated, is different and shows a more or less consistent and gentle decline and no increase in slope as it passes through the insulating render. This gradient reflects the lack of meaningful change in heat loss recorded for this wall between its pre and post-refurbishment phases.

Like Shrewsbury, the wall at Riddlecombe faces south and one could therefore expect to see dynamic responses to solar gain on sunny days at these locations. This is very evident in the animation of the interstitial hygrothermal data for the wall at Shrewsbury as it is from the plots of maximum temperature shown in Figure 18 (p. 41.) which shows significant reverse heat flow in this wall[6]. Despite the presence of internal wall insulation at Shrewsbury this solar gain must benefit internal conditions on these sunny days by reducing the internal to external transmission of heat. In general the dynamism of the animated data for Shrewsbury is in stark contrast to that of both Riddlecombe and Drewsteignton which are both significantly thicker walls and make the solid brick wall at Shrewsbury look like a lightweight construction. In particular the response to solar gain of the south-facing wall at Riddlecombe is very different to that of Shrewsbury and is not as pronounced, nor does it appear to extend significant heat deep into the body of the wall. This maybe a consequence of the light and thus reflective treatment found on the external surface of this wall, along with the effect of a layer of external insulation which might isolate the interior of the wall from exterior influences.

[6] To view the 2011 and 2012 interstitial hygrothermal gradient animations for all the walls in the SPAB Building Performance Survey visit www.archimetrics.co.uk

Moisture

The interstitial hygrothermal gradient monitoring carried out on behalf of the SPAB Building Performance Survey measures both temperature and relative humidity (RH) conditions in proximity to and through selected wall sections. RH readings are then used to plot dewpoint conditions (that is the point at which water vapour in the air begins to condense as a result of low temperatures) for these walls. From the measurements of temperature and RH converted to dewpoints it is also possible to calculate dewpoint margins (that is the degree of temperature drop required for dewpoint to be reached). Thus the dewpoint margin could be seen as an indication of the degree of risk posed to building fabric from the moisture that is present within material at a particular location.

All three walls monitored in the 2012 survey show, to a greater or lesser extent, a reduction in dewpoint margins compared to those calculated for the same walls pre-refurbishment in 2011. However, the degree to which this poses a positive risk to fabric, in that dewpoint conditions have been reached, is true for only one property, that of Riddlecombe. Here plots of the RH data show, over time, RH exceeding 100% at both sensor 4 towards the exterior and then further back into the wall at sensor 3 (Fig. 38, p. 68). The same trajectory, of moisture accumulating to the point of dewpoint and travelling back into the wall, can also be seen in the 2012 interstitial hygrothermal animation for this wall. (This is also shown in the 2012 static interstitial hygrothermal graph for Riddlecombe but this is unable to demonstrate the accumulative nature of the phenomenon nor its direction of travel, Figure 36 (p. 66). As has been previously noted in 2011, pre-refurbishment, the wall at Riddlecombe was found to have a raised moisture profile. However, it appears that post-refurbishment this condition is increasing, the cause of this is yet to be conclusively identified - more discussion concerning this trend can be found in the individual report on this property contained with Appendix A.

In general external conditions seem to be the principal driver behind interstitial moisture behaviour where changes in external temperature and RH are most profoundly reflected at the 4th sensor position (the sensor in closest proximity to the exterior conditions) and the tend to ripple back through the wall, seen as diminishing degrees of response from the other interstitial sensors. Exceptions to this would be the plot of RH over time produced for the first sensor in the wall build-up, sensor 1, in the wall at Drewsteignton. This sensor, which sits in the air gap between the PIR insulation and plasterboard finish of this wall is exclusively conditioned by changes to the internal environment in this room. Following the application of a gypsum skim coat to the plasterboard this sensor shows high levels of moisture which decrease as the plaster skim dries out. Subsequent to this the plots from sensor 1 then mirror those of internal room humidity indicating a high degree of permeability for the plasterboard and its finishes (which include a coat of emulsion paint).

During 2012 both Drewsteignton and Riddlecombe show RH rising within their walls which maybe the significant factor in the reduced dewpoint margins seen in these walls during this period of monitoring. This is surprising as orthodoxy suggests that dewpoint margins are most likely to be reduced (to the point of convergence) towards the exterior wall leaf during periods of cold winter weather yet here we find convergence (or near convergence in the case of Drewsteignton) occurring during the warmer summer months. The consequence of adding internal insulation to a wall will be to lower the temperature within the masonry element inevitably leading to an increase in RH levels. However, in the case of these two properties, only one has been fitted with internal insulation (Drewsteignton). There is the possibility that these could be examples of 'summer condensation' when interior and exterior vapour pressure differentials reverse causing vapour to travel from the exterior to the interior and thus condense deep within cooler parts of a wall section. However, it is unlikely that this can explain the moisture behaviour seen at Drewsteignton and Riddlecombe as periods of high interstitial RH coincide with peaks in external temperature and low atmospheric RH thus vapour pressure differentials (the norm being high interior pressure, low exterior) remain unchanged. Although both the walls at Drewsteignton and

Riddlecombe show a rising trend for RH there are some significant differences between the two walls. As has been previously noted levels of moisture found at Riddlecombe are sufficient to constitute a threat to fabric (as can be seen from the disappearance of the plots of sensor 3 and 4 from the RH graph for Riddlecombe as levels exceed 100% (Fig. 38, p. 68)). Whereas interstitial RH records from Drewsteignton, although high, do not exceed 100% over the monitoring period. Furthermore, the plots of RH from sensors 3 and 4 at Drewsteignton begin to reverse the rising trend and start to diminish towards the end of the monitoring period (Fig. 53, p. 87). The only RH measurement that continues to climb during this period is that recorded from sensor 2 which is positioned directly between the insulation and masonry interface in this wall.

The only wall of the three monitored which does not exhibit this trend of raised or rising RH is that of Shrewsbury. It is also the wall that is most extensively affected by external conditions (Fig. 20, p. 44). Plots of RH from sensors positioned within the masonry inner leaf of this wall, sensors 1 and 2, sit within a band that gently fluctuates between 80 - 90% RH and perhaps this stability is a reflection of both the moisture buffering and vapour-open nature of the materials used to internally insulate this wall. Also, in contrast to plots of RH derived from the walls at Riddlecombe and Drewsteignton, at Shrewsbury we see levels of RH recorded from sensors 3 and 4 (in the outer wall leaf) fall *below* those recorded from the inner part of the wall. This reflects the south-facing and open (as a result of decayed pointing) nature of the wall structure at Shrewsbury which allows the warm temperatures and low relative humidity of external conditions to penetrate and dry this part of the wall structure. This drying effect is particularly pronounced at the 4th node which is positioned in proximity to the exterior and shows exceptional drying. Here the dewpoint margin has increased in comparison with the margin calculated in 2011 and despite the reduced average dewpoint margin calculated from all 4 nodes for 2012. This is most likely a reflection of the longer and warmer period of time during which the 2012 monitoring took place.

Indoor Air Quality

Data gathered during the post refurbishment 2012 monitoring cycle for indoor air quality has allowed detailed plots to be produced for the three properties (Fig. 21, p. 47, Fig. 42, p. 73, & Fig. 55, p. 91). When the values recorded over this period for CO_2, room temperature and RH are averaged it can be seen that no significant change has taken place within the room at Drewsteignton. This is not surprising as the changes to this room, which is of a large area and volume, have been restricted to a small proportion of one external wall and therefore can not be expected to have had an influence upon the wider internal environment of the room. However, Shrewsbury and Riddlecombe are different. Both these buildings have undergone refurbishment which maybe expected to have reduced the air permeability (in the form of infiltration) of the structures. Therefore, average levels of CO_2 may have increased due to the reduced influence of external air. However the average CO_2 recorded over the monitoring period in 2012 at both properties has decreased in comparison with averages calculated for 2011. As CO_2 is a reflection of room occupancy this may indicate no more that the reduced occupancy of these rooms during the 2012 monitoring periods. Nevertheless, the levels of CO_2 recorded at Shrewsbury and Riddlecombe are startlingly different. The 2012 average at Shrewsbury of 574 - 95 ppm occupies a band commonly defined as an acceptable level of room CO_2. However, the average CO_2 at Riddlecombe, both before (2011) and after refurbishment (2012), is on the cusp of tolerable defined by CIBSE as being below 1000 ppm. These CO_2 measurements reflect both the air permeability of the dwellings as well as levels of occupancy and the house at Riddlecombe has a low rate of air exchange and a high level of occupancy compared with that of Shrewsbury. Furthermore, the low level of CO_2 averaged for Shrewsbury, which is close to background ambient external CO_2 levels, may reflect the influence of the large, uncapped chimney flue which extends into a room of limited volume ($30m^3$). As noted in the air permeability section of the report on Shrewsbury in Appendix A, the air flow through the building increased when the flue was uncovered and the effect of flues increases as the airtightness of a building improves. This could account for the lower level of CO_2 recorded in this location post-refurbishment.

Comfort and Fabric Risk

As in 2011 individual indoor temperature and relative humidity readings were plotted against an index of human comfort and fabric risk for the properties at Shrewsbury, Riddlecombe and Drewsteignton (Fig. 23, p. 50, Fig. 44 p. 76, & Fig. 56, p. 93-4). The 2012 graphs are plotted from data gathered over a longer time period than was the case in 2011 hence the increased density of temperature and RH indices given for 2012.

In plots of room temperature for both Shrewsbury and Drewsteignton we can see that temperatures have moved very slightly up the temperature scale towards an ideal zone of comfort. However, this is probably a reflection of the warmer temperatures in general during the longer 2012 monitoring period rather than any changes as a result of refurbishment, particularly as the degree of influence of the work undertaken at Drewsteignton (a small section of insulated wall) must be minimal. Room temperatures at Riddlecombe in 2012 remain largely unchanged between 2011 and 2012 although it should be noted that this property was unusual in being one of only two locations in the pre-refurbishment 2011 building performance survey to record a majority of temperatures within the ideal zone of human comfort. Unlike Shrewsbury and Drewsteignton, despite the longer monitoring period of 2012, overall room temperatures at Riddlecombe do not appear to be influenced by warmer external temperatures and this may offer comment on the quality of the heavyweight cob construction to buffer temperature extremes and provide a consistently comfortable environment all year round.

Measurements of room RH show increases in levels for all three properties over 2012, although the degree to which this is as a direct result of refurbishment work is unclear. All three rooms have seen the application of new wet finishes to interior wall surfaces which probably had an effect on internal room RH although the extent and duration of this influence is difficult to determine. The extent to which these raised levels of RH can be seen to pose a risk to fabric can be judged, to some extent, by the occasions on which plots of room RH in each of the buildings exceed the limiting isopleths for mould growth. (These provide an indication of the probability of the development of mould on various classes of building substrate as a result of raised levels of humidity.) Previously, in 2011, measurements of room RH in any of the seven properties under survey rarely crossed these limiting isopleths and hardly ever exceeded the threshold value of 80%. In 2012 at Drewsteignton and particularly in Riddlecombe we find a number of room measurements that are raised above 80% and in doing so exceed all three classes of isopleth including those that indicate favourable conditions for mould or fungal growth on timber and masonry substrates. As has been previously noted in a number of contexts within this discussion the wall at Riddlecombe exhibits a raised moisture level, coupled with this the house is of relatively high occupancy in relation to its overall area and has a low rate of air exchange. All these factors may combine to create conditions which maybe conducive to mould growth and therefore could appear to present a risk to fabric both within the wall and at room and wall surfaces. However, it should be noted that there is no evidence of surface mould growth yet within the room under study at Riddlecombe and the presence of lime finishes here may suppress mould and fungal responses. Furthermore the owner reports that in general the house is "more comfortable and cosier" since the completion of refurbishment work.

4. CONCLUSION

From the monitoring undertaken in 2012 at the properties in Shrewsbury, Riddlecombe and Drewsteignton it is possible to identify some interesting trends developing. However, it should be emphasised that because of the differences between the three buildings under discussion, as well as their different treatments, no direct comparisons can be made between them. Furthermore, monitoring is still on-going and the findings contained within this report relate to a relatively short period that extends from February to September 2012 (or February to May in the case of Shrewsbury). Therefore, the purpose of this report is to provide some broad indications of trends and tendencies in the hope that, as the monitoring continues, these will be brought into focus by additional data and be supplemented by information collected from the other buildings within the Building Performance Survey that are yet to have refurbishment work completed.

From the measurements of U-values it is possible to see substantial reductions in fabric heat loss through wall elements due to the application of wall insulation at all three properties. Reductions of 68 and 70% at Shrewsbury from 40mm of internal wall insulation, 87% at Drewsteignton with 100mm and a negligible 4% at Riddlecombe with 40mm of external insulating render. However the Riddlecombe value maybe compromised by the high moisture content of this wall. Once again there is a tendency for measured U-values to improve upon calculated U-values for refurbished walls but the degree of discrepancy between the two is much smaller to the extent that in many cases a calculated U-value may provide a reasonable approximation of heat loss for a refurbished solid wall.

The air permeability of both properties has also been reduced following refurbishment. In the case of Shrewsbury infiltration has been reduced by 23% and this has been significantly aided by the installation of secondary glazing on the first two floors. The improvement is much less significant for Riddlecombe which, at the time of re-testing, only measured a 3.6% reduction to infiltration. It should be note that the house at Riddlecombe had already been found to have a low rate of permeability pre-refurbishment in 2011 and now has an the air change rate at 50Pa of 6.9 air changes per hour (ach) which may be considered less than desirable.

Refurbishment measurements undertaken on all three properties have improved moisture conditions at the interior surface of the walls, this is a function of the addition of insulation to the internal face moving this leaf away from the solid masonry part of the wall component. At Riddlecombe the use of lime finishes on the interior surface of the wall seems to have contributed to a more stable moisture scenario at the internal face, however this ceases to be the case deeper into the wall. Interstitial RH levels appear to have risen in all three walls post-refurbishment and there are multiple possible reasons for this which are circumscribed by the limited period of monitoring undertaken thus far. Of note is the accumulating moisture within the wall at Riddlecombe that has attained dewpoint and seems to be moving back from the exterior wall face through the wall section. The wall at Drewsteignton also shows high levels of RH although whether these climb to present a dewpoint risk remains to be seen. The wall at Shrewsbury, although in poor external condition, shows the lowest value of internal wall RH and therefore the least dewpoint risk. Thus far, of the three walls studied, the interventions made at Shrewsbury seem to have managed a successful balance between the requirements of energy improvement and its potential risks.

With regards to indoor air quality and indoor conditions in general these do not seem to be significantly changed as a result of the refurbishment work. Levels of CO_2 recorded between 2011 and 2012 have reduced slightly in Shrewsbury and Riddlecombe and the average recorded at Riddlecombe remains on the cusp of acceptable at 950 ppm. The relative humidity recorded in the rooms has risen in all three properties, but more data is required before any conclusions can be drawn regarding changes, if any, to temperature or room RH within the three properties. Monitoring of interstitial temperature and RH along with internal and external conditions is on-going in the three properties ultimately allowing us to assess their performance over a complete 12-month cycle (or longer). This extended monitoring will allow us to clarify trends and further define links between performance responses and the energy efficiency refurbishment work undertaken at the properties. The results of this work, as well as the findings from the monitoring of the other refurbished properties involved in this study, will form the subject of the next SPAB Building Performance Survey report.

116 Abbeyforegate, Shrewsbury.
2012

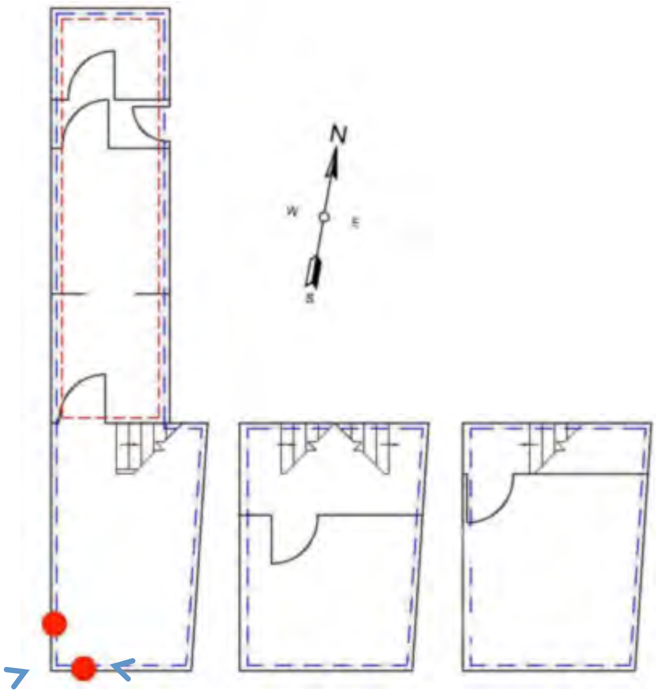
Description: End of terrace (originally mid-terrace) house, 2 storeys with attic dormer. Dating from 1820 but with earlier core. Brick with plain tiled roof, with elements of timber-framing and a modern single storey extension at rear accommodating a kitchen and bathroom.

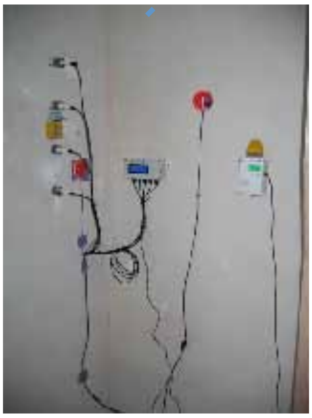
Refurbishment: Between February 2011 - December 2011 the following refurbishment work was undertaken at Abbeyforegate: internal insulation of all external walls on the ground and first floor with woodfibre board (excluding the rear single storey extension) and fitting of secondary double-glazing to ground and first floor sash windows on the front elevation.

Occupancy: 1 person.

Floor Area: 60m^2

Figure 2 – Plan of 116 Abbeyforegate, Shrewsbury, with ground floor on left hand side. The red dots indicate the locations of the monitoring equipment. The air permeability test perimeter is show in blue, with the secondary test zone shown in red.





Figures 3 - 4. Showing positions of in situ monitoring equipment at 116 Abbeyforegate, Shrewsbury, 2012.

U-VALUES

In situ U-value measurements were made at Abbeyforegate over the period 17th February - 17th March 2012. The south and west walls in the living room were measured at positions which corresponded with the locations of previous measurements taken in the winter of 2011 (Figs. 2 - 4). The results, along with the previous years measurements and standard U-value calculations made following the BR 443 method, are shown in Tables 2 & 3 below.

Un-insulated 2011				**Insulated 2012**			
Materials & Build Up internal - external	**mm**	***In situ* U value W/m²K**	**Calculated U-value W/m²K**	**Materials & Build Up** internal - external	**mm**	***In situ* U value W/m²K**	**Calculated U-value W/m²K**
				Lime plaster	8		
Gypsum skim	3			Woodfibre insulation	40		
Lime Plaster	12			Lime Plaster	12		
Brick	345			Brick	345		
Total	**360**	**1.48**	**1.52**	**Total**	**405**	**0.48**	**0.59**

Table 2. U-value results for South Wall, Ground floor Sitting Room, 116 Abbeyforegate, Shrewsbury, 2012.

Un-insulated 2011				**Insulated 2012**			
Materials & Build Up internal - external	**mm**	***In situ* U value W/m²K**	**Calculated U-value W/m²K**	**Materials & Build Up** internal - external	**mm**	***In situ* U value W/m²K**	**Calculated U-value W/m²K**
				Lime plaster	8		
Gypsum skim	2			Woodfibre insulation	40		
Lime Plaster	16			Lime Plaster	16		
Brick	228			Brick	228		
Insulating render	40			Insulating render	40		
Total	**286**	**2.06**	**1.71**	**Total**	**332**	**0.63**	**0.62**

Table 3. U-value results for West Wall, Ground floor Sitting Room, 116 Abbeyforegate, Shrewsbury, 2012.

The U-value measured in 2012, post-refurbishment, for the west-facing gable end wall, 0.63 W/m^2K, indicates greater heat loss than that measured for the adjacent un-rendered south facing wall, 0.48 W/m^2K. This repeats the pattern found in the previous winter's measurements (2.06 W/m^2K west, 1.48 W/m^2K south) and occurs despite the presence of a pre-existing insulating render that had been applied to the west wall prior to the start of this survey. It is likely that the higher degree of heat loss from the west facing wall is a result of the thinner cross section of this wall, 332mm as opposed to 405mm (286mm compared to 363mm in 2011). It is also possible that the U-value achieved by the south-facing wall reflects the contribution made by solar gain in slowing internal to external thermal transmissivity in this wall.

Previously, in 2011, the front south-facing wall recorded a U-value of 1.48 W/m^2K, in 2012, following the application of 40mm of woodfibre insulation board internally, a U-value of 0.48 W/m^2K was measured, a 68% reduction in heat loss for this wall. Similarly, the west gable end wall provided a U-value of 2.06 W/m^2K in 2011, whereas post-refurbishment in 2012 the wall measured 0.63 W/m^2K, a 70% reduction in heat loss. Therefore there has been an approximate two-third reduction in the heat loss measured as a U-value for these two ground floor walls at 116 Abbeyforegate following refurbishment. Interestingly there is reasonable correlation between the measured and calculated U-values for these walls post-refurbishment (0.48 W/m^2K measured, 0.59 W/m^2K calculated for the south wall and 0.63 W/m^2K measured compared with 0.62 W/m^2K calculated for the west). This is because of the effect of a layer of insulation and the methodology of a U-value calculation. An additional layer of insulating material can be accurately defined within a U-value calculation because the material is of known thickness and is accompanied by specific thermal conductivity data - this is often in contrast to the existing layers involved in the build-up of an element. In addition to this, this insulating layer, which has, after all, been introduced specifically for the purposes of improving thermal resistivity, will provide the single most significant contribution to the rate of overall heat loss of an element.[7]

AIR PERMEABILITY

Air permeability testing was carried out on the complete habitable volume at 116 Abbeyforegate on 15 February 2012, with both depressurisation and pressurisation of the building. A secondary test was carried out on the extension to the rear of the property alone. This test has the provision that windows in the original dwelling were not opened which may impede free air flow from outside the building. The relevant changes from the time of the 2011 test are the inclusion of woodfibre-based wall insulation and plaster to the ground and first floor, secondary glazing to the ground and first floor windows on the front elevation, permanent fixing of second floor loft hatch and filling of minor cracks. The extension to the rear of the property has not been altered and, apart from the filling of cracks, the second floor remains unchanged. It should be noted that some detailing was not complete at the time of testing, including the ground floor area of wall insulation awaiting plastering, missing first floor window sill, hole in first floor boards and no floor covering to the first floor room. Both test areas are identified in Figure 2. Interior and exterior conditions at the time of testing are noted in Table 4 and the results of the whole dwelling air permeability test are shown in Table 5.

Date of Test:	15 February 2012
Prevailing weather conditions at time of test:	Dry. 100% cloud cover. Wind speed (approx. 11.30 am) $1.3ms^{-1}$ average, $3ms^{-1}$ max External conditions at rear of dwelling: 9.0°C 82% RH (10.40am approx.)
Conditions inside dwelling:	Living room: 18.6°C 52% RH (approx. 12 noon)

Table 4. Interior and exterior conditions for air permeability test at 116 Abbeyforegate, Shrewsbury, 2012.

[7] For more discussion of the U-value calculating procedure, including its limitations in relation to solid walls see Rye, C. (2010). *The SPAB Research Report 1: The U-value Report*. Revised 2011. London: Society for the Protection of Ancient Buildings and Baker, P. (2011). *Technical Paper 10 - U-values and Traditional Buildings*, Edinburgh: Historic Scotland

	Units	Results	Comments
Whole dwelling			
Internal floor area (ground and first floors)	m^2	60	
Habitable building volume	m^3	134	
Dwelling envelope area i.e. surface area of living space	m^2	185	
Measured air flow	m^3h^{-1} @50 Pa	1570	Secondary glazing in use.
Air permeability test result at 50Pa	$m^3h^{-1}m^{-2}$ @50 Pa	8.5	m^3 of air per hour per m^2 of surface area of the living space.
Air changes per hour at 50Pa	ach@50 Pa	11.7	The number of times the complete volume of air in the property is changed per hour at the test pressure.

Table 5. Results for whole house air permeability test at 116 Abbeyforegate, Shrewsbury, 2012.

The air flow measured under the test conditions was 1570 m^3h^{-1}. Relating this result to the total surface area of the property, Table 5 shows the post-refurbishment air permeability of 116 Abbeyforegate is 8.5 $m^3h^{-1}m^{-2}$ @ 50 Pa, which is below the limiting air permeability of 10 $m^3h^{-1}m^{-2}$ @50 Pa under Approved Document L1A 2010 for new dwellings. Considering the items still to be completed and the results of the thermographic survey (detailed below), the air permeability of the building is likely to reduce further once these items have been completed. Relating the air flow to the building volume, the air change rate at 50 Pa pressure difference is 11.7 ach, representing the number of times per hour the total volume of air in the dwelling will change at this pressure. From Sherman[8], under normal conditions this would represent an air change rate of around 0.6 ach, which is above the level 0.4-0.5 ach considered as necessary for building occupants and their activities. The 2012 air permeability and air change test results are a significant improvement on the pre-refurbishment testing carried out in January 2011. The initial air permeability test of 116 Abbeyforegate gave a result of 11.0 $m^3h^{-1}m^{-2}$ @50 Pa

[8] from Ridley, I. et al, The impact of replacement windows on air infiltration and indoor air quality in buildings. International Journal of Ventilation 1(3) pp 209-218.

compared to 8.5 $m^3h^{-1}m^{-2}$ @50 Pa in 2012. The air change rate improved from 16.1 ach@ 50Pa to 11.7 ach @ 50Pa, representing a 23% improvement for both criteria.

The results for the secondary test on the extension to the rear of the property alone are shown in Table 6.

	Units	**Results**
Rear extension only		
Internal floor area	m^2	17
Volume	m^3	41
Surface area of living space	m^2	81
Measured air flow	m^3h^{-1} @50Pa	459
Air permeability test result at 50Pa	$m^3h^{-1}m^{-2}$ @50 Pa	5.6
Air changes per hour at 50Pa	ach@50 Pa	11.3

Table 6. Results for air permeability test on rear extension at 116 Abbeyforegate, Shrewsbury, 2012.

From Table 6, the measured air flow of 459 m^3h^{-1} @ 50 Pa equates to an air permeability of 5.6 $m^3h^{-1}m^{-2}$ @50 Pa for the extension. The pre-refurbishment test result in 2012 for this portion of the building provided a test result of 6.4. However, no refurbishment work has been carried on this portion of the dwelling. The difference in the test results may be explained by the fact that testing was carried out with the windows and secondary glazing in the remainder of the building closed and the improved air tightness in this area having a subsequent impact on the result achieved for the rear addition at 116 Abbeyforegate.

The impact of the secondary glazing was tested, with the dwelling pressure tested with the secondary glazing closed and then opened.

	Additional air flow when secondary glazing opened (m^3h^{-1} @50Pa)
Ground floor secondary glazing	112
First floor secondary glazing	58

Table 7. Results for secondary glazing air permeability test on rear extension at 116 Abbeyforegate, Shrewsbury, 2012.

As outlined in table 7, secondary glazing to the ground and first floor rooms reduced the air flow under a 50 Pa pressure differential by 170 m^3h^{-1}, equating to an 11% increase in the building air flow had the secondary glazing not been present. There were also two holes in the ground floor ceiling for light fittings which when uncovered increased the air flow by a further 2%.

Flues

Under the standard test procedure, chimneys and flues in the dwelling are excluded from the results. As with the 2011 test, no flow was apparent from the first floor fireplace. When it was uncovered, the ground floor flue was tested and an additional air flow of 880 m^3h^{-1} @50 Pa was noted, increasing the air flow through the building by 56%, compared to 47% from the 2011 result. The increased percentage is due to the improved air tightness of the dwelling, indicating that as air tightness improves the role played by flues becomes more significant. A similar flue test was carried out in 2011, when the additional air flow measured for the flue was 990 m^3h^{-1} @50 Pa. This means of testing flues is experimental and comparison between pre and post refurbishment test results has not previously been made. One explanation may be the improved air tightness of the dwelling in the post refurbishment result, reducing the ability for air flow, but this requires confirmation through further results. It should be noted the measured result under the test conditions will not directly relate to the air flows through chimneys when in use / not in use, but offers a simple comparison. Heat losses being incurred through the open flue are evident in the thermal images below.

THERMOGRAPHIC SURVEY

Thermal imaging was carried out to both the exterior and interior of 116 Abbeyforegate on 15 February 2012. Since there was 100% cloud cover on the test day, solar gain was not an issue during the 2012 survey and detail of the exterior could be seen. The thermographic survey of the building exterior was carried out before the building was pressure tested (i.e. under ambient conditions). (Note, the temperatures represented by a particular colour change from image to image and these should be crossed reference against the temperature scale on each image. The temperatures displayed in the top left hand corner are the surface temperatures measured at the centre of the cross-hairs appearing in the image.)

The front façade of the dwelling showed an elevated exterior wall temperature on the second floor corresponding to location of radiator beneath the window and this is shown in Figure 5. This area has not had internal wall insulation applied and it should be noted the radiators in the ground and first floor rooms had not yet been fitted.

Figure 4. 116 Abbeyforegate, Shrewsbury - front elevation, second floor.

Also evident was an area of elevated wall temperature at first floor level (shown in Figure 5). This was subsequently identified as where the central heating pipes which were sandwiched between the internal wall insulation and the masonry wall.

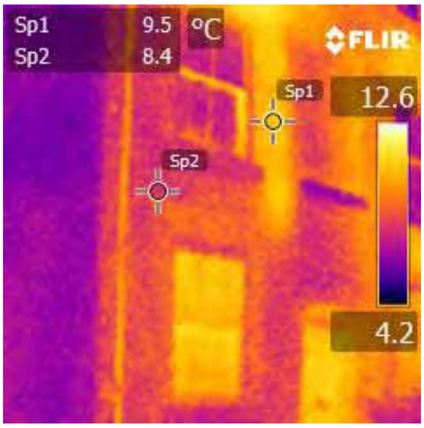


Figure 5. 116 Abbeyforegate, Shrewsbury – Front elevation at first floor level.

To the rear of the property, it was possible to clearly see the difference between the heated living space and unheated areas. Figure 6 shows the rear elevation of the bathroom, with a temperature difference of just under 1^{o}C between the bathroom and the loft space above.

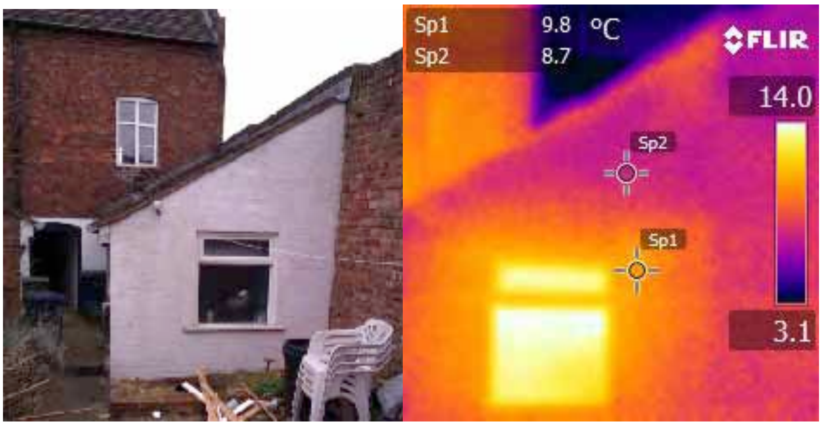


Figure 6. 116 Abbeyforegate, Shrewsbury – Rear elevation (bathroom)

On the west elevation of 116 Abbeyforegate, the path of the flue from the open fireplace in the living room can clearly be seen to the top of the building (Fig. 7) indicating this may be a route for substantial heat loss under normal conditions. It must be emphasised the fireplace has not been used by the occupant since he acquired the property. The thermal image also shows an apparent difference in the external wall temperature between the areas of the west elevation between the masonry wall and the insulating render which has been applied. Further investigation of this apparent temperature difference is required due to differences in emissivity between the two surfaces.

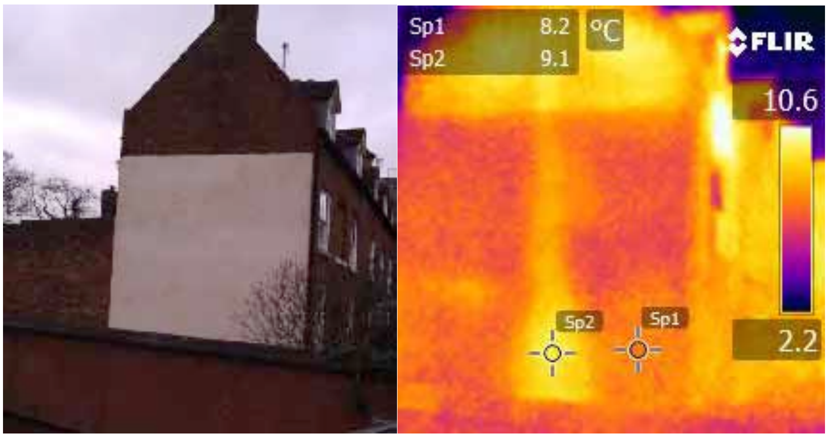


Figure 7. 116 Abbeyforegate, Shrewsbury – West elevation.

The thermographic survey of the interior of 116 Abbeyforegate was carried out whilst the building was depressurised, emphasising areas of ingress. The infiltration patterns for the rear addition and the second floor were generally as recorded in 2011, with ingress around windows and the loft hatch in the extension and around beams and at the ceiling / wall junction on the second floor. There was one exception, which is illustrated in Figure 8, where the second floor loft hatch has been sealed and does not show ingress. An image of the hatch from the 2011 survey is shown in Figure 9 for comparison.

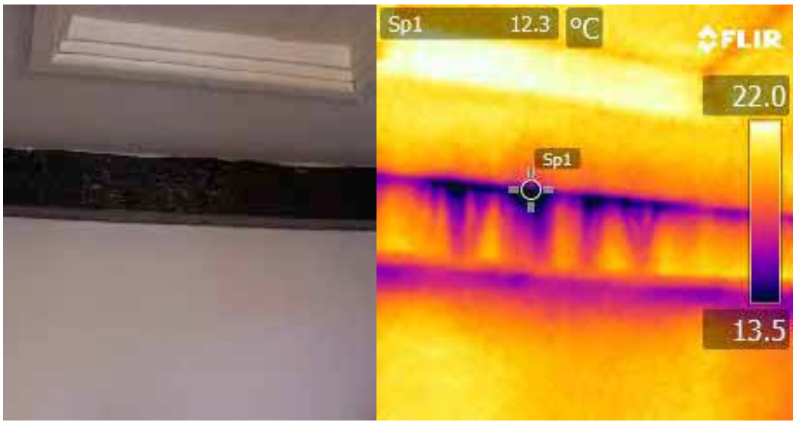


Figure 8. 116 Abbeyforegate, Shrewsbury – second floor ceiling.

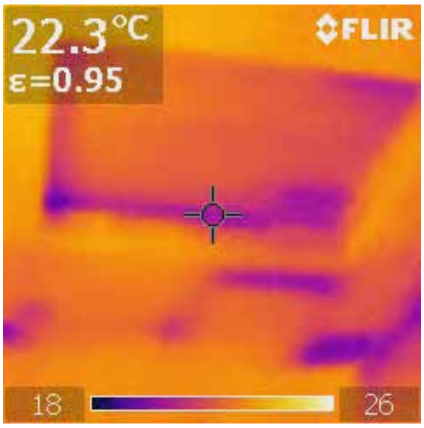


Figure 9. 116 Abbeyforegate, Shrewsbury – second floor ceiling. Thermal image of loft hatch from 2011 survey (image taken at 90^{o} to the 2012 view).

On the first floor, there was evidence of air ingress where areas of the building fabric were yet to be completed (shown in Figures 10 & 11).

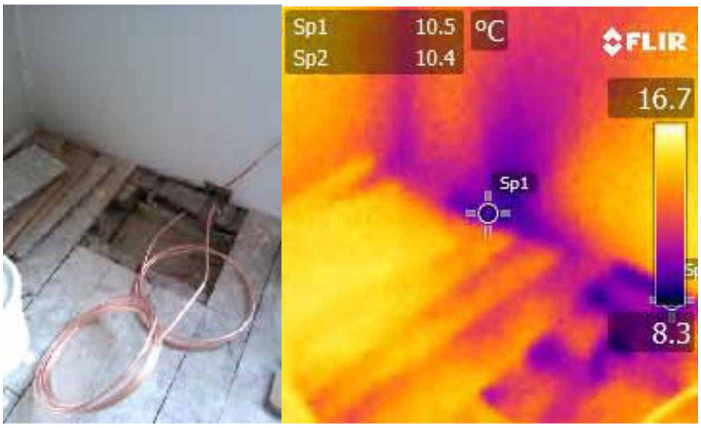


Figure 10. 116 Abbeyforegate, Shrewsbury – first floor, south wall, floor wall junction.

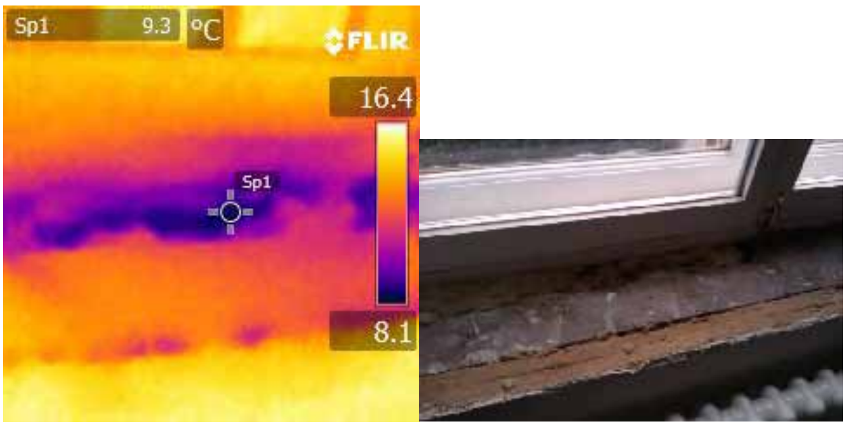


Figure 11. 116 Abbeyforegate, Shrewsbury – first floor, south wall, window cill

Also in evidence was a colder area on the first floor ceiling adjacent to the exterior wall, potentially due to air movement in the floor / ceiling void (shown in Figure 12).

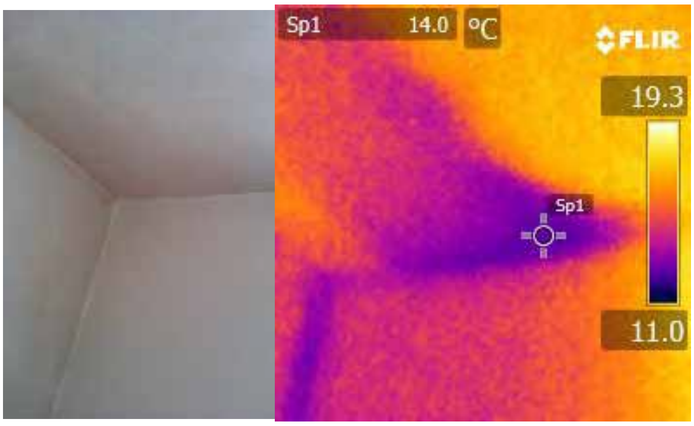


Figure 12. 116 Abbeyforegate, Shrewsbury – first floor, south wall, wall ceiling junction

In the ground floor living room, there is evidence of a thermal bridge on the ceiling adjacent to the exterior south wall, shown in Figure 13.

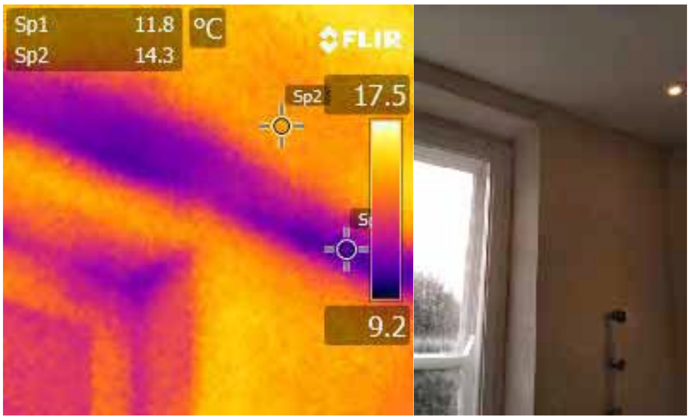


Figure 13. 116 Abbeyforegate, Shrewsbury – ground floor living room, south wall.

The light switch on the westerly exterior wall can clearly be seen as a cold spot in Figure 14.

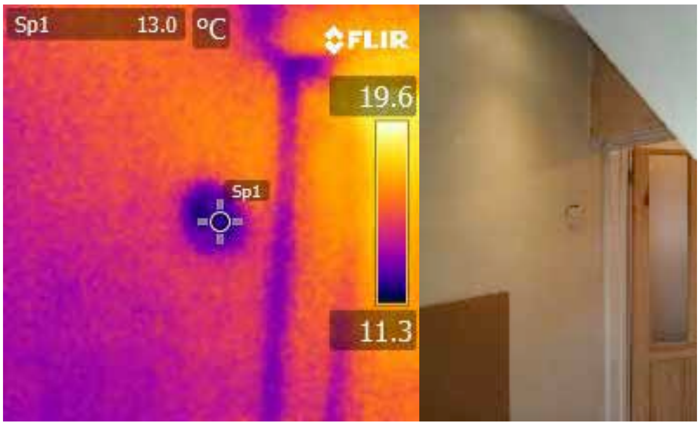


Figure 14. 116 Abbeyforegate, Shrewsbury – ground floor living room, west wall.

In the 2011 survey, the construction of the living room wall adjacent to the passageway was clearly evident in images shown in Figure 15. The wall has subsequently been insulated and now shows an even temperature.

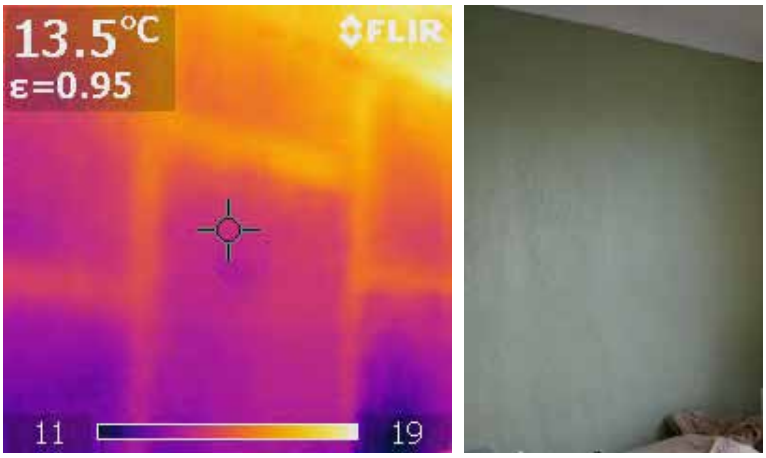


Figure 15. 116 Abbeyforegate, Shrewsbury 2011 thermographic survey results – ground floor living room, east wall.

MOISTURE

Surface and Sub-Surface Moisture

On 9th May 2012 two measurements were taken to record the moisture conditions of the refurbished interior wall surface of the south-facing living room wall at Abbeyforegate. A measurement of the surface, approximately 2mm deep, was taken using a twin-pinned resistivity probe and an additional capacitance reading was taken of conditions at approximately 40mm deep behind the interior wall face. Figure 16 plots these measurements alongside those previously taken in 2011 for the same wall pre-refurbishment, these values are plotted against a nominal moisture scale to a height of 2000mm above finished floor level.

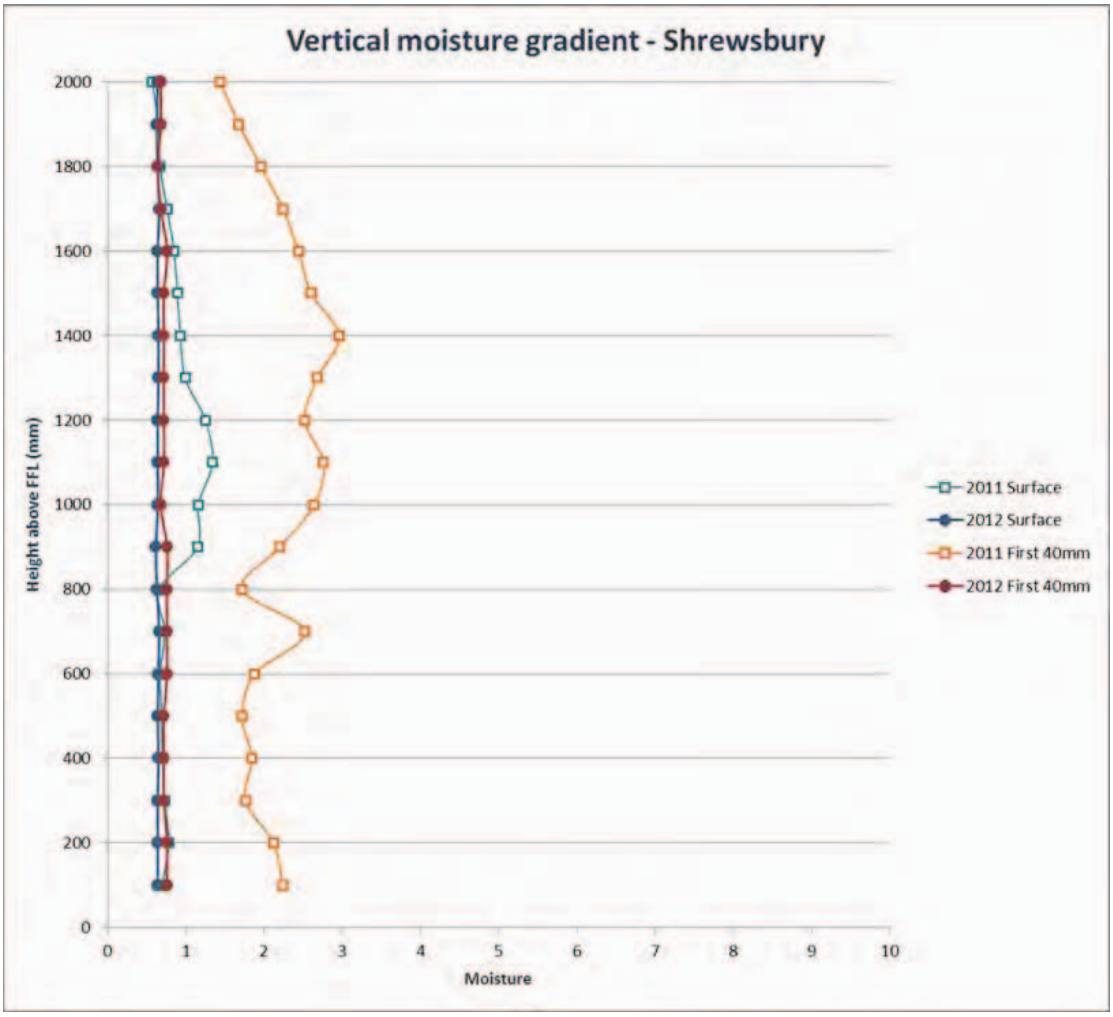


Figure 16. Pre and post refurbishment measurements of surface & sub-surface moisture at Abbeyforegate, Shrewsbury, 2011 & 2012.

Previously, in 2011, deflections in the profiles of both the surface and the sub-surface moisture measurements roughly mirrored one another and could possibly be attributed to the effect of moisture tracking inwards along a window sill which interrupted the wall at a height of approximately 800mm. In contrast the measurements of surface and sub-surface moisture conditions taken in 2012 run parallel to one another at the 'drier' end of the moisture scale and both are consistently stable up the full 2000mm height of the wall. The difference between the 2011 and 2012 profiles demonstrates the effect of adding internal wall insulation to the moisture conditions found in proximity to an internal wall surface. The surface of the internal wall has now been built-up, in this instance through the addition of 40mm of woodfibre board finished with 8mm of lime plaster and this means that the materials now being measured for moisture have altered from the original masonry to the new plaster and insulating material layer. It is therefore not surprising to find that these new layers are quite 'dry' as we have moved the zone of measurement into a more stable context away from the solid brick wall (built without a damp-proof course) which had in 2011 exhibited more dynamic variations of moisture as a result of the influence of sources of moisture such as precipitation or ground water.

Interstitial Hygrothermal Conditions

Figure 17. Interstitial, U-value and IAQ monitoring set up at Abbeyforegate, Shrewsbury, 2012.

Temperature and moisture measurements are being made through a section of south-facing brick wall of the living room at Abbeyforegate (Fig. 17). Combined temperature and relative humidity sensors are located at four points within the wall at the heights and depths given in Table 8 coupled with sensors to record internal and external conditions. Data from all these sensors, for the period 17th February - 13th April 2012, has been collected and used as the basis for the following analysis. The position of these sensors correspond with those of the pre-refurbishment monitoring carried out between 28th January - 11th February 2011

Build-up - internal - external	**Depth of material**	**Sensor no.**	**Height from finished floor level**	**Depth of sensor from internal surface**
Lime plaster finish	8 mm			
Woodfibre insulation	40 mm			
Lime plaster	12 mm			
Brick	345 mm	1	1875 mm	103 mm
		2	1725 mm	198 mm
		3	1575 mm	308 mm
		4	1425 mm	388 mm
Overall	405mm			

Table 8. Interstitial hygrothermal gradient sensor positions for Abbeyforegate, Shrewsbury, 2012.

Figure 18 below shows the average values of each sensor over the February - April 2012 monitoring period graphed as separate temperature and dewpoint gradients as well as the maximum and minimum values for these two elements recorded over the monitoring period. The values derived from the relative humidity sensors have been converted to dewpoints in order to indicate the likelihood of condensation forming within the wall. Figure 19 provides a comparative graph which overlays the 2012 data with the same data recorded during the 2011 pre-refurbishment interstitial hygrothermal gradient monitoring.

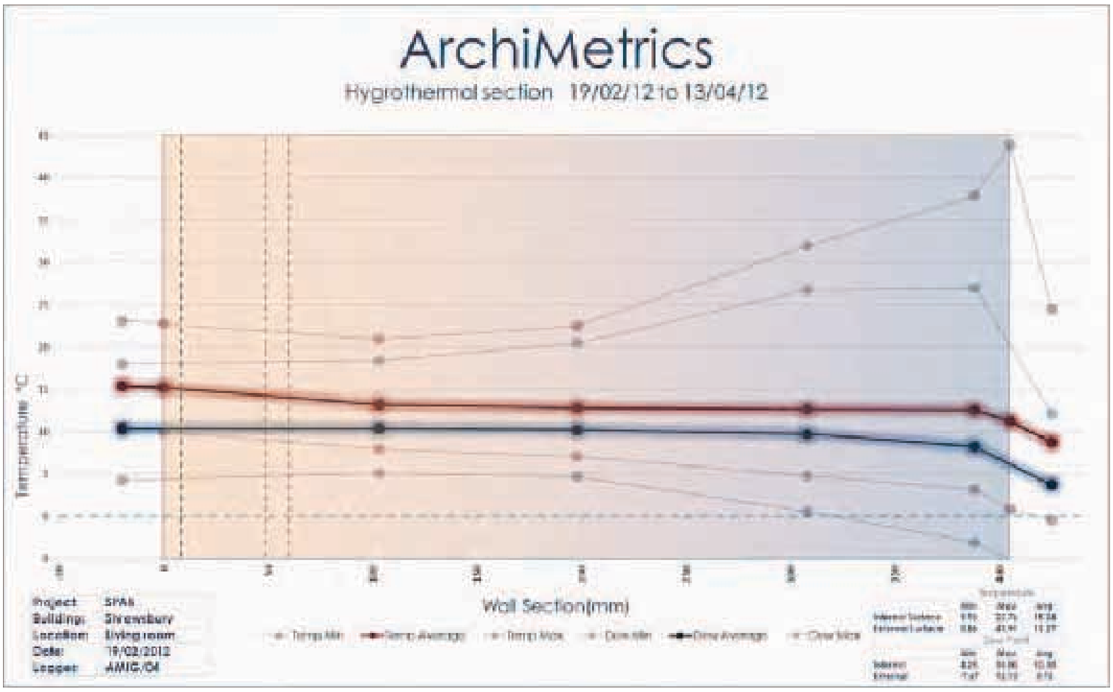


Figure 18. Temperature and dewpoint gradients for Abbeyforegate, Shrewsbury, 2012.

What can be observed from Figure 18 is the flattened temperature gradient now found through the masonry element of the 2012 wall following the insulation of its internal face. The steepest temperature drop occurs between the internal surface temperature and the first sensor in the wall and as such is a measurement which spans the insulating woodfibre layer. What is also worthy of note is the temperature gradient plotted by the maximum values on this graph which show temperatures falling across the wall from the exterior to the interior, reversing the trend normally found during the winter months. This is due to the wall's southern aspect which means that on sunny winter days this elevation will be heated by external solar radiation.

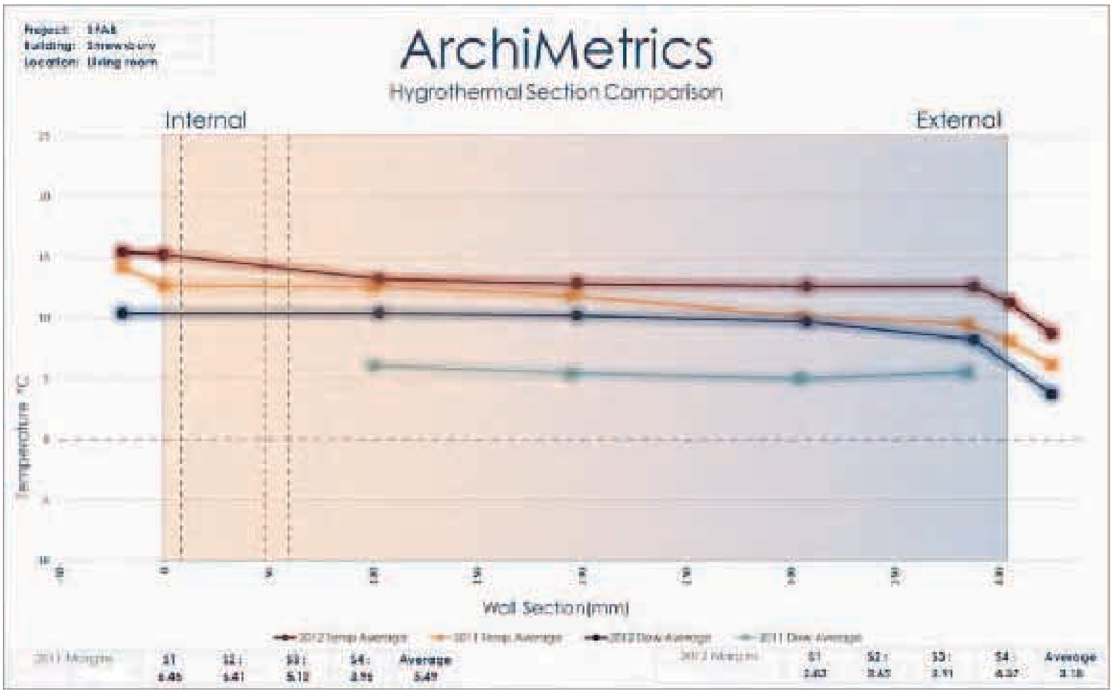


Figure 19. 2011 and 2012 Temperature and dewpoint gradient comparison for Abbeyforegate, Shrewsbury.

The comparison graph, Figure 19, shows the raised temperature on the internal side of the wall for the 2012 data and the drop of this gradient between the insulating layer and the first interstitial sensor node to a temperature of 12-13˚C which roughly coincides with that recorded in the previous year. Temperature measurements from the remaining three sensing nodes, however, show the flatten gradient previously noted and are higher than those record pre-refurbishment the previous year. The 2012 raised temperature gradient is not necessarily a result of improved thermal performance, it maybe more a function of milder winter weather and the extending period of 2012 monitoring which continued into warmer months and therefore raised the average temperature for this wall in general. In addition to the flattened temperature gradient seen in the 2012 measurements, an examination of the comparison chart, Figure 19, shows another significant difference between the 2011 and 2012 data, this time for interstitial moisture. This concerns the dewpoint margins, that is the temperature difference between the temperature gradient and the dewpoint gradient plotted for both wall sections. In 2011, the margin averaged across all four wall measurement nodes was 5.49˚C and 3.96˚C when calculated for just the fourth node in isolation which is sited close to the external surface. Therefore, in 2011 the wall would have required an overall temperature drop of 5.49˚C, or 3.96˚C at the outer node, in order for condensation to occur over the monitoring period. Following refurbishment, as can be seen in Figure 19, this dewpoint margin has narrowed and been reduced to 3.18˚C when averaged across all four nodes. This is possibly as a result of the masonry part of the wall fabric being cooled by the presence of an internal insulating layer which now prevents some of the heat from the room entering the original masonry part of the wall structure (hence also the flatter temperature gradient and the lower, refurbished, U-value measured for this wall). However, it is interesting to note that the same reduction in the 2012 dewpoint margin is not found when the outer node is looked at in isolation. Here the margin has increased from 3.96˚C to 4.37˚C. It was noted in the previous Building Performance Survey report, *SPAB Research Report 2: 2011,* that the dewpoint gradient measured for this wall in 2011 did not conform to the more standard pattern found elsewhere within the survey, where dewpoint and temperature gradients converge towards the exterior face of the wall. The report provided a commentary on the condition of the south-facing brick wall as an explanation for this anomaly, where it was suggested that the poor condition of the pointing had the effect of drying the air within the wall structure either due to air movement and/or air exchange. The external condition of the south-facing wall at 116 Abbeyforegate remained unchanged in 2012, however, within the body of the wall, lower masonry temperatures are now the dominant factor that determine the dewpoint margin for the majority of the masonry but this influence decreases as we move towards the exterior face of the wall where, closer to the exterior surface, the wall continues to experience significant air movement and this leads to an increased dewpoint margin for just this particular location.

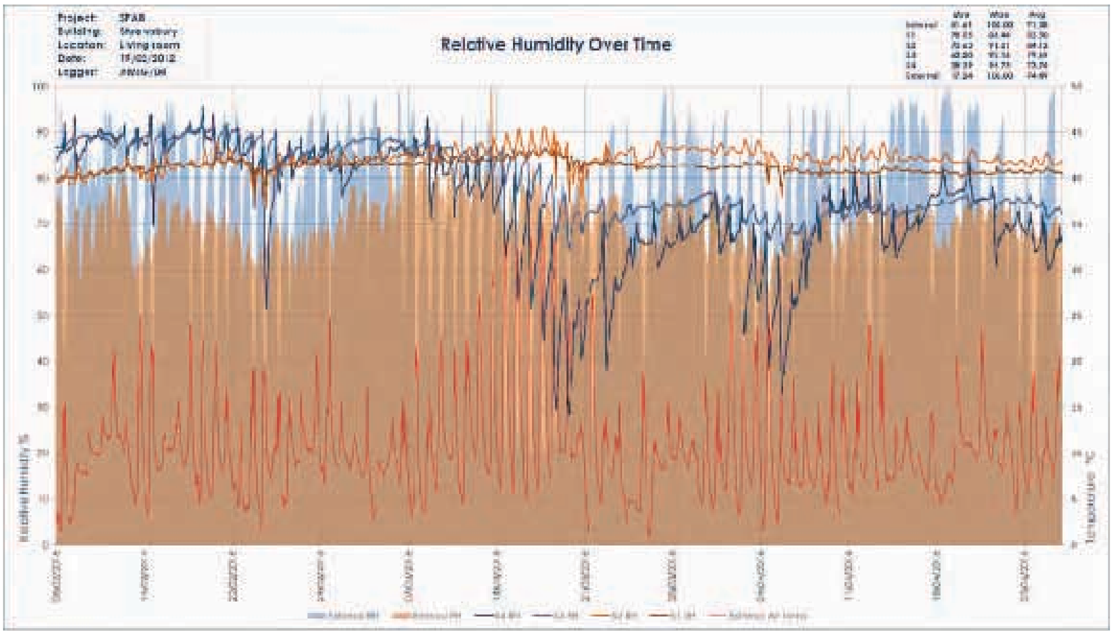


Figure 20. Plots of interstitial RH, internal room RH and external RH and temperature, Abbeyforegate, Shrewsbury, 2012.

By plotting levels of external air temperature, external and internal RH, as well as RH recorded at the interstitial sensors within the wall at Shrewsbury over time it is possible to see the evidence for the behaviour of moisture as vapour within the wall (Fig. 20). Conditions within the wall are affected by the external conditions (temperature and RH) and unsurprisingly this influence is most profound at the most extreme exterior sensor, sensor 4, whilst the responses from other sensors diminish as we move further back into the body of the wall away from these drivers. Of note is the switching of the RH plots for sensors 3 and 4 with those of sensors 1 and 2 which occurs during the week beginning 7th March 2012. Sensors 3 and 4 are sited within the external leaf of the solid wall whilst sensors 1 and 2 are further back towards the interior face. Levels of %RH at sensors 3 and 4 begin a steep decline during this week and from this point remain below those found towards the interior leaf of the wall for the rest of the monitored period shown. This occurs as a result of the temperature increase which occurs between 7th - 21st April which inevitably causes reduced atmospheric RH which is matched by a similar reduction, over time, in levels of RH recorded at sensor 4 and is mirrored, in a less profound way, at sensor 3. This period of warm weather seems to have dried the exterior leaf of the wall to the extent that following this event RH levels towards the exterior of the wall remain below those of the interior part. It is expected that during the move back from summer into winter, once again, one will see the interior and exterior wall plots of RH switch back to higher levels of RH towards the exterior in response to falling temperatures and increasing external RH. However, it is not just sensors 3 and 4 that behave in response to external conditions but plots of all four sensors in the wall seem to show this influence, albeit to a diminishing extent. This is a reflection of the open, porous nature of the brick wall and occurs largely as a result of the poor condition of the pointing of the mortar joints at this location which was noted in the previous report[9]. This allows the influence of the external environment to penetrate deep within the wall. Yet it is also interesting to note the stability of responses from sensors 1 and 2 which, whilst fluctuating to a degree, broadly remain within the 80 - 90% humidity range. The stability of the RH readings from sensors 1 and 2 may occur as a result of the moisture buffering qualities of the materials that have been applied to the internal face of the wall.

Sensor values for the wall were logged at 5-minute intervals and this information has been animated in order that changes in temperature and dewpoint maybe analysed over time. (To view the 2011 and 2012 interstitial hygrothermal gradient animations for 116 Abbeyforegate, visit www.archimetrics.co.uk.)

The animation from 2012 for Abbeyforegate presents a very different picture from that provided by the static averages from the monitoring period. Due to its south-facing aspect the thermal and moisture (dewpoint) behaviour of the wall is extremely dynamic. From the previous animation (from data recorded between 28th January - 11th February 2011) it was noted that, excluding periods of extreme weather, there was little temperature differential between interior and exterior at Abbeyforegate partly as a function of the thermal transmissivity of the wall structure and partly because of the quite low internal room temperatures maintained for the living room. Thus, during most of the

[9] Rye, C., Scott, C., Hubbard, D. (2011). *The SPAB Research Report 2: The Performance of Traditional Buildings - the SPAB Building Performance Survey 2011 Interim Findings*. London: The Society for the Protection of Ancient Buildings p 32.

monitoring period the wall appeared to be of little insulative effect. The 2012 animation, which covers a more extended period of monitoring, 17th February - 13th April 2012, shows some differences in the hygrothermal performance of the wall. The temperature drop through the insulation observed from the static average graph is repeated on an almost daily basis in the animation, the steepest gradient occurring (approximately a 7˚C temperature difference) not surprisingly when heat is input into the room during the evening heating cycle. This may suggest that with the addition of the woodfibre board the wall now has some insulative benefit although the temperature gradient through the masonry element, it now appears from the static graph to be quite flat. However the animation shows that the temperature in the wall is in almost constant flux in response to external temperatures and in particular solar gain where on sunny days the effect of heat on the external surface of the wall is transferred deep into the body of the wall. In debates concerning the merits or otherwise of internal wall insulation it is sometimes thought that this form of insulation will prevent external heat from benefiting internal room conditions. At Abbeyforegate the opposite appears to be the case. The animation for this wall shows the positive effective that the solar gain makes to interior temperatures during winter months when heat energy is being inputted into the room. The sun, by raising the temperature of the wall, allows more of the internal room heat to be retained for a longer period of time. This occurs as the raised temperatures in the masonry wall on the exterior side of the insulation slow down internal to external thermal transmissivity.

INDOOR AIR QUALITY

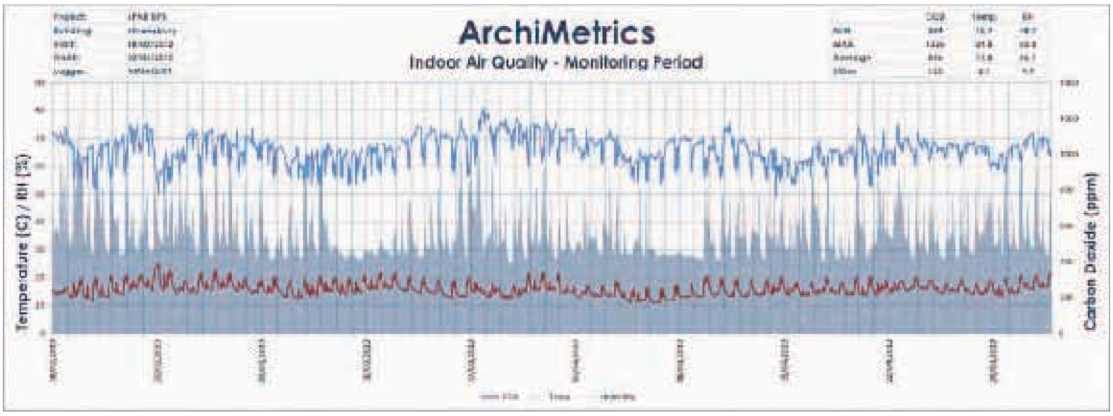


Figure 21. Indoor Air Quality (CO_2, temperature and RH) Abbeyforegate, Shrewsbury, 2012.

Property & Date	CO_2 (ppm)	Temp (˚C)	RH (%)
Abbeyforegate 28/01/11 - 11/02/11 (2 weeks)	702	15	50.6
Abbeyforegate 18/02/12 - 02/05/12	574	16	66.1
Abbeyforegate 18/02/12 - 03/03/12 (2 weeks)	595	17	66.1

Table 9. Indoor Conditions at Abbeyforegate, 2011 & 2012.

Figure 21 plots temperature, RH and CO_2 levels for the living room at 116 Abbeyforegate between the period 18th February - 2nd May 2012. Table 9 provides a summary of the indoor room conditions. The figures represent average values recorded during both the pre (2011) and post-refurbishment (2012) phases. The data that constituted the 2011 averaged values was collected over a two week period therefore averages for a two week period have been extracted from the 2012 data set and provided along with values for the extended monitoring period in order to provide an improved comparative base.

There would appear to be a trend in the 2012 data towards slightly warmer internal temperatures and a rise in RH. The improvement in room temperature may reflect a reduction in fabric and ventilation heat losses as a result of the addition of internal wall insulation and secondary double-glazing to this room or it may just reflect warmer external temperatures during the 2012 monitoring period (or a combination of both these influences). The air pressure tests suggest that the addition of secondary glazing has made a difference to levels of air infiltration for the property as a whole (reducing the air flow under a 50 Pa pressure differential by 170 m^3h^{-1}, see Table 7). This reduction in infiltration may explain the rise in levels of RH between the two measured years, however, values recorded for levels of CO_2 post refurbishment are lower than those recorded in the previous year and are closer to those commonly found for external air (between 350 - 450 ppm). This suggests that the quantity of external air present in the living room (which accommodates a large, uncapped chimney flue) has not altered significantly and therefore the increase in RH cannot be explained by reduced infiltration. The raised level of RH could, however, be explained by the nature of the refurbishment work that had recently taken place in the room, in particular the application of 8mm of lime plaster as a finish for the woodfibre board insulation. The higher levels of RH recorded during 2012 probably reflect moisture introduced into the room as a result of this plaster finish drying through evaporation. It is likely that over the extended period of monitoring that is currently in place at Abbeyforegate we can expect to see RH reach an equilibrium, once this plaster has dried out, which more properly reflects current levels of occupation and external/internal air balances.

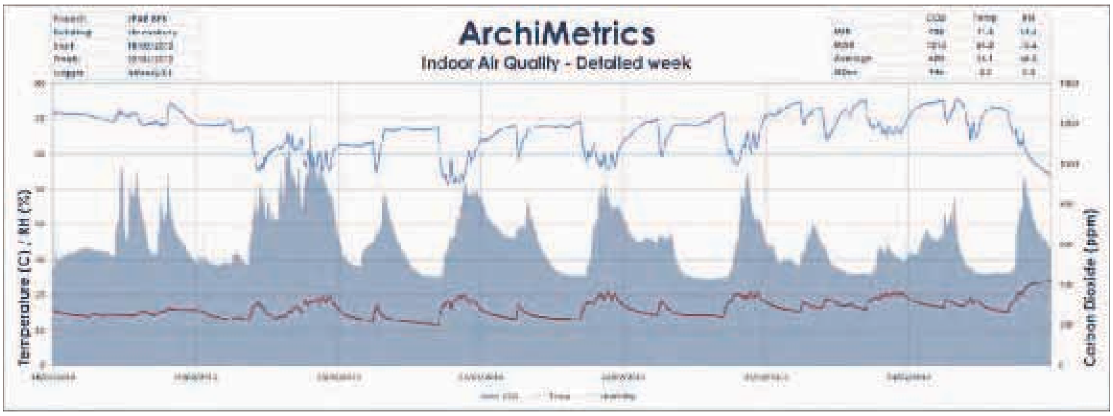


Figure 22. Detail - Indoor Air Quality (CO_2, temperature and RH) Abbeyforegate, Shrewsbury 18th - 24th February 2012.

A 'detailed' week, 18th - 24th February 2012, has also been plotted from the data gathered post-refurbishment (Fig. 22). From the plot of temperature (in red) it is possible to identify the heating cycle and the corresponding reduction in RH as the higher temperatures reduce the saturation percentage of the air. The CO_2 levels recorded map occupancy of the room at 116 Abbeyforegate during the week and from these it is also possible to see that the heating cycle is well-matched with the use of this room. As previously discussed, the CO_2 levels in Figure 22 also shows the significant influence of the open flue on room conditions; the rapid exchange of internal with external air as a result of the flue is shown, as following occupancy CO_2 levels rapidly return to background levels of CO_2 close to ambient external conditions.

COMFORT/FABRIC RISK

Individual indoor temperature and relative humidity readings were plotted against an index of human comfort and fabric risk. The 2012 results for Abbeyforegate recorded between 17th February - 9th May can be seen in Figure 23, with the 27th January - 11th February 2011 graph reproduced for comparative purposes in Figure 24. The 2012 graph, Figure 23, plots data gathered over a longer time period than was the case in 2011 hence the increased density of blue temperature and RH plots for this year.

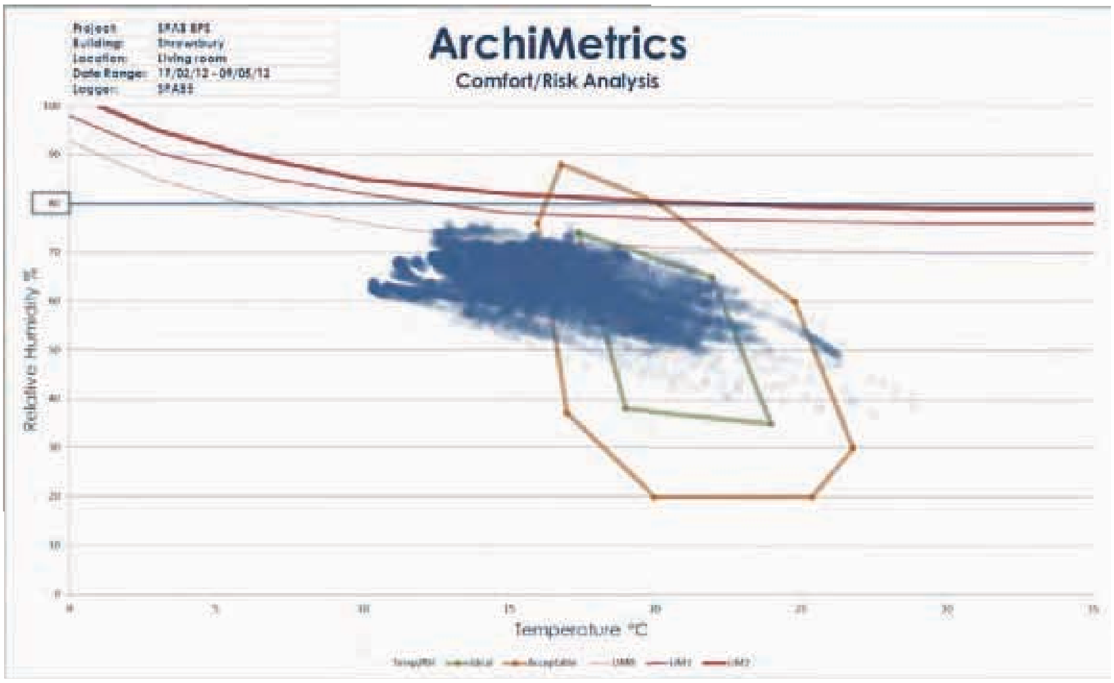


Figure 23. Comfort/Risk Analysis for Abbeyforegate, Shrewsbury, 2012.

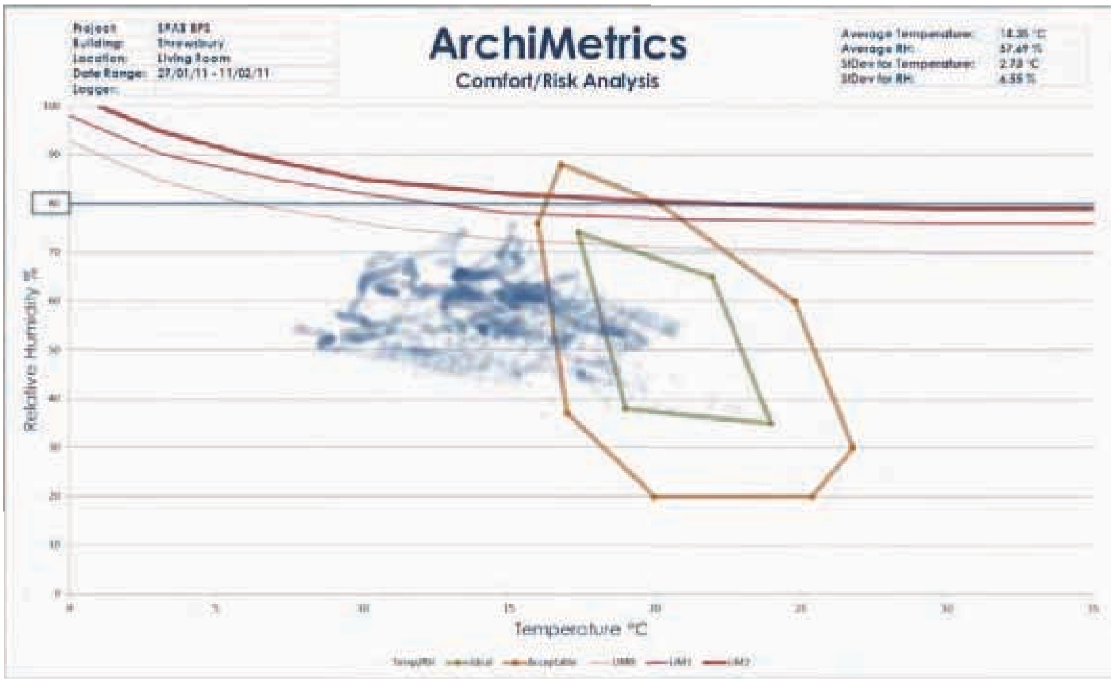


Figure 24. Comfort/Risk Analysis for Abbeyforegate, Shrewsbury, 2011.

In 2011, pre-refurbishment, the majority of the temperature/relative humidity measurements fell outside of the parameters deemed ideal for human comfort and mostly outside of the polygon that described acceptable limits (Fig. 24). In 2012, post-refurbishment, the balance of the graph has changed as temperatures have shifted up the horizontal temperature scale and readings are now centred within the 'acceptable' zone and also occupy more of the ideal zone (Fig. 23). The 1 - 2˚C increase in room temperature has placed the living room within more standard bounds of human comfort, although these temperatures may yet be on the low side for some individuals. This increase in temperature, as has been previously noted, has also been accompanied by raised levels of RH previously explained as the residual effect of the wet finishes applied to the wall surfaces in this room. Plots of 2012 temperature and RH are therefore also lifted within the graph up the vertical RH scale and now begin to intersect with one of the limiting isopleths for mould, (LIM 0 - ideal culture medium). They do not, however, intersect with the isopleths that indicate the potential for damage to timber or masonry fabric (LIM 1 and LIM 2).

The Firs, Riddlecombe, Devon.
2012

Description: Two storey, semi-detached, nineteenth-century cob cottage with early twentieth-century single storey addition in cob to right side and more recent extensions to rear. Mainly new timber double-glazed units.

Refurbishment: Work at The Firs, Riddlecombe included the removal of external cement render, walls were repaired and re-rendered with an insulating lime render. Internally gypsum plasters have been replaced with lime and limewash finishes. Floors in the older part of the house have been insulated. Particular attention has been paid to air tightness detailing through the house.

Occupancy: Family of 5.

Floor Area: 86m^2

Figure 25. Plan of The Firs, Riddlecombe (ground floor on right hand side).

Location of monitoring equipment shown by red dot. Air permeability test perimeter shown in blue, with secondary test zone indicated with red dotted line.

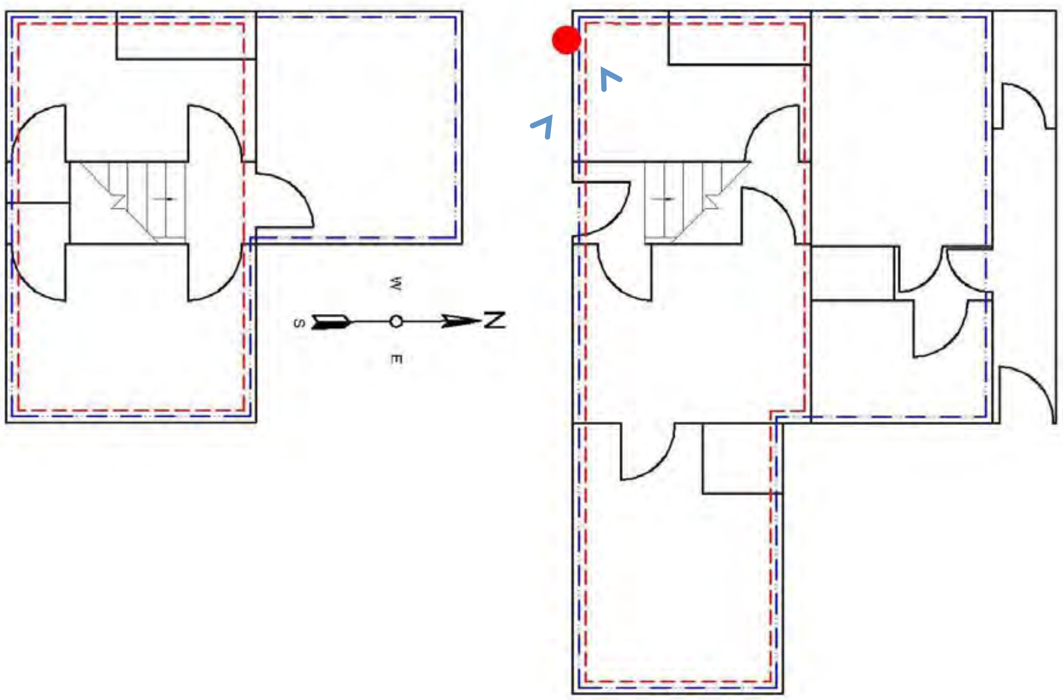


Figure 26. Positions of in situ monitoring equipment at The Firs Riddlecombe 2012.

U-VALUES

Between 7th February - 28th February 2012 an *in situ* U-value measurement was made for the ground floor, south-facing wall of the small home office at Riddlecombe (Figs. 25 & 26). The result, along with a standard U-value calculation made following the BR 443 method is shown in Table 10 as well as the results of the 2011 pre-refurbishment U-value measurement and calculation. The 2011 *in situ* U-value given in Table 10 is taken from the measurement made at 1790mm above finished floor level as this equates with the position of the 2012 measurement.

Un-insulated 2011				**Insulated 2012**			
Materials & Build Up internal - external	**mm**	***In situ* U value W/m²K**	**Calculated U-value W/m²K**	**Materials & Build Up** internal - external	**mm**	***In situ* U value W/m²K**	**Calculated U-value W/m²K**
Gypsum skim	3			Limewash	1		
Lime Plaster	20			Lime Plaster	25		
Cob	580			Cob	580		
Stone	37			Stone	37		
Cement render	40			Insulating render	40		
Total	**680**	**0.76**	**0.93**	**Total**	**683**	**0.72**	**0.60**

Table 10. In situ and calculated U-value results for The Firs, Riddlecombe 2011 & 2012.

The theoretical thermal benefit of replacing the cement render with an insulating alternative can be seen in the two U-values that are calculated for the wall at Riddlecombe; 0.93 W/m^{2}K in 2011, pre-refurbishment, with the lower U-value of 0.60 W/m^{2}K calculated post-refurbishment in 2012, a supposed 35% reduction in heat loss[10]. However, the measured *in situ* U-values for this wall show a very much smaller percentage reduction in heat loss for the wall of only 4%, 0.76 W/m^{2}K measured in 2011 compared with the slightly reduced U-value of 0.72 W/m^{2}K measured in 2012. In 2011 the measured U-value had conformed to the expected pattern for a traditional wall where measurements most often return lower than calculated U-values whereas this trend has reversed in 2012 and the calculated number is the lower of the pair of U-values. There are a few possible reasons for this reversal of measured and calculated trend and the small alteration in heat loss as measured for the wall post-refurbishment. As has been noted in the previous section concerning the property in Shrewsbury, we can expect calculated U-values post refurbishment to have better correlation with measured U-values as the addition of an insulating layer (of known thickness and thermal conductivity) should be the single most significant factor to determine the thermal transmissivity of the overall wall. Nevertheless, this does not appear to be the case with regard to the wall at Riddlecombe where the calculated and measured U-values are quite divergent. This points to several possibilities, either, that the thermal conductivity ascribed to the insulating render does not reflect its performance and/or that its performance and maybe the performance of the wall in general is being compromised in some way. It was noted in the previous Interim Report that of all the walls surveyed, the cob wall at Riddlecombe had the lowest dewpoint margin which suggested a high moisture content within the body of the wall as a result of cracks in the former external cement render. The internal surface and sub-surface of this wall also recorded high moisture 'values' in 2011. On returning to Riddlecombe in 2012 to re-install interstitial gradient monitoring material found within the body of the wall was discovered to be wet (as indeed had been elements of the original cores drilled from the wall in 2011). The interstitial monitoring undertaken in 2012 has found that levels of moisture with the wall are high and rising (this is discussed in more detail within the Moisture Section of this report) therefore it is possible that the thermal

[10] For assumptions used in the U-value calculation for the thermal conductivity of cob see Rye, C., Scott, C., Hubbard, D. (2011). *The SPAB Research Report 2: The Performance of Traditional Buildings - the SPAB Building Performance Survey 2011 Interim Findings*. London: The Society for the Protection of Ancient Buildings, p. 73.

transmissivity of the wall is increased by its raised moisture content and so the wall does not perform to its calculated estimate of heat loss and there is little thermal benefit derived from the insulating render.

AIR PERMEABILITY

Air permeability testing was carried out on the complete habitable volume at The Firs on 17 February 2012, depressurising and pressurising the dwelling. As an additional test, the original part of the building was examined alone (Fig. 25), though this has the reservation that it was not possible to open the door and windows in the extensions excluded from this space which may impede free air flow from outside the building. Interior and exterior conditions at the time of testing are noted in Table 11 and the results of the whole dwelling air permeability test are shown in Table 12.

Date of Test:	17 February 2012
Prevailing weather conditions at time of test:	100% cloud cover, no precipitation at time of testing, but damp underfoot. Wind 1.6 ms^{-1} average, 3.3 ms^{-1} maximum (approx.. 3.00pm) External shade conditions 10°C 93% RH (11.00am approx.)
Conditions inside dwelling:	Living room 18°C 69% RH (approx.1.15pm); Kitchen 20°C 70% RH (approx. 3.00pm)

Table 11. Interior and exterior conditions for air permeability test at The Firs, Riddlecombe.

	Units	Results	Comments
Whole dwelling			
Internal floor area (ground and first floors)	m^2	86	
Habitable building volume	m^3	189	
Dwelling envelope area i.e. surface area of living space	m^2	245	
Measured air flow	m^3h^{-1}	1308	External door from conservatory open.
Air permeability test result at 50Pa	$m^3h^{-1}m^{-2}$ @50 Pa	5.4	m^3 of air per hour per m^2 of surface area of the living space.
Air changes per hour at 50Pa	ach@50 Pa	6.9	The number of times the complete volume of air in the property is changed per hour at the test pressure.

Table 12. Results for whole house air permeability test at The Firs, Riddlecombe.

Under the test conditions, the air flow measured for the property as a whole was 1308 m^3h^{-1}. Related to the total surface area of the property, Table 12 shows this equates to an air permeability of 5.4 $m^3h^{-1}m^{-2}$ @ 50 Pa. These results are slightly better than the 2011 results, which were 1355 m^3h^{-1} and 5.5 $m^3h^{-1}m^{-2}$ @ 50 Pa respectively but represent only a 3.5% reduction. The 2012 air permeability result is well within the limiting air permeability applied to new buildings under Approved Document L1A 2010. Relating the dwelling volume to the measured air flow, the air change rate at 50Pa is 6.9 ach, representing the number of times per hour the total volume of air in the building will change at this pressure difference. From Sherman[11], this would represent an air change rate of 0.3, which is lower than orthodoxy.

In order to consider the cob dwelling (both 19th and 20th century parts) separately from the extensions to the rear of the building, a stage test was also carried out to isolate the older part of the dwelling (Fig. 25). This test

[11] from Ridley, I. et al, The impact of replacement windows on air infiltration and indoor air quality in buildings. International Journal of Ventilation 1(3) pp 209-218.

does not truly reflect the air permeability figure because the outer doors were closed rather than open to the outdoors (which has the effect of making the older part of the building look tighter than it is), but they do help to put the different parts of building into context and follows the methodology applied for the 2011 testing. The results of this test are detailed in Table 13 and are consistent with the 2011 test results of an air flow of 927 m^3h^{-1} @ 50 Pa, an air permeability 5.0 $m^3h^{-1}m^{-2}$ @ 50 Pa and an air change rate of 7.5 ach @ 50Pa.

	Units	**Results**
Older part of building (including sitting room)		
Internal floor area (ground and first floors)	m^2	54
Habitable building volume	m^3	124
Dwelling envelope area i.e. surface area of living space	m^2	184
Measured air flow	m^3h^{-1}	924
Air permeability test result at 50Pa	$m^3h^{-1}m^{-2}$ @50 Pa	5.0
Air changes per hour at 50Pa	ach@50 Pa	7.5

Table 13. Air permeability results for cob components of The Firs, Riddlecombe.

Flues

Under the standard test procedure, chimneys and flues in the dwelling are excluded from the results. The Firs has two flues which show an air flow under the test conditions. At the time of the 2011 testing, wood burning stoves were fitted to both of these flues. However, in 2012 the stove from the flue in the sitting room (single storey, 20th century cob) had been removed and a chimney balloon loosely fitted within the flue pipe. As shown in Table 14, when the chimney balloon was removed, the measured additional air flow under the test conditions increased by 158 m^3h^{-1} @50Pa. This represents an increase in air flow through the whole dwelling of 12% when the chimney balloon is removed. This measurement does not directly relate to the air flows through chimneys when either in use or not in use.

	Additional m^3h^{-1} @50Pa
Chimney balloon loosely fitted – comparison between flue pipe taped over and tape removed	12
Comparison between chimney balloon in place and flue pipe taped and chimney balloon removed.	158

Table 14. The Firs, Riddlecombe – air flows relating to Sitting Room flue under air permeability test conditions.

THERMOGRAPHIC SURVEY

Thermal imaging was carried out inside Riddlecombe on 17 February 2012. The weather conditions permitted images to be taken of both the interior and exterior of The Firs, the exterior images when the building was under normal conditions and the interior images whilst the building was depressurised. (Please note, the temperature represented by a particular colour change from image to image – please cross reference with the temperature scale on each image. The temperatures displayed in the top left hand corner are the surface temperatures measured at the centre of the cross-hairs appearing in the image.)

A thermographic survey of the exterior of Riddlecombe was carried out under ambient conditions. The south-facing façade showed some variations in temperature. In Figure 27, the variation is due to an area of wall being set back, whereas in Figure 28, there is no change in wall thickness. This cooler area does not correspond to the stone plinth visible from thermal images at the same location from inside the building shown in Figure 30.

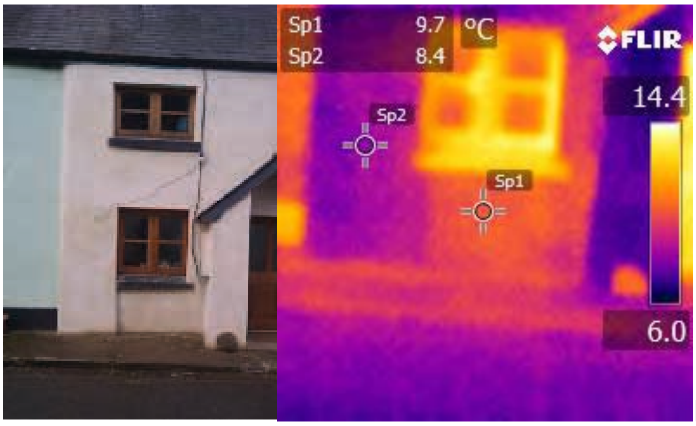


Figure 27. The Firs, Riddlecombe – south-facing façade, set back.

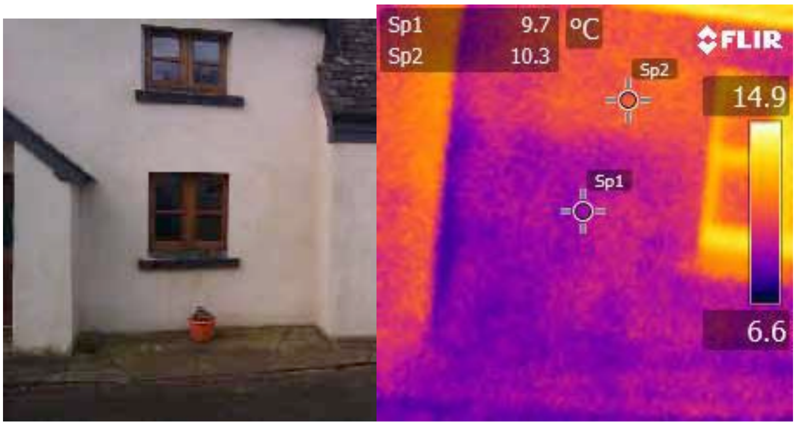


Figure 28. The Firs, Riddlecombe – south-facing façade, flush.

To the rear of the property, a thermal bridge above the bathroom window is visible (Fig. 29) anticipated to be the lintel. This is in the later addition to the building.

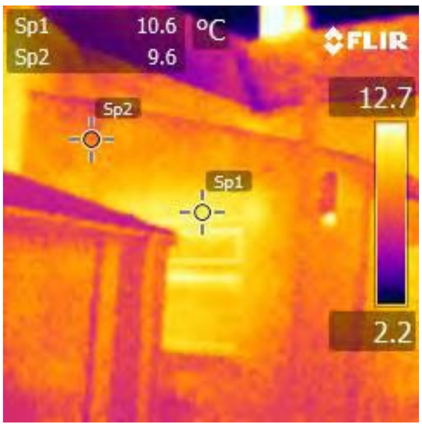


Figure 29. The Firs, Riddlecombe – east-facing bathroom window.

Inside The Firs, the colder stone plinth is visible when the south wall is viewed and is shown in Figure 30.

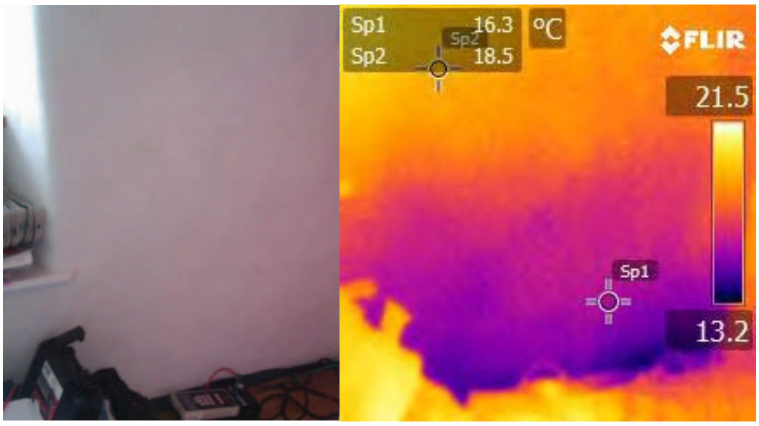


Figure 30. The Firs, Riddlecombe – living room, south facing wall, plinth.

The windows installed prior to the 2011 study showed no evidence of leakage; however there was ingress around the window in Bedroom 1, where plasterwork was still to be completed (Fig. 31). Ingress around beams remained as per the 2011 study.

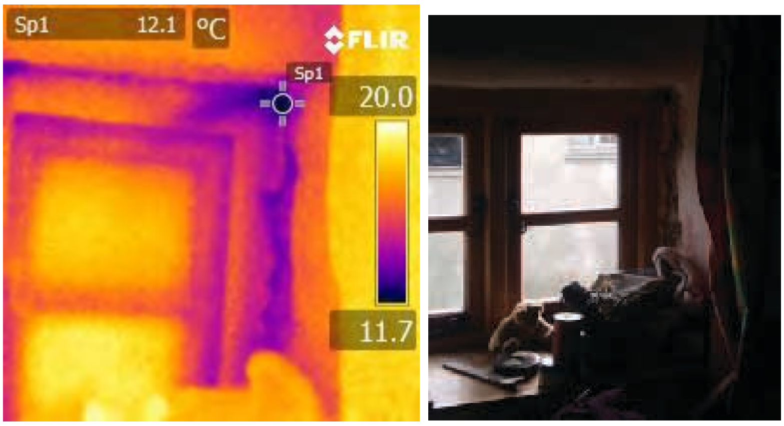


Figure 31. The Firs, Riddlecombe – Bedroom1, south facing wall.

With respect to the later additions, the draught proofing to the rear door reduced the level of ingress, but some was still evident. At the time of survey the loft hatch in the rear passage had not been draught proofed and showed ingress (Fig. 32). It was also noted the missing areas of insulation in the rear bedroom ceiling remained visible under thermographic survey (shown in Fig.

33). It is understood that subsequent to this survey this ceiling has been improved.

Figure 32. The Firs, Riddlecombe – rear passage, loft hatch.

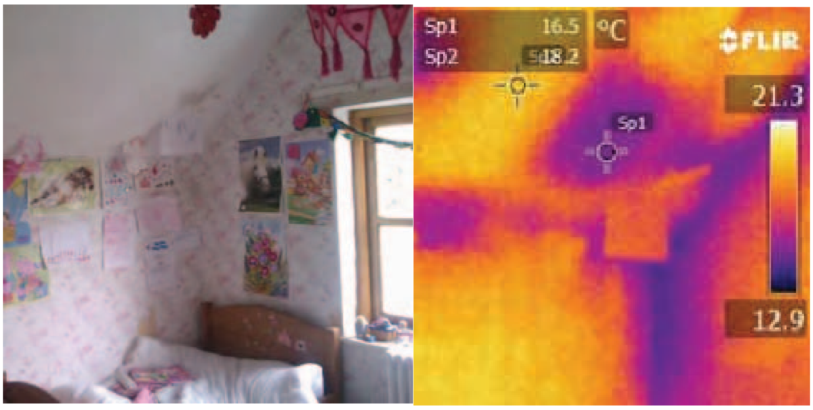


Figure 33. The Firs, Riddlecombe – rear bedroom (Bedroom 2).

MOISTURE

Surface and Sub-Surface Moisture

On 28th February 2012 two measurements were taken to record the moisture conditions of the interior wall surface of the south-facing office room wall at The Firs, Riddlecombe. A measurement of the surface, approximately 2mm deep, was taken using a twin-pinned resistivity probe and an additional capacitance reading was taken of conditions at approximately 40mm deep behind the interior wall face. Figure 34 plots these measurements alongside those previously taken in 2011 for the same wall, pre-refurbishment, these values are plotted against a nominal moisture scale to a height of 2000mm above finished floor level.

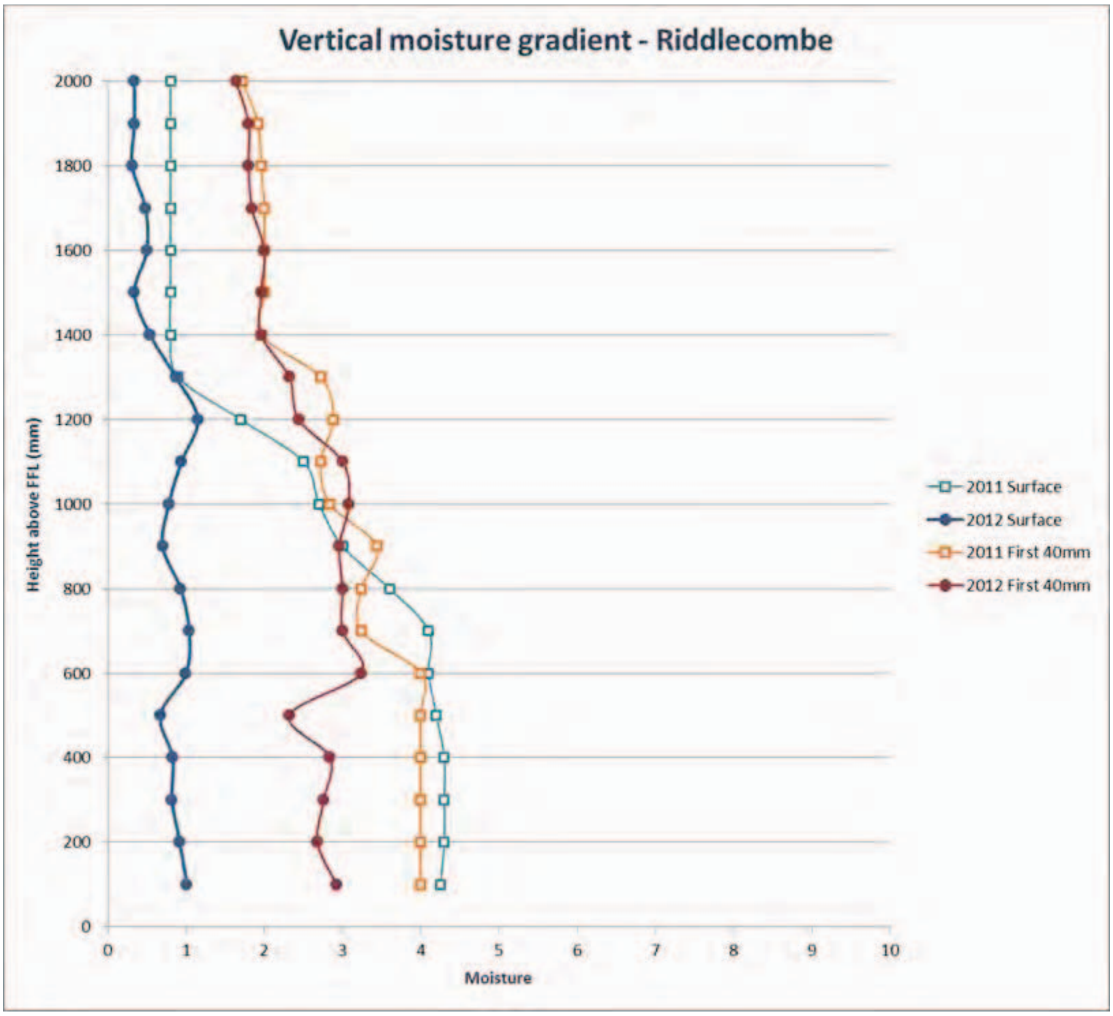


Figure 34. Pre and post refurbishment measurements of surface & sub-surface moisture at The Firs, Riddlecombe, 2011 & 2012.

The moisture values recorded on 7th February 2012 show that moisture at the surface and sub-surface of the interior wall face has decreased in comparison with measurements made the previous year (Fig. 34). This is particularly the case up to 1200mm - 1400mm above the finished floor level, within the 'rising damp' zone where, previously in 2011, the wall appeared to reflect a high level of moisture concentration at its base possibly as a result of the capillary action of ground water. The concentration of moisture in the base of the wall seems to have diminished somewhat which maybe as a result of the alteration of internal and external finishes to more moisture permeable materials. Lime finishes may allow the buffering and evaporation of residual moisture in the wall more readily and could explain the improvement in moisture measurements in general and particularly for those made at the surface level of this wall. The moisture load at the base of the wall may also be benefitting from the application of a stabilising coat of mortar to the interior and exterior base up to a height of 300mm which may keep rising ground water away from the zone of measurement and also protect this lower part of the wall from the build-up of surface water outside from the concrete paving surface which abuts the wall. Above 1200 - 1400mm, away from the possible pressure of ground water or otherwise, the measures broadly repeat those of 2011 with a slight shift towards the drier end of the scale for the surface measurements, again as a reflection of permeable finishes perhaps, however, moisture at the sub-surface level seems to be little changed.

Interstitial Hygrothermal Conditions

Figure 35. Interstitial, U-value and IAQ monitoring set up at The Firs, Riddlecombe, 2012.

Temperature and moisture measurements are being made through a section of south-facing wall of the office room at Riddlecombe (Fig. 35). Combined temperature and relative humidity sensors are located at four points within the wall at the heights and depths given in Table 15 coupled with sensors to record internal and external conditions. Data from all these sensors, for the period 7th February - 9th September 2012, has been collected and used as the basis for the following analysis. The positions of these sensors corresponds with those of the pre-refurbishment monitoring carried out between 25th February - 11th March 2011.

Build-up - internal - external	**Depth of material**	**Sensor no.**	**Height from finished floor level**	**Depth of sensor from internal surface**
Limewash	1mm			
Lime plaster	25mm			
Cob	580mm	Sensor 1	1800mm	50mm
		Sensor 2	1600mm	225mm
		Sensor 3	1400mm	400mm
		Sensor 4	1200mm	580mm
Masonry	75mm			
Insulating Lime render	40mm			
Lime Render skim	4mm			
Overall	725mm			

Table 15. Interstitial hygrothermal gradient sensor positions for The Firs, Riddlecombe, 2012.

Figure 36 shows the average values of each sensor over the February - September 2012 monitoring period graphed as separate temperature and dewpoint gradients, as well as the maximum and minimum values for these two elements recorded over the monitoring period. The values derived from the relative humidity sensors have been converted to dewpoints in order to indicate the likelihood of condensation forming within the wall. Figure 37 provides a comparative graph which overlays the 2012 data with the same data recorded during the 2011 pre-refurbishment interstitial hygrothermal gradient monitoring.

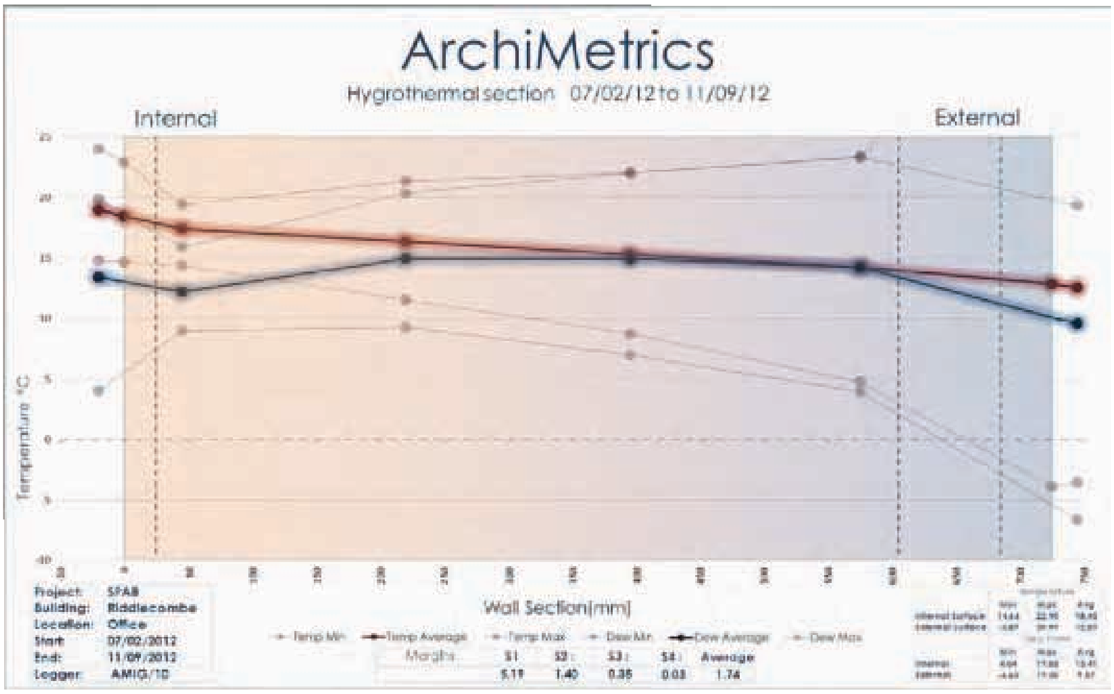


Figure 36. Temperature and dewpoint gradients for The Firs, Riddlecombe, 2012.

What is immediately of note from the 2012 graph in Figure 36 is the converging temperature and dewpoint gradients at both the third and fourth interstitial nodes and this pattern is repeated for the maximum values in this graph. The minimum values do not show converging plots of temperature and dewpoint this may indicate that at lower temperatures the wall does not seem to experience such high moisture responses to the extent that dewpoint saturation is not reached. More detail concerning the moisture vapour responses of the wall at Riddlecombe can be found in the section on Relative Humidity below.

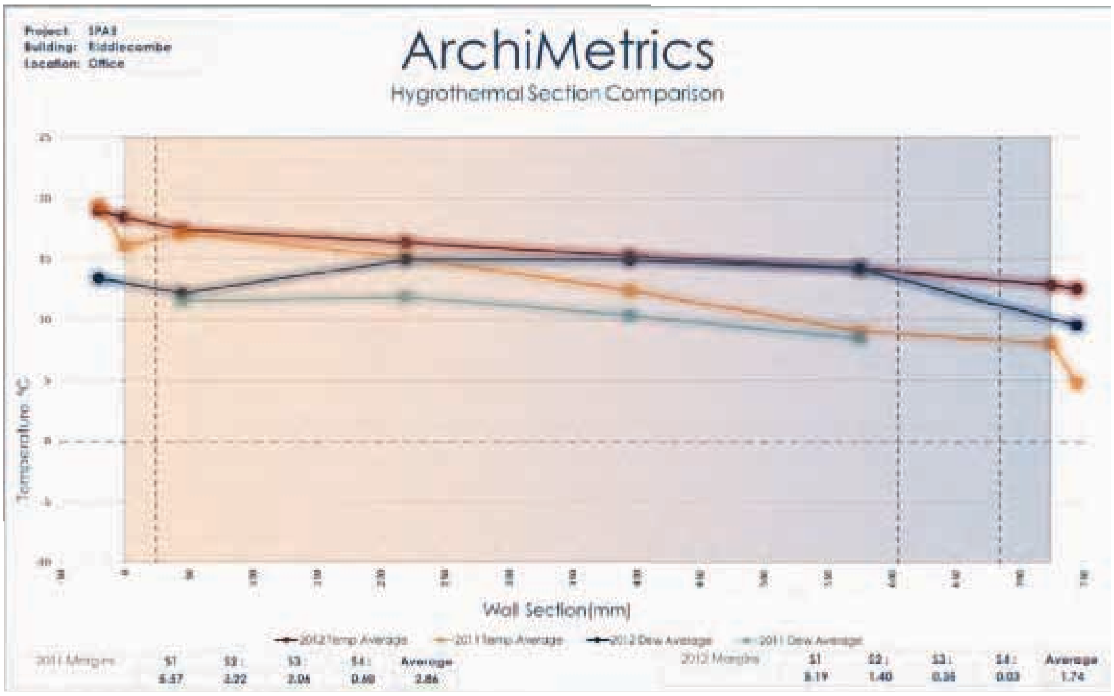


Figure 37. 2011 & 2012 Temperature and dewpoint gradient comparison for The Firs, Riddlecombe.

In comparison with the 2011 values, we can again see that, like the example at Shrewsbury, the temperature gradient recorded in 2012 indicates higher temperatures than those achieved from the 2011 monitored data (Fig. 37). This is not an indication of the thermal improvement of the wall (as demonstrated by the virtually unchanged measured U-value for this wall post-refurbishment) but rather a factor of the extended monitoring currently being undertaken which means that the temperature gradient reflects the recording of spring and summer heat, raising average temperatures in general.

An examination of the 2011 gradients for this wall shows a position of near convergence between the temperature and dewpoint gradients at a depth of 580mm within the wall (sensor 4) with the margin between the two calculated as 0.6˚C (2.86˚C is the average margin calculated for all four nodes). At the time it was suggested that the higher moisture content, with the possibility of condensation indicated at this point, was a result of water penetration through the cracked external cement render. It is interesting to see that despite the removal of this failing render and its replacement with a more permeable lime-based alternative not only does moisture continue to be present within the cob wall indeed it would appear that it is accumulating. Two sensors within the wall (nodes 3 and 4 at 400mm and 580mm deep respectively) now indicate dewpoint/temperature convergence with dewpoint margins of 0.35 and 0.3˚C. Overall the average dewpoint margin for the whole wall (taken across all four nodes) has been reduced by 40% from 2.86˚C to 1.74˚C. The reasons for this change are not obvious and the accumulation of moisture suggests that moisture is becoming trapped within the wall as it is currently configured. During construction and refurbishment processes there is the possibility that moisture will be introduced into building materials from the addition of water used in finishes etc. However, the data presented at Riddlecombe indicates that construction moisture is not the cause of the high moisture content found within the wall not least because this does not explain the *accumulation* of high RH values (calculated as dewpoints) moving back into the centre of the wall. The accumulation of moisture over time suggests an on-going source for this moisture.

Relative Humidity

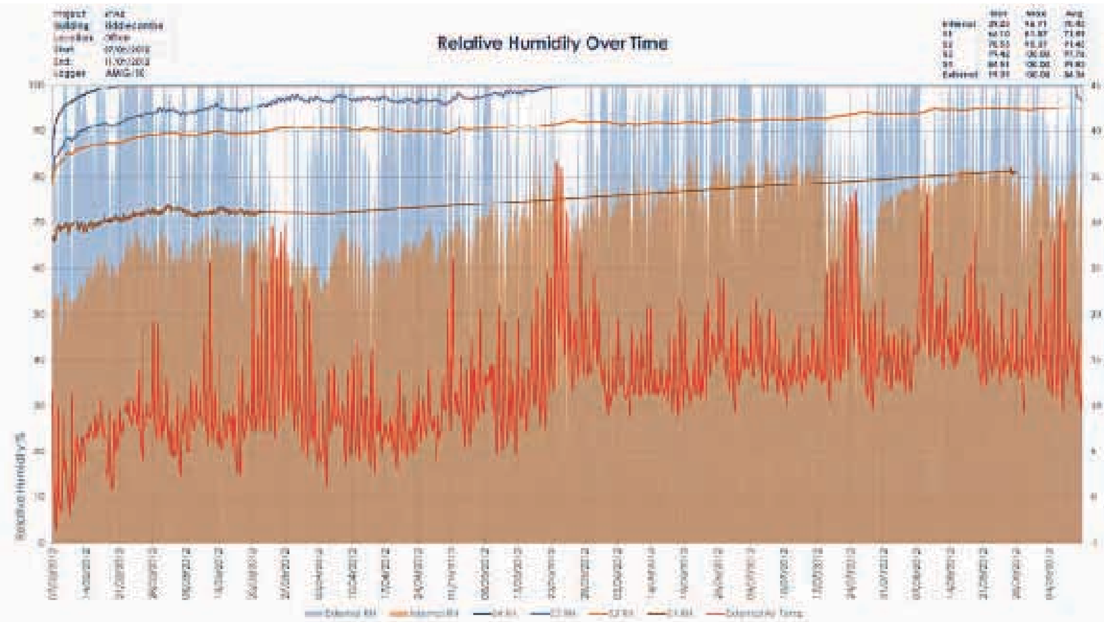


Figure 38. Plots of interstitial RH, internal room RH and external RH and temperature, The Firs, Riddlecombe 2012.

By plotting levels of external air temperature, external and internal RH, as well as RH recorded at the interstitial sensors within the wall at Riddlecombe over time it is possible to see evidence for the accumulation of moisture taking place within the wall, previously identified from dewpoint data. The exterior RH sensor at node 4, which showed a reduced dewpoint margin of 0.3˚C, quickly disappears above the 100% RH scale within two weeks of the commencement of post-refurbishment monitoring in 2012. Sensor 3, 180mm back from this, towards the centre of the wall also exceeds the RH scale approximately 16 weeks into the monitoring programme and RH levels at sensor 2 can also be seen to be steadily rising. (The data for sensor 1 is incomplete as this sensor failed and has now been replaced.)

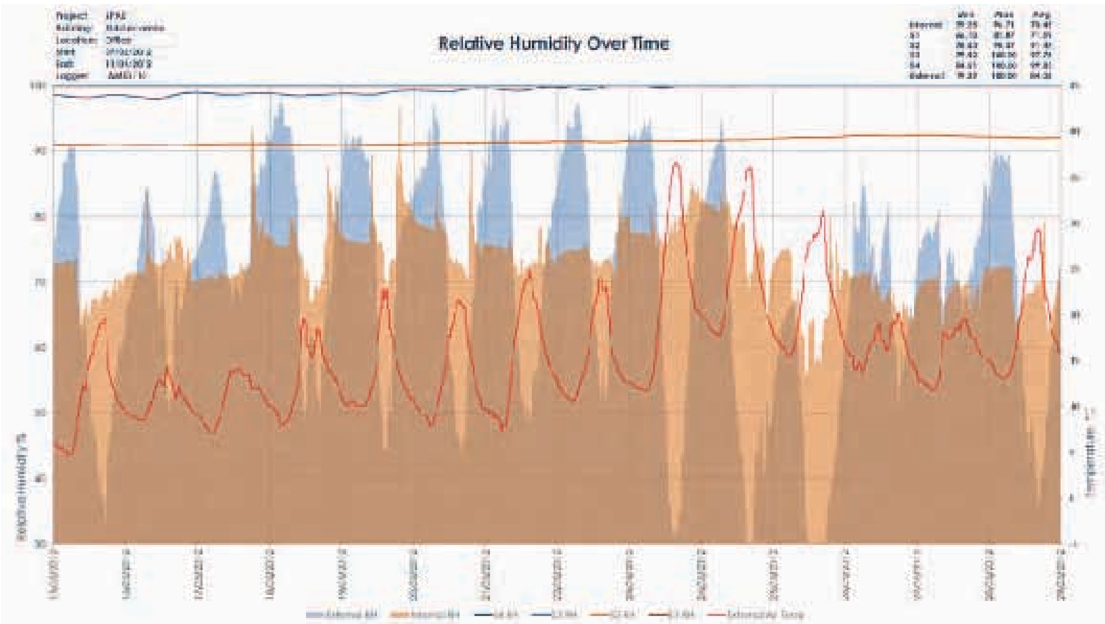


Figure 39. Detail - plots of interstitial RH, internal room RH and external RH and temperature, The Firs, Riddlecombe, 15th - 29th May 2012.

Figure 39 shows a detailed plot of the RH values for the wall at Riddlecombe between 15th - 29th May. It is during these two weeks that the level of RH measured at sensor 3 exceeds 100%. It appears that this occurs in parallel with rising external temperatures and a similar although somewhat delayed and less pronounced increase can be seen in sensor 2 readings (this increase is more visible in Figure 38). Significantly, following the rise in gradient on sensor 2, RH values do not return to previous levels when temperatures diminish. As has been noted previously RH continues to rise over the monitoring period. In contrast to the wall at Shrewsbury where interstitial RH more or less maps that of external temperature and RH i.e. when temperatures rise interstitial RH falls the opposite appears to be happening in the wall at Riddlecombe. RH increases with external temperature increase and continues to accumulate over time. This leads us to speculate that the raised temperatures are causing the moisture vapour in the wall to increase perhaps as some sort of hygroscopic effect as a result of heat and that the accumulation may be explained by the inability of the wall to allow enough of this vapour to evaporate overtime.

Resistivity Measurements

To complicate matters it was discovered, during the course of re-rendering, that the section of the cob wall being monitored was in fact faced with a masonry buttress (Fig. 40). Therefore the presence of this buttress, made in a different material to that of the earth wall may or may not have a bearing on the moisture behaviour that is currently being monitored within the cob. In order to verify the findings at Riddlecombe we are undertaking additional monitoring to measure, through resistivity, the moisture content of the cob 200mm back from the external face (one measurement is taken through and behind the buttress and one above it away from the influence of the masonry (Fig. 41)). These measurements have so far returned indicative moisture content values for these areas of around 3.9 - 4.1% suggesting a raised moisture level which backs up both on-site observations of wet material extracted from the sensor holes when monitoring equipment was re-installed in 2012 as well as the convergent dewpoint readings taken via the interstitial hygrothermal gradient monitors and plots of interstitial RH. Interestingly, these moisture content values were found both above and behind the buttress suggesting that the raised moisture extends beyond the zone of hygrothermal monitoring which is installed in proximity to the buttress.

Figure 40. The Firs, Riddlecombe front elevation showing masonry buttress bottom left of frame.

Figure 41. Moisture content resistivity probes in external wall face, The Firs, Riddlecombe, September 2012.

Sensor values for the wall were logged at 5-minute intervals and this information has been animated in order that changes in temperature and dewpoint maybe analysed over time. (To view the 2011 and 2012 interstitial gradients animation for The Firs, Riddlecombe, visit www.archimetrics.co.uk).

The animated data shows the temperature and dewpoint values measured at the fourth node (580mm in from internal surface) beginning to coalesce at the start of the monitoring period (07/02/12) and within 11 days (by 18/02/12) the two points are conjoined and continue to be united for the remaining 7 months of the animated data. A similar pattern is then repeated for the next intermural third node where the temperature and dewpoint values have begun to coalesce early on, by 26/02/12 they begin to intersect with each other and by 18/05/12 they have completely conjoined presenting the pattern seen in the static average figures. This shows that the high moisture readings are moving over time back from the exterior edge of the wall (at an approximate depth of 580mm) towards the interior of the wall as moisture accumulates.

The relationship between the more external fourth node and fluctuations in external temperature are interesting to note and are in contrast to the thermal behaviour of the brick wall in Shrewsbury. The fourth node acts as a form of break between the extremes of external temperature and the interior of the wall. At Shrewsbury raised external temperatures are passed deep into the body of the wall in the form of a delayed sort of 'Mexican Wave' effect, at Riddlecombe. However, raised external temperatures track back into the wall as far as the fourth node (the most external of the intermural sensors) but no further. The more dynamic response exhibited by the wall in Shrewsbury, in contrast to that of Riddlecombe, is possibly a refection of differences in wall thickness and the contrasting treatments of the external surface of these walls, which are both south-facing. The dark brick at Shrewsbury is more readily able to absorb solar radiation and therefore transfer this back deep into the thinner wall section whereas the cob wall at Riddlecombe, finished with a smooth light-coloured coat of render, is an ideal reflective surface which repels solar radiation meaning far smaller quantities of this heat can transferred into the cob. The third temperature sensing node sits roughly in the centre of the wall and the heavyweight nature of the wall's response can be seen in the degree of movement, or rather the lack of it, at this sensing position (and indeed from the nodes either side of this). Although the period of the animation spans extremes of temperature from winter right through to summer (40˚C to - 4˚C) in this part of the wall temperature fluctuates only within a narrow 10 - 12˚C band.

INDOOR AIR QUALITY

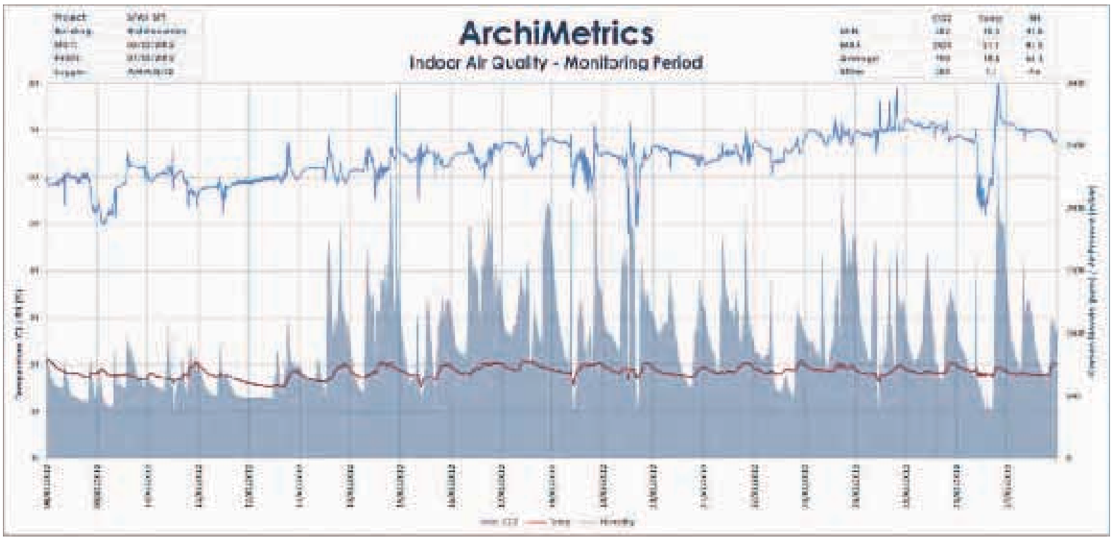


Figure 42. Indoor Air Quality (CO_2, temperature and RH), The Firs, Riddlecombe, 2012.

Figure 42 plots temperature, RH and CO_2 levels for the monitored room, which is used as an office, at The Firs, Riddlecombe between the period 8th February - 27th February 2012. Table 16 provides a summary of the indoor room conditions, the figures represent average values recorded during both the pre (2011) and post-refurbishment (2012) phases.

Property & Date	**CO_2 (ppm)**	**Temp (˚C)**	**RH (%)**
Riddlecombe (25/02/11 - 11/03/11)	1097.5	19.5	60.4
Riddlecombe (08/02/12 - 27/02/12)	950	18.4	64.1

Table 16. Indoor Conditions at The Firs, Riddlecombe 2011 & 2012.

Interestingly, two of the conditions that might be expected to have increased in value post-refurbishment, CO_2 and temperature, have in fact slightly decreased and only levels of RH in the office have risen slightly. The slight decrease in both the CO_2 and temperature figures for the office at Riddlecombe in 2012 may just be as a result of specific circumstances during the times of the two short monitoring periods (15 days in 2011, 19 days in 2012) for example, if the office was not in use quite as often this may account for the decreases. Despite attention being paid to air tightness detailing as part of the refurbishment at Riddlecombe the house had already recorded quite a low infiltration rate at the time of the 2011 pre-refurbishment test (5.5 $m^2h^{-1}m^3$ @ 50Pa, 7.2 ach). This had not altered significantly at the time of re-testing in 2012 which returned figures of 5.4 $m^2h^{-1}m^3$ @ 50Pa, or 6.9 ach @ 50 Pa. Similarly there is not a great deal of change between the CO_2 figures recorded between 2011 and 2012, and both are on the high side of acceptable levels of CO_2. It is interesting that despite these quite high levels of CO_2 RH levels for the room are not as high as one might expect given the degree of occupancy in relation to the small area of the office (7m^2 approximately). Whilst RH is raised from the previous 2011 value this could be attributed, as in Shrewsbury, to the effect of wet lime plaster finishes as part of the internal refurbishment but the degree of change is not great and perhaps the reason that RH levels are not higher than the 64.1% average can be ascribed to the buffering ability of the lime finishes (plaster and limewash) to absorb and slowly release moisture depending upon local conditions which in a confined space such as the office may have a significant relationship with overall room RH.

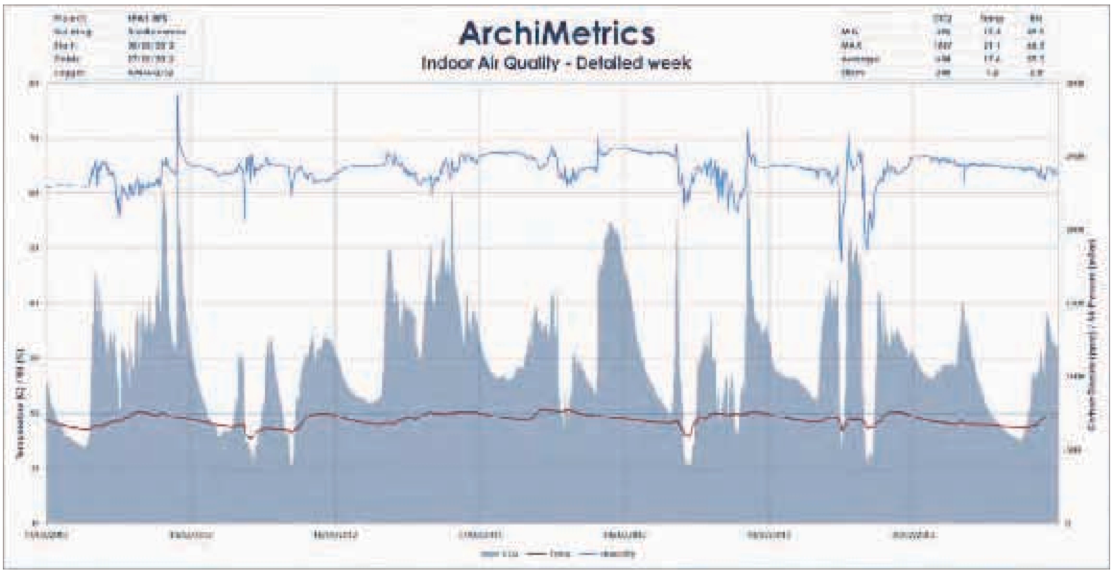


Figure 43. Detail - indoor Air Quality (CO_2, temperature and RH) The Firs, Riddlecombe 14th - 20th February, 2012.

An examination of a 'detailed week', Figure 43, for Riddlecombe clearly shows purge ventilation (window-opening) in relation to undesirable levels of CO_2 in the office. When CO_2 levels peak above 2250 ppm this is often followed by a steep drop back down to background levels. This is similar to the pattern found at Shrewsbury but there the steep drops indicated an increase in air flow as the result of a large uncapped chimney flue which occupies a proportion of the living room space. In contrast to this at Riddlecombe we can also see a different more gently decay which occurs when the office ceases to be occupied but in the absence of purge ventilation on these occasions the return to background CO_2 levels takes place over a longer period of time and hence shows as a more gradual decline.

COMFORT & FABRIC RISK

Individual indoor temperature and room relative humidity readings have also plotted against an index of human comfort and fabric risk. The 2012 results for Riddlecombe recorded between 7th February - 11th September can be seen in Figure 44, with the 25th February - 11th March 2011 graph reproduced for comparative purposes in Figure 45.

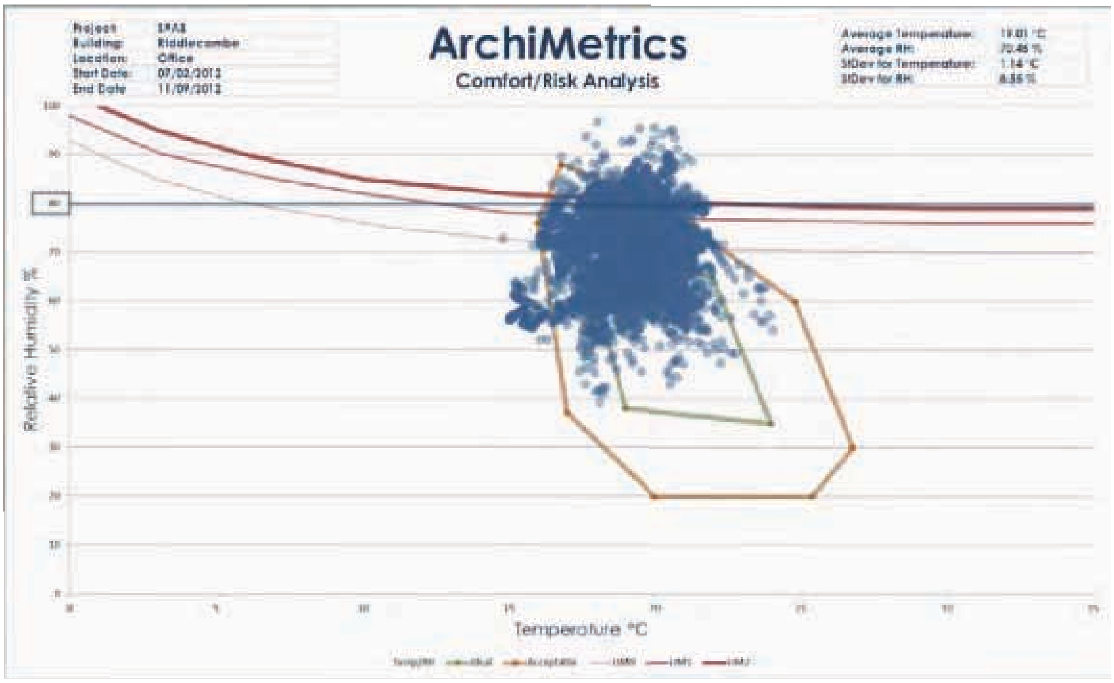


Figure 44. Comfort/Risk Analysis for The Firs, Riddlecombe, 2012.

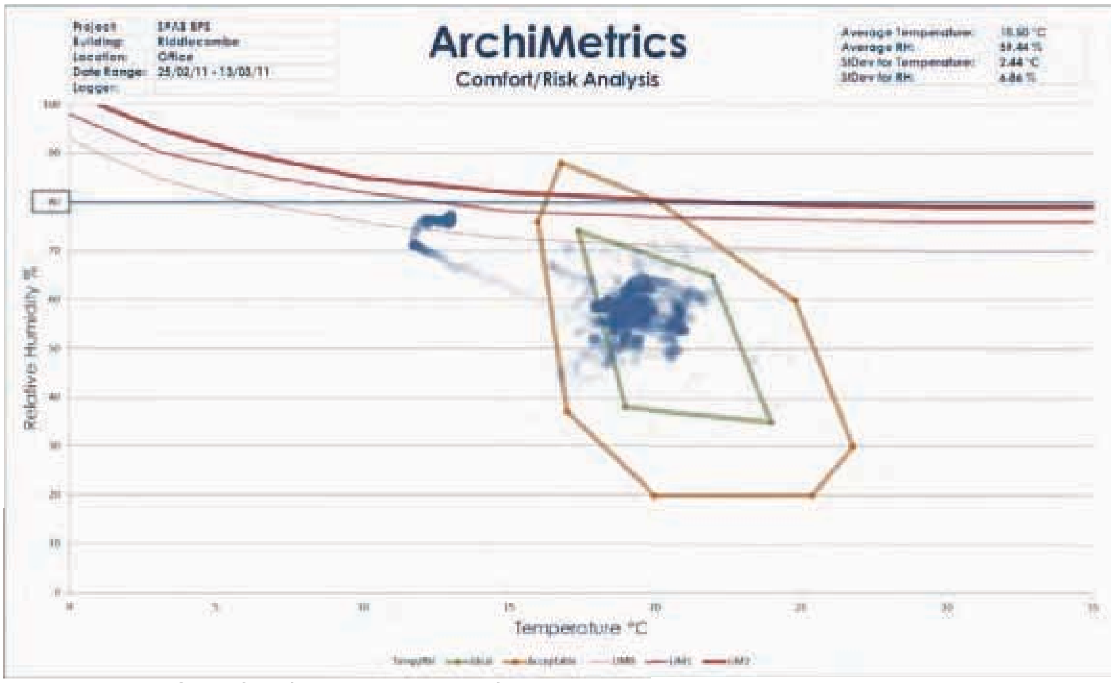


Figure 46. Comfort/Risk Analysis for The Firs, Riddlecombe, 2011.

The 2012 graph, Figure 45, plots data gathered over a much longer time period (7 months) than was the case in 2011 (15 days) hence the increased density of blue temperature and RH plots for this year.

Figure 45 from data recorded between 7th February - 11th September 2012 shows a different (and logically) much greater range of temperature and RH spread for the office in Riddlecombe. It also presents a very different picture to that contained within the short period of temperature and RH monitoring conducted as part of the indoor air quality (IAQ) survey taken in the earlier part of the year where temperatures were fractionally lower than previously record and RH only slightly raised. In 2011, again from monitoring conducted over a much shorter winter time period, conditions in the office had conformed well to the 'comfort index' as temperatures sat mostly within the 'ideal' polygon and apart from a short aberration RH was below all the limiting isopleths for mould growth. The 2012 graph would suggest, that for the majority of this monitoring period (which has included the spring and summer months) temperatures have stayed within this 'ideal' comfort zone. However, RH is raised with a proportion of readings lying above the limiting isopleths for mould growth for all three substrates. Of all the houses monitored in this study Riddlecombe has the highest occupancy level, 5 persons and one of the smallest overall areas, $86m^2$, therefore one could expect higher levels of RH to be found in such a building. Likewise, as has been previously noted, there seems to be raised moisture levels within the wall of the study and this too might have an influence on RH measurements in this room. This monitoring has taken place during the warmer part of an uncharacteristically wet year (even for the south-west). In order for a more complete picture of indoor room conditions to be drawn the continued monitoring at Riddlecombe will allow a year-long analysis to see how this spread is affected by the autumn and winter months. It is worth noting that the owner of the building reports that in general conditions in the house are more comfortable as a result of the refurbishment work.

Mill House, Drewsteignton, Devon.
2012

Description: A barn built in granite dating from the nineteenth century or possibly earlier converted to a dwelling in 1970s with a modern extension added to the south east. UPVC double glazed windows throughout.

Refurbishment: No refurbishment work has yet taken place at Drewsteignton. However, for experimental purposes a short section of wall that was subject to monitoring in 2011 has been internally insulated using PIR insulation.

Occupancy: 2 persons.

Floor Area: 325m^2

Figure 47. Plan of Mill House, Drewsteignton, with ground floor on left hand side.

The red dot indicates the location of the monitoring equipment. The air permeability perimeter of the 2011 test is shown in blue, with the secondary test zone shown in red.

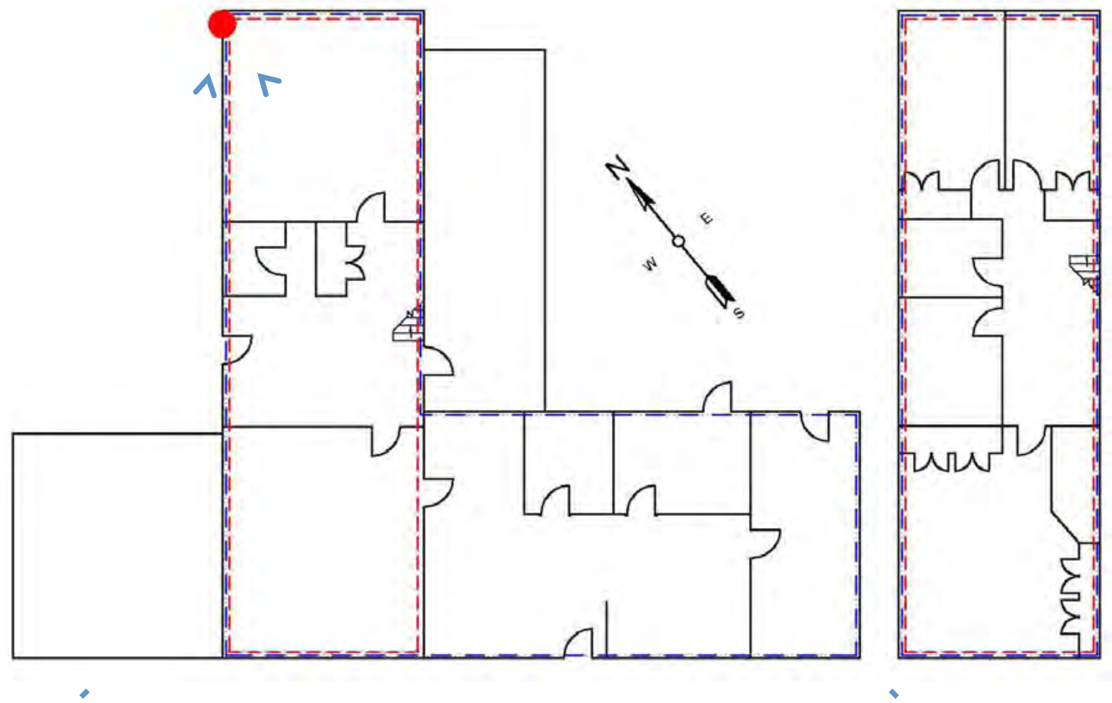


Figure 48. Positions of in situ monitoring equipment at Mill House, Drewsteignton, 2012.

U-VALUES

Between 7th - 28th February 2012 an *in situ* U-value measurement was taken on the insulated west wall of the ground floor office room (Figs. 47 & 48). The result along with standard U-value calculations made following the BR 443 method are shown in Table 17 below. The 2011 *in situ* U-value given in Table 17 is taken from the measurement made at 1800mm above finished floor level as this equates with the position of the 2012 measurement.

Un-insulated 2011				**Insulated 2012**			
Materials & Build Up internal - external	**mm**	***In situ* U value W/m²K**	**Calculated U-value W/m²K**	**Materials & Build Up** internal - external	**mm**	***In situ* U value W/m²K**	**Calculated U-value W/m²K**
				Gypsum skim	3		
				Plasterboard	12.5		
				Air gap	25		
				PIR Board	100		
Gypsum skim	3			Tanking & gypsum	3		
Lime Plaster	20			Lime Plaster	20		
Granite	580			Granite	580		
Total	**603**	**1.20**	**2.45**	**Total**	**744**	**0.16**	**0.19**

Table 17. In situ and calculated U-value results for Mill House, Drewsteignton 2011 & 2012.

The addition of 100mm of polyisocyanurate board (plus air gap and plasterboard) has made a significant difference to the heat loss measured as an *in situ* U-value for this section of wall, reducing it from the 1.20 W/m^{2}K measured from the uninsulated wall in 2011 to 0.16 W/m^{2}K, an 87% reduction. The 2012 measured U-value improves upon the calculated U-value for the equivalent wall build-up which is also the pattern normally found for most traditional walls in their existing condition i.e. pre-refurbishment. As has been referenced in previous reports better correlation between measured and calculated U-values for refurbished walls can be expected due to the defined nature of the additional material and its overriding significance, as an insulator, in terms of determining heat loss for an element. Therefore when there is a tendency for calculations to overestimate heat loss in a refurbished traditional wall, albeit within a narrow margin, this could perhaps be explained by the effect of the pessimistic calculation of heat loss that is made for the masonry element of these walls. The tendency for calculations to overestimate heat loss in solid masonry walls is commonly seen in measured and calculated U-value comparison results for existing, non refurbished wall elements and is noticeable in the 2011 figures for this wall at Drewsteignton[12].

AIR PERMEABILITY

No air permeability test has been undertaken for Drewsteignton in 2012 as no works have been undertaken that would impinge on infiltration for the property. However work to refurbish the south-east wing is planned for 2013 and it is anticipated that once this has been completed a new air permeability test will be conducted and the results reported in the next Building Performance report.

MOISTURE

Surface and Sub-surface Moisture

On 28th February 2012 two measurements were taken to record the moisture conditions of the interior wall surface of the test section of west-facing wall of the study at Mill House, Drewsteignton. A measurement of the surface, approximately 2mm deep, was taken using a twin-pinned resistivity probe and an additional capacitance reading was taken of conditions at approximately 40mm deep behind the interior wall face. Figure 49 plots these measurements

[12] See Rye, C. (2010). *The SPAB Research Report 1: The U-value Report*. Revised 2011. London: Society for the Protection of Ancient Buildings and Baker, P. (2011). *Technical Paper 10 - U-values and Traditional Buildings*, Edinburgh: Historic Scotland

alongside those previously taken in 2011 for the same wall, pre-refurbishment, these values are measured against a nominal moisture scale to a height of 2000mm above finished floor level.

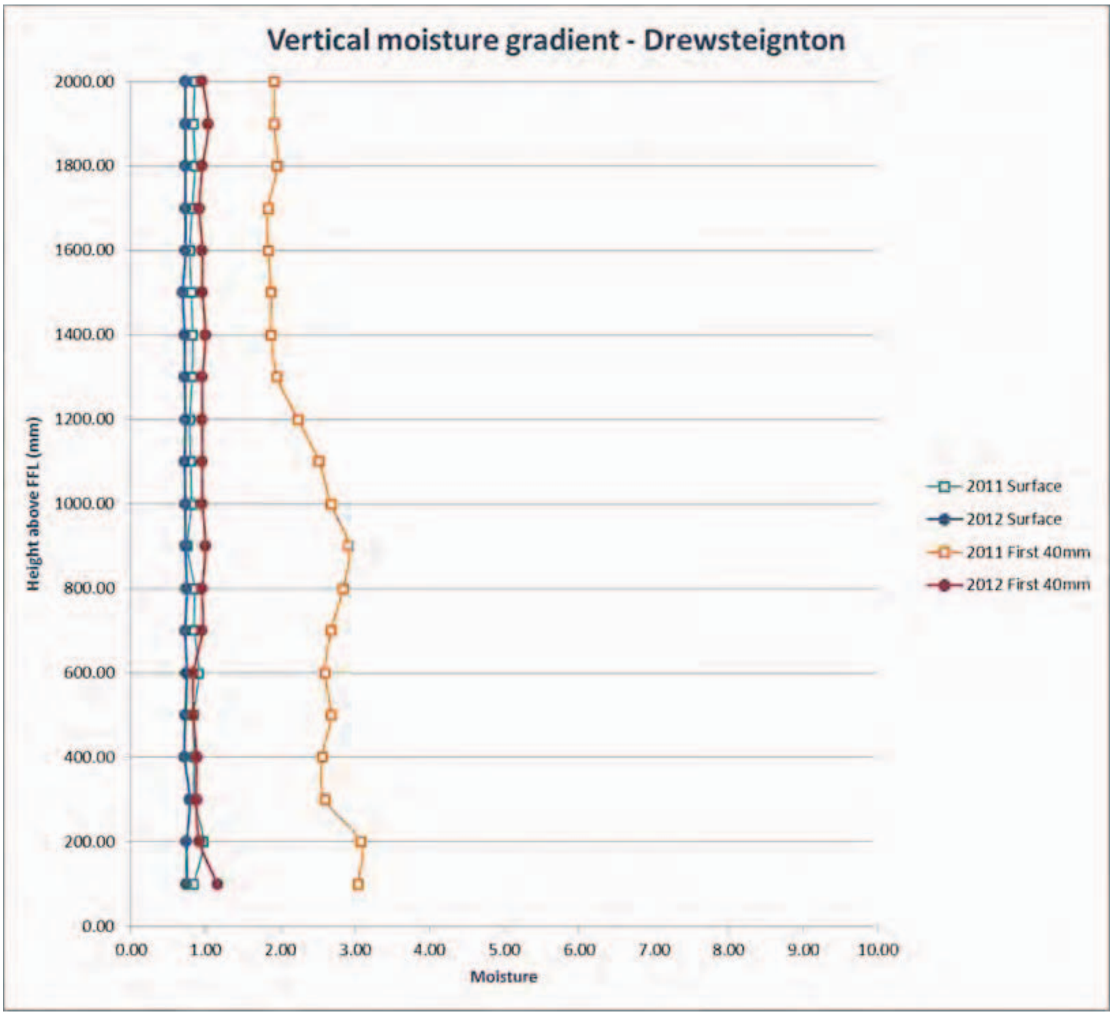


Figure 49. Pre and post refurbishment measurements of surface & sub-surface moisture at Mill House Test Wall, Drewsteignton, 2011 & 2012

Rather like the graph for surface moisture at Shrewsbury, which was for a wall which had also been internally insulated, Figure 49 shows both 2012 surface and sub-surface measurements of the test wall at Drewsteignton to be at the 'dry' end of the nominal moisture scale. Here they are also accompanied by the measurements of surface moisture taken in 2011, whereas the sub-surface measurements from 2011 (40mm into masonry of wall) do show a more erratic gradient which indicates at least a slightly raised moisture level for this part of the wall below the height of 1200 - 1400mm. The changes observed in these gradients following the application of internal wall insulation are perhaps not surprising when one considers the depth of measurements and materials now involved in the wall build-up. The depth of the wall has increased by around 140 mm and this increase has all been to the internal face of the wall, so like Shrewsbury the moisture-measuring instruments are no longer looking into the solid masonry part of the wall (where previously higher moisture levels were found) but are now providing readings of the new gypsum and plasterboard surface. The sub-surface capacitance reading is now measuring the wall about 25mm behind the plasterboard looking at levels of moisture found roughly at the air gap/polyisocyanurate board interface. These new materials, away from the sources of moisture that are potentially present in a pre-1919 solid wall, such as ground water and precipitation, mean that the internal surface and sub-surface of the test wall is found to be quite 'dry' although it maybe that different degrees of moisture are present in other, earlier, parts of the construction.

Interstitial Moisture

Figure 50. Interstitial, U-value and IAQ monitoring set up at Mill House, Drewsteignton, 2012.

Temperature and moisture measurements are being made through the test section of west-facing wall of the study room at Mill House (Fig. 50). Combined temperature and relative humidity sensors are located at four points within the wall at the heights and depths given in Table 18 coupled with sensors to record internal and external conditions. Data from all these sensors, for the period 7th February - 9th September 2012, has been collected and used as the basis for the following analysis. The positions of sensors 3 and 4 in the 2012 monitoring correspond with those of the pre-refurbishment monitoring carried out in 2011 (albeit sensor 3 now occupies the 2011 sensor 2 core). However, sensors 1 and 2 have now been positioned to provide readings from the air gap behind the plasterboard finish and at the insulation/masonry interface.

Build-up - **internal - external**	**Depth of material**	**Sensor no.**	**Height from finished floor level**	**Depth of sensor from internal surface**
Gypsum skim	3			
Plasterboard	12.5			
Air gap	25	Sensor 1	1730mm	30mm
PIR Board	100	Sensor 2	1580mm	140mm
Tanking & gypsum	3			
Lime Plaster	20			
Granite	580	Sensor 3	1430mm	340mm
		Sensor 4	1280mm	610mm
Total	**744**			

Table 18. Interstitial gradient sensor record for Mill House, Drewsteignton, 2012.

Figure 51 below shows the average values of each sensor over the February - September 2012 monitoring period graphed as separate temperature and dewpoint gradients, as well as the maximum and minimum values for these two gradients recorded over the monitoring period. The values derived from the relative humidity sensors have been converted to dewpoints in order to indicate the likelihood of condensation forming within the wall. Figure 52 provides a comparative graph which overlays the 2012 data with the same data recorded during the 2011 pre-refurbishment interstitial hygrothermal gradient monitoring.

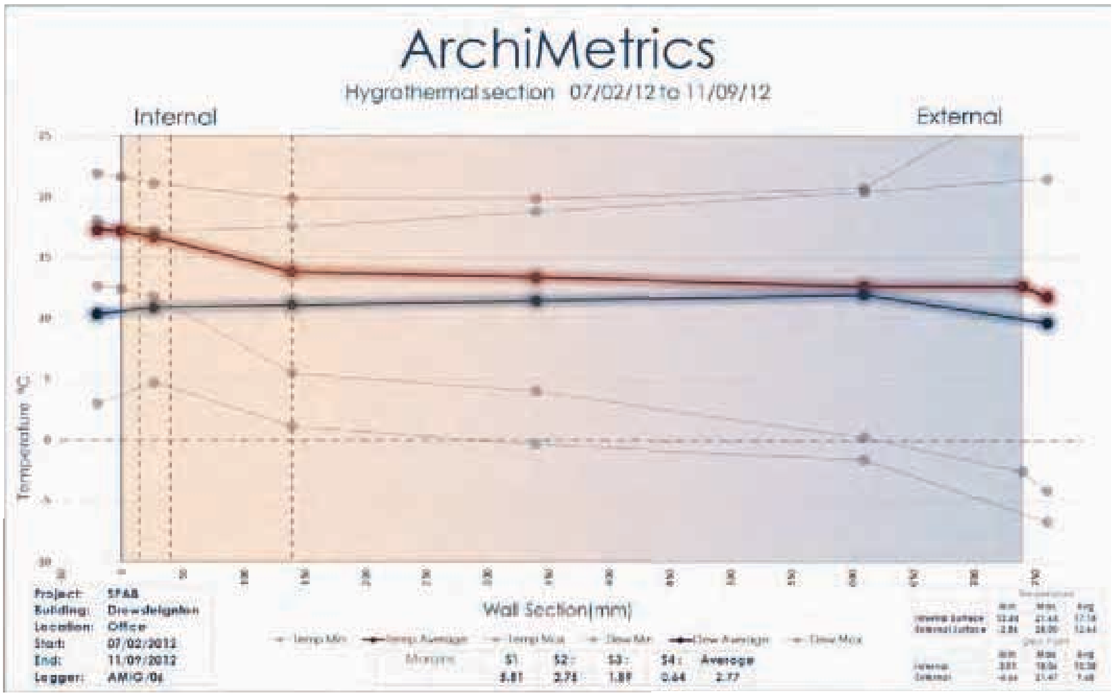


Figure 51. Temperature and dewpoint gradients for Mill House, Drewsteignton, 2012.

In a similar but more pronounced way to that found for the internally insulated wall at Shrewsbury, the steepest fall in the temperature gradient for the test wall at Drewsteignton occurs, appropriately enough, through the insulated portion of the wall build-up (Fig. 51). And following this, also in a similar way to Shrewsbury, the temperature gradient through the masonry part of the wall is virtually flat with only a few degrees of temperature difference between sensor 2 located behind the insulation and sensor 4 positioned behind the exterior face of the wall. A significant difference, however, between this graph and that produced for Shrewsbury can be seen in the plotting of the maximum values over the monitored period. The monitored wall in Shrewsbury is south-facing and on sunny days this showed a very pronounced reversal of heat flow from the exterior back into the wall, with the external surface temperature peaking at around 45˚C. At Drewsteignton although it is possible to see a reversal of heat flow through the wall up to the point of insulation from the plot of the maximum values this is much less pronounced and the external surface temperatures only peak at 28˚C. This is due to the different orientation of this wall which faces west and therefore receives direct sunlight for a much shorter period of time on sunny days.

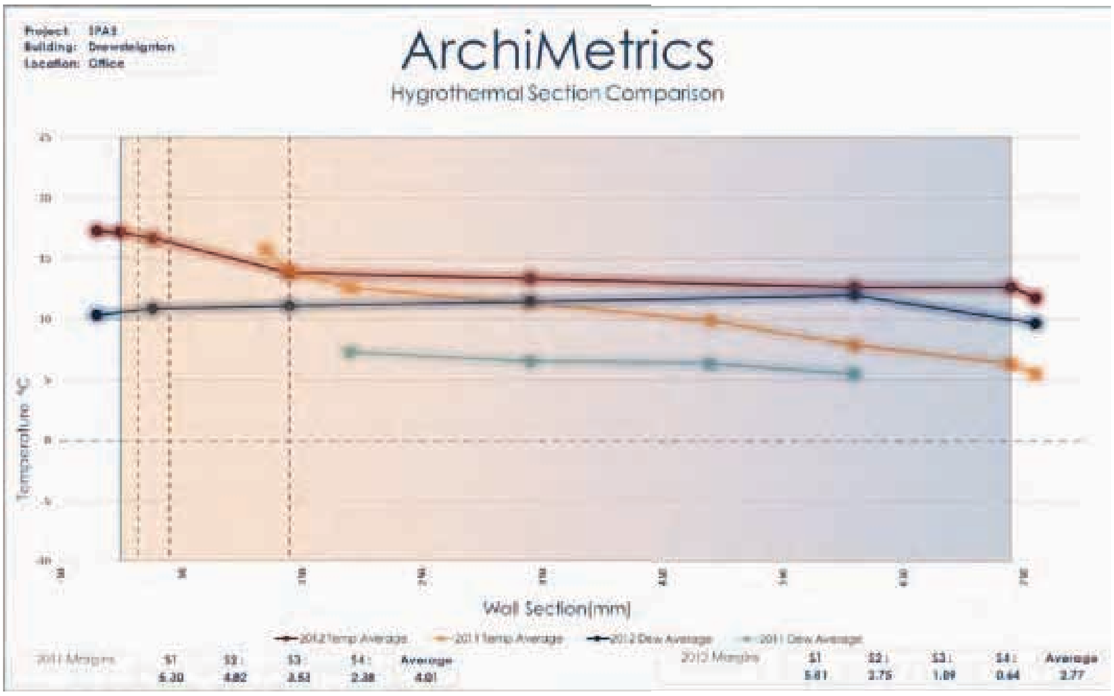


Figure 52. 2011 & 2012 temperature and dewpoint gradient comparison for Mill House, Drewsteignton.

Figure 52 allows a comparison to be made between the 2011 and 2012 interstitial hygrothermal gradient monitoring. As with the previous examples at Shrewsbury and Riddlecombe the generally raised temperature gradient through the masonry part of the wall seen in the 2012 readings is not as a result of the wall's improved thermal performance but is a factor of the duration of the monitoring which has been extended and now includes the warmer spring and summer parts of the year. One striking thing about Figure 52 is the change in dewpoint gradients between the two years. The 2011 data (drawn in pale blue and orange) conforms to an understanding of orthodoxy in terms of dewpoint behaviour, that is; temperature and dewpoint will tend to coalesce towards the colder exterior extremes of a building element. This pattern can be seen in the 2011 temperature and dewpoint gradients. It can also be seen in the gradients drawn from the 2012 monitored data, the difference being that, despite generally raised temperatures which might improve the dewpoint margin, the dewpoint is also raised and begins to converge towards the temperature gradient around the 4th node. The dewpoint margin that was calculated across all four nodes in 2011 was 4.01˚C, with the outer node in isolation calculated as 2.38˚C. From the 2012 data the dewpoint margin across all four nodes has reduced by 31% to 2.77˚C and by 73% for the fourth node alone, which at 0.64˚C is moving towards saturation point.

Relative Humidity

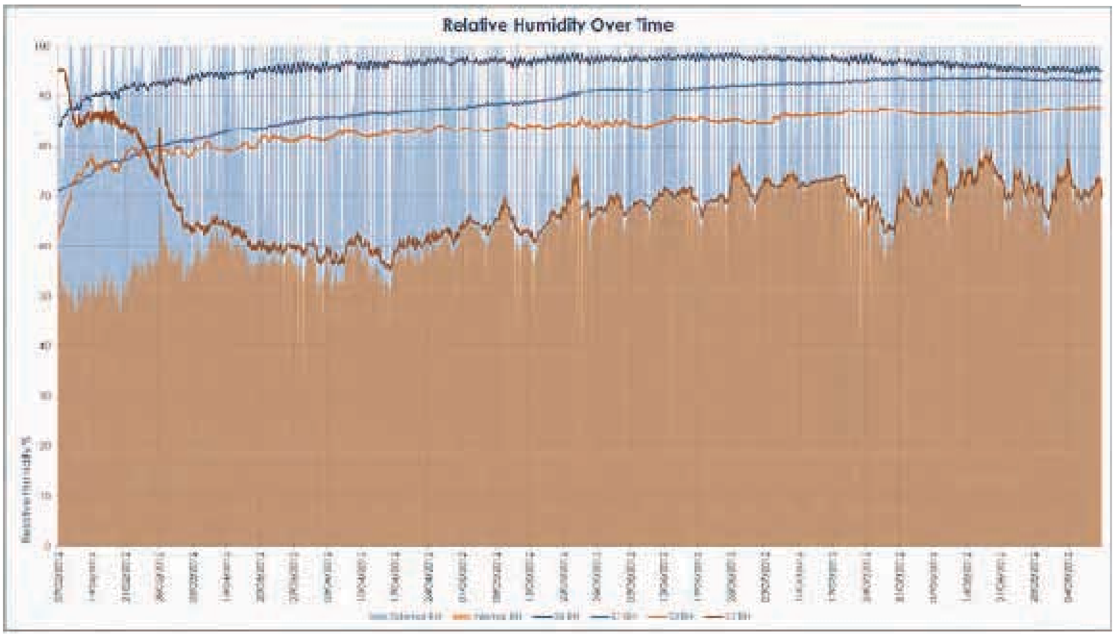


Figure 53. Plots of interstitial RH, internal room RH and external RH and temperature, test wall, *Mill House, Drewsteignton 2012*.

By plotting levels of internal and external RH as well as those recorded at the interstitial sensors in the test wall at Mill House over time it is possible to see a trend developing within the masonry part of the wall (Fig. 53). Sensors 2, 3 and 4 all show RH rising during the monitoring period. The exception to this is sensor 1 located in the air gap behind the plasterboard drylining. This initially had shown quite high levels of RH which have fallen away and by around 6th March 2012 start to come into a steady relationship with measurements of internal room RH. The RH gradient for sensor 1 can be explained by the drying of the moisture that was bound with the gypsum plaster skim which had been applied to the interior surface of the plasterboard (this can be seen as patches of damp in Figure 50). It is interesting to note the length of time taken for this drying to occur. Also worthy of note is that, following this decline, the level of RH behind the plasterboard tracks that of internal room RH, suggesting that the drylining finish, complete with a coat of emulsion paint, is highly permeable and that the water vapour within the air in the room is easily able to move through the drylining into the air gap behind with the result that room and air gap RH are more or less equivalent. Sensors 2, 3 and 4 however are located adjacent to and within the original masonry part of the wall and these show a different picture where levels of RH are seen to mostly increase during the monitoring period.

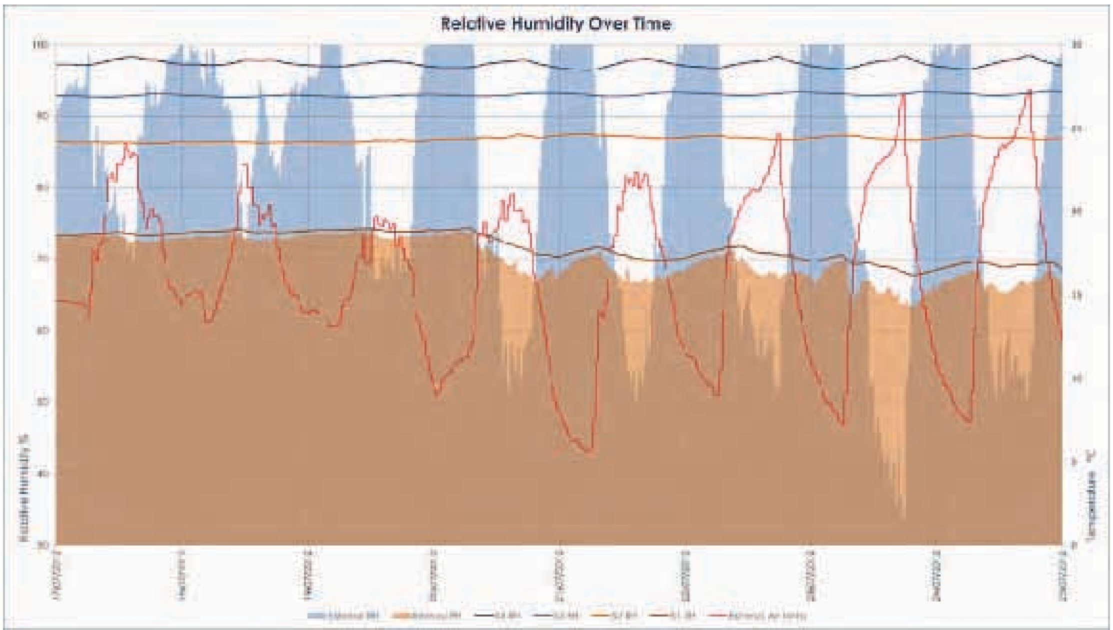


Figure 54. Detail - plots of interstitial RH, internal room RH and external RH and temperature. test wall, Mill House, Drewsteignton, 2012.

A plot of a 'detailed' week of RH data from Drewsteignton shows some interesting trends. Here again, like the wall at Riddlecombe, it is possible to see interstitial RH responding to raised external temperature, albeit without the accompanying accumulation in moisture vapour seen at Riddlecombe (Fig. 54). The peaks in RH shown from sensor 4 appear to be a direct response to spikes in temperature (these spikes are particularly pronounced and can be explained as the period of time during the day that the west-facing wall received direct sunshine). It is also possible to see a similar but less pronounced response in RH at both sensor 3 and sensor 2 but this is offset in time, an echo of what has occurred nearer to the external surface, which maybe due to the heavyweight nature of the granite wall which results in a slow and flattened thermal response and as a consequence retards and diminishes the wall's deeper interstitial RH responses. Towards the end of the monitoring period shown in Figure 53 it can be seen that levels of RH, having increased at sensor 3 and 4 begin to diminish whilst those recorded at sensor 2 positioned directly between the insulation and masonry continue to increase. It will be interesting to observe the trends of the plots from the interstitial sensors within the wall at Drewsteignton as the monitoring moves from summer back to winter, this will be commented upon in future reports.

The general increase in RH seen from these three sensors returns us to the dewpoint gradient for the test wall at Drewsteignton and the reduced dewpoint margin calculated for the wall, particularly for the 4th node. Orthodoxy suggests that dewpoint is more likely to be reached on or in proximity to the external face of a wall during the winter months when the saturation point of air is reduced by lower external temperatures. However, here in the wall at Drewsteignton at node 4 we find dewpoint and temperature converging during the warmer spring and summer months and from Figure 53 it can be seen that the reduction of the dewpoint margin mostly likely occurs as a result of the increase in RH in the masonry over the monitoring period. There maybe a number of reasons for this; as has been shown the wall's RH response is tied to external RH and although the RH of external air normally decreases during the warmer summer months we have experienced unusually high quantities of rain during the spring and summer months of 2012 while this monitoring was being carried out. This may in turn have increased the moisture load of the stone wall and thus raised the RH levels found within the fabric. In addition, the poor summer weather has meant a reduced number of sunshine hours and this lack of solar heat may have depressed temperatures within the wall. The combination of depressed masonry temperatures and wetter wall fabric as a result of this particular pattern of weather could mean that the wall has been brought closer to dewpoint than would normally be the case. Or these two effects, of colder and wetter fabric, could also be occurring as a result of the insulation that has been applied to the internal face of the wall cooling the fabric by preventing heat from the interior penetrating into body of the wall and/or causing the fabric to retain moisture in someway, perhaps by preventing the evaporation of moisture from the interior face. The interstitial hygrothermal gradient monitoring is on-going at Mill House (as it is in the other properties within this survey) and this longer-term monitoring should allow a more detailed understanding of the principal drivers that are affecting the wall's thermal and moisture response over the long term.

Sensor values for the wall were logged at 5-minute intervals and this information has been animated in order that changes in temperature and dewpoint maybe analysed over time. (To view the 2011 and 2012 interstitial gradient animations for Mill House, Drewsteignton, visit www.archimetrics.co.uk.)

The 2012 interstitial hygrothermal gradient animation clearly shows over time a number of phenomena described above; the temperature gradient steadily climbs up the temperature scale as the monitoring moves from winter through spring to summer. It is possible to see the dewpoint (calculated from %RH) declining at node 1 as the drylining dries out and then settling into an equilibrium with internal room dewpoint. Throughout the animation the dewpoint gradient within the masonry part of the wall gradually closes towards the temperature gradient and remain in close proximity to one another although the two plots never completely intersect. In general the heavy weight nature of the wall can be seen from the relative inertia observed from the temperature responses in sensors 2 and 3 towards the centre of the wall, their fluctuations are less pronounced than those of sensor 4 which is positioned at the exterior extremity and therefore is more affected by external temperature change.

INDOOR AIR QUALITY

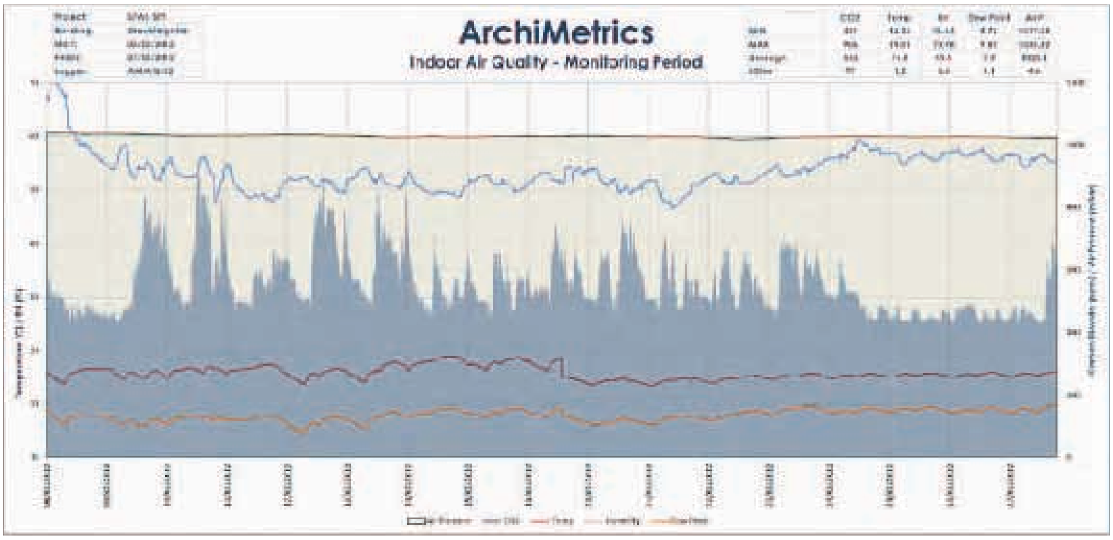


Figure 55. Indoor Air Quality (CO_2, temperature, RH, dewpoint and air pressure) Mill House, Drewsteignton, 2012.

Figure 55 plots temperature, RH, CO_2, dewpoint and air pressure levels for the office room at Mill House, Drewsteignton, between the period 8th February - 27th February 2012. Table 19 provides a summary of the indoor room conditions, the figures represent average values recorded in 2011 and 2012.

Property & Date	**CO_2 (ppm)**	**Temp (˚C)**	**RH (%)**
Drewsteignton (04/03/11 - 18/03/12)	581	16.8	55.13
Drewsteignton (08/02/12 - 27/02/12)	553	15.8	59.7

Table 19. Indoor Conditions at Mill House, Drewsteignton, 2011 & 2012.

Given that no general refurbishment work has taken place in this particular room at Mill House it is perhaps not surprising there is very little difference between the values recorded in 2011 and those gathered in 2012. The insulated section of test wall measures only $5.6m^2$, roughly 13% of the overall external wall surface of the room, therefore there will be no general benefit to the air temperature of this room as a result of the addition of this insulation. In fact there is a slight dip in the average temperature found in 2012 which can perhaps be explained by the fact that the 2012 measurements were taken somewhat earlier in the year, in February, so temperatures may have been somewhat cooler compared to those in March which was the period of the previous 2011 measurements. There is a slight rise in average room RH recorded in 2012 and this could be explained by the addition of a wet finish to the test section of wall which, as has been previously discussed, raised RH levels in proximity to this for a time.

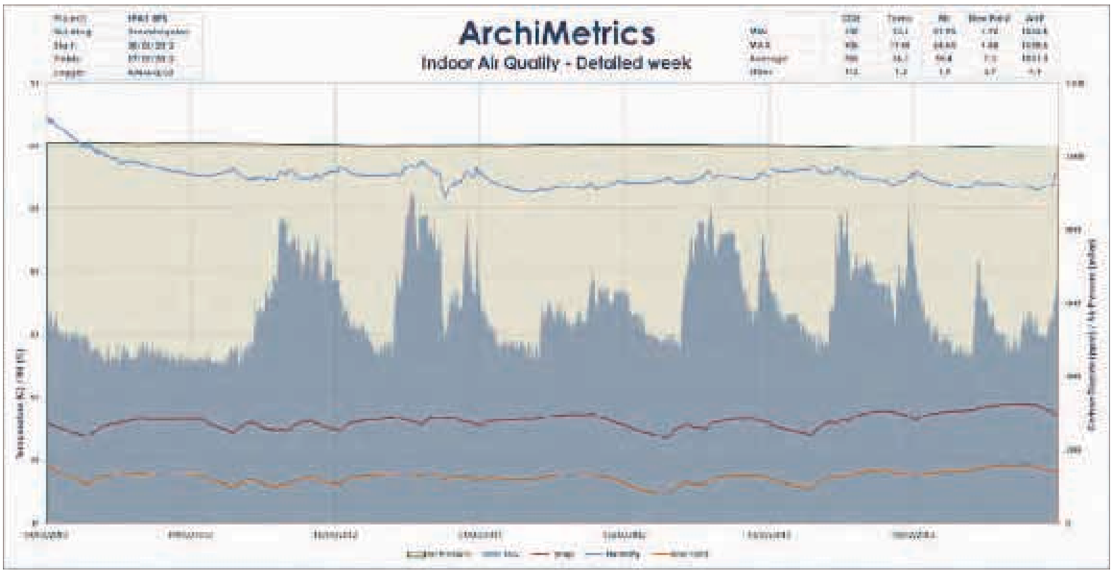


Figure 55. Detail - indoor air quality (CO_2, temperature, RH, dewpoint and air pressure) 8th - 14th February, Mill House, Drewsteignton 2012.

Periods of occupancy of the study at Mill House can be seen in the raised measurements of CO_2 for most days in the week 8th - 14th February (Fig. 55). There are occasional steep falls in CO_2 which could be explained either by window opening or accidental purge ventilation or just high external wind speeds and then elsewhere there are rather more gentle decays as the room more slowly returns to its normal background levels of CO_2. The average CO_2 for this detailed week remains on the low side at 585 ppm, within acceptable limits for good air quality and even the maximum value recorded for this week, of 906 ppm, remains below the ASHRAE recommended limit of 1000 ppm. There is very little change in RH in relation to occupancy, and this, as well as the reasonable CO_2 levels measured at Drewsteignton are most likely as a result of the large overall volume of the room (88m^3).

COMFORT & FABRIC RISK

Individual indoor temperature and room relative humidity readings have also been plotted against an index of human comfort and fabric risk. The 2012 results for Drewsteignton recorded between 7th February - 11th September 2012 can be seen in Figure 56, with the 4th - 18th March 2011 graph reproduced for comparative purposes in Figure 57.

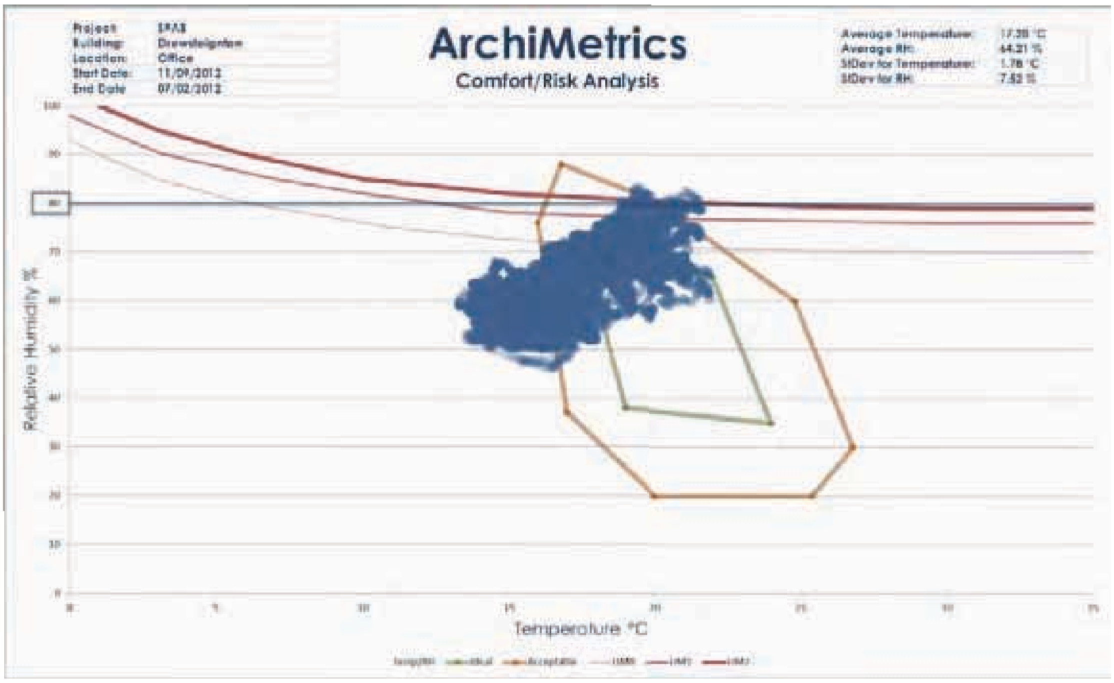


Figure 56. Comfort/Risk Analysis for Mill House, Drewsteignton, 2012.

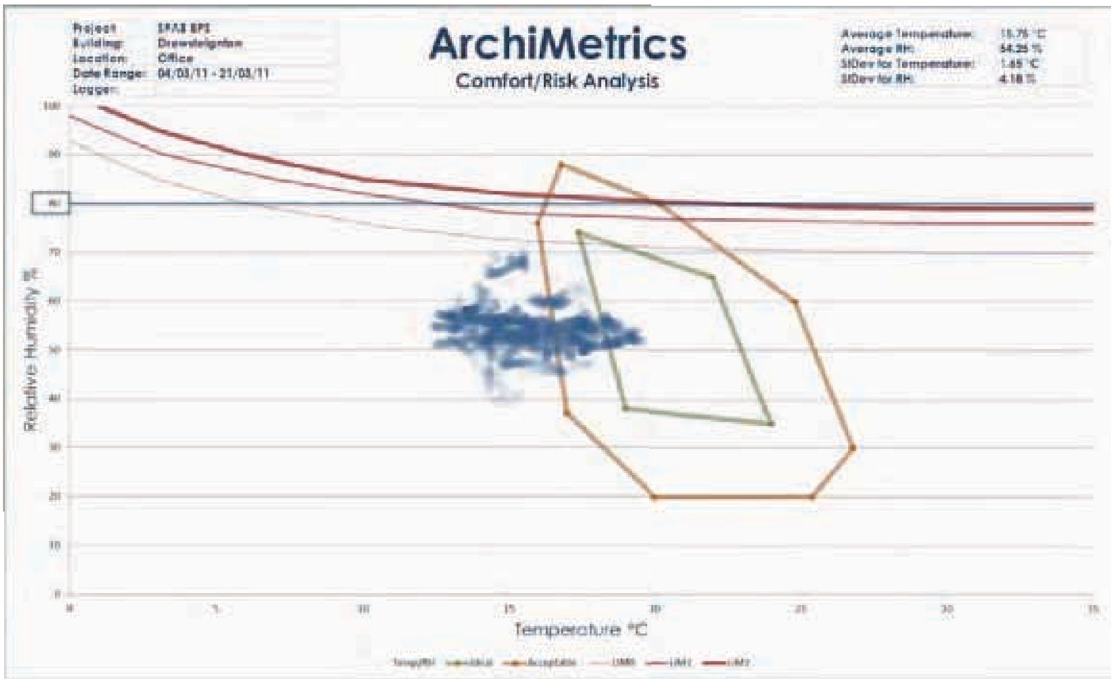


Figure 57. Comfort/Risk Analysis for Mill House, Drewsteignton, 2011.

The 2012 graph (Fig. 56) plots data gathered over a much longer time period (7 months) than was the case in 2011 (15 days) hence the increased density of blue temperature and RH plots for this year.

Figure 56 from the 2012 data shows that in comparison with the much shorter period of monitoring carried out in 2011 temperature and RH is in general higher. This maybe because the 2012 graph includes measurements that extend through the spring and summer and therefore incorporate what has been an unusually wet year. Figure 56 from 2012 places the temperature of the room mostly within the bounds of the 'acceptable' polygon that defines a range of temperatures for human comfort, whereas in the previous shorter winter monitoring of 2011 the majority of temperatures sat outside of this polygon at the colder end of the temperature scale. RH between the two years also shows very different levels for the reasons previously given, although it is interesting to note that over the extended 2012 period part of the RH record now does bisect the limiting isopleths for mould growth including peaking briefly above 80% normally regarded as the upper limit beyond which conditions become conducive for mould growth on both timber and masonry substrates.

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