Solid wall heat losses and the potential for energy saving

The nature of solid walls in situ

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Notes

This report is part of a collection of outputs from the BEIS research project investigating the savings achieved with the installation of solid wall insulation. These will be made available on the project web site where a summary of the project can also be found (see http://www.bre.co.uk/swi).

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Executive Summary

Previous work by BRE and others has identified that U-values of solid wall dwellings measured in situ are lower than the generally assumed value of 2.1 W/m²K.

In order to investigate the likely reasons for measured U-values being lower than the generally assumed value, BRE has undertaken an extensive programme of research into the thermal performance of solid walls. This report outlines the results of a detailed investigation of the nature of solid walls in situ to understand whether differences between our usual assumptions about these walls, and their true nature, can help explain these differences between the measured values and the historic assumptions. This has taken the form of a combination of fieldwork, laboratory experiments and theoretical work.

Following this work, we can conclude that there is now good evidence to support a revision to the assumed U-value for uninsulated solid walls to approximately 1.75 W/m²K. The lower U-values seem likely to result from the following factors, which are supported by evidence from this research:

a) Additional air cavities within the wall. In particular, there is typically missing mortar in the collar joints of the wall, and at the perpends. There are also often broken bricks and snapped header bricks forming part of the inner leaf of the wall and frogs forming additional cavities.

b) Lower moisture contents than typically assumed. Rather than assuming 5% by volume as the moisture content, median values measured by this work were 0.8% for brick and 2.8% for mortar. This has the effect of significantly lowering the U-value of the wall.

c) Walls are also generally thicker than has generally been assumed.

The fieldwork visited 137 dwellings. In 87 of these, dust samples and/or brick samples were obtained in order to better understand the properties of the bricks and mortar used in the construction of the walls. Additional valuable information was obtained through a visual inspection of the internal structure of these walls following the removal of a brick. Other fieldwork visits, to three dwellings, obtained extensive dust drillings from all facades of the dwelling in order to ascertain how moisture content may vary over the extent of all walls.

The laboratory investigations included the construction of six solid walls for testing in the hot box apparatus at the National Physical Laboratory (NPL). This apparatus is able to measure the U-value of these walls directly, under controlled laboratory conditions. These tests included the construction of walls which aimed to mimic the observations from the fieldwork.

Alongside this, measurements of the thermal conductivity of 24 bricks were also made using the Guarded Heat Flow Meter apparatus at NPL. These have been supplemented by measurements of the thermal conductivity of an additional 33 bricks using the Hukseflux TP01 sensor. Further investigations have also been made using a thermal needle probe which allows for the measurement of thermal conductivity in situ.

The key findings from the fieldwork investigations in the 87 dwellings where bricks were removed and/or samples taken were:

a) The space between stretcher bricks, known as the collar joint, was seldom fully filled with mortar. The median percentage of the exposed area estimated to be filled with mortar was 67%. Traditional calculations assume that all joints within a wall are filled with mortar, and air spaces in these joints will lead to lower (improved) U-values.

b) Perpend joints were also seldom fully filled with mortar. The median percentage of the exposed perpend area estimated to be filled with mortar was 70%. The air spaces in these joints will lead to lower U-values.

c) Where a brick contained a frog, if it was found on the top face of the brick (brick laid “frog-up”) then it was almost always fully filled with mortar. If it was found on the bottom face of the brick (brick laid “frog-down”) it was very seldom filled with mortar. The air space created by the frogs will lead to lower U-values.

d) Broken or damaged bricks forming part of the wall were relatively common. Snapped header bricks or partial or deformed bricks forming the inner leaf were revealed in approximately 1 in 10 cases. These generally resulted in additional air cavities, which will lead to lower U-values.

e) Bricks were generally very dry. The median moisture content of brick and dust samples by volume was 0.7%. Some bricks, however, were extremely wet with a median moisture content of over 15%. Typical assumptions in calculations are that bricks have a moisture content of 5% by volume. If bricks are significantly drier than this, it will act to reduce their conductivity and the U-value of the wall.

f) Mortar was slightly wetter, although generally also dry. The median moisture content of mortar by volume was ~2.8%. Some mortar, however, was also extremely wet with a median moisture content of over 15%. Mortar is generally assumed to have a moisture content of 5% by volume. If mortar is, in reality, drier than this, it will act to reduce its conductivity and the U-value of the wall.

g) The median dry density of bricks was higher than the generally assumed value. The median measured density was 1,804 kg/m^3 rather than the often assumed 1,750 kg/m^3. There is a general relationship between density and thermal conductivity, with denser bricks likely to be more conductive giving rise to walls with a higher U-value.

The testing of the built walls in the hot box provided some laboratory validation of the U-values of solid wall structures which we had built. The walls that we had built in order to replicate many of the features observed in the fieldwork had U-values of between 1.69 W/m^{2}K and 1.96 W/m^{2}K.

The tests on brick thermal conductivity allowed the derivation of a new relationship between density of the samples and the brick thermal conductivity. There are considerable doubts over the validity of historic thermal conductivity measurements, and these new measurements revealed conductivity to be higher than many older measurements.

The measurements also revealed that, even within bricks from the same batch, thermal conductivity can vary by up to a third between samples.

Of the three dwellings where extensive dust drillings were taken for moisture content, it was found that moisture content varied significantly across the extent of the walls from less than 1% in some areas to greater than 10% in others. Even in adjacent areas, the moisture content showed substantial variation.

The final part of this research has applied the findings of the work to the theoretical calculation of wall U-values, in an attempt to reconcile the measured and theoretical calculated values.

The first part of this has examined the effect of including the fieldwork and laboratory observations within the calculation of a typical solid wall; i.e. one with a typical thermal conductivity, moisture content and internal structure, to determine a new average value for a solid brick wall. The fieldwork has provided strong evidence to suggest refinements to the calculation of U-values to incorporate additional air cavities within the wall, and refined default moisture and density values. This has the effect of reducing the theoretical U-value from 2.1 W/m^{2}K to 1.77 W/m^{2}K for a typical wall, of the sort identified in the fieldwork.

It remains difficult, however, to obtain a good match between theoretical calculations and measured U-values on any individual wall, even when we include observations on the type of brick and moisture content. We can associate this with the heterogeneity of the wall structure, and the known variation in moisture content and brick thermal conductivity across the walls of a dwelling as revealed by this work; i.e. the limited observations made at the sampling location may not represent the situation in the exact locations where the U-value is being measured by the heat flux plates.

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1 Introduction

There are approximately 23.4 million dwellings in England. Of these, approximately 25% - 30% are of solid wall construction. Insulating these dwellings could deliver significant carbon dioxide emissions savings as they have some of the poorest performing walls in the housing stock however previous research has identified a gap between calculated savings and actual realised energy savings following the application of solid wall insulation. Typically, the actual savings achieved are less than predicted. This gap affects the potential energy, cost and carbon savings from solid wall insulation which makes the intervention a less cost-effective measure to install, with potentially significant impacts on Government policy.

One of the reasons why the predicted savings are not being achieved is that the solid walls are performing better than expected in their unimproved state. Previous work by BRE and others [8, 9, 10] has cast considerable doubt over long-held assumptions on the thermal performance of uninsulated solid walls. Existing assumptions have been challenged through extensive in situ measurements, across a wide spectrum of solid walled dwellings. These studies raised important questions about why existing solid walls may be performing better than had been previously assumed and a key aim of the solid wall insulation research programme was to understand why this may be the case.

This report presents the results of a programme of research which attempted to address whether the nature of solid walls in situ can be reconciled with the measured U-values.

The research programme consisted of a number of different, but linked, areas of investigation. The first of these consisted of a large fieldwork programme examining heat losses from existing, unimproved, solid walled dwellings alongside additional, more intrusive, investigations of the physical nature of the wall itself. Alongside this, a series of laboratory tests have been undertaken to provide additional insight, under controlled laboratory conditions, into the nature of solid walls in situ. Finally, revised theoretical calculations of the U-values of walls have been performed to understand whether the new knowledge, as generated from the fieldwork and laboratory tests, can help explain why U-values in solid wall dwellings are lower than had generally been assumed.

1.1 Background

Context: Historical U-values and previous BEIS U-values work

It is important to be able to accurately estimate the U-values of uninsulated solid walls for many reasons. Among these are the need to determine the likely cost and carbon savings from insulation measures, the need to accurately size heating appliances, and the need to be able to estimate the heating costs of dwellings for Energy Performance Certificates. This type of dwelling represents around one-third of all dwellings in the UK, yet basic details about the constitution of the walls of these dwellings, and the implications for thermal performance, are not well understood.

2.1 W/m^{2}K as the default for solid wall U-values

Recent editions of key guidance documents, such as CIBSE guides [14] and RdSAP Appendix S [15], all list the U-value of a wall as 2.1 W/m^{2}K. This value has a long heritage, and has been broadly supported by some theoretical calculations, and some experimental work.

The earliest work of this sort focussed on experiment. This includes tests undertaken in the 1920s on behalf of the Government's Building Research Board (the predecessor to the Building Research Station (BRS), and subsequent Building Research Establishment). One of these publications includes an assessment of the thermal properties of a solid brick wall, which had been produced by BRS scientists in conjunction with the National Physical Laboratory (NPL) [2]. The ‘hot box’ work which we have recently undertaken and present here, bears many similarities to these early tests.

Slightly later work, undertaken by BRS in the 1930s in its specifically designed “Wall Laboratory”, also aimed to measure the thermal conductivity of solid brick walls. This work, produced by Dufton, provided measured U-values of between 2.2 and 2.6 W/m^{2}K [1].

The modern origin of the default solid wall U-values appears to be in the form of the production of the 1970 IVHE guide [4] (the forerunner of today’s CIBSE guide). For this guide, BRE’s Loudon [3] produced theoretical calculations of numerous building elements of different types, including solid walls. These theoretical calculations were compared to experimental measurements, and considered to be satisfactory. Indeed, the theoretical calculations of U-values for solid walls were compared to the measurements of U-values undertaken by Dufton in the BRS Wall Laboratory in the 1930s described above [1]. Of these original measurements made in the Wall Laboratory, however, Loudon noted several deficiencies and additional observations. In particular:

“U-values of masonry walls slowly decreased as moisture dried out, and changed noticeably when the walls were left in place for a second or third heating season. Most of the measurements were made during the first year after erection and the U-values were higher than for typical walls.”

Loudon proposed updated methodologies for various elements of the calculation, including the assumed moisture content of bricks (5% by volume for exposed, and 1% for sheltered) which are generally used today. In the 1970 IVHE guide, based on these assumptions, a value of 2.1 W/m^{2}K was proposed for the U-value of a solid wall.

Later editions of the guide [e.g. 5, 14] (now the CIBSE guide) continued to employ theoretical assumptions, maintaining the modern value for the U-value of a solid wall of 2.1 W/m^{2}K. This was taken into RdSAP Appendix S when this was first produced in 2005 in support of the introduction of Energy Performance Certificates (EPCs).

The assumption that 2.1 W/m^{2}K is a suitable representation of the U-value of solid walls appears to have remained unchallenged until fairly recently. Although some very early unpublished work undertaken in the BRS Experimental House in 1935, using an ‘in situ’ technique, measured U-values of between 1.5 and 1.8 [12] these findings appear to have been soon superseded by the Wall Laboratory findings [1] measuring higher U-values, and which were later compared to the theoretical assumptions in the 1970 IVHE guide. In 1993, Ward [6] produced some in situ U-value measurements which were below 2.1 W/m^{2}K, but the number of measurements made was relatively small. It was not until larger scale work, in anticipation of a programme of solid wall insulation being rolled out in the UK, that the value first began to be seriously challenged. Initial work undertaken by BSRIA and the Energy Saving Trust [7], measured U-values in solid wall dwellings in advance of a programme of insulation. These measurements indicated a significantly lower U-value than the default value of 2.1 W/m^{2}K. Other work, for example, Rhee-Duverne & Baker [8] and SPAB [9] indicated similar findings, although often on unusual dwelling types (e.g. historic buildings).

To confirm these findings a more systematic survey was required. To achieve this, BRE was asked to carry out in situ measurements of wall U-values in a sample of solid wall dwellings across England. This took the form of visits to 118 solid wall dwellings, together with more detailed investigations in a subsample of those [10].

The average measured U-values returned by the BRE survey for solid walls are shown in Table 1. Also shown are the average calculated U-values.

The averages of the measured values for solid walls are lower than (i.e. better performing than) the standard values used in the RdSAP methodology, and below the mean of the theoretical calculated U-value produced using observations about the walls that were measured.

Wide variations in U-values within the measurements were observed, which may indicate variability within the walls, or may indicate some variability within the measurement process itself (or indeed both). The results for solid walls are broadly in line with the findings of other work, including the BSRIA/EST Solid Wall Insulation Field Trials [7], in that the measured U-values of solid walls are significantly below those calculated and assumed in RdSAP.

Table 1: Summary of results from BRE in situ U-values study

Wall type	Number of cases	**Measured U-values: mean (95% CI) W/m²K**[*]	**Measured U-values: median W/m²K**	*Calculated U-values: mean (standard deviation) W/m²K*	*Calculated U-values: Median W/m²K*
Solid wall, standard[a]	85	**1.65 (+/- 0.07)** **(1.57 excluding +5% correction)**	**1.67** **(1.59 excluding +5% correction)**	*1.90*	*1.92*
Solid wall, non-standard[a]	33	**1.34** **(1.28 excluding +5% correction)**	**1.34** **(1.28 excluding +5% correction)**	*1.91*	*1.68*

Note a) Solid wall standard cases are solid brick walls with a thickness < 330mm. Solid wall non-standard cases are brick walls with a thickness >= 330mm and solid walls constructed of a material other than brick (such as stone or concrete).

The BRE survey collected limited data on brick density and moisture content using a core-drill from a small further sample of 10 solid walls. The additional data acted to align calculated and measured values in some, but not all, of the cases examined. The drilling process had revealed that, in all of the cases examined, mortar density was very low, or possibly completely absent, in the space between the stretcher bricks, known as the collar joint, in these walls. The best alignment, on average, for this wall type was found to be when calculations were performed combining data on moisture and density with the assumption that the gap between stretcher bricks was filled with air (as was supported by these observations).

1.2 The solid wall insulation research project

In 2012, our understanding of why the U-values of solid walls were being measured lower than the standard value of 2.1 W/m²K was limited. Some initial insights had been gained by the previous programmes of research, but these required confirmation and many questions were outstanding.

In particular, questions on the validity of the measurement process, and on our level of understanding of the real internal make-up of solid walls in situ. In order to address these research questions, BRE was commissioned by the Department of Energy and Climate Change (whose responsibilities now lie with the Department of Business, Energy and Industrial Strategy) to undertake an extensive programme of research into solid wall dwellings, and the measurement process for U-values.

The report "*In situ measurement method review"* which formed part of this project [16] provides an assessment of the measurement process, and provides significant confidence in the suitability of the method employed for measuring U-values in situ. In particular, it concludes that the results from the measurements align well with the results obtained in a laboratory hot box in both steady state and dynamic conditions. It recommends, however, an upwards adjustment in measured U-values of 5% in order to account for a small systematic error in using the default calibration factors of the measurement equipment (this value being derived both experimentally, by comparison with the hot box, and through thermal modelling of the measurement system and calibration setup). This small adjustment alone, however, is insufficient to explain the gap between the average measured and calculated U-values of solid walls.

It seems most likely, therefore, that the majority of the discrepancy between theory and measurement results from our knowledge of the inputs into the calculation – i.e. the details of the solid wall which are input into the theoretical calculations. This report sets out the findings from the elements of the project which have assessed the nature of solid walls in situ.

The programme included the following items:

Fieldwork: A programme of fieldwork where U-value measurements were undertaken alongside an examination of the interior of the wall and the removal of brick and dust samples. This included the removal of a brick to inspect the interior of the wall, and removal of a sample of brick for density and moisture testing.

Laboratory hot-box tests: Six solid walls of different configurations were built in the laboratory at the National Physical Laboratory (NPL) and tested in their guarded hot-box apparatus. These tests were designed to identify, in a laboratory environment, the effect on U-values of the fieldwork observations.

Moisture tests: Extensive moisture tests at three dwellings were undertaken to determine the extent that moisture may vary across different facades of the same solid wall building.

Laboratory thermal conductivity measurements: Brick samples returned from the fieldwork were tested for thermal conductivity at NPL in their guarded heat flow meter apparatus. Additional tests were undertaken by BRE using a transient measurement technique.

In situ thermal conductivity measurements: A thermal needle probe was tested in the field to assess whether thermal conductivity could be readily assessed in situ.

Consideration of the implications of findings for theoretical U-value calculations of a typical wall: The assumptions made in the theoretical calculation of U-values for a typical wall were reassessed in light of the fieldwork findings. The effect on the calculated U-values was assessed.

Comparison of revised theoretical and measured U-values: Finally, the measured results from the fieldwork and the theoretical calculated U-values were compared at an aggregate level (i.e. in terms of averages) and on a case-by-case level.

This report is structured in two parts. Part A outlines the results of the fieldwork and laboratory experiments on the nature of solid walls as found in situ. This is followed in Part B by the assessment of the implications of the results from the fieldwork and laboratory experiments on the calculations of theoretical U-values.

Part A: Fieldwork and laboratory experiments

2 Fieldwork component 1: Measurement of U-values in situ and detailed investigation of the nature of solid walls.

The previous BRE U-value study [10] showed that there is a difference between the measured and calculated U-values for the solid walls studied and that this difference was not completely explained by the observations made in that study. The report on the in situ measurement technique [16], undertaken alongside the work presented here, concludes that, aside from a small correction, the in situ measurement process is fit for purpose. It seems highly likely, therefore, that many of the reasons for discrepancies between the theoretical calculated and measured U-values relate to the assumptions made in the calculation about the wall construction or materials used.

To better understand the true nature of solid walls in situ, an assessment of the internal structure and properties of solid walls, alongside direct measurements of their thermal performance (i.e. their U-values) was considered to be required. The assessment was to include investigation of the physical nature of the wall (i.e. spaces between bricks, levels of mortar fill) and investigation of materials properties such as brick densities and moisture contents.

In order to investigate this, BRE recruited and then visited 137 dwellings to undertake measurements of U-values and related wall characteristics. In 87 of these dwellings, additional detailed investigations of the wall were undertaken alongside in situ U-value measurements. The field investigations of the wall included the removal of a brick and inspection of the void created, removal of a brick sample from the back of each brick (to obtain density and moisture content, and in some cases direct thermal conductivity measurements), and dust sampling from bricks and mortar for moisture content.

Dwellings were selected for these measurements primarily from those originally visited as part of the English Housing Survey (EHS) [17], and from a sample provided by a number of Housing Associations of solid wall dwellings selected for the pre- and post-insulation study which is reported on separately in the report *“Closing the Gap. Pre-, post-insulation field trial”* [13].

This section of this report outlines the results of these investigations, and interprets these in the context of understanding the nature of solid walls in situ.

2.1 Fieldwork methodology

The objectives of the fieldwork were to measure the wall U-values in situ and to investigate the nature of the wall through additional investigations of the wall composition.

2.1.1 Heat flux and U-values

The U-value measurement methodology builds on that used for the previous in situ U-values work undertaken by BRE, and which has been validated through other strands of the solid wall insulation research programme. For this work, additional heat flux plates were employed, with up to four used in each dwelling instead of the usual two.

The heat flux through a building element, such as a wall, is equal to the flow of heat (in watts) divided by its area (in m²). Hence, it is expressed in W/m² and is sometimes referred to as ‘power density’. Under steady-state conditions, a U-value can be calculated by dividing the heat flux through a wall by the difference in temperature across the same wall. In practice, the situation is complicated by the need to consider fluctuating temperatures, surface temperatures, radiant temperatures and the effect of thermal storage. This is taken account of by monitoring over a period of time that allows the result to converge to a reasonably steady value (typically at least two weeks).

The equipment used in the fieldwork

The fieldwork installed various items of monitoring equipment within occupied housing in order to measure the U-values of the walls. For each dwelling the heat flux was monitored by affixing Hukseflux HFP01 heat flux plates (HFPs) to the internal surface of the wall and recording readings for a continuous period of two weeks using Eltek dataloggers. Spot measurements were taken every minute, and averaged over a 15 minute period before being recorded by the datalogger. The heat flux plates are shown in Figure 1. Internal and external temperatures were also measured using thermistors and were recorded using the same Eltek dataloggers. Where it was difficult to measure external temperatures using wired thermistors, Gemini Tinytag temperature dataloggers were used. Pictures of both types of dataloggers are shown in Figure 2 and Figure 3. The heat flux plates shown in Figure 1 each generate a voltage which is directly proportional to the heat flux. The manufacturer, Hukseflux, has provided a calibration factor for each heat flux plate indicating the relationship between the voltage that a plate generates and the heat flux passing through it. Typically, each heat flux plate generates between 40 and 70 microvolts for a heat flux of 1 W/m². All heat flux plates were recalibrated by Hukseflux for this fieldwork, providing new calibration factors where required.

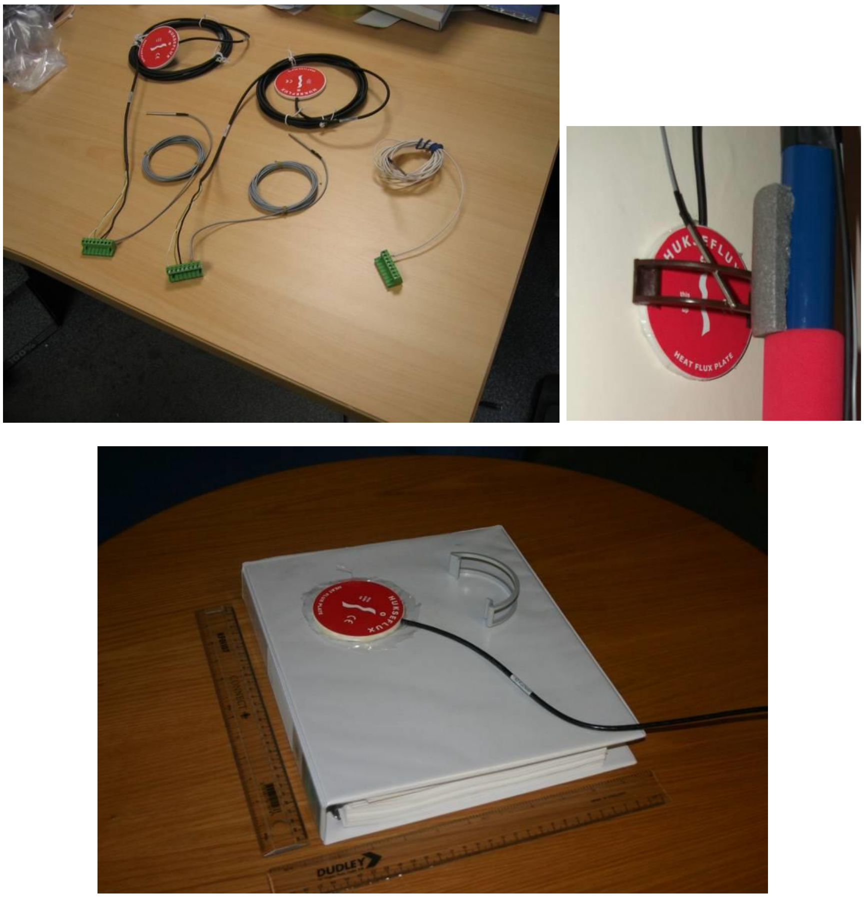

Figure 1: The sensing equipment used for monitoring the heat flux and temperatures. The Hukseflux heat flux plates (circular plates) measure heat flux (in watts per square metre) and the thermistor sensors (silver tubes) measure temperature.

Mounting the heat flux plates

The HFPs need to be placed firmly against the wall with a good thermal contact, without affecting the heat flow in the vicinity of the plate. This is achieved by applying a constant pressure using a flexible gutter clamp supported by a vertical ‘teleprop’ pole, as has been done successfully in previous BRE work, e.g. [10]. In order to ensure a good thermal contact, a flexible substrate was used consisting of a thin layer of petroleum jelly and a very thin layer of polythene (cling film) to protect the internal finish. An example of the equipment installed in a dwelling is shown in Figure 2. In each dwelling to be monitored, it was decided that in order to provide a better range of U-values, up to four heat flux plates would be used, with a minimum of two, in line with guidance in ISO 9869 [18] (note that only two of the four plates are shown in the image in Figure 2).

Internal air temperatures were monitored adjacent to the HFPs using thermistors (one thermistor was used per HFP), attached at a distance of approximately 20 mm from the wall. In order to avoid potential problems caused by radiant heat sources, the HFPs were sited away from sources of heat such as radiators, TVs and lamps.

Where practical, external air temperatures were monitored using thermistors attached to the same datalogger with the wires connecting the thermistor to the datalogger passed through a window. The wires were thin and robust enough that a window could be closed and locked without damaging either the wires or the window. Where this was not practical, such as when the nearest window was too far away, independent dataloggers (Tinytags) were used to monitor external temperature.

Data from the HFPs and the thermistors were recorded using an 8-channel Eltek 851L logger. This is shown in Figure 3.

Figure 2: The equipment installed in an occupied dwelling (left hand picture) showing the heat flux plates (red discs) and indoor temperature sensors supported by teleprops (blue poles) and clamps. Also shown is a Tinytag datalogger (right hand picture) attached to the outside wall (in a location out of direct sunlight)

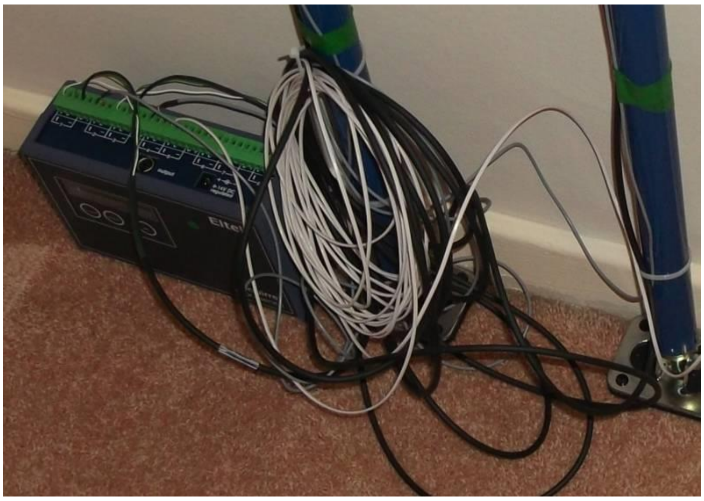

Figure 3: An Eltek 851L datalogger, recording EMF and thermistor readings from the sensing equipment

Selecting a suitable location

Installation locations varied from dwelling to dwelling and were usually a balance of ideal placement and practical constraints such as space. Equipment was installed both upstairs and downstairs and in a variety of rooms in the dwellings studied. Bathrooms and kitchens were, however, avoided because of the fluctuating temperatures and humidity in these rooms. Locations were sought with a large wall area, ideally with a north facing aspect.

Owing to the possible effects of inhomogeneities in wall constructions, it was important to determine the representativeness of the positions for the HFPs. A thermal imaging camera was used for this purpose. Where an inhomogeneous wall was identified, the installers aimed to place the HFP in a position which was broadly representative of the wall as a whole, i.e. in a location which the thermal imaging indicated was at a temperature which represents the average of the wall as a whole.

Internal temperatures were measured adjacent to every HFP. This was done to account for vertical temperature stratification internally, allowing them to be sited at different heights. Teams were advised not to place heat flux plates within 50 cm of a floor or ceiling to avoid problems from thermal bridging.

Thermal bridging at junctions and around openings

The proximity of window openings and door openings as well as partition walls, party walls, floors and ceilings can have an effect upon the heat flow and each can, if close enough to the heat flux plates, distort the measured U-value. Heat flux plates were therefore positioned away from junctions and openings. In order to highlight at the analysis stage where there was a risk of the U-value being distorted by this effect, the distance between the HFPs and any thermal bridges was noted.

Duration of monitoring

Since heat flux is affected by thermal storage effects, continuous monitoring over a period of time is necessary to allow the result to converge before a U-value can be evaluated. In this study, heat flux was monitored for a minimum of two weeks for all cases in line with previous work of this type.

2.1.2 Additional investigations to refine calculated U-values

In 89 of the dwellings visited additional investigations were undertaken to provide additional information on the internal structure of the wall, and the density and moisture content on the wall materials.

Investigations of the internal structure of the walls

To investigate the internal structure of the wall, a stretcher brick was removed from the wall and the void created was inspected (an example is shown in Figure 4). Photographs of the void space were also taken. A number of features were noted including:

a) The proportion of the joint between stretchers, known as the collar joint, filled by mortar.

b) The width of the collar joint.

c) The proportion of the vertical joints (perpend joints) filled by mortar.

d) The presence of any frogs or drillings in the bricks, and whether laid frog-up or frog-down.

e) The dimensions of any frog within the brick and the proportion of the frog filled with mortar.

f) The presence of any snapped headers or broken bricks within the inner leaf of the wall.

g) Any other observations.

Figure 4: Opening revealed following removal of brick. The amount of mortar present, the presence and position of any frogs and other internal features were examined.

2.1.3 Obtaining samples to provide information on density and moisture content

A variety of samples were obtained in order to provide additional information on the density of the bricks, and the moisture content of the bricks and mortar. In order to maintain occupant participation levels, no more than one brick sample, one dust sample of brick and one dust sample of mortar were collected from each dwelling.

To obtain a sample suitable for the measurement of density and moisture content of the brick, a small cuboid was cut from one of the back corners of the brick which had been removed for inspection (an example of a removed portion of brick is shown in Figure 5 and 6). Samples of mortar were also removed from the inter-stretcher area for analysis of moisture content.

Figures 5 and 6: A brick where a sample has been cut off, and a sample of brick from the back of a removed brick (dimensions of this sample are approximately 30mm x 30mm x 60mm. Larger samples were taken in the second fieldwork period to allow for direct testing of thermal conductivity as described in Section 4).

Removed samples were immediately wrapped in polythene to preserve moisture within the sample. The removal of these samples allowed the measurement of bulk brick density and the moisture content of the brick and mortar. In addition to solid samples, dust samples of brick and mortar were also taken to provide additional data on the moisture content of the walls. Brick and mortar dust was collected and immediately sealed in airtight phials and then taken to the laboratory for testing. Slow drill speeds and new drill bits were used to reduce the risk of moisture being lost from the samples as a result of heat generated by the drilling process. This is in line with the best practice for collecting samples of this type, as described in Good Repair Guide 33 [11], which should minimise any errors introduced through the sample collection process.

To obtain the moisture content, all samples were weighed, oven-dried and then re-weighed, and the change in weight recorded which could be converted into an estimate of moisture content. Bulk density of the sample was determined using the method described in BS EN 993-1 [25].

2.1.4 Results

A total of 137 dwellings were visited as part of this work. These are summarised in Table 2 below. It should be noted that the sample used for these cases is determined by the requirement for the additional tests to be carried out, or because a dwelling is in the pre- and post-insulation sample. For these reasons the sample cannot be considered truly random or representative of all solid brick walls. For example, rendered properties were generally excluded from the sample with additional investigations and many of the walls for which no additional tests were carried out are in the social sector (as they form part of the pre/post sample). Any bias within the sample, however, seems likely to have relatively small effect as discussed in section 2.1.7 below.

Table 2 Number and type of measurements made as part of the fieldwork.

Wall type	Additional investigations (i.e. brick removal, sample collection etc.)?	Number of cases
Solid wall (brick)	Yes	89
Solid wall (brick)	No	38
Solid wall (stone)	No	10
TOTAL		137

2.1.5 Measured U-values results

Following the field data collection period, the loggers were downloaded and measured U-values were calculated from the data collected. This section of the report outlines these results. Overall results are shown, alongside specific results where the data have been additionally filtered for quality, or for comparability with earlier work.

2.1.5.1 Analysis of the U-values data

The field measurements used dataloggers to store the data on heat flow and temperatures used to determine the measured U-values of the walls. The process for analysing the data is summarised below.

The format of the field data

The fieldwork phase of the project led to the creation of data files containing recorded heat flows and temperatures averaged over time intervals not exceeding 30 minutes. In general, these intervals were 15 minutes (excepting some of the external temperature data). The data in these files enable the subsequent determination of the U-values using the analysis methods given in ISO 9869 [18].

Obtaining the U-value

For each survey case the following procedure was employed to calculate U-values.

If a dataset consists of n consecutive heat flux readings, q_1, q_2, ... q_n (in W/m²), n corresponding internal temperatures, $T_{i,1}$, $T_{i,2}$, ... $T_{i,n}$ (in °C) and n corresponding external temperatures, $T_{e,1}$, $T_{e,2}$, ... $T_{e,n}$ (in °C), (each taken at times t_1, t_2, … t_n) then the U-value will be calculated as follows:

$$U = (\Sigma_k q_k / n) / [(\Sigma_k T_{i,k} / n) - (\Sigma_k T_{e,k} / n)] \qquad \textit{Equation 1}$$

Where $(\Sigma_k q_k / n)$ is the mean heat flux, $(\Sigma_k T_{i,k} / n)$ is the mean internal temperature (measured in the air close to the heat flux plate) and $(\Sigma_k T_{e,k} / n)$ is the mean external temperature. For accurate measurements the indoor temperature probe should be only a few centimetres from the centre of the heat flux plate.

In order to clarify the integration time over which the U-value is determined, it may be written as

$U(t_1, t_2)$

For an accurate U-value, the value of $(t_2 - t_1)$ should be at least two weeks (in the case of an occupied dwelling) and at least a few days (in the case of a hot box with steady temperature conditions), although examination of the data over shorter periods can provide a useful check on the quality of the data.

If C is the manufacturer’s calibration factor for the first heat flux plate and C´ the calibration factor for the second heat flux plate, and ε and ε´ the corresponding EMF (i.e. the voltage) generated by the heat flux plate, then

$q_k = \varepsilon_k / C$

$q'_k = \varepsilon'_k / C'$

We may calculate the U-value at the first heat flux plate from the data using the following formula:

$U(t_1, t_n) = (1 / C) (\Sigma_k \varepsilon_k / n) / [(\Sigma_k T_{i,k} / n) - (\Sigma_k T_{e,k} / n)]$ *Equation 2*

And we may calculate the U-value at the second heat flux plate from the data using the following formula:

$U' (t_1, t_n) = (1 / C) (\Sigma_k \varepsilon'_k / n) / [(\Sigma_k T'_{i,k} / n) - (\Sigma_k T'_{e,k} / n)]$ *Equation 3*

Thermal mass

The above equation (*Equation 1*) is based on the assumption that thermal storage effects are negligible. In practice, thermal mass will have an impact upon the measured U-value, but the error in the U-value should be small provided the measurements are at least two weeks in duration and provided the mean internal temperature is at least 10°C higher than the mean external temperature. It is possible to apply approximate corrections to the data to compensate for the effects of thermal storage and methods for doing this are given in ISO 9869 [18]. These methods typically make use of information about the wall construction (i.e. materials, densities, thicknesses etc.) and the accuracy of the thermal storage corrections can be reduced if the wall construction is not known precisely (such as for existing dwellings covered by this study). No thermal mass corrections, therefore, are applied to the results.

Resistance of heat flux plate and substrate

When measuring a U-value, the thermal resistance of the heat flux plate and substrate leads to an underestimation of the U-value. A final correction, based on an assessment of the differences between the calibration setup and their use on a wall (see details in the report, “*In situ measurement method review”* [16]) is made in the final stage. This acts to increase U-values by 5%.

Therefore, the final U-value becomes:

$U_{FINAL} = U * 1.05$ *Equation 4*

2.1.5.2 Obtaining a quality dataset

As with all fieldwork, returned data vary in quality due to field and experimental conditions. Prior to analysis and interpretation, therefore, it is important to filter the returned data for quality.

Data quality can be improved by the application of certain cleaning processes to remove potentially problematic cases or data. This comes with the advantage that the overall quality of the data is improved, but the disadvantage of dropping cases (increasing the statistical uncertainty). Applying very strict filters will reduce our sample size too far to allow any meaningful analysis, and the approach to data cleaning requires a balance between these two factors. For the analysis of the U-value data the following approach was taken:

- U-value measurements are particularly dependent on cold weather maintaining a sufficient difference between internal and external temperatures. For the survey period, however, two successive mild winters made this challenging. Firstly, the difference between the internal and external temperature was used to filter out cases. As stated above, the mean internal temperature should ideally be at least 10 °C higher than the external temperature so as to reduce the error on the U-value results. Due to relatively warm temperatures for part of the monitoring period, 35 percent of households failed to meet this criterion. Rather than removing more than a third of the data, cases were removed if the difference between the internal and external temperature was less than 7.5 °C (15 percent of cases).

- A further quality check, outlined in ISO 9869 [18] is that the U-value obtained from the first two thirds of the data should not differ by more than 5% to the latter two thirds of the data. To apply this, the results from individual HFPs that failed this requirement were removed from the dataset, as long as the remaining HFPs met the requirement. However, cases were entirely removed when data from two or more loggers failed the requirement (17 percent of cases).
- Outliers were identified based on wide discrepancies between the logger results (>= 0.5 W/m^{2}K). These cases were removed (7 percent of cases) and indicates that there may be additional error associate with the results, or greater variation in the wall itself.
- Finally, four cases were removed from analysis based on observations of potential thermal bridges close to where measurements were taken, and due to uncertainty in the interpretation of these results.

Applying these checks produces a reduced dataset for U-value measurements, of 92 cases, which we can use with increased confidence.

2.1.5.3 Headline results

The U-values for different wall types are summarised in Table 3.

For comparability to the results presented in the 2012 U-value study (described in Table 1), these are split into standard solid walls (brick construction which is a single header brick thick, or two brick widths, with a plaster internal finish) and non-standard walls (including one-and-a-half header brick thick walls, walls with plasterboard internal finish, and stone walls).

Table 3: Measured U-values of standard and non-standard walls.

		Measured U-value	
	Cases	**Mean measured U-value (W/m^{2}K)**	**Median measured U-value and Interquartile Range (W/m^{2}K)**
Standard brick wall	73	1.77 +/- 0.05	1.77 (IQR = 0.30)
Non-standard wall	19	1.20 +/- 0.21	1.27 (IQR = 0.63)

A frequency distribution of the results for standard solid walls is shown below in Figure 7.

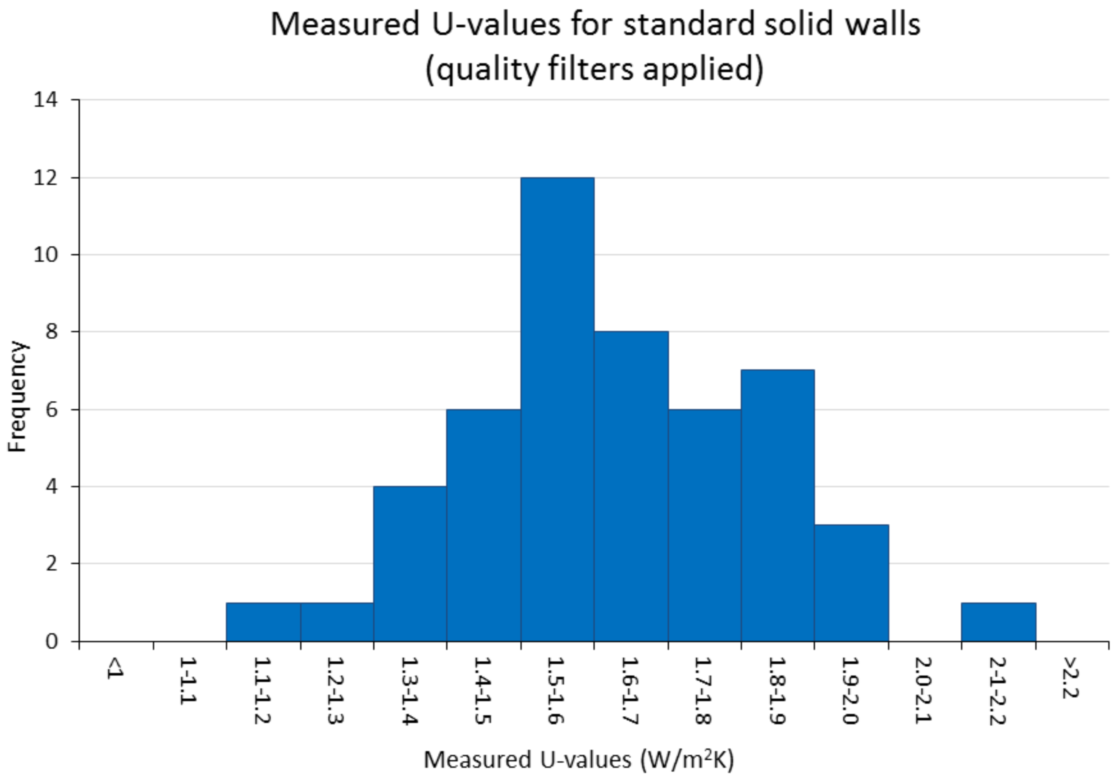

Figure 7: Distribution of measured U-values for standard solid walls, as measured in the fieldwork.

It was previously reported, in the 2012 study of in situ measurements of wall U-values in English Housing [10], and shown in Table 1 in Section 1, that the mean measured U-value of single brick thick solid walls was 1.65 +/- 0.07 W/m^{2}K (including the 5% systematic adjustment specified in [16]). These 2012 data have also been re-analysed to apply additional quality filters to align the results with those shown here, so that the two can be compared. Cases were removed with an internal-to-external temperature difference of less than 7.5 °C, and three outliers that were highlighted in the report were also removed from analysis. In addition, the results were already selected based on a maximum difference between logger readings of 0.5 W/m^{2}K, and results were filtered so as to include only standard brick walls with an internal wet plaster finish. The mean measured U-value from the revised 2012 data was 1.71 +/- 0.09 W/m^{2}K, based on the resultant 56 cases. These results are, therefore, not significantly different to the results from the new measurements, which supports a U-value for standard solid walls of approximately 1.75 W/m^{2}K.

2.1.5.4 Results from brick removals, sample collections and other wall measurements

One of the key aspects of the fieldwork was to undertake a series of additional investigations of the walls, including the removal of bricks, the collection and analysis of brick and mortar samples and measurements of key characteristics of the wall. A total of 89 walls were examined in this way (although a few of these only had partial investigations, such as dust drillings only, for practical reasons or because of householder preference).

The results of the additional investigations are described below, summarising the main findings that were identified throughout the fieldwork.

Collar joints

The area between two stretcher bricks, known as the collar joint, was examined following the removal of the brick. The field technician examined the void created, as well as the back of the brick, and estimated (by eye) the proportion of the collar joint which was filled with mortar (and the proportion filled with air). The width of the collar joint (i.e. the distance between the facing and backing bricks) was also measured. The technician also took photographs of the exposed void. These photographs were used to validate the original on-site assessment of the proportion of mortar in the collar joint at the analysis stage. A photograph of an exposed collar joint is shown below in Figure 8.

Across the 82 cases where the collar joint was examined, the space between the facing and backing bricks was seldom fully filled with mortar. The median percentage of the exposed area estimated to be filled with mortar was 67%. The interquartile range was 50% between 34% (at the 25th percentile) and 84% (at the 75th percentile). The distribution of mortar fractions is shown below in Figure 9.

Figure 8: Exposed collar joint showing area of missing mortar. Some mortar remains attached (e.g. in the top left of the exposed inner leaf), with other regions showing staining (e.g. bottom right of the exposed inner leaf). The central portion of the inner leaf shows no staining, suggesting little or no mortar was present.

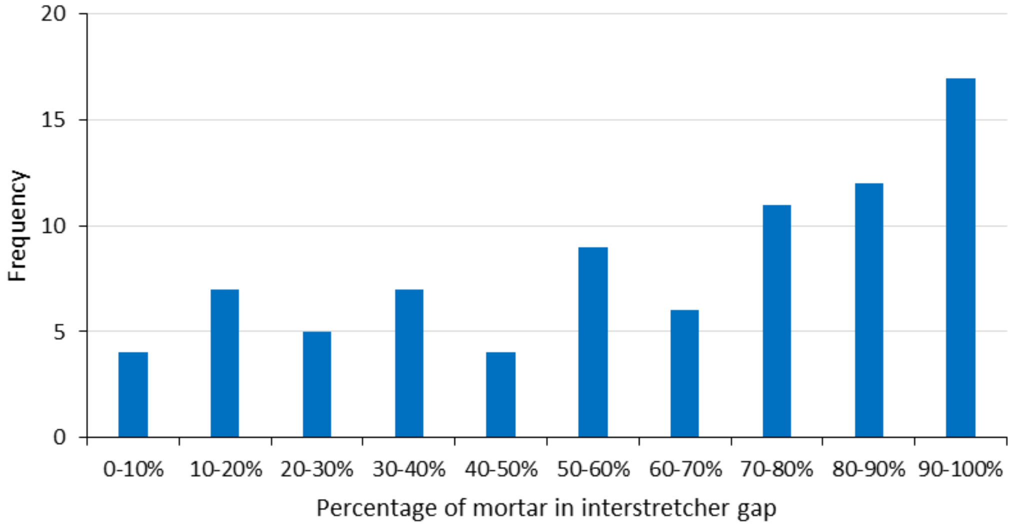

Figure 9: Percentage of mortar in collar joint, as observed in fieldwork

In general, when calculations of U-values of solid walls are made, air gaps present in collar joints are not considered. In terms of the thermal performance of the wall, however, the collar joint air cavities will act to reduce heat losses from the wall and decrease the wall U-value. The effect of taking these into account is described in Sections 7 and 8 below.

Perpend joints

When the brick was removed, the vertical joints, known as perpends were also examined for the proportion of the exposed surface area filled with mortar. This assessment was made through the on-site examination by the field technician who examined the perpend area exposed when the brick was removed, as well as the adjacent surface on the removed brick itself. The extent of fill at the perpends was often easiest to ascertain by looking at the roof of the void created by the removal of the brick, where the perpends of the upper course were visible (see Figure 10 below). The technician also took photographs of the perpend joints, and these were used to validate the original on-site observations by a second member of the BRE team at the analysis stage. The on-site technician was also encouraged to factor into the assessment any observations from their experience of removing bricks by the stitch-drilling technique. For example, the depth at which the drill bit ceases to encounter resistance when drilling may indicate where the mortar ends and a cavity begins.

Figure 10: Example of missing mortar in perpend joints. Looking upwards at exposed bricks in the upper course at the top of the void, the extent of mortar in the perpend joints can be seen. In this example, the perpends can be estimated to be approximately 50% filled.

As with the collar joint gap, perpends were also seldom fully filled with mortar. The median percentage of the exposed perpend area estimated to be filled with mortar was 70% based on results from 82 cases. The interquartile range was 32% between 50% (at the 25th percentile) and 82% (at the 75th percentile). This is shown in Figure 11 below.

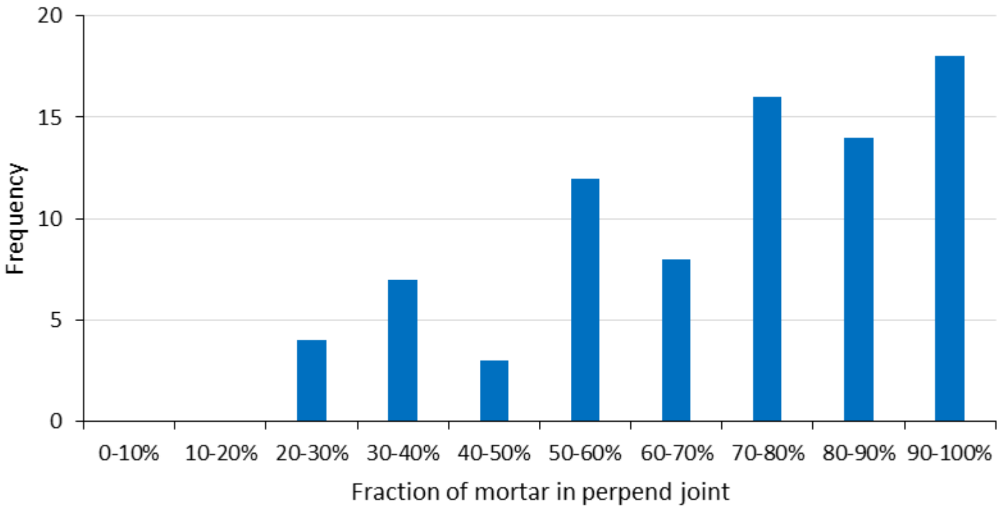

Figure 11: Percentage of mortar in perpend joints, as observed from fieldwork

Like the collar joint air cavities, these cavities are not generally taken into account in theoretical calculations and will act to reduce heat losses from the wall and decrease the wall U-value. The effect of taking these into account is described in Sections 7 and 8 below.

Bed joints

When the brick was removed the horizontal joints between each brick course, known as the bed joints, both above and below the brick (including any mortar attached to the brick) were examined. In almost all cases, the bed joints were fully filled with mortar. This is to be expected, as when bricks are laid, the bed joints are generally covered in a layer of mortar before applying each brick course. Therefore, no further investigations were made on bed joints.

Frogs

When the brick was removed, the technician identified whether the brick contained one, or two, frogs. They were asked to note if the bricks had been laid ‘frog-up’ (i.e. on the top face of the bricks), or ‘frog-down’ (on the bottom face of the brick). They were also asked to measure the dimensions of the frogs, and to identify if the frogs were filled with mortar (and if not, what proportion of the frog had been filled).

A photograph of a wall built with ‘frog-down’ bricks is shown below in Figure 12.

Figure 12: Frog-down bricks. The cavity created by the frog in the brick is clearly visible. The on-site technicians were able to ascertain that any cavity was genuine (and not simply created by falling mortar following the brick removal) by looking along the course. This example also shows evidence of an imperfect brick being used (the back face of the upper left brick in the in the upper course is broken) – see below.

Overall, 45% of the 82 bricks removed contained frogs. Generally, only a single frog was present (only 12% of all bricks contained two frogs – one on each side of the brick). Of all bricks with a single frog, 52% of bricks were laid frog-up, and 48% laid frog-down (note that, because only a single brick was removed it is not possible to tell if the wall was built with a mixture of frog-up and frog-down bricks). Frog-up bricks were almost always fully filled with mortar whereas frog-down were very seldom fully filled with mortar. The distributions of mortar fill for frog-up and frog-down bricks are shown in the Figures 13 and 14 below.

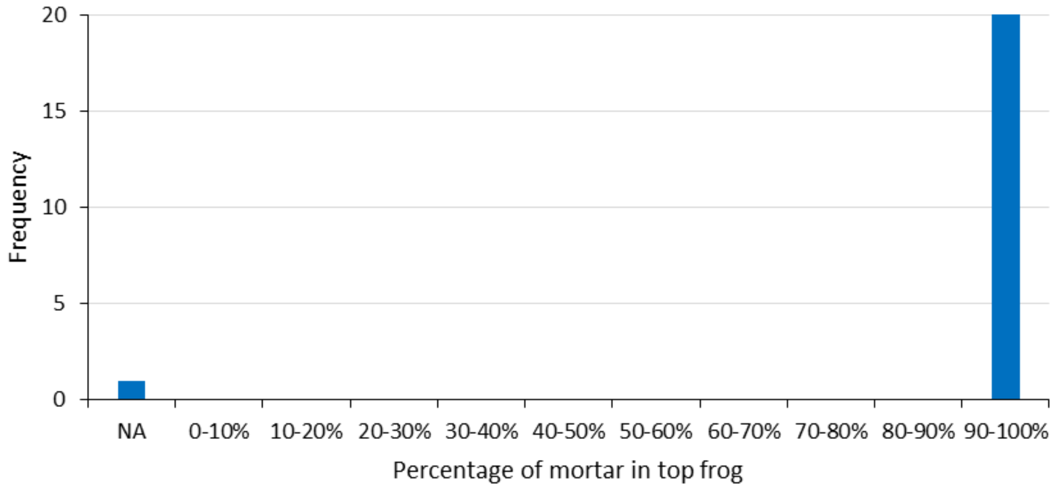

Figure 13: Percentage of mortar in frogs found on the top face of bricks, from fieldwork

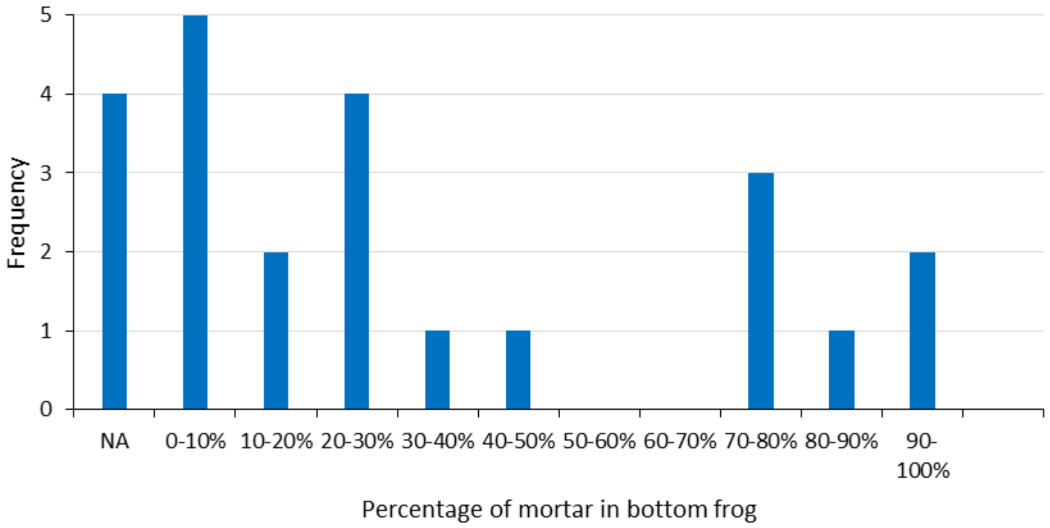

Figure 14: Percentage of mortar in frogs found on the bottom face of bricks, from fieldwork

The dimensions of frogs also varied, for those cases where measurement was possible (mortar or other practical reasons sometimes prevented this). The median volume of the frogs where measurements were taken was 76 cm^3. The distribution of frog volumes is shown in Figure 15 below.

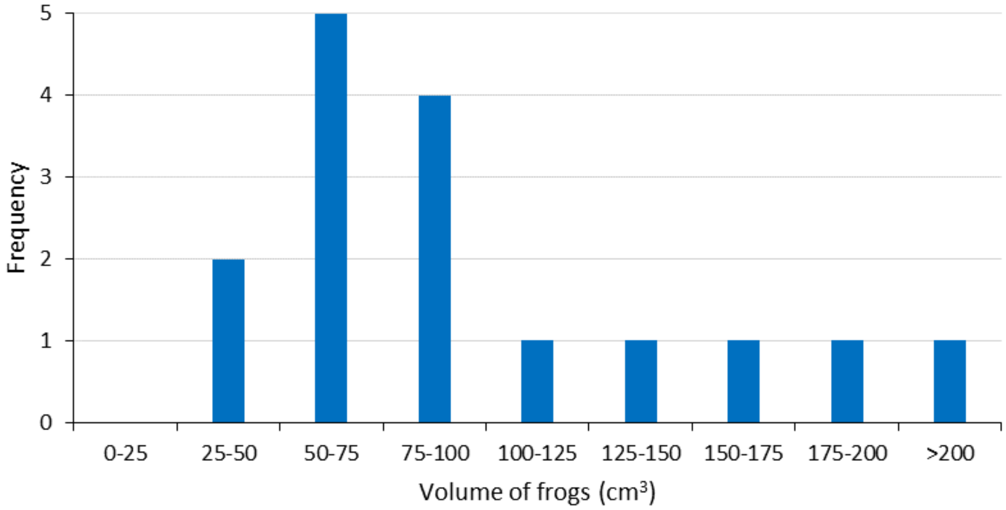

Figure 15: Volume of frogs for those where measurement was possible in the field

Frogs are not generally taken into account in the theoretical calculation of wall U-values. The prevalence of air-filled frog-down bricks in particular, however, is likely to act to insulate the wall and decrease the wall U-value.

Brick bats and imperfect bricks

One unexpected finding when removing the bricks, was the discovery of a relatively high number of irregularly shaped and broken bricks, known as brick bats, within the walls. Although the outer surface of the wall appeared very uniform, when the brick was removed it was not uncommon to find imperfect bricks used in the inner leaf of the wall, or for a header brick to be incomplete or split. Brick bats or irregular bricks were revealed in 9% of cases. The imperfections were sometimes rudimentarily filled with snots of rough mortar, or left as cavities within the wall.

Photographs of brickbats used in the walls are shown in Figures 16 and 17 below to illustrate the type of observations seen in this aspect of the fieldwork.

Figures 16 and 17: The use of broken bricks / brick bats on the inner leaf (*left)* and in place of a full header brick (*right)* introduce air cavities into the wall structure. These types of features were found in ~9% of walls examined.

As with the other types of air cavities identified within the wall, those caused by split and broken bricks will act to reduce heat loss form the wall and decrease the wall U-value. The effect of taking this into account is included in Sections 7 and 8 below.

Perforated bricks

Only one example of a perforated brick was found, indicating that these are likely to be rare across all solid wall dwellings. Evidence from the hot-box experiments, described in section 3 of this report, suggest that perforations in a brick can act to reduce the U-value of the wall. A photograph of the perforated brick is shown in Figure 18 below.

Figure 18: A perforated brick found in one of the walls examined

Moisture content of bricks

The moisture content of bricks is a key input into the theoretical calculation of the wall U-value, with a moisture correction factor applied in the calculation of the thermal conductivity of bricks from density measurements. When the brick was removed, a small section was cut off from the back of the brick and immediately wrapped in polythene to retain moisture (see Figures 5 and 6). Testing was undertaken within the UKAS accredited laboratories (no.0578) at BRE. This requires the weighing of the “wet” sample, before drying in an oven accompanied by repeated weighing until no further change in weight is observed.

In general, the brick samples were very dry. The median moisture content of the brick samples was 0.7% by volume. Around a third of the measured brick samples ranged in moisture content from 2% to 15%. However, one brick was extremely wet with a moisture content of over 20%. The distribution of measured moisture content by volume is shown in Figure 19 below.

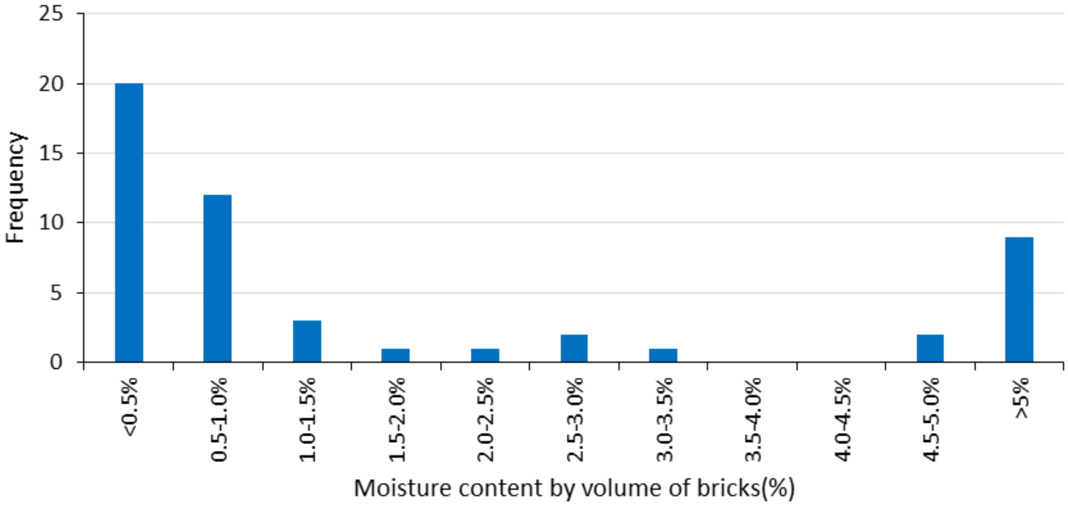

Figure 19: Distribution of moisture content by volume of brick samples.

Moisture content of mortar

Mortar dust drillings were also taken by the field technicians on site, which were placed in airtight containers ready for testing. Overall, mortar was generally dry, although slightly wetter than the brick samples. The median moisture content of mortar was 2.8% by volume. Around two thirds of the measured mortar samples ranged in moisture content from 2% to 15%, yet 5 cases showed very wet mortar samples, with moisture contents reaching 31% in one (the same case with the high brick moisture content). The distribution of mortar moisture content by volume is shown in Figure 20 below.

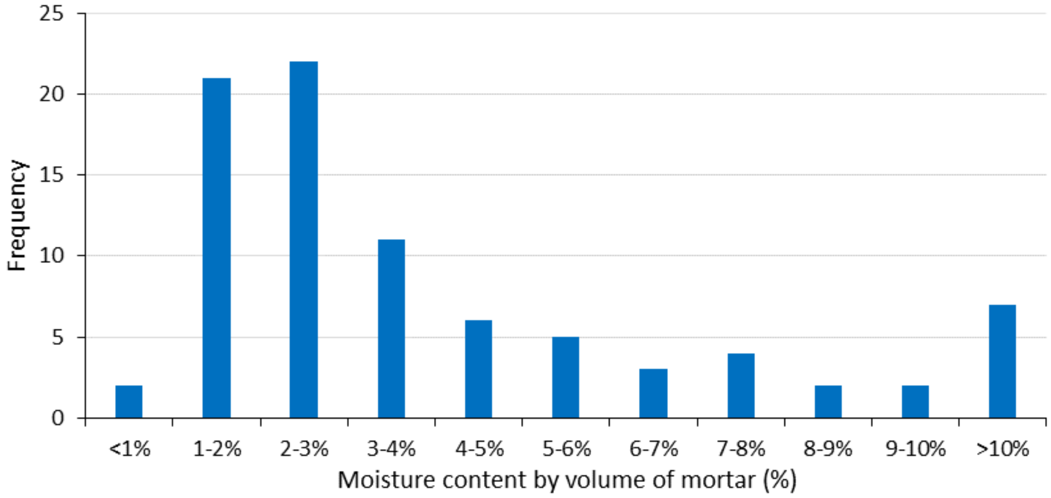

Figure 20: Distribution of moisture content by volume of mortar samples

Brick density

The bulk density[1] of the bricks was determined using the methodology outlined in BS EN 993-1 [25]. Higher density bricks are likely to be more conductive, and will result in higher U-values.

The median bulk density of bricks was higher than that generally assumed in theoretical calculations. The median measured density was approximately 1,805 kg/m^3 rather than the often assumed 1,750 kg/m^3. There was also considerable variation in the density of the samples. The interquartile range of densities was 135 kg/m^3, with the 25th percentile at 1,726 kg/m^3 and the 75th percentile at 1,861 kg/m^3. The distribution of brick densities is shown in Figure 25 below.

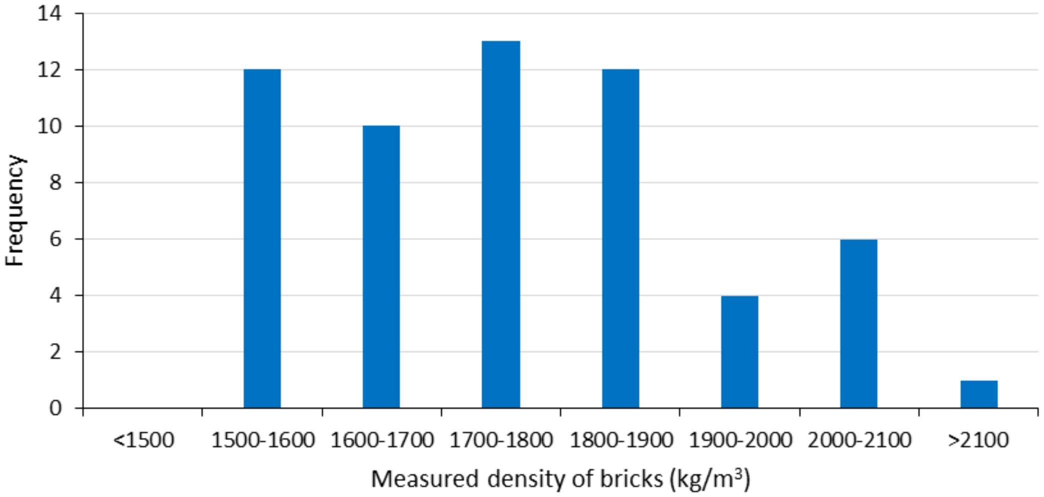

Figure 25: Distribution of brick densities from fieldwork samples

Brick dimensions

Measurements were also taken of the stretcher length and header width. The median stretcher length was measured to be 230 mm, and the median header width was 109 mm. The interquartile range of the stretcher length was 5 mm, between 225 mm (at the 25th percentile), and 230 mm (at the 75th percentile). The interquartile range of the header width was 4 mm, between 106 mm (at the 25th percentile), and 110 mm (at the 75th percentile). This brick length is consistent with bricks being approximately 9” in length.

Wall thickness

Thicker walls are likely to have lower U-values. Where possible, the wall thickness (of the U-value test wall) was measured using digital callipers (for 53% of measurements). If this was not practical (for example due to restricted window opening space), the wall thickness was measured using a steel rule (35% of measurements), or was estimated from another wall location (12%). The median wall

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[1] Bulk density is the ratio of the mass of the dry material of a porous body to its bulk volume. Bulk volume is the sum of the volumes of the solid material, the open pores and the closed pores in a porous body.

thickness of all walls, based on 130 measurements, was 257 mm. The interquartile range was 32 mm, between 250 mm (at the 25th percentile), and 282 mm (at the 75th percentile).

The majority of cases were one brick thick walls (i.e. the length of one header brick). These had a median wall thickness of 252 mm, and interquartile range of 21 mm (249 mm to 270 mm at the 25th and 75th percentile, respectively). The thicker walls of this type were associated with rendered properties, and those with an internal dry lining (plasterboard finish). The thickness of these walls implies a plaster thickness of approximately 20 mm. This is thicker than the usual assumption of approximately 12 mm (and a subsequent total wall thickness of approximately 240 mm). This additional thickness is likely to reduce the U-value of the wall.

The remainder of the walls were one-and-a-half brick thick walls (6% of measured values) and stone walls (8% of measured values), with a median wall thickness of 399 mm and 529 mm, respectively.

2.1.6 Relationships between measured U-values and observations about the wall

The removal of a brick, and the collection of samples, allows for the additional patterns in the measured data to be investigated. This gives some indications where further work could be fruitful, although none of the results can be considered statistically significant with the current sample. To confirm the significance of these results a larger sample is required, and the effect of multiple factors should be tested. The main areas where numerical differences were observed, and where additional investigation may be fruitful are described below.

Average U-values were compared for groups with different thermal conductivity values, brick densities and moisture content. For cases where the measured density of a brick sample from the test wall was greater than 1850 kg/m^3, the measured U-value was higher (mean U-value = 1.83 W/m^{2}K +/- 0.12) than bricks with lower density values (mean = 1.70 W/m^{2}K +/- 0.06). Because of the relatively small sample sizes the confidence intervals between these estimates overlap, but it suggests that a higher rate of heat loss may be occurring in walls with bricks of high density which would be in line with our expectations. Additional measurements, particularly in walls of high density bricks, would be required to confirm these results.

Thermal conductivity is also dependent on the moisture content of bricks, however, the measured U-value did not vary as might be expected with brick moisture content where investigations of this type were carried out. The mean U-value was 1.75 W/m^{2}K +/- 0.07 when moisture content by volume was less than 1%, and the mean U-value was 1.70 W/m^{2}K +/- 0.07 when the moisture content was greater than 1%. The reason for this could be due to natural variation within the wall (see section 6 for additional evidence relating to this), where the brick sample tested is not representative of other bricks in the same wall, or that other aspects of the wall also vary in an inconsistent way (e.g. brick density). Further work on the effect of moisture content on conductivity for walls of this type is recommended.

The proportion of air within perpends and inter-stretcher gaps, and the orientation of the wall, may also be influencing factors on the U-value, and would be worth further investigation with a larger sample size. Results indicate that the measured U-value may be greater when the proportion of air gaps in both perpend and collar joints is less than 25% (mean U-value = 1.78 W/m^{2}K +/- 0.09), compared with walls where that proportion is greater than 50% (mean U-value = 1.7 W/m^{2}K +/- 0.11).

2.1.7 Limitations of the fieldwork

Although the fieldwork programme is the largest investigation of this type undertaken, there are still numerous limitations which need to be considered when interpreting the results.

Sample

The sample chosen for detailed investigation is a combination of owner-occupied cases visited as part of the EHS, with additional dwellings provided by housing associations. Certain dwelling types have been excluded. In particular, this includes all mid-terrace and those with very small floor areas (for practical reasons of measuring U-values), leasehold properties and flats (which are generally too difficult to obtain the necessary permissions for sample removal work) and rendered dwellings (because of difficulties in obtaining samples and removing bricks). The sample cannot, therefore, be said to be truly representative of all dwellings in the stock. Having said this, with the possible exception of moisture content, the likelihood of the sample differing greatly from the stock as a whole seems low.

Although social sector dwellings are over-represented in our sample, it seems unlikely that the construction of these dwellings would be very different from the vast majority of owner occupied dwellings. Indeed, solid wall dwellings in the social sector will generally predate the establishment of the social tenure as we recognise it today and will have been acquired by the social sector many years after they were built. Although acquisitions of this type will generally have been of lower value dwellings, there is no evidence to suggest that this will be reflected in the nature of the walls themselves. Similarly, there is no evidence to suggest that the exclusion of mid-terraces and leasehold houses will have an effect on the observations. The exclusion of flats, however, may be significant. It is likely that, because of the greater height of the walls of many flats, they may have required different construction techniques, and possibly thicker (one-and-a-half-brick thick) walls.

The exclusion of rendered dwellings may also be significant, particularly for moisture content. Although a layer of render may provide some protection to a wall, rendered dwellings are also more likely to be found in more exposed locations (hence the need for render). As a result, the moisture content may be systematically different to those without render. The results also generally relate to brick built walls, and would not be particularly relevant for, for example, single leaf walls of stone blocks.

Measurements

U-value measurements should ideally be made out of direct sunlight and when there is at least a ten degree temperature difference between the indoor and outdoor environments. This means that the best time of year to conduct these measurements is in mid-winter and the best location is on a north-facing wall. It is possible that north-facing walls are different from the other walls of the dwelling and therefore the measurements may not be totally representative of all walls in a dwelling. For example, the fact that prevailing winds in the UK are south-westerly could mean that north-facing walls are drier than the other walls of a dwelling (particularly those facing south and west). Moisture content variations are discussed in more detail later. The detailed investigations for this project were conducted by removing a single brick; usually from the same face as the U-value measurement. This provided a very detailed picture of the structure of the wall; and the density and moisture content of the brick, at that one location and it is assumed that this is representative of how the entire dwelling was constructed. It is reasonable to assume this given that the dwelling would likely have been constructed at one time however it is possible that this is not the case.

2.1.8 Discussion of fieldwork results

The results from the fieldwork have revealed significant new information about the nature of solid walls in situ. The measurements of U-values have confirmed the previous U-value results undertaken in 2012, and supports a default U-value of approximately 1.75 W/m^{2}K for solid brick walls of a single-brick thickness. The internal examination of the wall has revealed a number of interesting features, which can help explain why the U-value is lower than the originally assumed value of 2.1 W/m^{2}K.

Wall cavities

In a number of places, the joints within the wall are not filled with mortar. This will create a cavity which will act to reduce the U-value of the wall. Were these cavities to be interconnected it is possible that they could act as a thermal bypass, but this level of interconnection seems unlikely given the usual pattern of bed joints being (generally) fully filled with mortar.

Cavities created within the collar joint can be understood with reference to the process used by the bricklayer when building a solid wall (see, for example modern bricklaying guides [e.g. 26] and Lynch's guide [27]). When a solid wall is built, it is generally constructed by building the outer layer of brickwork on each course first – i.e. the facing bricks which will be visible externally are put in place along each course ahead of the backing bricks which form the inner leaf. Once this layer of brick work is in place the backing bricks are placed (a process known as 'backing up' or 'backing in'). It is not good practice, however, to place the mortar on the face of the backing brick which will form the back of the collar joint prior to laying it, as this risks pushing the facing brick out of position. Instead, either the mortar bed should have been prepared with ample mortar to allow it to fill the collar as the brick is laid, or mortar should be pushed down between the joint. It is clear that this process seems likely to be imperfect and (even when followed) is likely to lead to cavities being created in the wall.

Another source of cavities may be the use of non-standard techniques at the time of construction. These include 'grouting' and 'larrying' used by builders in the Victorian period and early 20th century. These techniques, described in sources which are contemporary to this period (e.g. [28], [29]), involved pouring a liquid mortar into the joints of a wall (rather than placing mortar in the traditional method) relying on evaporation to set the mortar often leaving cavities within the work. Another technique, described in Hammond's 1899 guide 'Practical Bricklaying' [30] as being in use for very thinly jointed properties, is to 'butter' a thin layer of mortar to the back and front edges of the brick before it is laid, rather than laying a thick mortar bed, leaving an air cavity under each brick.

The fieldwork also identified a relatively high propensity of imperfect bricks and brick bats having been used. While there are legitimate structural reasons for using brick bats, for example around the quoins (external wall junctions), one can speculate that this was also done for economic reasons, in order to successfully employ all bricks, even those which were broken and incomplete. Such bats may have been relatively common when we consider the methods used for both producing the bricks, and transporting them to site, which would have been very basic compared to today's industrialised and quality controlled processes. Lynch [27] also describes how Flemish bond walls in particular have brick bats replacing full headers in situations where 'careless bricklayers' have allowed the inside gauge of the brickwork to run out of sync with the external work. This situation tended to occur where the walls were laid with gauged bricks, with the outer work being laid with a lime putty point, often meaning that the outer and inner work of the same course did not correspond in height. In these situations, bonding across the wall using a proper header was often only possible in the relatively unusual situations where the courses fell even. Lynch comments that this type of work would often cause these walls to split in two along their width. This wall defect is also described in a BRE newsletter [31]. The use of poorer quality bricks for the inner leaf of the walls is also to be expected for purely economic reasons. Searle [32] describes how some brick manufacturers, particularly before 1914, would get rid of poor quality bricks by erecting *'workmen's houses in populous districts'*.

Brick density and moisture content

The median brick density is slightly higher than that generally assumed, which should correspond with a higher thermal conductivity than generally assumed. The bricks, however, are much drier than generally assumed which will act to reduce the thermal conductivity. In this situation, the moisture content is so much lower than the usually assumed 5% moisture content, that this counteracts the effect of the increased density, leading to an overall lower thermal conductivity for the bricks.

Summary

The fieldwork has provided, for the first time, new evidence to revise the calculation of solid walls. The data collected on the internal structure of the wall indicates that the walls are considerably more complicated than had previously been assumed, and that many of the default values we employ in our standard calculations may not reflect the real condition of these elements. The effect of this on the calculated U-value of a typical solid wall, and on the fieldwork cases themselves, is described in sections 7 and 8 of this report.

3 Reproducing field observations in the laboratory – experiments in the NPL hot box apparatus

The fieldwork observations provide important insights into the nature of solid walls in situ. In order to determine the effect of these observations experimentally, and to provide validation of the U-values we observe in situ for solid walls, we designed a series of additional experiments to be undertaken in a controlled laboratory environment. The effects of these observations on theoretical calculated U-values are then compared in Sections 7 and 8.

The experiments took the form of a series of laboratory tests which were carried out at the National Physical Laboratory (NPL). For these tests, six 1.2m x 1.2m solid wall sections were built, incorporating the key observations from the fieldwork. The U-values were then measured within NPL's hot-box apparatus, which is able to directly measure wall U-values.

3.1 Research questions for hot-box work

Our principal objective for the hot-box was to provide some fundamental 'benchmark' U-values for a selection of solid walls. We wanted to measure, under laboratory conditions, the U-values of solid walls which had been constructed in a manner that we believed represented the wall structures we were observing in the fieldwork and to see if these were broadly aligned with our field observations. Aside from the very early work from the 1930s in the BRS wall laboratory [1], we are not aware of these types of tests having been carried out previously, and we felt it was an essential step to confirm our in situ measurements and confirm some of our initial findings in relation to solid walls.

Further to this we had some more specific questions which we felt may be informed by comparing the different hot-box measurements. Although aspects of these comparisons would prove very challenging, for example accounting for differentials in moisture content (see Section 3.3), we considered that these comparisons may help to provide some general findings relating to the walls. In particular, comparisons may allow the following to be addressed:

- What is the difference in U-value between a 'perfectly' built wall and one with the types of air gaps we observe in the field?
- What is the effect of different mortar bed thicknesses on the U-value of the wall?
- What is the effect of different brick types, of different densities, on the U-value of a wall?
- What is the effect of using a perforated brick in the construction?
- What is the effect of different bonding patterns on the U-value of wall?

3.2 Measuring U-values in the hot-box

The measurements were carried out in the NPL wall guarded hot-box. This measurement apparatus was accredited by UKAS to be able to carry out thermal performance measurements on structures as specified by BS EN ISO 8990 [20]. A schematic diagram of this apparatus is given in Figure 27 which identifies the various control systems and temperature sensors that are used. Photographs of the box itself are shown in Figures 28, 29 and 30 for reference.

The measurement uncertainty using this apparatus has been calculated using the methodology specified in the BIPM document; *Evaluation of measurement data - Guide to the expression of uncertainty in measurement* (often referred to as the GUM) [21]. For measurements on test elements mounted in an expanded polystyrene surround panel (as our measurements were) the overall expanded uncertainty is estimated to be within ± 5.5 %, based on a standard uncertainty multiplied by a coverage factor $k = 2$, providing a coverage probability of approximately 95 %.

Thermal transmittance or U-value (W/m^2.K) is defined in BS EN ISO 7345:1996 [19] as heat flow rate in the steady state divided by area and by the temperature difference between the surroundings on each side of a system.

When measuring U-values in a hot box apparatus the temperature of the surroundings is defined in BS EN ISO 8990 [20] as the environmental temperature, the derivation of which is shown below in Equation 5:

$$T_n = \frac{T_a \frac{\emptyset}{A} + E h_r \; T_a - T_r \; T_s}{\frac{\emptyset}{A} + E h_r \; T_a - T_r}$$

Equation 5

T_n = Environmental temperature (°C)

T_a = Air temperature (°C)

Φ = Power through the test element (W)

A = Area of the test element (m2)

E = Emissivity of surface

h_r = Radiant heat transfer coefficient (W/m2.K)

T_r = Mean radiant temperature of surroundings (baffle temperature)

T_s = Surface temperature (°C)

To calculate the environmental temperatures the following temperatures must be measured:

a) Hot and Cold test element surface (9 thermocouples)

b) Hot and Cold baffle surfaces (16 thermocouples)

c) Hot and Cold air (16 thermocouples)

d) Heat flux density through the test element (the apparatus is designed such that when operated correctly the total power supplied to the hot chamber heater is all transferred through the test element and surround panel with negligible losses and gains.

The boundary conditions that were established for the measurements were:

- Warm air temperature (approximately) 22.5 °C
- Cold air temperature (approximately) 2.5 °C
- Total surface resistance 0.17 (m^2.K)/W

This total surface resistance value is achieved by ensuring the air flow rate in the hot chamber is that due to natural convection, which will produce a surface resistance value of ~ 0.13 (m^{2}K)/W. The air flow rate in the cold chamber is adjusted to produce a surface resistance value of ~ 0.04 (m^{2}K)/W.

Because U-value is a steady state thermal property the test elements and the apparatus have to be allowed to reach the condition where all the temperatures and the power through the test element are constant (i.e. at equilibrium), then five sets of readings are taken at two-hour intervals and the results averaged to derive the U-value from the measured data. The time taken to reach this equilibrium condition depends on the mass of the test element and its thermal diffusivity.

The technique that was used was to install test elements measuring 1.2 m x 1.2 m x a of maximum 0.35 m thick in an aperture in a 0.35 m thick surround panel made from high density expanded polystyrene (see Figure 26). The thermal conductivity of this EPS material has been measured in the NPL 610 mm guarded hot plate apparatus. The surface temperature of this surround panel is measured using 8 thermocouples on both the hot and cold surfaces. The heat transfer through the surround panel during the measurement is then derived from these data and the thickness of the surround panel. This power is then deducted from the total power delivered to the hot box to derive the power through the test element. Thermal equilibrium was judged to be when the temperatures and power were constant.

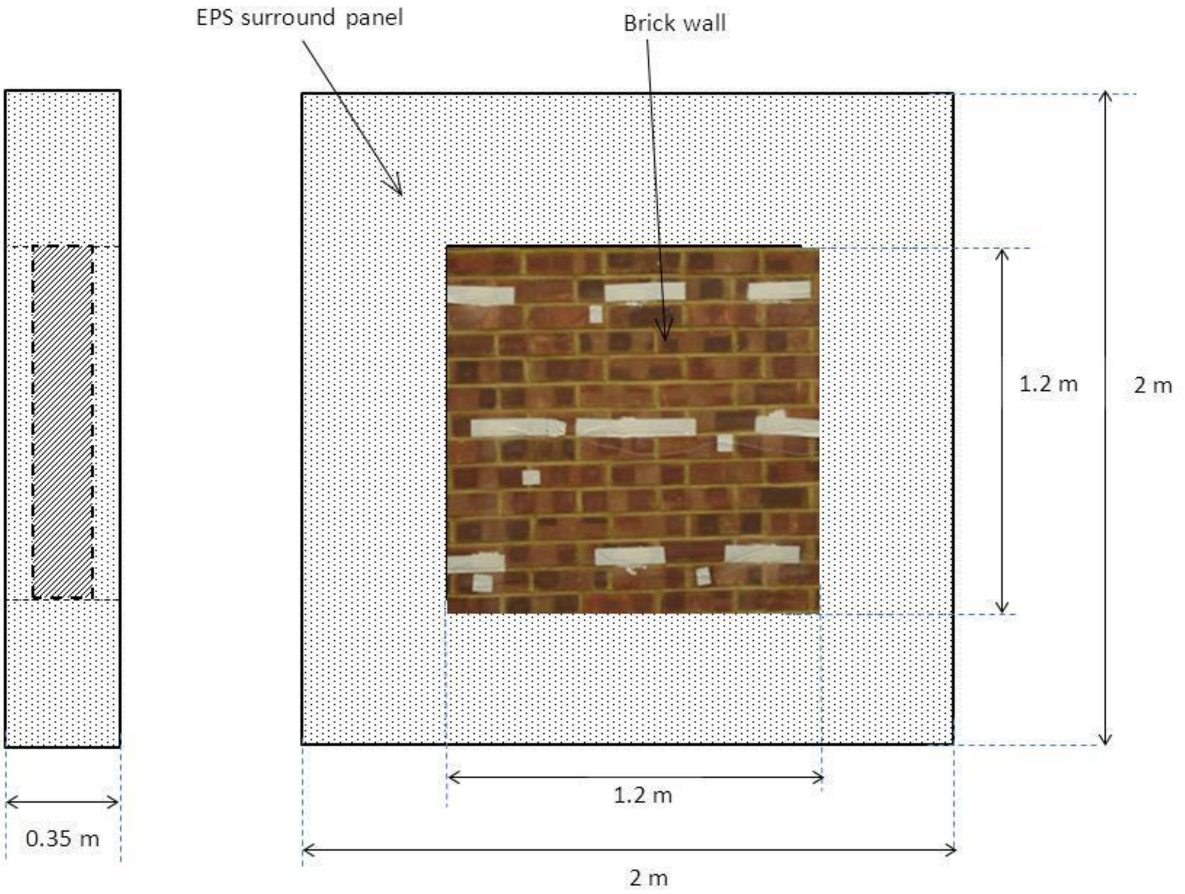

Figure 26: A wall and EPS surround assemblage used within the hot-box apparatus.

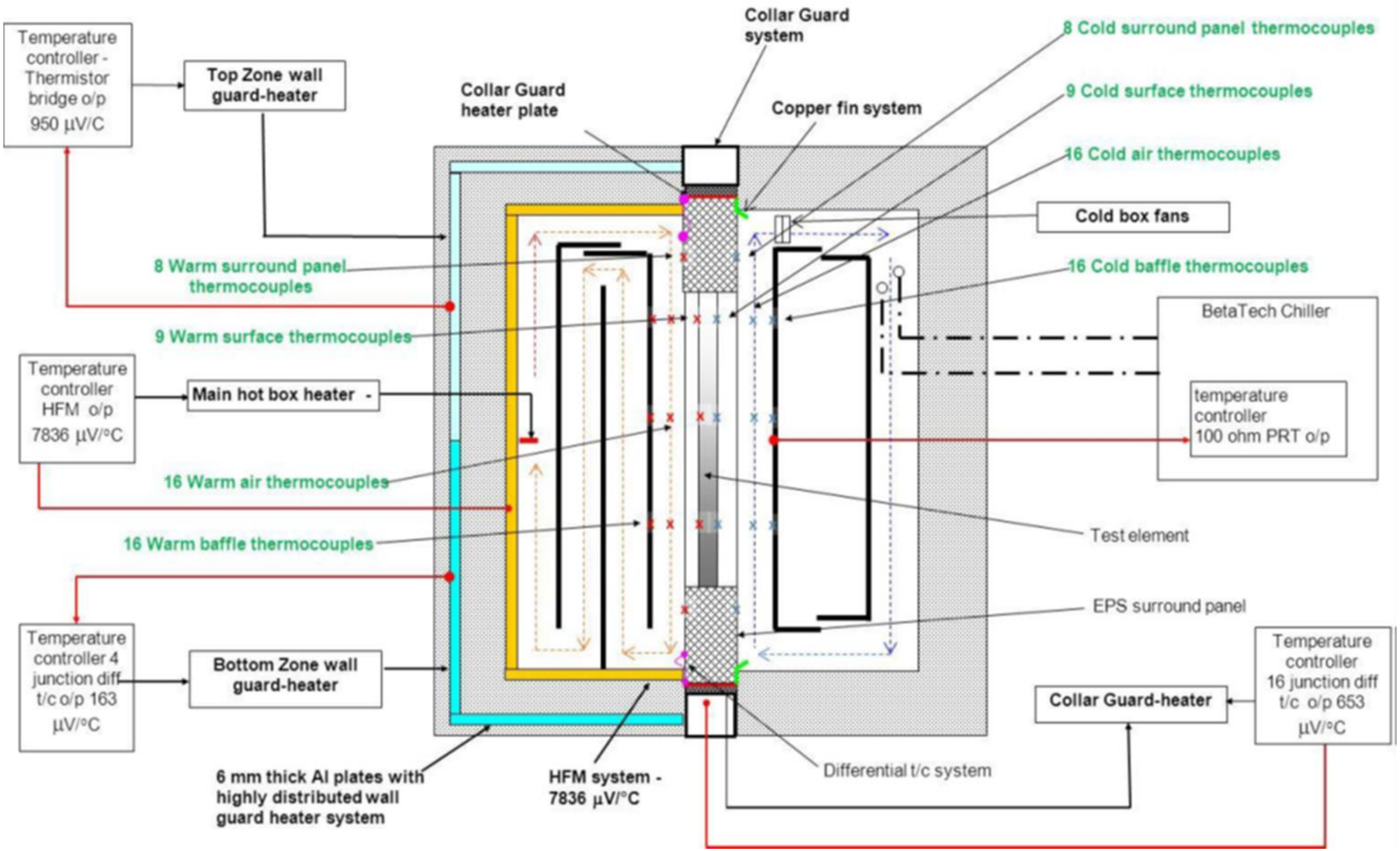

Figure 27: Schematic diagram of the NPL Wall Hot-Box Apparatus

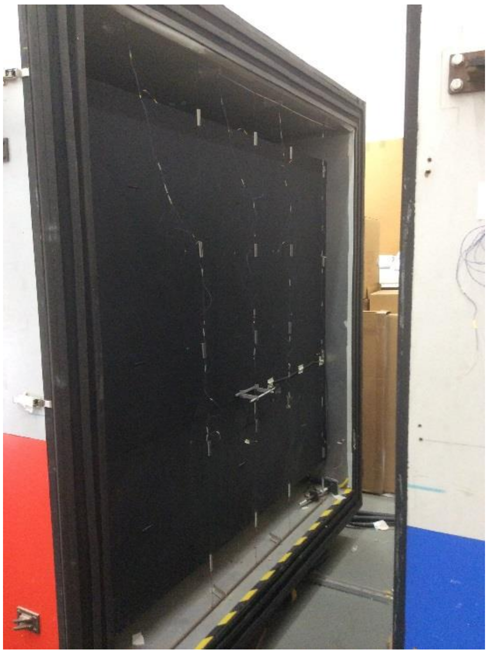

Figure 28, 29 and 30: Photographs of the NPL Wall Hot-Box Apparatus. The hot side of the box, marked in red is on the left hand side of the photographs. The cold side, marked in blue, is on the right hand side.

3.2.1 Constructing the walls and placing within the hot-box

The building of the walls and the placing of the walls within the hot-box apparatus itself raised numerous technical and practical challenges. BRE and NPL were able to design specific and bespoke solutions to ensure that these heavyweight masonry panels could be successfully tested.

3.2.1.1 Building the walls

In order to represent the construction methods and techniques used at the time when the majority of solid walls were built, a specialist historic buildings consultant, Dr Gerard Lynch, advised on the construction techniques to be used. He provided recommendations on the types of techniques likely to have been in use at the time when solid wall dwellings were built. The walls were built in the hot-box laboratory at NPL by another specialist, with specific expertise in historic buildings techniques.

In order to reproduce the cavities observed in the fieldwork, imperfect (but often used) techniques were used, including the failure to apply mortar to the collar joints and laying bricks with only minimal care taken to fill the vertical wall joints.

In total six different walls were constructed, using three different types of reclaimed bricks. The first brick, was a reclaimed red brick originally used in a mid-Victorian farmhouse in Bedfordshire. This brick was chosen as being indicative of bricks of this age, of medium density and relatively high level of uniformity. It was also frogless. This type of brick is likely to have been made from the top ‘callow’ layer of the Oxford clay deposits in this region, or from local boulder clay [33]. The second brick type used was a London Stock brick, a low density yellow brick of quite irregular dimensions and structure containing numerous inclusions and imperfections and which was used widely in the Capital. The final brick used is a high density brick with a gazed finish, which has been acquired from Wolverton in Bedfordshire. This brick is relatively unusual, as shown in the fieldwork, but one nineteenth century example was found and bricks of this type are known to have been made from the late nineteenth century by manufacturers such as Robert Beart’s brickworks at Arlesey in Cambridgeshire [33]. It was of interest to know how walls containing these type of bricks performed, as it was anticipated that the perforations may lead to lower thermal conductivities and U-values [34].

Some characteristics of the construction were identical for all walls:

- All mortar was a lime mortar mix. The mix selected was 1:3 Lime to Sand (with the lime being NHL5). This was selected by BRE’s historic buildings experts with reference to literature [24].
- All plaster was a modern gypsum ‘hardwall’ plaster (ancient lime based plasters are likely to have been replaced in many existing solid wall dwellings).

Constructing the walls, and inserting into the NPL wall guarded hot-box was challenging and required careful planning and design. In particular, the following points needed to be adhered to:

- The walls needed to be built accurately - (1197 mm ± 3 mm) x (1197 mm ± 3 mm) – with square corners.
- The sides of the walls had to be flat and as smooth as possible.
- The bricks used to build all the walls needed be kept as dry as possible – including the cut bricks (cut dry). This is to minimise the time to condition the walls to be in equilibrium with the moisture levels in the hot-box laboratory.
- The bottom row of each wall had to be a row of headers – to ensure the wall is as robust as possible for when it is moved.
- The wall needed to be moved safely from the position where it was built into the hot-box apparatus itself.

To meet these requirements a special jig for building the walls, incorporating an “A” frame, was designed and built. The building jig provided an accurate template to ensure that the walls are made exactly to specification (1197 mm ± 3 mm) x (1197 mm ± 3 mm). This was important to ensure they could be clamped into the wall handling frames and to ensure that they would fit into the aperture in the EPS surround panel. It also ensured that these free standing wall panels can be built safely in the vertical position.

A summary of the walls produced is shown in Table 4 below. Photographs of the walls are shown in Figures 31 to 40.

Table 4: Walls configurations tested in the NPL hotbox.

BRE Wall number	Mortar bed thickness	Bonding pattern	Extent of mortar fill	Brick type
	mm			
1	12	Flemish	Full (all joints)	Bedfordshire Red
2	8	Flemish	Full (all joints)	Bedfordshire Red
3	12	Flemish	Partial (cavities in some joints)	Bedfordshire Red
4	12	English Garden Wall (3 course stretcher)	Partial (cavities in some joints)	Bedfordshire Red
5	12	Flemish	Partial (cavities in some joints)	London Stock
6	12	Flemish	Partial (cavities in some joints)	Perforated Wolverton brick

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Figure 31: Two of the BRE built walls which are held in place within the specifically designed blue ‘moving frames’ to allow them to be lifted into the hot-box.

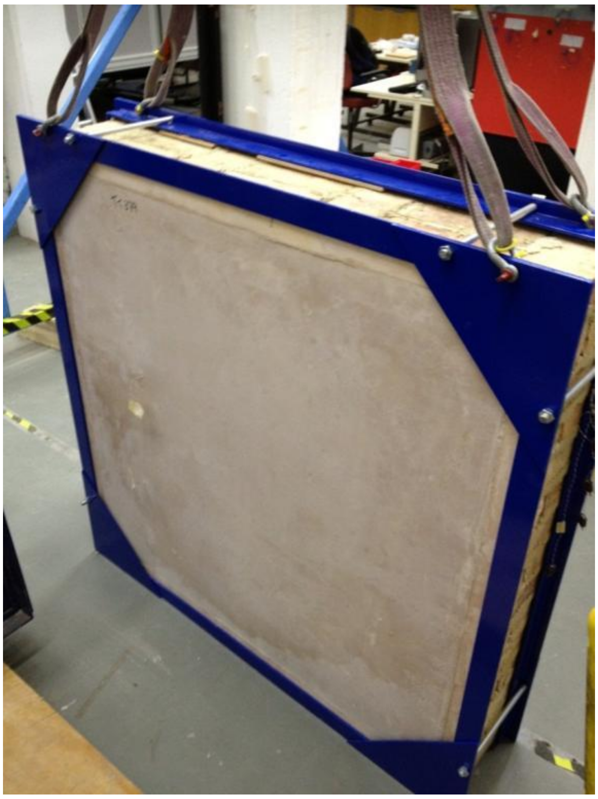

Figure 32: Each wall was plastered with a gypsum ‘hardwall’ plaster. This is a modern plaster, as it is our assumption that many ancient plasters will have been replaced.

Figure 33: At the construction stage, each wall was built within a wooden frame which could be removed allowing the moving frame to be attached. The wooden frame can be seen surrounding this wall (Wall 4, built with an English Garden Wall Bond).

Figure 34: Walls 3 to 6 all incorporated the types of small cavities which we had observed in the field. Shown are the partial filling of joints with mortar in Wall 3, particularly in the collar joints and perpends, which matches observations from the fieldwork

Figure 35: Wall 1

Figure 36: Wall 2

Figure 37: Wall 3

Figure 38: Wall 4

Figure 39: Wall 5

Figure 40: Wall 6

3.2.1.2 Moving the built walls into the hot box

Once the walls were built, the next challenge was to move them into the hot-box, and surround panel, itself. To achieve this a special steel moving-frame was used.

The steel frame, however, could not simply be clamped to the newly built wall as this would have resulted in damage to the plaster. This problem was anticipated, and to ensure the plaster was not damaged during the moving process a 47 mm wide strip of 12 mm thick plywood was fixed around the perimeter of the warm face of the wall prior to plastering. The plywood was fixed with normal wood screws and rawl plugs. When it was time for the wall to be moved the plywood was removed, and the steel moving frame was fastened against the brick surfaces. In this way the wall was ready to be lifted into position. Additional modifications needed to be made to the hot box panel itself in order to accommodate the heavy masonry wall panels. This took the form of a special collar guard system and surround panel which were designed and built with a removable top section. This allowed the wall panels to be lifted in from above using a two tonne gantry crane. This is shown in Figure 41 and Figure 42. During the process of installing the wall into the hot-box surround panel, aluminium beams were clamped into position to ensure the wall was stable prior to being finally fixed into the surround panel. Once in the hot-box surround panel the wall could be wheeled into position on castors.

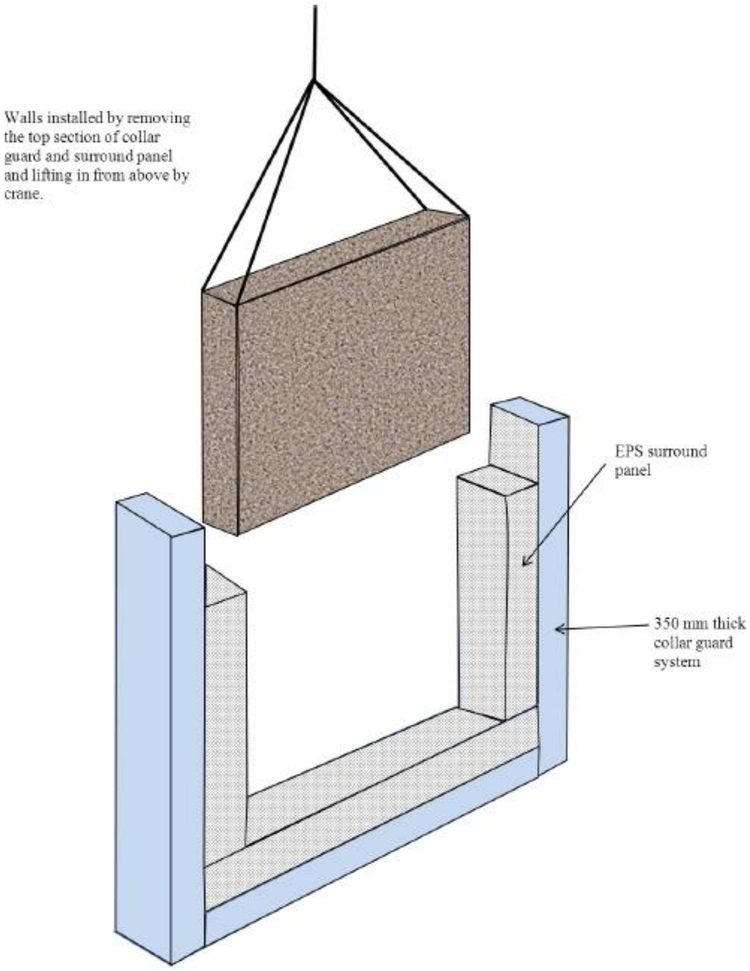

Figure 41: The walls (within their moving frames) were lifted into the EPS hot-box surround panel which incorporated a removable collar guard. The frame was then removed.

Figure 42: A completed wall, within the EPS guarding, ready to be placed into the hot-box. Once in this position the wall could be rolled into place on castors.

3.3 Controlling for differential moisture contents between walls

As described above, a secondary objective for the hot-box work, after the principal objective of benchmarking of solid walls in the laboratory, was to try to compare the results between the walls. One of the key challenges when comparing the walls was to attempt to control for the moisture contents. Ideally, each wall would have been fully dried in a large oven prior to being placed in the hot-box. Loudon [3], commenting on the early work done using the BRS Wall Laboratory, noted that the measured U-values of the walls would generally fall significantly in the second and third years after construction, compared to the values measured in the first year. He believed that this was most likely due to the continued reduction in the moisture content of the walls as they dried. Ideally, therefore, we would have liked to have carried out our tests when the effect of moisture could be discounted. The size of the walls meant, however, that there was no practical way of drying the entire wall.

As an alternative we may have wished to test each wall in its fully conditioned state (i.e. having reached an equilibrium level of moisture) when we would have the best chance of moisture contents being equivalent in each wall. For practical reasons of time and availability of the laboratory equipment, however, this was not possible and an alternative approach was required.

One further option considered for this was to attempt to estimate data on the moisture content of each wall at the time of each test from changes in the wall weights or measurements and apply a moisture correction (see Section 7). This approach however, requires a high level of confidence in both the moisture measurements, and the moisture correction method itself. As described in sections 6 and 7.1 below we know that moisture can vary significantly across the extent of a wall, and have concerns about the accuracy of moisture corrections. This approach, therefore, seems unsuitable.

Instead, we used data on the weights of the walls collected for extended periods before and after each test to determine:

a) The equilibrium position – i.e. the time when the wall was no longer consistently losing weight.
b) The amount of water that remained in the wall, ahead of this equilibrium position, at the time of each test.

We also undertook multiple tests on Wall 3, our key reference wall, which the others are generally compared to. In this way we have been able to choose the best measurement for comparison, and should minimise the effect of differential moisture contents between the two walls being compared.

Table 5 below shows which walls are able to be compared and the age, in days after construction, of each wall. Graphs of the weights of each wall are shown in Appendix A.

Table 5: Matrix of hot box tests used in comparisons.

Test	Wall to be compared (and age in days after construction)	Estimated difference between weight at test date and equilibrium position	Reference test used for comparison (and age in days after construction)	Estimated difference between weight at test date and equilibrium position	Comments
Effect of different mortar thicknesses	Wall 1 (127 days)	~8kg (+/-0.5kg)	Wall 2 (136 days)	~8kg (+/-0.5kg)	Both walls for this comparison are the same age since build, and contain equivalent moisture.
Effect of micro cavities	Wall 3A (133 days)	~4kg (+/-0.5kg)	Wall 2 (136 days)	~8kg (+/-0.5kg)	The volume of mortar used in each wall was very different for these two walls, which may help explain the differences in remaining weight of water. This comparison was chosen as the most suitable due to similar age of wall from construction.
Effect of different bonding type	Wall 4 (288 days)	~2.5kg (+/-0.5kg)	Wall 3B (146 days)	~3kg (+/-0.5kg)	
Effect of different brick type (London Stock)	Wall 5 (213 days)	At equilibrium	Wall 3C (768 days)	At equilibrium	The lower density London Stock bricks reached equilibrium more rapidly than the denser brick types
Effect of different brick type (Wolverton drilled brick)	Wall 6 (204 days)	~2kg (+/-0.5kg)	Wall 3B (146 days)	~3kg (+/-0.5kg)	

3.4 Results

The results from the six walls are shown in tables 6 to 18 below. The results are interpreted and discussed below the tables of results. All walls were tested once, with the exception of wall 3 (our main reference wall) which was tested three times. This wall would have had a different moisture content each time it was tested.

Table 6: Wall characteristics and hot-box results for Wall 1.

BRE Wall number 1		
NPL ID Number		TT379
Mortar bed thickness	mm	12
Bonding pattern		Flemish
Extent of mortar fill		Full (all joints)
Brick type		Bedfordshire Red
Plaster type		Hardwall (gypsum)
Measured brick density	kg/m^3	1,731 to 1,759
Date of test		25/04/2014
Age of wall at test (from build)	Days	127
Estimated moisture remaining to be lost ahead of equilibrium	kg	~ 8
Warm environmental temperature	(°C)	22.88
Cold environmental temperature	(°C)	1.82
Environmental temperature difference	(°C)	21.05
Measured U-value (Hot box power)	(W/m^2.K)	2.033
Confidence interval (+/-5.5%)	(W/m^2.K)	1.921 - 2.145

Table 7: Wall characteristics and hot-box results for Wall 2.

BRE Wall number 2		
NPL ID Number		TT380
Mortar bed thickness	mm	8
Bonding pattern		Flemish
Extent of mortar fill		Full (all joints)
Brick type		Bedfordshire Red
Plaster type		Hardwall (gypsum)
Measured brick density	kg/m^3	1,731 to 1,759
Date of test		09/06/2014
Age of wall at test (from build)	Days	136
Estimated moisture remaining to be lost ahead of equilibrium	kg	~8
Warm environmental temperature	(°C)	23.02
Cold environmental temperature	(°C)	1.73
Environmental temperature difference	(°C)	21.29
Measured U-value (Hot box power)	(W/m^2.K)	2.029
Confidence interval (+/- 5.5%)	(W/m^2.K)	1.917 - 2.141

Table 8: Wall characteristics and hot-box results for Wall 3.

BRE Wall number 3				
BRE Test reference		**3A**	**3B**	**3C**
NPL ID number		TT381A	TT381B	TT386A
Mortar bed thickness	mm	12		
Bonding pattern		Flemish		
Extent of mortar fill		Partial (cavities in some joints)		
Brick type		Bedfordshire Red		
Plaster type		Hardwall (gypsum)		
Measured brick density	kg/m^3	1,731 to 1,759		
Date of test		11/07/2014	24/07/2014	02/06/2015
Age of wall at test (from build)		133	146	477
Estimated moisture remaining to be lost ahead of equilibrium	kg	~ 4	~ 3	Zero (at equilibrium)
Warm environmental temperature	(°C)	23.11	23.01	22.95
Cold environmental temperature	(°C)	1.75	1.77	1.76
Environmental temperature difference	(°C)	21.36	21.24	21.19
Measured U-value (Hot box power)	(W/m^2.K)	1.958	1.945	1.877
Confidence interval (+/-5.5%)	(W/m^2.K)	1.850 - 2.066	1.838 - 2.052	1.774 - 1.980

Table 9: Wall characteristics and hot-box results for Wall 4.

BRE Wall number 4		
NPL ID Number		TT382
Mortar bed thickness	mm	12
Bonding pattern		English Garden Wall (3 course stretcher)
Extent of mortar fill		Partial (cavities in some joints)
Brick type		Bedfordshire Red
Plaster type		Hardwall (gypsum)
Measured brick density	kg/m^3	1,731 to 1,759
Date of test		15/01/2015
Age of wall at test (from build)		288
Estimated moisture remaining to be lost ahead of equilibrium	kg	2.5
Warm environmental temperature	(°C)	22.98
Cold environmental temperature	(°C)	1.6
Environmental temperature difference	(°C)	21.38
Measured U-value (Hot box power)	(W/m^2.K)	1.89
Confidence interval (+/-5.5%)		1.786 - 1.994

Table 10: Wall characteristics and hot-box results for Wall 5.

BRE Wall number 5		
NPL ID Number		TT383
Mortar bed thickness	mm	12
Bonding pattern		Flemish
Extent of mortar fill		Partial (cavities in some joints)
Brick type		London Stock
Plaster type		Hardwall (gypsum)
Measured brick density	kg/m^3	1,410
Date of test		02/02/2015
Age of wall at test (from build)		213
Estimated moisture remaining to be lost ahead of equilibrium	kg	At equilibrium
Warm environmental temperature	(°C)	23.2
Cold environmental temperature	(°C)	1.64
Environmental temperature difference	(°C)	21.55
Measured U-value (Hot box power)	(W/m^2.K)	1.685
Confidence interval (+/-5.5%)	(W/m^2.K)	1.592 - 1.778

Table 11: Wall characteristics and hot-box results for Wall 6.

BRE Wall number 6		
NPL ID Number		TT384
Mortar bed thickness	mm	12
Bonding pattern		Flemish
Extent of mortar fill		Partial (cavities in some joints)
Brick type		Wolverton (Perforated) brick
Plaster type		Hardwall (gypsum)
Measured brick density	kg/m^3	2,046 (non-perforated section)
Date of test		20/02/2015
Age of wall at test (from build)		204
Estimated moisture remaining to be lost ahead of equilibrium	kg	2
Warm environmental temperature	(°C)	23.02
Cold environmental temperature	(°C)	1.65
Environmental temperature difference	(°C)	21.37
Measured U-value (Hot box power)	(W/m^2.K)	1.917
95% confidence interval (+/-5.5%)	(W/m^2.K)	1.812 - 2.022

Table 12: Hot box results for all walls.

BRE Wall number	NPL ID Number	Mortar bed thickness	Bonding pattern	Extent of mortar fill	Brick type	Plaster type	Age of wall since built (days)	Estimated moisture remaining to be lost ahead of equilibrium (kg)	Measured U-value (Hot box power)	Measured U-value 95% confidence interval (+/- 5.5%)
		mm							(W/m^2.K)	(W/m^2.K)
1	TT379	12	Flemish	Full (all joints)	Bedfordshire Red	Hardwall (gypsum)	127	8	2.033	1.921 - 2.145
2	TT380	8	Flemish	Full (all joints)	Bedfordshire Red	Hardwall (gypsum)	136	8	2.029	1.917 - 2.141
3A	TT381A	12	Flemish	Partial (cavities in some joints)	Bedfordshire Red	Hardwall (gypsum)	133	4	1.958	1.850 - 2.066
3B	TT381B	12	Flemish	Partial (cavities in some joints)	Bedfordshire Red	Hardwall (gypsum)	146	3	1.945	1.838 - 2.052
3C	TT386A	12	Flemish	Partial (cavities in some joints)	Bedfordshire Red	Hardwall (gypsum)	477	At equilibrium	1.877	1.774 - 1.980
4	TT382	12	English Garden Wall (3 course stretcher)	Partial (cavities in some joints)	Bedfordshire Red	Hardwall (gypsum)	288	2.5	1.890	1.786 - 1.994
5	TT383	12	Flemish	Partial (cavities in some joints)	London Stock	Hardwall (gypsum)	213	At equilibrium	1.685	1.592 - 1.778
6	TT384	12	Flemish	Partial (cavities in some joints)	Wolverton (Perforated) brick	Hardwall (gypsum)	204	2	1.917	1.812 - 2.022

3.5 Interpretation of hot box results

As outlined above, our principal objective of the hot-box tests was to obtain some fundamental measurements of solid wall U-values in a laboratory environment, in order to reconfirm our in situ measurements. Therefore, the first observation to be made from the results is of the overall spread and pattern of U-values measured by the NPL hot-box.

In general, the measured U-values are close to where we would expect from theoretical calculations for these walls. For walls 1 & 2, the measured U-value is very close to 2.1 W/m^{2}K which is the U-value assumed in RdSAP, and historic theoretical calculations, for solid walls - but which is not supported by in situ measurements, as outlined in section 1 above. The original experimental basis for this value [1, 3] used a laboratory test of a brick wall, which seems likely to have been constructed in a similar way to our walls. The density of the bricks used for walls 1 and 2 (approximately 1,750 kg/m^3) is equivalent to that used in the traditional calculations of U-values. The overall moisture content of the wall is unknown, but we can assume it to be relatively high, due to the walls being relatively recently built prior to testing. The majority of the moisture will have originally have been in the newly applied mortar, and an unknown quantity of this moisture will have transferred into the bricks since the time of construction.

Walls 3 to 6 were all built with small cavities ‘designed’ within them. For those built with Bedfordshire Red Bricks (variations of Wall 3) it is noticeable that the built walls still return U-values which are slightly *above* the mean U-values recorded in situ*,* (although close to this at the bottom of the confidence interval for the wall at moisture equilibrium)*.* This may be because we have not adequately accounted for the cavities within the wall (e.g. no brick bats or imperfect bricks were used), or it may be for another unknown reason. The difference, however, is not unduly large and provides additional evidence in support of a value less than 2.1 W/m^{2}K for walls of this type.

We can also attempt to compare the results from the six hot-box tests to each other and consider some more specific questions. It is noted above, however, that there are inherent difficulties in this due to the complicating factor of moisture content. The following questions can be considered:

What is the effect of different mortar bed thicknesses on the U-value of the wall?

A comparison between walls 1 and 2 tested the effect of different mortar thicknesses. Wall 1 was constructed with thick mortar beds and perpends (approximately 10mm on average). Wall 2 was constructed with a narrower 8mm mortar bed thickness. Both walls were constructed using the same brick types, and all mortar joints were fully filled. In this way the two walls could be considered as homogeneous as possible, and as similar to each other as possible. The age of these two walls since build is almost identical, as is the amount of moisture remaining in the wall ahead of equilibrium.

Both walls measured almost identical U-values – i.e. approximately 2.0 W/m^{2}K. We can therefore conclude that there is no evidence from these measurements that different mortar bed thicknesses significantly affect the U-value. In these cases, although the thermal conductivity is expected to be different to that of brick, the additional mortar from the thicker joints has a very small effect on the overall U-value. This is also the results expected by theoretical calculations which indicate that it would have an effect of the order 0.02 W/m^{2}K.

This has an implication for the assessment of the U-values in the field, in that the thickness of the mortar bed is unlikely to be a good predictor of U-value.

What is the effect on the U-value of the wall of introducing cavities within the joints?

In the construction of walls 1 and 2, all joints were fully filled with mortar across their full extent – i.e. no gaps were left in perpend joints, bed joints, or between stretcher bricks. In walls 3 to 6, however, gaps were left in the joints to reflect the building practices believed to be in place at the time solid wall dwellings were being built. These gaps attempted to replicate the extent of mortar fill seen in the fieldwork (see section 2). To consider the effect of the introduction of these small cavities, we can compare wall tests 2 and 3A, which were identical in other regards. The wall weight data, however, suggests that there remains approximately 8kg of water in wall 2, compared to only 4kg in wall 3A. There should have been less water used in the construction of wall 3A than in wall 2 as much less mortar was used (creating the cavities), which may help explain these differences. There is, therefore, a need to have additional caution in this specific comparison. The measured U-value of wall 3A is approximately 1.96 W/m^{2}K compared to 2.03 W/m^{2}K in wall 2. This difference is not significant given the uncertainty of the measurement itself, and given the additional uncertainties we cannot say with confidence that this difference is due to the introduction of the cavities.

The implication of these findings is in providing corroborating evidence that the introduction of small cavities into the wall is likely to reduce the U-value of the wall, and that our fieldwork observations of such cavities are consistent with lower measured U-values.

What is the effect of different brick types, or different densities, on the U-value of a wall?

Three different brick types were used, all of which had been reclaimed from old solid wall dwellings following demolition. Studying the wall weight data, we can choose the most appropriate comparisons. The London Stock built wall (wall 5) reached equilibrium more quickly than the other walls (which is probably related to the brick density, porosity and permeability) and is best compared with the test 3C which is the Bedfordshire Red Brick wall at equilibrium. This comparison is of U-values from wall 3C (Bedfordshire Red Brick) at 1.88 W/m^{2}K and wall 5 (London Stock) at 1.69 W/m^{2}K. This comparison is close to what we would expect for these brick types, although the confidence intervals for these measurements do overlap and we cannot therefore say this difference is significant.

Wall 6 (the Wolverton perforated brick) is best compared to wall 3B. The wall 3B U-value was 1.95 W/m^{2}K and the wall 6 U-value was 1.92 W/m^{2}K. Although the Wolverton brick is the most dense brick of the three examined, it incorporates large perforations within it, which may be acting to reduce the overall U-value of the wall and bring it closer to the U-value of the wall built with the less dense Bedfordshire brick. This would be in line with our understanding of the thermal performance of perforated bricks [34]. The wall built with this brick acts as a good example of where a wall may look like a “standard” solid wall from the outside, but other invisible internal features (in this case holes within the brick itself) can act to reduce its thermal transmittance.

These results provide experimental evidence of the effect of density on the wall U-value. It provides some reassurance that bricks of lower density, if these could be identified in the field, are likely to result in lower U-values (and higher densities vice-versa).

What is the effect of different bonding patterns on the U-value of wall?

Five of the six walls were built with Flemish bond, which consists of alternate stretcher and header bricks along every course of the wall. This bonding pattern was identified as the most common binding pattern in use in solid wall dwellings in England, following re-analysis of the 2012 U-values study data referred to above in section 1. We would expect the greater proportion of stretcher bricks in the English Garden Wall Bond wall to reduce the U-value of the wall, because of the increased likelihood of cavities being present within walls with this type of bond pattern (recall that both walls incorporate cavities through incomplete mortar fill). Wall 4 was built with an English Garden Wall (3-stretcher) bond, to investigate the effect of this alternative bonding pattern, which could be compared with wall 3B which was built in an otherwise identical way. English Garden Wall (3-stretcher) bond consists of a full course of header bricks, separated by three full courses of stretcher bricks. This can be seen in the photographs of wall 4 above. The measured U-value of the English Garden Wall (3-stretcher) bond wall was 1.89 W/m^{2}K, compared to 1.95 W/m^{2}K for the Flemish Bond wall. This difference is in the direction and of a magnitude expected although this difference cannot be said to be significant.

This finding also has implications for the field assessment of U-values. The type of bonding can be identified by the surveyor, and may be able to be used to provide better estimates of U-values.

4 Measured thermal conductivity of bricks

In addition to the hot-box tests, NPL conducted a series of tests on the thermal conductivity of brick samples. In the theoretical calculation of U-values, the thermal conductivity of the brick is calculated using an assumed relationship between the brick density and its conductivity (plus a correction for moisture content). The direct measurement of thermal conductivity of bricks has been undertaken in order to understand how well we are inferring this from estimates of brick density.

In particular, following discussions between BRE and NPL, there are significant concerns that many historic measurements of thermal conductivity may not be valid. NPL's thermal conductivity experts believe that, in the past, it is extremely unlikely that many historic measurements of brick thermal conductivity dealt with important issues such as thermal contact resistance issues in a way that would be considered acceptable within the current framework of international measurement standards. As a result, we might expect that historic measured values may be significantly lower than the true thermal conductivity values[2].

The opportunity to undertake some tests on bricks, using modern equipment, allows us to challenge existing assumed relationships and propose alternatives if required.

4.1 Existing relationships

There are two main sources which are used when attempting to infer a thermal conductivity from a brick density. The first of these is the Jakob relationship [35] which is described in his work published in 1949. This is shown in the Table 19 below. The second of these is the relationship described in the 1999 Thermal Values report [36] developed for the production of ISO 10456, which drew together numerous measurements from across Europe. Due to the nature of the Thermal Values data (which were compiled from numerous sources in different countries) it is not possible to identify the provenance of many of the measurements. It does seem likely, however, that many of the data items used in this report are quite old[3].

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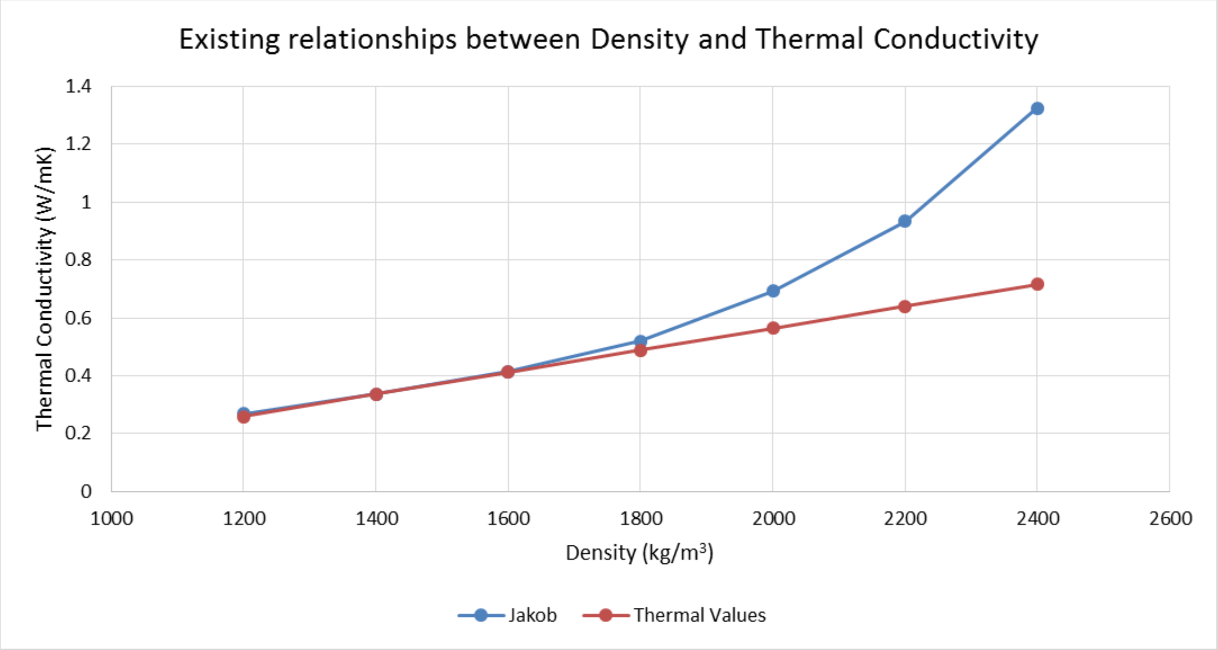
[2] See NPL statement here: http://www.npl.co.uk/news/understanding-thermal-performance-of-buildings

[3] Report lead author, Brian Anderson, Pers. Comm.

Table 13 and Figure 43: Jakob and Thermal Values relationships between density and thermal conductivity (λ)

Dry density (kg/m^3)	Jakob: Thermal Conductivity (for bone dry building materials) (W/mK) (from [12])	Thermal Values (ISO 10456): Thermal Conductivity (for brick) (W/mK) (from [13])
1,200	0.268	0.260
1,400	0.337	0.336
1,600	0.415	0.412
1,800	0.519	0.488
2,000	0.692	0.564
2,200	0.934	0.640
2,400	1.323	0.716



Whereas the Thermal Values relationship is linear, the Jakob relationship is not. Although the Jakob relationship is for building materials in general, he outlines that the value of λ for most inorganic building materials is almost the same. Jakob [35] further outlines that the non-linear relationship derives from the decrease in porosity of the material. The Jakob relationship was later confirmed based on measurements undertaken by Ball in 1968 [37].

The collection of samples from the fieldwork, described in Section 2 above, provided the opportunity to re-examine these relationships, and conduct measurements using modern equipment and techniques at NPL.

Measuring the thermal conductivity of bricks is reasonably challenging due to their high thermal conductivity and the limitations of the physical size of the bricks. The classic thermal conductivity method is the 305 mm x 305 mm guarded hot plate apparatus but this requires a test piece measuring 305 mm x 305 mm x ~45 mm thick – which would require fabricating from a number of bricks. The method we used was a smaller steady-state apparatus referred to as a Guarded Heat Flow Meter Apparatus. This apparatus conforms to ASTM E1530-11 and is a UKAS accredited test service (UKAS 0002).

A total of 24 samples were able to be measured by this apparatus. These are referred to as sample Group A. The measurements on sample Group A were carried out at a mean temperature of 10 °C. The test specimen specification for this apparatus is as follows:

a) Thickness: 20 mm.

b) Diameter: 50.8 mm. (Within the range 50.6 mm to 51.0 mm)

c) Parallelism: Variation in thickness was required to be less than 0.025 mm.

d) Flatness: Both round faces were required to be flat, to better than 0.025 mm.

All the thermal conductivity measurements were carried out on test samples that had been oven dried. This allows for the samples to be tested without the influence of moisture. The oven dried weight and physical dimensions were used to calculate the dry density of the brick samples NPL tested. Seven samples are from the bricks used in the NPL hot-box described in Section 3. The remaining samples are from bricks removed from dwellings visited in the fieldwork, described in Section 2 above.

All samples in sample Group A were cut into flat discs, 50mm in diameter and 20mm in thickness. This machining is required to be completed to a high level of precision in order to correctly determine the brick conductivity.

The thermal resistance was measured using a single sided 50mm guarded heat flow meter apparatus (a Holometrix TCA-200LT-A). Thermal resistance was measured at 10°C. In this apparatus the specimen is mounted horizontally with heat flow upwards, with lateral heat flow minimised by additional edge guard heating. A thin heat transfer layer was used to reduce the thermal resistance of the interfaces between the sample and heated surfaces. The apparatus is calibrated using the NPL Perspex reference material.

The results of the measurements for sample Group A, as measured using the NPL guarded heat flow meter apparatus (converted from thermal resistance to thermal conductivity) are shown in Table 20 below.

Table 14: NPL Guarded Heat Flow Meter results for sample Group A specimens.

Reference	Density (kg/m3)	Measured Thermal Conductivity (W/mK)
Bedfordshire Red - B1A Long side face	1,748	0.792
Bedfordshire Red -B1B Small header face	1,759	0.793
Bedfordshire Red - B2A Long side face	1,754	0.653
Bedfordshire Red - B3A Long side face	1,748	0.711
Bedfordshire Red - B4A Long side face	1,731	0.614
London Stock - Long side face	1,410	0.595
Wolverton (non-perforated section) - Long side face	2,046	0.955
E140	1,729	0.763
E142	1,768	0.635
E188	1,736	0.588
E189	1,755	0.585
E190	1,706	0.585
E215	1,491	0.685
E222	1,686	0.667
E225	1,844	0.669
E269	1,800	0.733
E171	1,688	0.649
E205	1,567	0.635
E227	1,812	0.504
E285	1,631	0.604
E296	1,820	0.658
E299	1,850	0.763
E301	1,756	0.522
E305	2,169	1.053

The first observation relating to these measurements is about the variation in the first five samples: those collected from the otherwise identical Bedfordshire Red bricks. These samples were cut from four different bricks, from the same batch (and known to have originally been reclaimed from the same building). Samples 1 and 2 were cut from the same brick, but with the samples obtained from two different faces to examine whether thermal resistance would differ in two orientations, possibly due to any anisotropy in the clay materials of the brick itself. The two measurements in the two orientations were very close, providing an estimate of thermal conductivity of 0.792 W/mK and 0.793 W/mK respectively, suggesting that for these two samples at least the effect of any anisotropy in the brick was negligible. Recalling that all of these bricks are from the same source, it is striking how different the measured thermal conductivities are for bricks of very similar densities. This is shown in Figure 44 below. The range in measured values is 0.178 W/mK, around a mean value of 0.713 W/mK. The range is, therefore, approximately 25% of the mean value (and 33% between the largest and smallest values). This range of values, for the same type of brick, is important to note when we consider that we have only been removing a single sample of brick in the fieldwork, which may not be representative of all bricks within the wall. This has implications for attempts to reconcile calculated U-values with measured U-values, as described in section 8 below, which we can expect to be difficult due to only a single brick sample being obtained from each survey case.

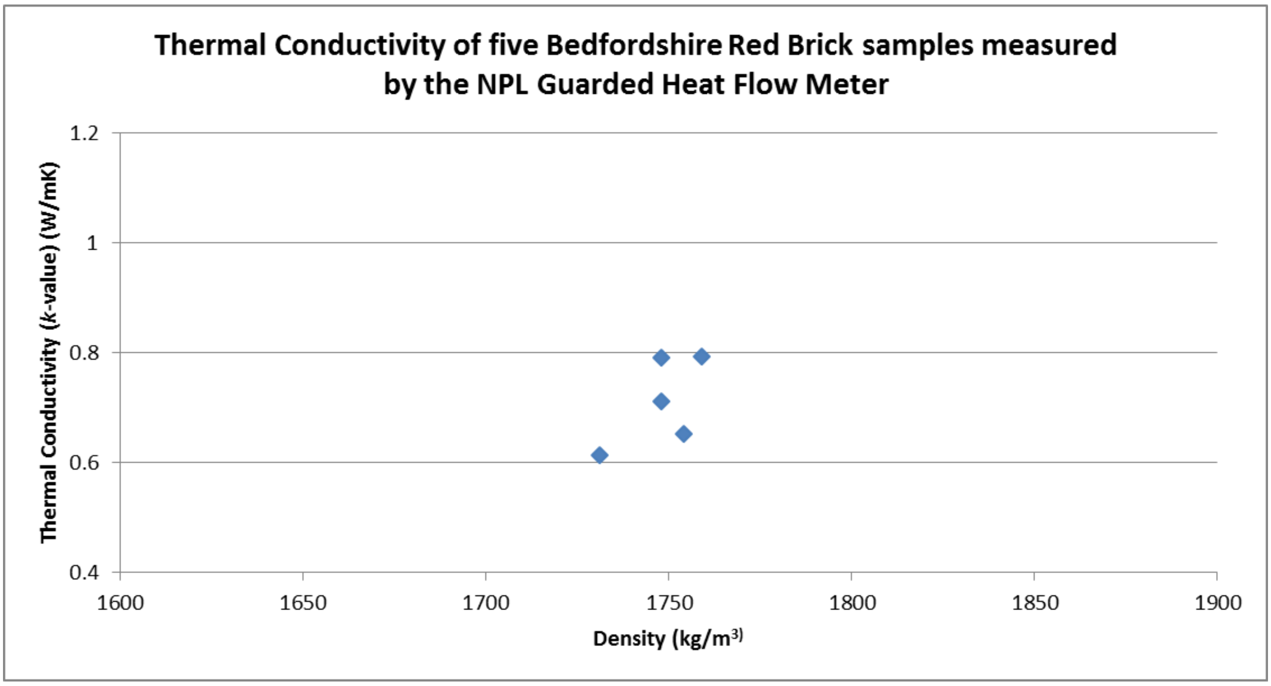


Figure 44: Variation in thermal conductivity within Bedfordshire Red Bricks, as measured by the NPL guarded hot plate apparatus.

By plotting the measured brick densities against the NPL measured thermal conductivities, we can examine the relationship between the two. Figure 45 below shows all results produced using the NPL guarded heat flow meter apparatus.

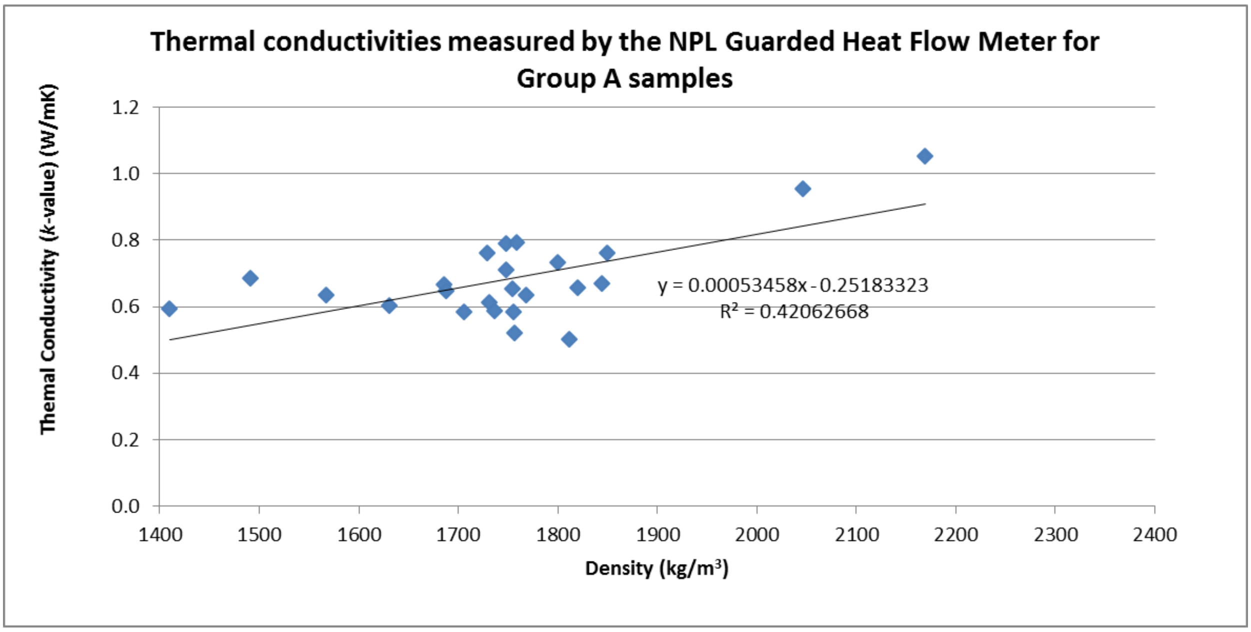


Figure 45: All results measured using the NPL guarded heat flow meter apparatus (Bedfordshire Red Bricks disaggregated).

In Figure 45, five of the 24 measurements (over one-fifth) are from the same type of bricks – i.e. the Bedfordshire Red Brick used in the hot box walls described in Section 3 above. We have, therefore, produced a second version of this chart which uses a mean value for the Bedfordshire Red Brick measurements to reduce the influence of this single brick type on the results. This is shown in Figure 46 below. The effect on the best-fit line is very minor.

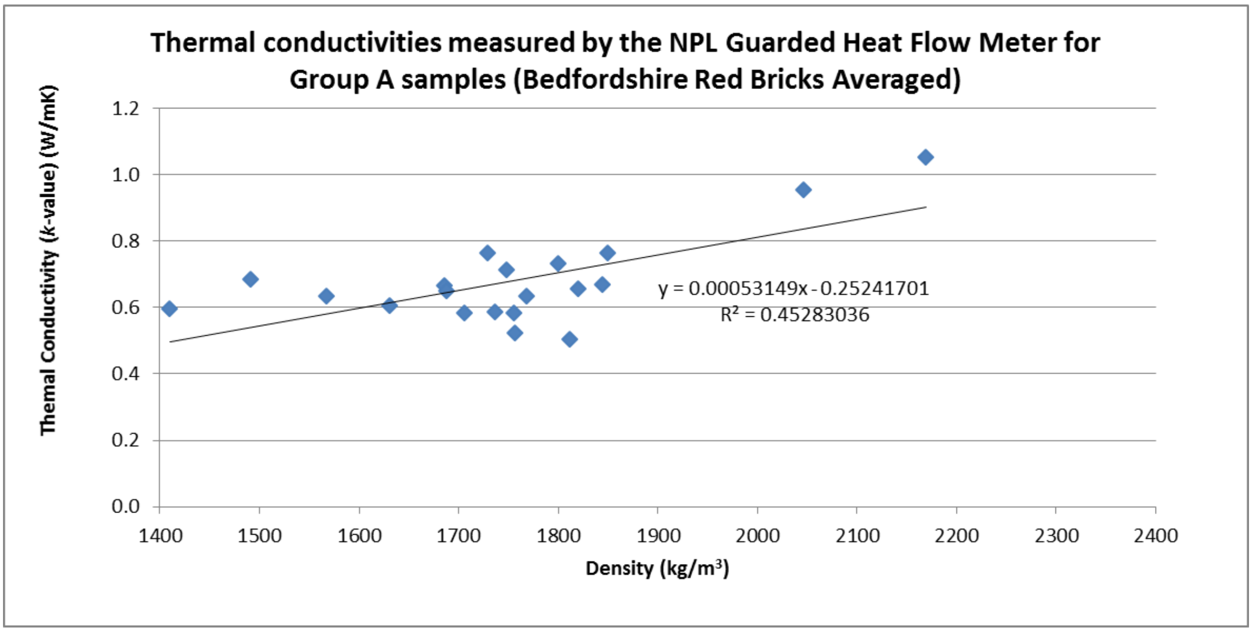


Figure 46: All results measured using the NPL guarded heat flow meter apparatus (Bedfordshire Red Bricks averaged).

Although a best fit line is shown for both these charts, the line of best fit is heavily influenced by the effect of the two densest bricks examined (densities 2,046 and 2,169 kg/m^3). Excluding these two single observations results in a much weaker correlation, and a different relationship. As a result, we are reluctant to use this relationship without more data. Such data can be provided through an alternative measurement technique which is able to test smaller samples.

The majority of the samples collected through the fieldwork component of this project, described in Section 2, are too small to successfully measure using the guarded heat flow meter. We have, therefore, been trialling an alternative piece of apparatus for the measurement of thermal conductivity, manufactured by Hukseflux in the Netherlands.

This apparatus, the TP01, consists of a thin foil sensor containing an embedded heating element. The sensor is clamped between two test samples (which have been dried), and the heat flow out of the sensor is monitored. The rate of heat flow is converted into a thermal conductivity. Full details of this sensor are described in Appendix B.

Our initial task in this assessment was to conduct a comparison of the results obtained from this sensor, and the guarded heat flow meter measurements produced by NPL. This comparison is shown in Figure 47 below. A good correlation can be seen and we can conclude that, for these materials, the sensor is providing estimates of thermal conductivity in line with those of the more established guarded heat flow meter approach.

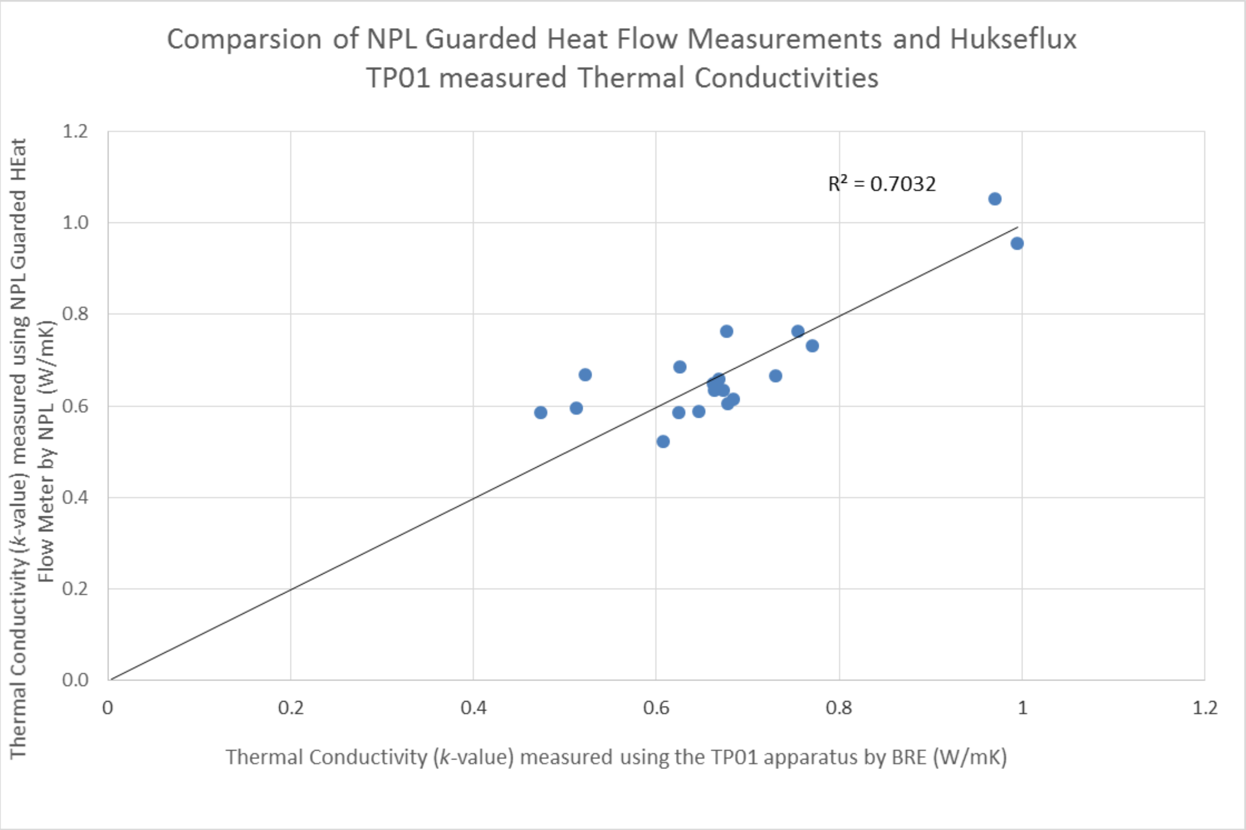


Figure 47: Comparison between the NPL guarded heat flow meter measurements and the TP01 apparatus measurements for sample Group A. A good correlation can be seen.

We can also plot the relationship between the sample density and thermal conductivity for sample Group A, which is derived using the TP01 apparatus. This is shown in figure 48 below. The best fit line produced from the TP01 results, and the best fit line produced from the NPL guarded heat flow meter data shown in Figures 46 above, are very similar. These two comparisons provide us with some confidence in the results from the TP01 apparatus.

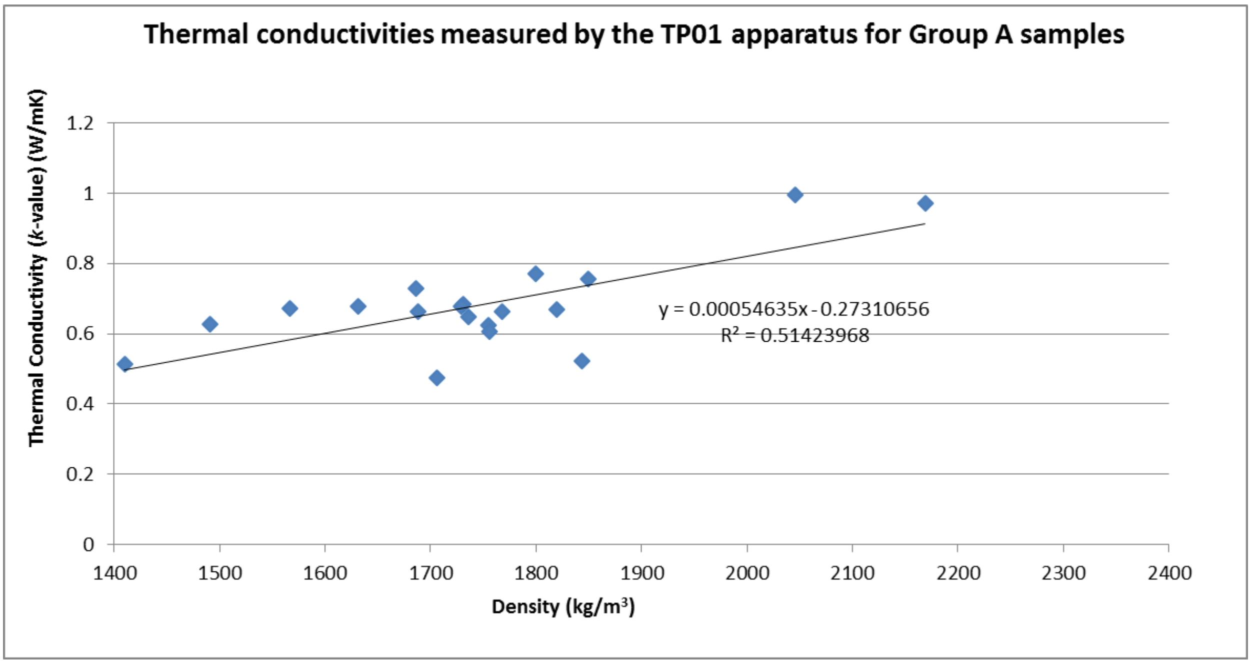


Figure 48 Thermal conductivities measured using the TP01 apparatus for Group A samples (Bedfordshire Red Bricks disaggregated). The chart is very similar to the results tested using the NPL guarded heat flow meter shown in Figure 45.

Using the TP01 apparatus allowed the measurement of thermal conductivity of many more samples. In total, an additional 33 samples could be tested. These additional samples are referred to as Group B. For these samples, which were irregular cut blocks from the fieldwork, bulk density was determined using the method described in BS EN 993-01. The results for all samples (Group A and Group B) measured using the TP01 sensor are shown in Table 15 below.

Table 15: All thermal conductivity measurements, as measured using the TP01 apparatus (those in dark blue are TP01 results from the same bricks tested using the NPL guarded heat flow meter).

Reference	**Bulk density (kg/m^3)**	**Measured Thermal Conductivity using TP01 apparatus (W/mK)**
Wall 4 (TT382) - Bedford Red - B4A Long side face	1731	0.685
Wall 5 (TT383) - London Stock - Long side face	1410	0.513
Wall 6 (TT384) - Wolverton (with holes) - Long side face	2046	0.995
E140	1729	0.677
E142	1768	0.664

E188	1736	0.647
E189	1755	0.624
E190	1706	0.474
E215	1491	0.626
E222	1686	0.730
E225	1844	0.522
E269	1800	0.771
E171	1688	0.662
E205	1567	0.673
E285	1631	0.678
E296	1820	0.669
E299	1850	0.755
E301	1756	0.608
E305	2169	0.970
W21	1741	0.691
E36	1811	0.541
W12	1684	0.716
U20	1828	0.629
W22	1888	0.601
W32	1815	0.601
U26	1864	0.643
E72	1587	0.697
U53	1802	0.679
E32	1521	0.639
W29	1512	0.578
U31	1736	0.746

U6	1553	0.481
E50	2026	1.095
E40	1544	0.632
U5	1665	0.727
E2	2308	0.693
E29	2095	0.820
W33	1826	0.559
E75	2075	0.925
U28	1787	0.725
W31	1747	0.624
E31	1786	0.604
E86	1859	0.747
U36	1841	0.584
U27	1729	0.716
U8	1657	0.679
E38	1996	0.728
W10	1627	0.749
E236	1682	0.828
W17	1882	0.785
E8	2041	0.796
E292	1685	0.766
E16	2001	0.838
U29	1987	0.627
E231	1717	0.707

The results from all samples tested using the TP01 apparatus are plotted in Figure 49 below (this includes the TP01 results from Group A samples – i.e. those also tested using the NPL guarded heat flow meter). The chart below this, Figure 50, uses the guarded heat flow meter data for those samples where it is available, and HP01 apparatus data where it is not. Also plotted on all charts are linear lines of best fit. The charts are very similar, with similar best fit lines.

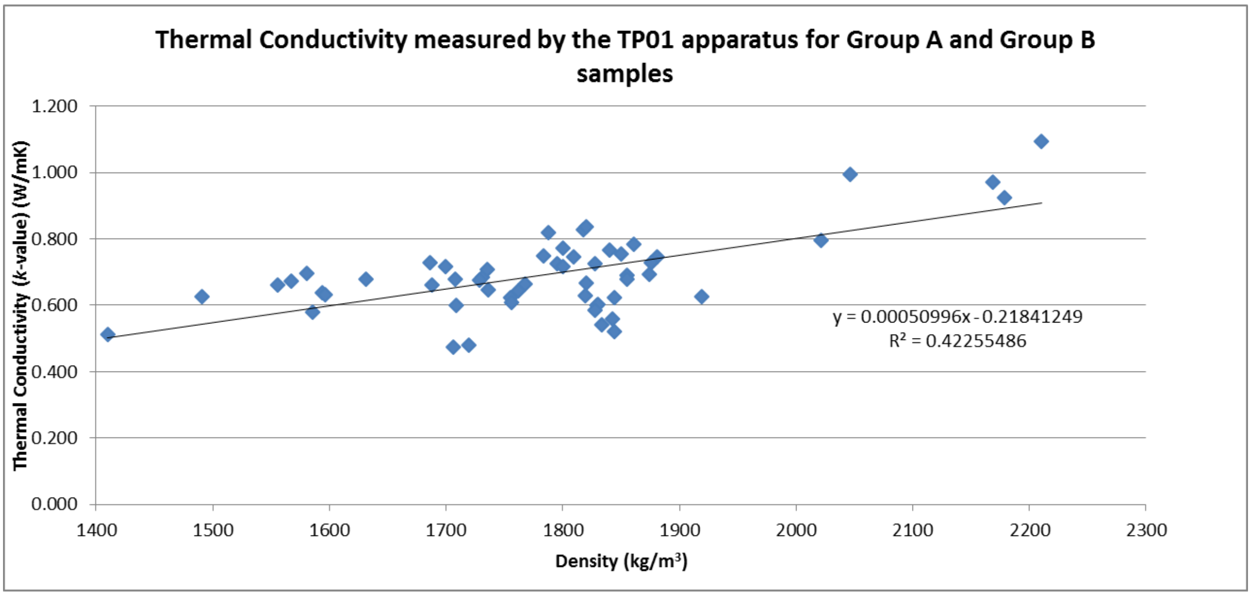


Figure 49: All measurements made using the TP01 apparatus (Bedfordshire Red Bricks disaggregated).

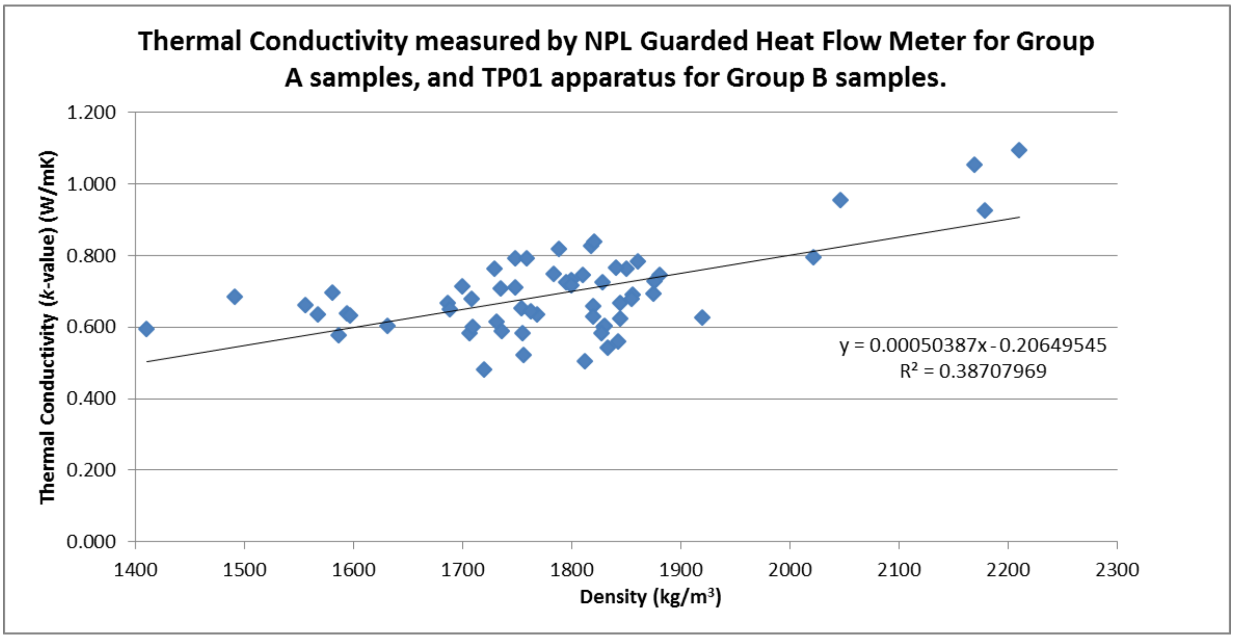


Figure 50: Combination of measurements made using the NPL guarded heat flow meter from Group A samples (Bedfordshire Red Bricks disaggregated), and TP01 apparatus for Group B samples.

The calculated thermal conductivities for a range of densities, using each of the best fit lines generated and shown in Figures 46, 49 and 50 are shown in Table 16 below. It can be seen that the curves give results that are relatively close to one another, in particular around the middle range of densities which will be found in most brick samples (see Section 2 above).

A value for brick density of 1,750 kg/m^3 is generally assumed in U-value calculations, and was supported by the fieldwork undertaken for this project. Data from this project suggests a dry conductivity of ~0.68 W/mK may be appropriate as a default assumption for this type of brick.

Table 16: Calculated thermal conductivities for different densities, based on best fit lines shown in Figures 46, 49 and 50.

Density	**NPL Guarded Hot Plate data only (From Figure 46)**	**TP01 apparatus data only (From Figure 49)**	**Combined Guarded Hot Plate and TP01 data (From Figure 50)**
1400	0.497	0.496	0.499
1500	0.550	0.547	0.549
1600	0.603	0.598	0.600
1650	0.630	0.623	0.625
1700	0.657	0.649	0.650
1750	0.684	0.674	0.675
1800	0.710	0.700	0.700
1850	0.737	0.725	0.726
1900	0.764	0.751	0.751
2000	0.817	0.802	0.801
2100	0.871	0.853	0.852
2200	0.924	0.903	0.902
2300	0.978	0.954	0.952
2400	1.031	1.005	1.003

Inspecting this table, it is apparent that there is very little difference between the different subsets of results. We need to choose one of these best-fit lines, and it seems most appropriate to identify that which uses a combination of the NPL guarded heat flow data and the TP01 data as best describing the relationship between density and thermal conductivity. This is based on the largest number of data items and, although the HP01 results have been obtained through a novel measurement methodology, the differences between these and the NPL guarded heat flow meter results (for those tested with both techniques) are very small.

This relationship is expressed as:

$$\lambda = 0.00050387\rho - 0.20649545 \qquad \textit{Equation 6}$$

Where λ is thermal conductivity (W/mK) *and* ρ is density (kg/m^3)

Earlier in this section we raised questions about whether historic relationships between density and thermal conductivity can be considered valid, given known deficiencies in some of the methodologies used in the past. In particular, experts at NPL are of the opinion that old measurements of thermal conductivities may be too low. It is, therefore, of great interest to compare the relationship described above to the historic relationships. Shown in Table 17 are the results obtained using the newly derived relationship and the Jakob and Thermal Value curves. It can be seen that the newly derived relationship gives higher thermal conductivities than the existing curves, for bricks below 2,200 kg/m^3, supporting the hypothesis that older measurements may be too low. Above this density, however, the Jakob curve predicts higher conductivities, but the Thermal Values continues to predict lower than the newly derived relationship. It should be noted, however, that bricks greater than 2,200 kg/m^3 in density are relatively rare according to our fieldwork findings (see Section 2).

Table 17: Comparison of new curve and the Jakob and Thermal Values (ISO 10456) curves. It is recommended that the relationship derived from Equation 6 is used in future calculations.

Density	From Equation 6 (and Figure 39)	Jakob	Thermal Values / ISO 10456
1400	0.498923	0.33735	0.336071
1600	0.599697	0.4152	0.412105
1800	0.700471	0.519	0.488139
2000	0.801245	0.692	0.564173
2200	0.902019	0.9342	0.640207
2400	1.002793	1.32345	0.716241

4.1.1 Thermal conductivity of mortar

A thermal conductivity measurement of a single mortar specimen was also made using the NPL guarded heat flow meter apparatus. A large enough sample could not be obtained from the field, therefore, this specimen was created at the same time as the walls produced for the hot-box (described in Section 3) were constructed. The mortar used in these walls was a lime-mortar mix, considered likely to be representative of the type of mortar in use in solid wall dwellings.

This mortar, however, is very granular. As a result, the specimen could not be produced to the required level of parallelism and flatness required by the NPL test, and the uncertainty on the measurement is significantly increased, with the true value potentially up to 25% above this. Data on the thermal conductivity of mortar, however, is very scarce and the results are included here, despite these reservations to provide an indication of the conductivity of this important material.

The measured value, and the top of the potential range, are shown in Table 18 below.

Table 18: Measured Thermal Conductivity of Lime Mortar sample

Material	Density	Measured Thermal Conductivity using NPL Guarded Heat Flow Meter apparatus (W/mK) (n.b. required flatness and parallelism could not be achieved)	Top of potential Thermal Conductivity range – assuming measured value is 25% too low.
Lime mortar sample	1612	0.435	0.580

5 In situ measurements of Thermal Conductivity using a needle probe

As part of this project we have also tested the possibility of measuring brick thermal conductivity directly using a thermal needle probe. The system tested is the Hukseflux TP07 thermal needle system. Previous work in this area has already been conducted by Pilkington et al, [38, 39], which showed that consistent thermal conductivity results could be obtained in the field, even of inhomogeneous materials. In addition, minor temperature fluctuations in the environment were not found to have a significant effect on thermal conductivity results, providing confidence in the thermal needle as a viable technique to directly measure thermal conductivity in solid walls.

Advantages of using a thermal probe system are:

- It is relatively un-intrusive: bricks do not need to be removed from the wall, instead a small hole is drilled into the centre of a header brick.
- It is simple and fast: measurements can be taken on a timescale of minutes, and equipment is easy to use.

The thermal conductivity, measured using a thermal needle system, is based on a non-steady-state probe technique, where the probe is heated and the time it takes for the sensor to detect a change in temperature is measured. This follows the transient line source method, where:

$$\Delta T = \frac{Q}{4\pi\lambda}(lnt + C)$$

In this equation, ΔT is the change in temperature (K), Q is the power from the heater (W/m), λ is the thermal conductivity of the material (W/mK), t is the time (s) and C is a constant. The thermal conductivity can be calculated, once the transient period has passed. This is indicated in Figure 51 where the linear portion of the graph is used (typically after 100 seconds), based on analysis of ΔT and t.

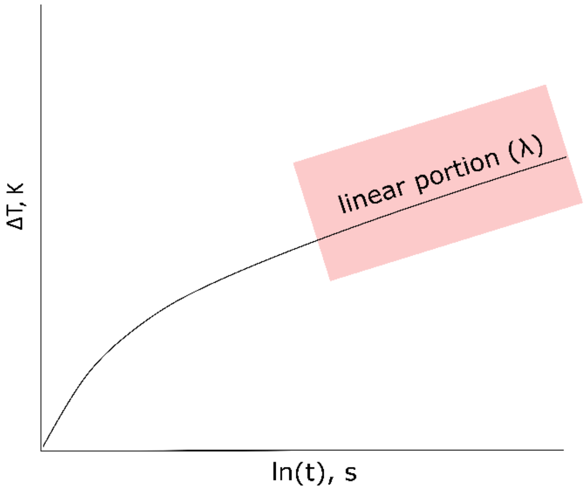


Figure 51 – Relationship between the change in temperature and time.

From this, the thermal conductivity can be calculated, where the linear best fit line becomes:

$$\frac{4\pi\Delta T}{Q} = \frac{1}{\lambda}(lnt + C)$$

For the non-steady-state probe method to be valid, the following is assumed:

- The thermal needle is not moved during the measurement
- There is good contact between the needle and the measured material
- The material is homogenous
- The material is thermally stable

To investigate the potential for this technique to directly measure thermal conductivity, BRE undertook thermal needle measurements as part of the solid wall project.

5.1 Method

In order to investigate the performance of the thermal needle against alternative methods, tests were conducted at the same solid wall dwellings where brick samples had also been removed, albeit on different bricks for practical reasons. This was so that the results from the thermal needle tests could be compared to:

- Thermal conductivity measurements in a stable environment using the bricks removed from solid wall properties
- Estimates of thermal conductivity, calculated based on measured moisture content and density of removed bricks

Thermal conductivity measurements were taken at these dwellings, using a Hukseflux TP07 thermal needle. A procedure similar to that used by Pilkington et al, [38] was implemented:

- Firstly, holes were drilled in the outer brick of the wall to be tested
- A conductive medium was inserted, ensuring no air bubbles
- The Hukseflux TP07 thermal needle was inserted into the hole, and the measurement process begun
- Once thermal equilibrium was reached (as indicated on the display unit), heat was applied for 300 seconds, at 3V
- The sensor output was plotted against time, and the thermal conductivity was calculated at different stages of the measurement by using the temperature difference between two points in time, and the heater power
- The control unit automatically selects four stages of the linear graph (Figure 1), and calculates the thermal conductivity at each stage. From this the average thermal conductivity and standard deviation was obtained.

The thermal needle was used in preference on the same wall where the removed brick was located (although on a different brick), however, where this was not possible an alternative wall was used (in all cases where this was required, measurements were taken on the same wall on which the U-value was measured). The standard deviation was displayed as a percentage of the thermal conductivity and was used as a quality indicator. When this reading was >0.1, the thermal conductivity reading was discarded and the process was repeated. Measurements were often also repeated to ensure that readings were taken with a stable probe position and with good contact between the brick and the probe by the use of a contact medium.

5.2 Results and discussion

Thermal needle measurements were taken in 37 dwellings with solid walls, with reliable thermal conductivity measurements obtained for 76% of these cases. Measurements were taken in both brick and stone dwellings, but results from stone wall dwellings all showed high standard deviations, therefore results could not be further analysed with confidence. In addition, two brick walls had large standard deviations associated with the readings, and were removed from further analysis.

The accuracy of thermal conductivity measurements has been reported as +/- 6% +0.04 W/mK, based upon the following assumptions:

- The thermal needle does not move before and during the measurement
- No temperature changes occur, other than from the thermal needle heat source
- Thermal equilibrium is reached before taking a thermal conductivity measurement
- There is good thermal contact between the needle and the brick (toothpaste is used as a thermal medium)
- The bricks are homogenous

The median thermal conductivity, based on 28 measurements was 0.72 W/mK +/- 0.083 W/mK. The interquartile range was 0.38 W/mK, between 0.58 W/mK at the 25th percentile, and 0.95 W/mK at the 75th percentile. In comparison, results from NPL guarded heat flow meter and TP01 sensor on the thermal conductivity of brick samples, described in section 5 above, produced median values of 0.65 W/mK and 0.68 W/mK, albeit in the dry state, rather than the in situ wet state, for 16 and 18 cases, respectively, with an interquartile range of 0.1 W/mK for both. The distribution of these results is shown in the box plot in Figure 52.

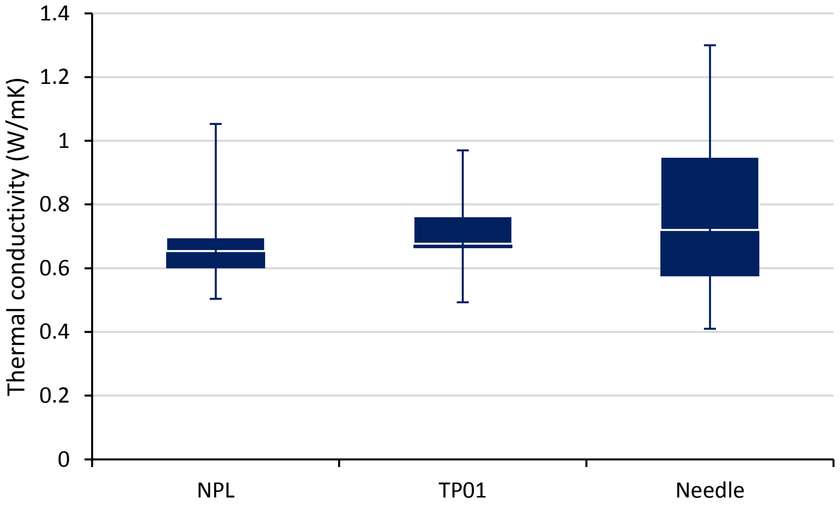


Figure 52 – Boxplot of the measured thermal conductivity, from NPL, TP01 and thermal needle methods. Note that the NPL and TP01 results are in the dry state, and the thermal needle in wet in situ state.

Thermal conductivity measurements from the NPL guarded heat flow meter and TP01 sensor were conducted in the dry state. Therefore, results have been displayed below for all cases, and for only those cases with low moisture content which may provide a better comparison with the measured thermal conductivity data (Table 19). In addition, the correlation between the thermal conductivity measurements from the thermal needle and the measurements conducted in the dry state, are indicated by the R^2 value, which shows how much variance the two methods share. The R^2 values are high (at approximately 0.5), indicating a strong relationship between the different methods of determining thermal conductivity of brick samples.

Table 19 - Median thermal conductivities and interquartile range for the different methods, as well as R^2 values of NPL guarded heat flow meter and TP01 results against the thermal needle measurements.

All brick walls, and using assumptions	**Thermal needle**	**NPL**		**TP01**	
		All cases	Cases with <2% moisture	All cases	Cases with <2% moisture
Count	28	16	12	18	12
Median λ (W/mK)	0.72	0.654	0.654	0.677	0.677
IQR (W/mK)	0.375	0.097	0.077	0.101	0.106
R^2		0.501	0.521	0.49	0.456

The relationship between the NPL/TP01 measurements, and thermal needle measurements, for cases with low moisture only, are shown in Figures 53 and 54. Due to small sample sizes, results should be interpreted with caution, however results indicate a strong relationship between the in situ and lab measurements.

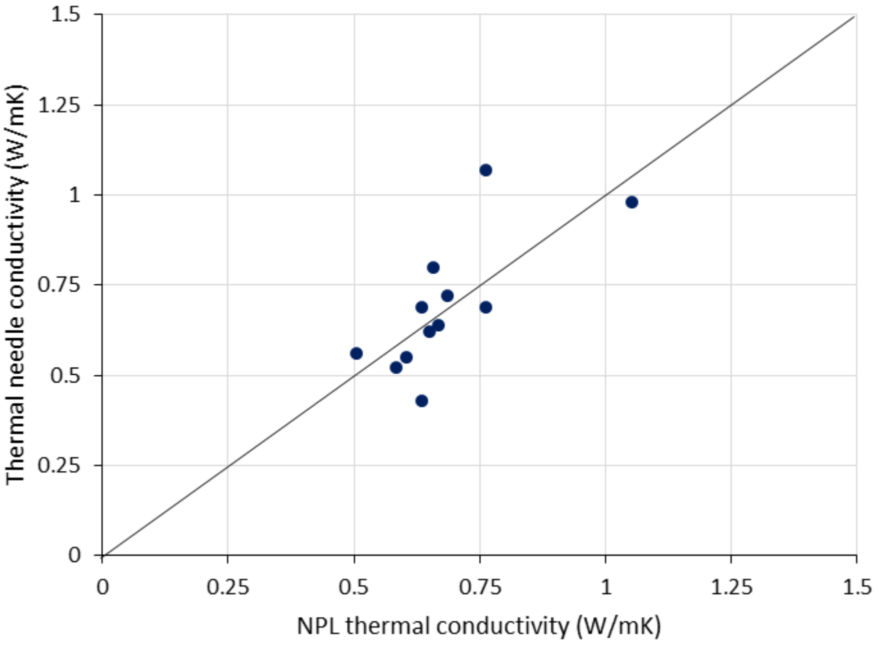


Figure 53 - Thermal conductivity values from NPL and thermal needle measurements.

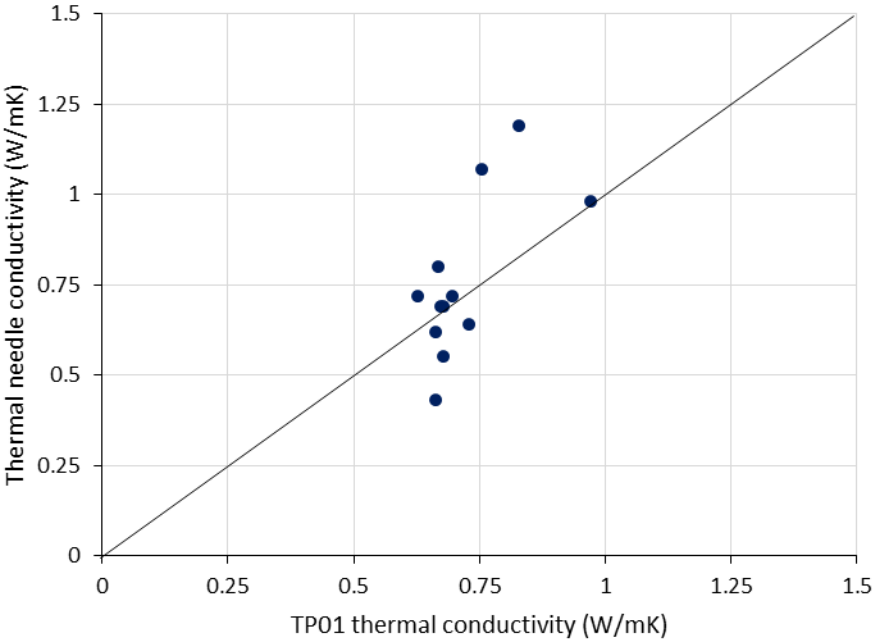


Figure 54 - Thermal conductivity values from TP01 and thermal needle measurements.

5.3 Conclusions

Results from thermal needle tests are encouraging, with the median thermal conductivity reading comparable to tests conducted in a stable environment. Variation between results is expected for several reasons. Firstly, there is likely to be some error due to the heterogeneity of samples, with the compared tests being conducted in different brick samples. In addition, the assumptions for the thermal needle measurements may not always be met in practice. Despite this, the correlation between the thermal needle results and tests conducted in the dry state was high.

Based on this initial work we would recommend that this technique is investigated further. The measurement process is quick, taking between 10 and 30 minutes, and as such it has the potential to be a viable survey tool. It is recommended that in future work: reference materials are tested; multiple measurements on the same wall, and on the same brick, are conducted; and the quality and accuracy of data are analysed in more detail by review of the visual data. In addition, the determination of stone wall thermal conductivity values requires additional investigations.

6 Moisture content variation across the walls of three solid wall dwellings

The presence of moisture within a wall will act to increase its thermal conductivity and U-value. Several variants for accounting for moisture have been proposed and used (e.g. ISO10456, Jakob, DIN 51692 [22]). However, it is also recognised that the moisture content of different sections of a wall may vary significantly across its extent. Indeed, it has been argued in previous BRE work that the concept of the “moisture content of a wall” is not particularly appropriate because of this variation [40].

It is important for us to understand whether this is the case in solid wall dwellings of the type we are visiting, and the possible variation across and between facades, when we are interpreting the results from brick and dust samples returned from fieldwork. In order to investigate this, BRE undertook a series of measurements of moisture content of bricks and mortar in three dwellings in 2015 and 2016.

6.1 Results from investigations

Dwelling 1

The first dwelling visited was an unrendered, semi-detached solid wall dwelling in the East of England. The dwelling was in a relatively sheltered, suburban location. Dust drillings were taken in multiple locations across all facades, as shown in the diagram below, in line with the methodology outlined in Good Repair Guide 33 [11]. Photographs of the front, rear and side walls of the dwelling are shown below in Figure 55, 56 and 57. Scaffold was used to provide access to various heights to allow the collection of the dust drillings.

Drillings were taken at three depths, in nine locations on each façade. The dust was recovered using a rotary percussive drill using a 9 mm bit. The dust samples were stored in glass vials.

The samples were oven dried at 105 °C until they achieved a constant mass.

Figure 55, 56 and 57: Dwelling 1 visited for first moisture drilling tests

One of the areas we wished to investigate was whether the moisture content of the walls varied with depth of drilling. Figure 58 below indicates that the moisture content by volume did not vary to a significant degree.

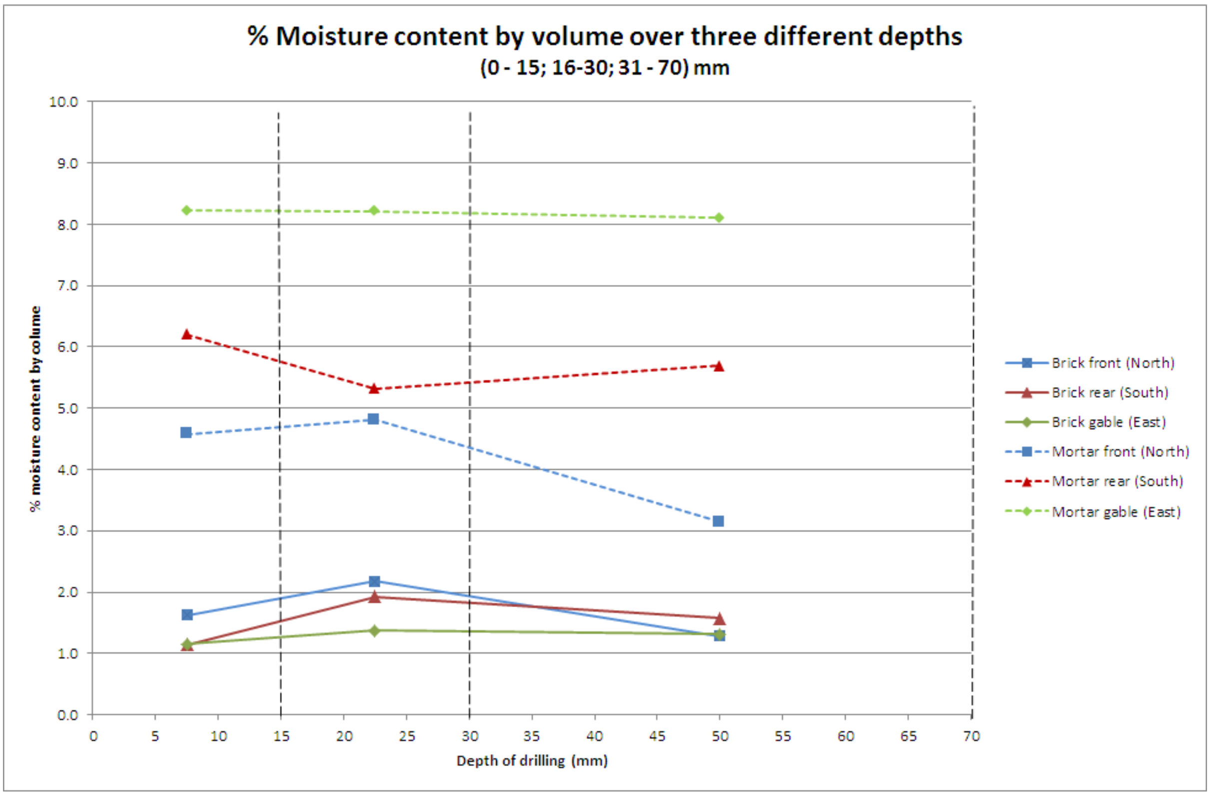
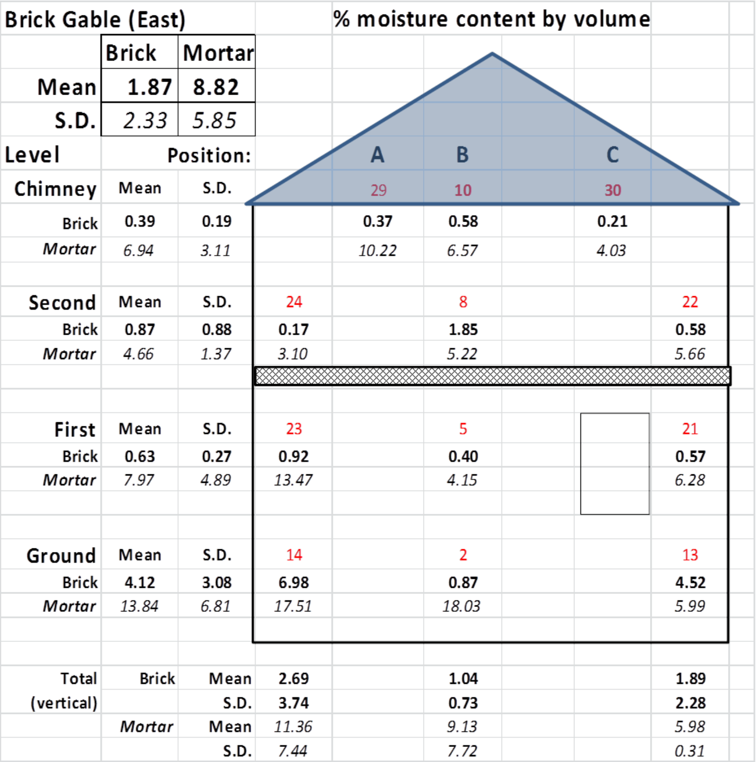
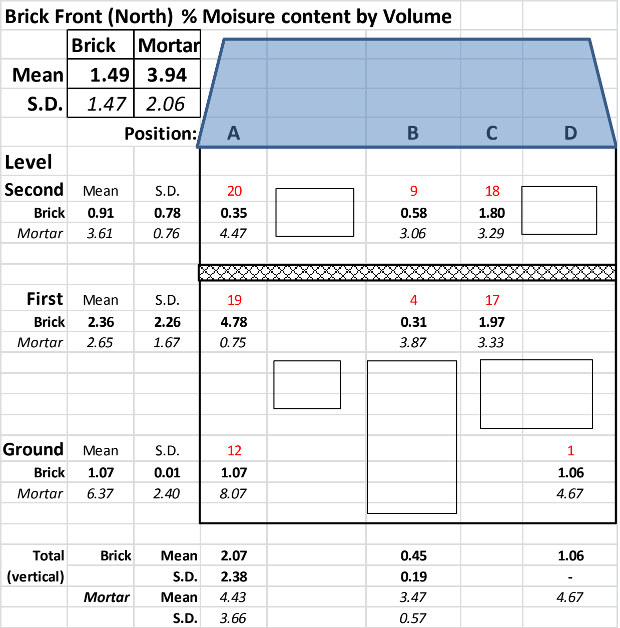


Figure 58: Variation in moisture content by volume at different drilling depths.

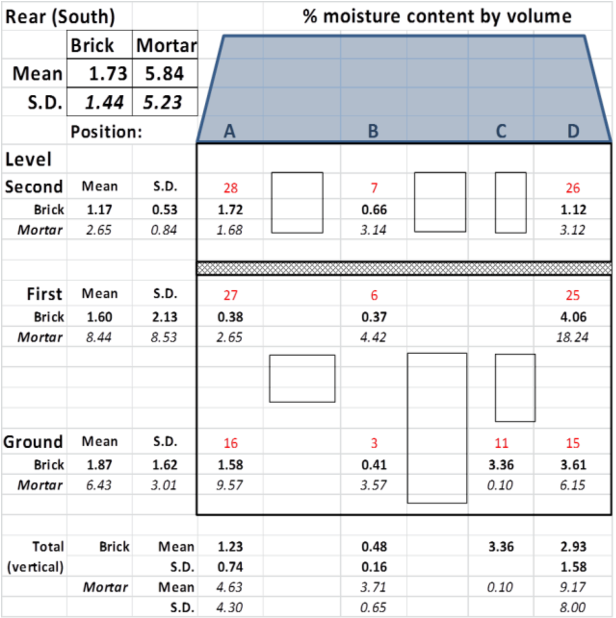
A key objective of this work is to ascertain the extent to which moisture may vary within and between facades of a solid wall dwelling. This can be seen in the three figures below, figures 59, 60 and 61, which indicate the drilling locations, and the moisture content for each location (expressed as a mean value of the drillings at each location).



Brick Gable (East)			% moisture content by volume				
	Brick	Mortar					
Mean	1.87	8.82					
S.D.	*2.33*	*5.85*					
Level		Position:		A	B	C	
Chimney	Mean	S.D.		29	10	30	
Brick	0.39	0.19		0.37	0.58	0.21	
Mortar	*6.94*	*3.11*		*10.22*	*6.57*	*4.03*	
Second	Mean	S.D.	24		8		22
Brick	0.87	0.88	0.17		1.85		0.58
Mortar	*4.66*	*1.37*	*3.10*		*5.22*		*5.66*
First	Mean	S.D.	23		5		21
Brick	0.63	0.27	0.92		0.40		0.57
Mortar	*7.97*	*4.89*	*13.47*		*4.15*		*6.28*
Ground	Mean	S.D.	14		2		13
Brick	4.12	3.08	6.98		0.87		4.52
Mortar	*13.84*	*6.81*	*17.51*		*18.03*		*5.99*
Total	Brick	Mean	2.69		1.04		1.89
(vertical)		S.D.	3.74		0.73		2.28
	Mortar	Mean	*11.36*		*9.13*		*5.98*
		S.D.	*7.44*		*7.72*		*0.31*



Brick Front (North) % Moisure content by Volume						
	Brick	Mortar				
Mean	1.49	3.94				
S.D.	*1.47*	*2.06*				
		Position:	A	B	C	D
Level						
Second	Mean	S.D.	20	9	18	
Brick	0.91	0.78	0.35	0.58	1.80	
Mortar	*3.61*	*0.76*	*4.47*	*3.06*	*3.29*	
First	Mean	S.D.	19	4	17	
Brick	2.36	2.26	4.78	0.31	1.97	
Mortar	*2.65*	*1.67*	*0.75*	*3.87*	*3.33*	
Ground	Mean	S.D.	12			1
Brick	1.07	0.01	1.07			1.06
Mortar	*6.37*	*2.40*	*8.07*			*4.67*
Total	Brick	Mean	2.07	0.45		1.06
(vertical)		S.D.	2.38	0.19		-
	Mortar	Mean	*4.43*	*3.47*		*4.67*
		S.D.	*3.66*	*0.57*		



Rear (South)			% moisture content by volume			
	Brick	Mortar				
Mean	1.73	5.84				
S.D.	*1.44*	*5.23*				
	Position:		A	B	C	D
Level						
Second	Mean	S.D.	28	7		26
Brick	1.17	0.53	1.72	0.66		1.12
Mortar	*2.65*	*0.84*	*1.68*	*3.14*		*3.12*
First	Mean	S.D.	27	6		25
Brick	1.60	2.13	0.38	0.37		4.06
Mortar	*8.44*	*8.53*	*2.65*	*4.42*		*18.24*
Ground	Mean	S.D.	16	3	11	15
Brick	1.87	1.62	1.58	0.41	3.36	3.61
Mortar	*6.43*	*3.01*	*9.57*	*3.57*	*0.10*	*6.15*
Total	Brick	Mean	1.23	0.48	3.36	2.93
(vertical)		S.D.	0.74	0.16		1.58
	Mortar	Mean	*4.63*	*3.71*	*0.10*	*9.17*
		S.D.	*4.30*	*0.65*		*8.00*

Figures 59, 60 and 61: Results of moisture drilling results in dwelling 1.

Inspection of the diagrams above indicates that the moisture content of both the bricks and the mortar vary significantly across each of the façades. Brick moisture content by volume varies from 0.21% to 6.98%, with mortar moisture content varying from 0.10% to 18.24%. It may be that local features (e.g. run off from downpipes or sills, local rising damp etc.) may help to explain these differences. It is, however, evident that a single measurement of moisture cannot be said to be representative of the moisture content in another location in the same dwelling. The implications for U-values are described later in the discussion section of the report.

Dwellings 2 & 3

Two further dwellings visited were in a different location in the East of England.

These dwellings were a pair of semi-detached houses, shown in Figure 62 below, situated on the east side of the street on the north face of a steep chalk hill. The narrow front gardens extend down to the pavement and on to the road. The front plot of the left hand house of the pair has been concreted to create a hard standing for vehicles. Each house is built of brickwork which had been rendered and painted.

Dust sampling at the properties

BRE attended site on 04 and 07 July 2016 to take dust drilling samples of the render and brickwork. The required access scaffold was incomplete on 04 July so samples from ground level only (locations 1 to 18) were taken. Samples from first floor and eaves level were recovered on 07 July.

Sample (A) was taken from the render which varied from 3 to 5 mm thick. A second sample, (B), was taken from the sample hole and comprises brick or mortar. Sample (B) was a nominal 40 mm thick but was predominantly a red brick colour.

The dust drilling was recovered using rotary percussive drill using a 9 mm bit. The dust samples were stored in glass vials.

The samples were oven dried at 105 °C until they achieved a constant mass.

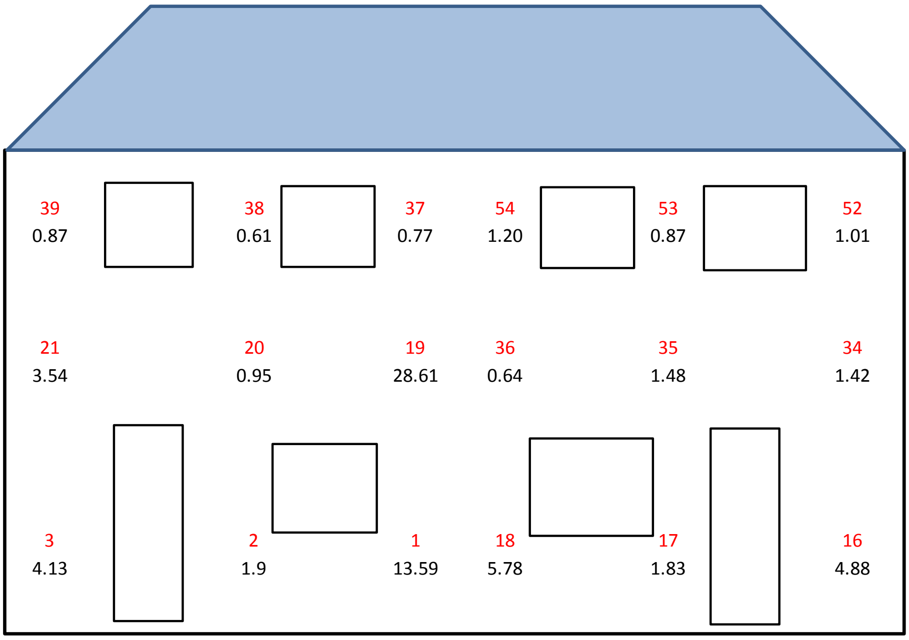
Figure 62: Dwellings 2 and 3 visited for moisture dust drillings.

The results of the dust drillings are shown in the Figures 63 to 66 below.

Front view

% Moisture content by Volume

Mean	**6.11**
S.D.	***9.38***
Median	**1.90**

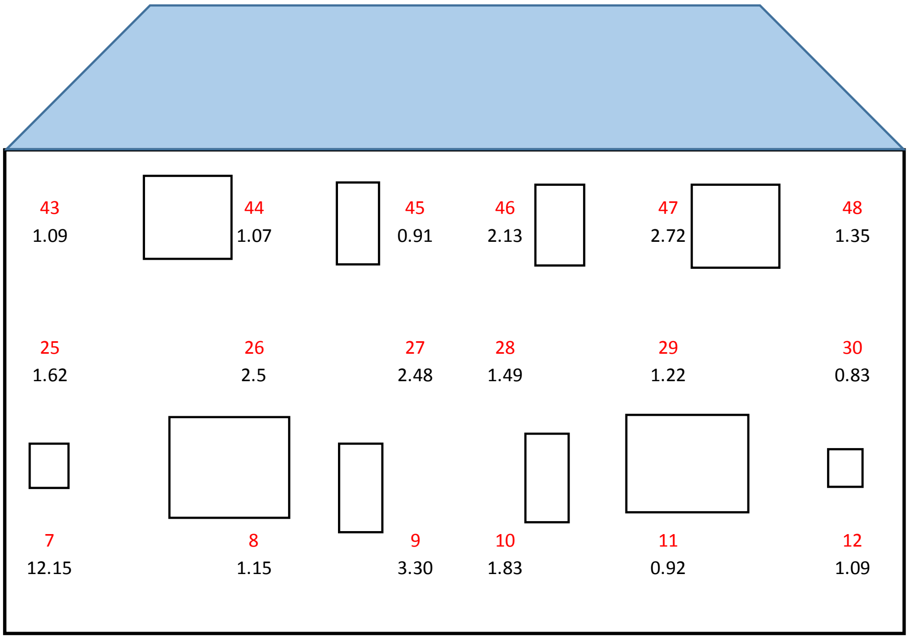


Level								
Eaves	Mean	S.D.	39	38	37	54	53	52
Brick	**0.89**	**0.20**	0.87	0.61	0.77	1.20	0.87	1.01
First	Mean	S.D.	21	20	19	36	35	34
Brick	**6.11**	**11.07**	3.54	0.95	28.61	0.64	1.48	1.42
Ground	Mean	S.D.	3	2	1	18	17	16
Brick	**5.35**	**4.34**	4.13	1.9	13.59	5.78	1.83	4.88
Total		**Mean**	**2.85**	**1.15**	**14.33**	**2.54**	**1.39**	**2.44**
(vertical)		**S.D.**	**1.74**	**0.67**	**13.94**	**2.82**	**0.48**	**2.13**

Rear view

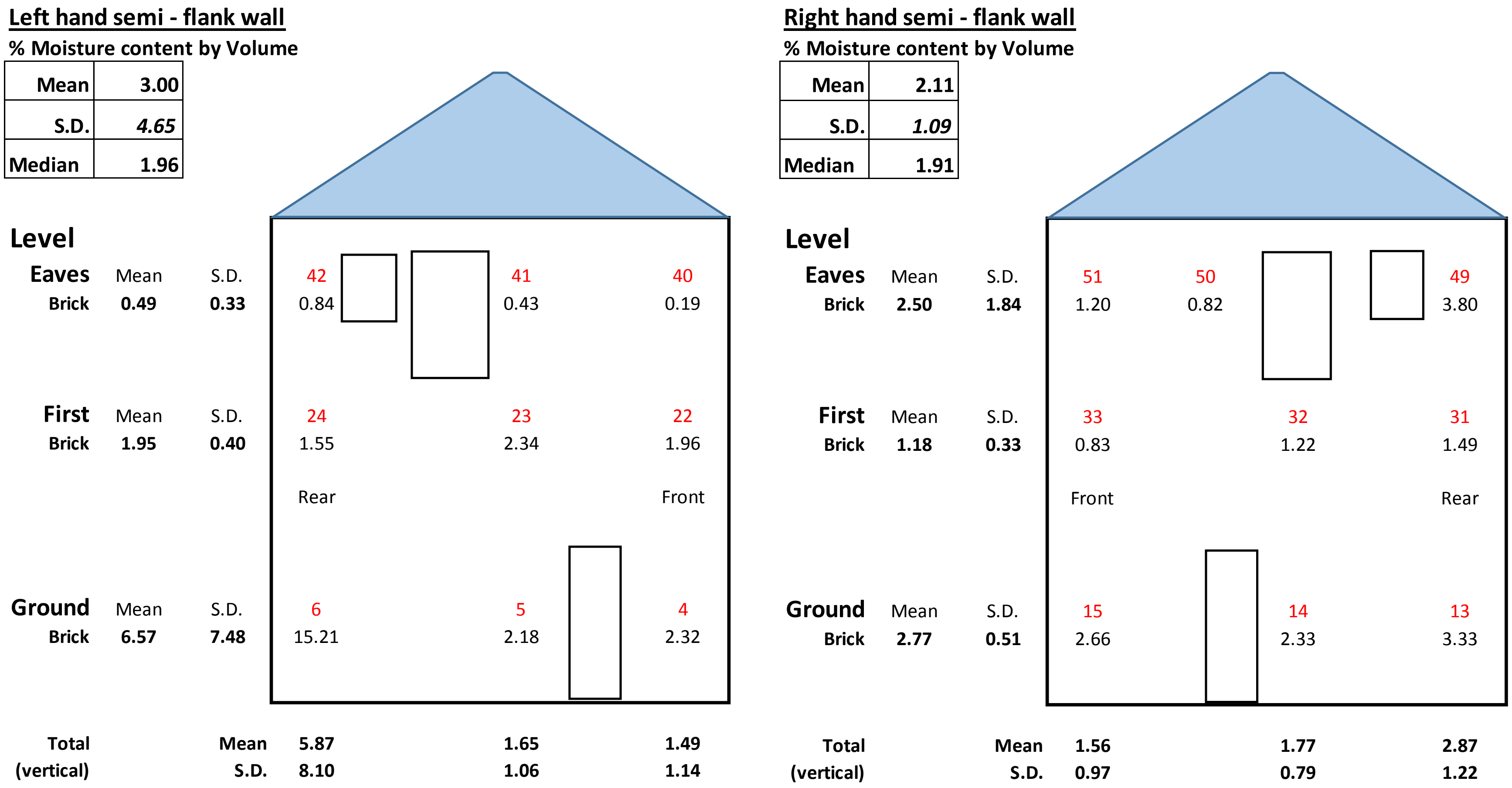
% Moisture content by Volume

Mean	**2.92**
S.D.	***3.56***
Median	**1.62**



Level								
Eaves	Mean	S.D.	43	44	45	46	47	48
Brick	**1.54**	**0.72**	1.09	1.07	0.91	2.13	2.72	1.35
First	Mean	S.D.	25	26	27	28	29	30
Brick	**1.69**	**0.68**	1.62	2.5	2.48	1.49	1.22	0.83
Ground	Mean	S.D.	7	8	9	10	11	12
Brick	**3.41**	**4.37**	12.15	1.15	3.30	1.83	0.92	1.09
Total		**Mean**	**4.95**	**1.58**	**2.23**	**1.82**	**1.62**	**1.09**
(vertical)		**S.D.**	**6.24**	**0.81**	**1.21**	**0.32**	**0.97**	**0.26**

Figures 63 and 64: Results of moisture drillings from dwellings 2 and 3 (Front & Rear view).



Left hand semi - flank wall

% Moisture content by Volume

Mean	**3.00**
S.D.	***4.65***
Median	**1.96**

Level	Mean	S.D.	Rear		Front
Eaves **Brick**	**0.49**	**0.33**	42 0.84	41 0.43	40 0.19
First **Brick**	**1.95**	**0.40**	24 1.55	23 2.34	22 1.96
Ground **Brick**	**6.57**	**7.48**	6 15.21	5 2.18	4 2.32
Total (vertical)		**Mean**	**5.87**	**1.65**	**1.49**
		S.D.	**8.10**	**1.06**	**1.14**

Right hand semi - flank wall

% Moisture content by Volume

Mean	**2.11**
S.D.	***1.09***
Median	**1.91**

Level	Mean	S.D.	Front		Rear
Eaves **Brick**	**2.50**	**1.84**	51 1.20	50 0.82	49 3.80
First **Brick**	**1.18**	**0.33**	33 0.83	32 1.22	31 1.49
Ground **Brick**	**2.77**	**0.51**	15 2.66	14 2.33	13 3.33
Total (vertical)		**Mean**	**1.56**	**1.77**	**2.87**
		S.D.	**0.97**	**0.79**	**1.22**

Figure 65 and 66: Results of moisture drillings from dwellings 2 and 3 (Flank Walls).

There are several areas of the ground floor masonry which have elevated moisture contents in both the render and brickwork. This is particularly evident at the side and rear of the left-hand house. In other locations, the brickwork moisture content was above that of the render. This appears to suggest that there is local rising damp.

As noted on site, the plinth masonry (painted black) had been rendered. However, there was no bell-cast and the joint between the plinth render and the façade render, although visible, did not contain a break in the render across the DPC. At the rear of the right hand dwelling, a portion of render had become detached at plinth level. The brickwork appeared locally damp and had green algae growing on the exposed brick face. The proximity of concrete paths to the house walls would be expected to trap moisture against the house.

The samples from the upper elevations, first floor and eaves were generally all dry apart from one on the first floor location front of the left-hand dwelling. The majority of the upper level brickwork was drier than the render samples.

As with the initial dwelling, it is apparent that the moisture content of the walls can vary significantly across the façades of the dwelling. In a similar way many of the very highest moisture content readings can be associated with disrepair or faults, such as a bridged DPC leading to rising damp issues. Nevertheless, it acts to highlight how the return of a single sample to provide data on moisture content is insufficient in describing the moisture content of the entire dwelling.

6.2 Discussion

The effect of varying moisture content on wall U-values

Of interest, for our purposes, is what the effect of the varying moisture content could be on the measured U-values of the wall. Using the data from dwelling 1, this has been done. Shown in the three diagrams below, Figures 67, 68 and 69, are how U-values may vary, for a brick of the same assumed density (1,750 kg/m^3) under the different moisture contents measured across the dwelling (n.b. due to the effect of the ISO 10456 correction at high moisture values, the Jakob moisture correction has been used for this example).

It can be seen that the theoretical U-values can vary from between 1.57 W/m^{2}K to 2.06 W/m^{2}K (a variation of approximately 40%) because of the differences in moisture content. This variation is greater than is introduced by the small cavities identified through the fieldwork.

This result is particularly important in the context of attempting to reconcile measured U-values with calculated U-values. It is clear from this work that the moisture content of the wall varies to an extent which will result in U-values across the wall being very different depending on the location measured, because of variation in moisture content. We cannot, therefore, expect that a single brick or mortar sample, which for practical reasons is not is co-located with the U-value measurement, will be able to adequately reflect the appropriate moisture content.

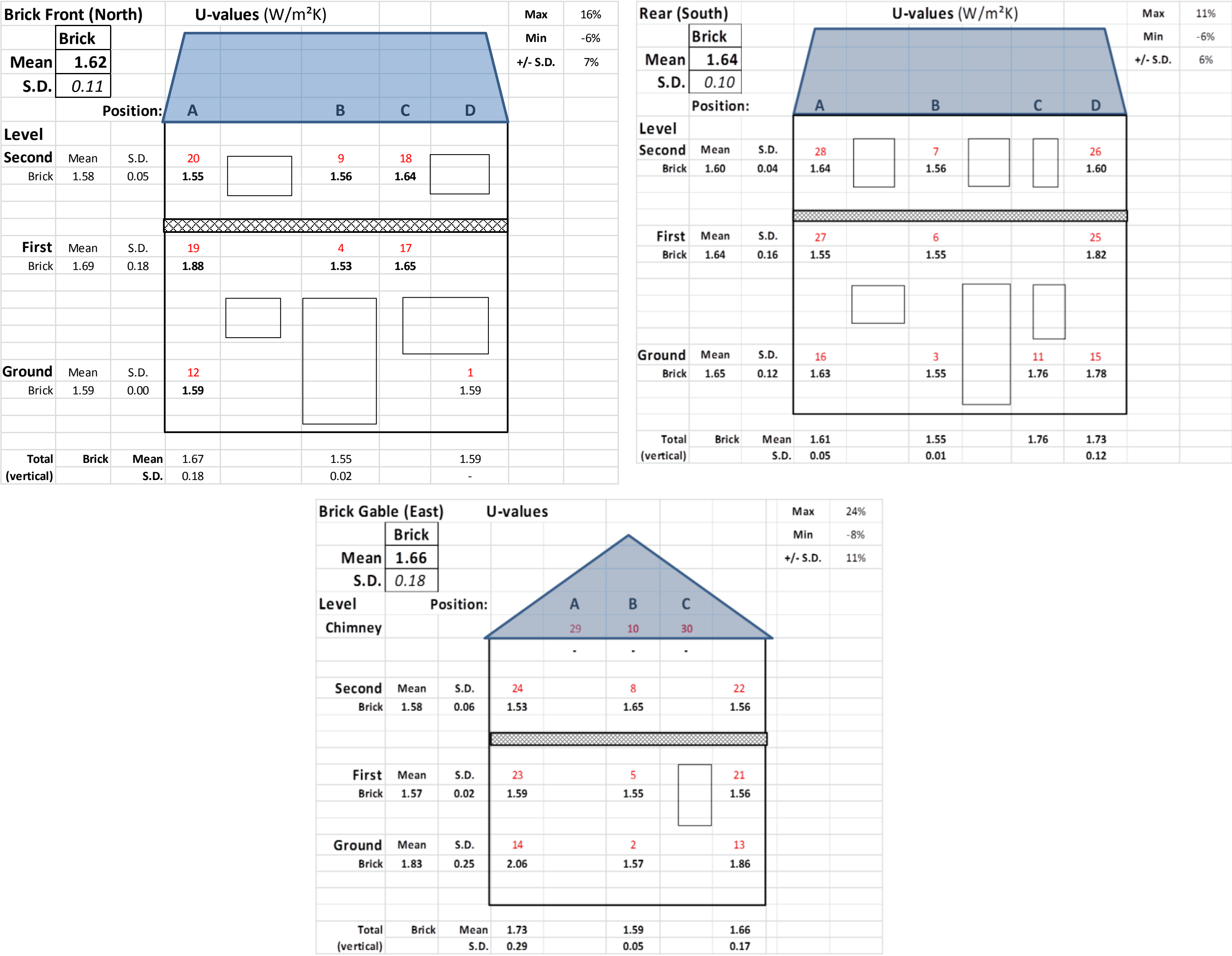


Figure 67, 68 and 69: The effect on U-values of the different moisture contents observed in dwelling 1.

Part B: Modifying theoretical U-value calculations based on results of fieldwork and laboratory experiments

7 Revising theoretical U-value calculations following the fieldwork observations

As outlined in the introduction and background section of this report, one of the key research questions which we have attempted to address within this research is whether the assumptions which are typically used for theoretical U-values calculations do not adequately reflect the nature of solid walls in situ, and whether this may help to explain why measured U-values are lower than conventional theory suggests they should be. This part of this report examines the effect of revising the input assumptions into the theoretical calculation of U-values, both at the level of a 'typical' wall and at the individual case level for the fieldwork cases.

Comparison of measured and calculated values provides an indication of how well theoretical models of heat losses are matched by observation. The calculated U-value is based upon the type of wall (i.e. solid), the measured wall thickness, the nature of the internal and external wall surface and the other field observations (including the observations following the brick removal, and the results from laboratory tests on the brick and mortar samples).

7.1 A choice of moisture corrections

Ahead of the calculation of theoretical calculated U-values a choice needs to be made as to the moisture correction to apply, which will correct the thermal conductivities to account for the presence of moisture. Several different corrections have been proposed and used in the past, with most prominent being the Jakob correction and the correction proposed in ISO 10456. Other alternatives include methodologies used in other countries, such as the German moisture correction used in DIN.

The Jakob correction, proposed by Jakob in 1949 [35], is an empirically derived relationship and has been validated in the past by Arnold [41] and also by Ball [37] and Pratt [42]. These measurements are, however, very old and may suffer from systematic deficiencies of the type described in Section 5 of this report. Furthermore, more recent reanalysis of these data by Clarke and Yangtse has questioned the validity of this correction [22].

The ISO 10456 correction [43] is the formula used within the ISO international standard, but this method applies a very simple exponential formula which apply very large corrections for high moisture contents (considerably higher than other methods). Other options for corrections include the German DIN 52612 and other national standards.

In choosing the correction to apply, we have considered the available evidence and the appropriateness of the correction for our specific application. As a result of this, we have decided to use the internationally agreed standard outlined in ISO 10456, but for the purposes of our comparison with measured U-values have restricted the correction to a maximum value of 20% moisture by volume in order to remove the extreme effect of the correction at high moisture contents. As with the relationship between brick density and thermal conductivity, it is apparent that the appropriateness of moisture corrections to be applied to thermal conductivity estimates is an area which we would recommend is revisited as a priority.

7.2 Revising theoretical U-value calculations for a 'typical' solid wall

The fieldwork described in Section 2 has identified a number of elements in the wall that are not usually taken into account in the calculation of solid wall U-values. In particular, the fieldwork identified numerous air cavities in solid walls created by missing mortar, broken bricks or frogs. It also identified that the moisture content of the bricks and mortar was lower than is generally assumed, and that the walls were thicker than generally assumed.

This section of this report examines the likely effect of these changes on the theoretical calculated U-value for a typical wall, and compares the typical assumptions which result in a U-value of 2.1 W/m²K (the standard value in the CIBSE guide, and RdSAP) with a revised calculation which uses inputs into the calculation which are much more closely aligned with our fieldwork observations[4]. Note that this section of the report looks at the effect on an example wall only. The effect of applying each individual field observation to the relevant fieldwork case is described in Section 8 below.

Example 1 represents a solid wall with no air gaps and this construction is similar to traditional CIBSE assumptions. Example 2 represents a wall with some air gaps, and this second example is based partly on recent field measurements.

Both walls are wet-plastered internally, this being typical of existing solid walls in the UK, and for both examples the brick bond pattern is “Flemish Bond”. The two examples are summarised in Table 20 as follows:

Table 20: Details of the example U-value calculations for typical cases

Quantity	**Example 1 Similar to traditional CIBSE assumptions**	**Example 2a Observed typical value**
Thickness of wall	228	252
Length of stretchers	215	230
Thickness of bed joints	10	10
Width of perpend joints	10	10
Moisture content of brick by volume	5	0.7
Moisture content of mortar by volume	5	1.7
Thermal conductivity of brick in wet state	0.77[5]	0.74
Thermal conductivity of lime mortar in wet state	0.7	0.46
Air percentage of perpend	nil (i.e. no air gaps)	30
Air percentage in collar joint	nil (i.e. no air gaps)	33
Proportion of brick bats	nil (i.e. all bricks intact)	9
Frog depths in the bricks	frogless	5

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[4] These two worked examples are presented in the same format as shown in the BRE Trust publication “U-Values Calculations in Practice” [44] which readers should refer to for additional worked examples of other wall types, and an overview of U-Value calculations.

[5] The revised thermal conductivities used the revised relationship as set out in Section 4.

Type of internal finish	Hard plaster	Hard plaster
Type of brick bond pattern	Flemish Bond	Flemish Bond
Thickness of plaster	13	22
Number of heat flow paths considered in the calculation	4	12

The solid brick walls consist of 215 mm of Flemish Bond brickwork and internal plaster. The bricks measure 215 mm by 102.5 mm horizontally and 65 mm vertically. The bed joints and the perpends are all 10 mm wide.

Example 1

For Example 1, which is a ‘traditional’ calculation of the heat flow through a solid wall there are four heat flow paths and four surface layers: Path 1 consists of the path through the stretchers, running through the plaster, then through the inner stretcher, then through 10 mm of mortar and then through the outer stretcher. Path 2 consists of the path through the headers, running through 13 mm of plaster and 215 mm of brick. Paths 3 and 4 consist of the paths through the bedjoints and perpends, in addition to the 13 mm of plaster.

The heat flow paths for Example 1 can be described as shown in Table 21:

Table 21: Heat flow paths for Example 1

	Path 1 stretcher	**Path 2 header**	**Path 3 perpends**	**Path 4 bed joints**	**Thickness (mm)**
Layer 1	plaster	plaster	Plaster	plaster	13
Layer 2	stretcher	header	mortar	mortar	102.5
Layer 3	mortar	header	mortar	mortar	10
Layer 4	stretcher	header	mortar	mortar	102.5
fraction of area	0.5521	0.2632	0.0514	0.1333	228

In the above table;

- the area fraction for bed joints is calculated as (10 mm)/(10 mm + 65 mm),
- the area fraction for perpend joints is calculated as (65 mm)/(65 mm + 10 mm) * (2 * 10 mm) / (215 mm + 102.5 mm + 2 * 10 mm),
- the area fraction for stretchers is calculated as (65 mm)/(65 mm + 10 mm) * (215 mm) / (215 mm + 102.5 mm + 2 * 10 mm) and
- the area fraction for headers is (65 mm)/(65 mm + 10 mm) * (102.5 mm) / (215 mm + 102.5 mm + 2 * 10 mm).

The thermal conductivities are as follows in Table 22:

Table 22: Thermal conductivities for example 1.

	Path 1	Path 2	Path 3	Path 4	Thickness (mm)
Layer 1	0.57	0.57	0.57	0.57	13
Layer 2	0.77	0.77	0.7	0.7	102.5
Layer 3	0.7	0.77	0.7	0.7	10
Layer 4	0.77	0.77	0.7	0.7	102.5
					228

The thermal resistances for Example 1 are as follows in Table 23:

Table 23: Thermal resistances for Example 1.

	Path 1	Path 2	Path 3	Path 4	TOTAL
Surface	0.1300	0.1300	0.1300	0.1300	-
Layer 1	0.0228	0.0228	0.0228	0.0228	-
Layer 2	0.1331	0.1331	0.1464	0.1464	-
Layer 3	0.0143	0.0130	0.0143	0.0143	-
Layer 4	0.1331	0.1331	0.1464	0.1464	-
Surface	0.0400	0.0400	0.0400	0.0400	-
TOTAL resistance	0.4733	0.4720	0.4999	0.4999	-
Area fraction	0.5521	0.2632	0.0514	0.1333	-
Fraction/R	1.1665	0.5576	0.1028	0.2667	2.0935

The sum of the values of (fraction/R) is therefore 2.0935 W/m^{2}K, and this value is considered to be the upper limit of thermal resistance (as defined in BS EN ISO 6946).

The values of (Fraction/resistance) are as follows in Table 24:

Table 24: Values of Fraction / Resistance for Example 1.

	Path 1	Path 2	Path 3	Path 4	1/TOTAL
Surface	4.247	2.025	0.395	1.025	0.1300
Layer 1	24.215	11.544	2.254	5.846	0.023
Layer 2	4.148	1.977	0.351	0.911	0.135
Layer 3	38.608	20.246	3.594	9.322	0.014
Layer 4	4.148	1.977	0.351	0.911	0.135
Surface	13.803	6.580	1.285	3.333	0.040
TOTAL	-	-	-	-	0.477
1/TOTAL	-	-	-	-	2.094

The lower limit (as defined in BS EN ISO 6946) is therefore 2.094 m^2K/W

From the above, the overall thermal transmittance of the wall is 2.094 W/m^2K. By standard rounding conventions, this gives a U-value of **2.1 W/m^2K**. This agrees with the U-value that has traditionally been assumed in the CIBSE guides and used in RdSAP for solid walls [see Table S6, Appendix S of RdSAP 2009 version 9.91 (January 2012)]. This example is included in order to understand how a value of 2.1 W/m^2K is achieved, and for comparison with a value which incorporates the field observations described below.

Example 2

The calculation described in Example 2 attempts to include the main observations from the fieldwork. In particular, it contains air gaps in the wall, and reduces the thermal conductivity of the brick (from 0.77 to 0.65 W/mK) to account for the lower moisture content. This requires a significantly more detailed calculation to be carried out, with three times the number of heat flow paths, and twice as many surface layers required (i.e. a matrix of 16 calculation elements has increased to 96 elements). In total, the calculation now needs to takes 12 heat flow paths into account.

The details of the calculation for Example 2 are shown in the Tables 25 to 31 below.

Table 25: Details of heat flow paths in Example 2.

	Path 1 header, via 5 mm frog	Path 2 header, not frog	Path 3 stretcher, via frog, mortar in collar joint	Path 4 stretcher, not frog, mortar in collar joint	Path 5 stretcher, via frog, air in collar joint	Path 6 stretcher, not frog, air in collar joint	Path 7 bed joint	Path 8 perpend joint	Path 9 split header frog, mortar in collar joint	Path 10 split header, not frog, mortar in collar joint	Path 11 split header, frog, air in collar joint	Path 12 split header, not frog, air in collar joint	Thickness, mm
Surface	-	-	-	-	-	-	-	-	-	-	-	-	0
Layer 1	plaster	plaster	plaster	plaster	plaster	plaster	plaster	plaster	plaster	plaster	plaster	plaster	22
Layer 2	brick	brick	brick	brick	brick	brick	mortar	mortar	brick	brick	brick	brick	20
Layer 3	air	brick	air	brick	air	brick	mortar	air	air	brick	air	brick	70
Layer 4	air	brick	brick	brick	brick	brick	mortar	air	mortar	brick	air	brick	20
Layer 5	air	brick	mortar	mortar	air	air	mortar	air	mortar	mortar	air	air	10
Layer 6	air	brick	brick	brick	brick	brick	mortar	air	mortar	brick	air	brick	20
Layer 7	air	brick	air	brick	air	brick	mortar	air	air	brick	air	brick	70
Layer 8	brick	brick	brick	brick	brick	brick	mortar	mortar	brick	brick	brick	brick	20
Surface	-	-	-	-	-	-	-	-	-	-	-	-	0
fraction	0.0112	0.2283	0.02422	0.3623	0.01038	0.1553	0.13333	0.0514	0.0008	0.0158	0.0003	0.0068	

Table 26: Thermal conductivities for Example 2.

	Path 1 header, via 5 mm frog	Path 2 header, not frog	Path 3 stretcher, via frog, mortar in collar joint	Path 4 stretcher, not frog, mortar in collar joint	Path 5 stretcher, via frog, air in collar joint	Path 6 stretcher, not frog, air in collar joint	Path 7 bed joint	Path 8 perpend joint	Path 9 split header frog, mortar in collar joint	Path 10 split header, not frog, mortar in collar joint	Path 11 split header, frog, air in collar joint	Path 12 split header, not frog, air in collar joint	Thick-ness, mm
Surface	-	-	-	-	-	-	-	-	-	-	-	-	0
Layer 1	λplaster = 0.57	λplaster = 0.57	λplaster = 0.57	λplaster = 0.57	λplaster = 0.57	0.57	0.57	0.57	0.57	0.57	0.57	0.57	22
Layer 2	λbrick = 0.74	λbrick = 0.74	λbrick = 0.74	λbrick = 0.74	λbrick = 0.74	0.74	λmortar = 0.49	0.49	0.74	0.74	0.74	0.74	20
Layer 3	λa(175,5,0.818)	0.74	λa(62.5,5,0.818)	0.74	λa(62.5,5,0.818)	0.74	0.49	λa(175,10,0.818)	λa(62.5,5,0.818)	0.74	λa(175,5,0.818)	0.74	70
Layer 4	λa(175,5,0.818)	0.74	0.74	0.74	0.74	0.74	0.49	λa(175,10,0.818)	0.49	0.74	λa(175,5,0.818)	0.74	20
Layer 5	λa(175,5,0.818)	0.74	λmortar = 0.49	λmortar = 0.49	λa(10,65,0.818)	λa(10,65,0.818)	0.49	λa(175,10,0.818)	0.49	0.49	λa(175,5,0.818)	λa(10,65,0.818)	10
Layer 6	λa(175,5,0.818)	0.74	0.74	0.74	0.74	0.74	0.49	λa(175,10,0.818)	0.49	0.74	λa(175,5,0.818)	0.74	20
Layer 7	λa(175,5,0.818)	0.74	λa(62.5,5,0.818)	0.74	λa(62.5,5,0.818)	0.74	0.49	λa(175,10,0.818)	λa(62.5,5,0.818)	0.74	λa(175,5,0.818)	0.74	70
Layer 8	0.65	0.74	0.74	0.74	0.74	0.74	0.49	0.49	0.74	0.74	0.74	0.74	20
Surface	-	-	-	-	-	-	-	-	-	-	-	-	0
fraction	0.0112	0.2283	0.02422	0.3623	0.01038	0.1553	0.133333333	0.0514	0.0008	0.0158	0.0003	0.0068	

$\lambda_a(d,b,E)$ is the thermal conductivity of an airspace of thickness d (dimension parallel to heat flow), with smaller lateral dimension b (lesser dimension perpendicular to heat flow) and intersurface emittance E (as defined in equation B.3 of ISO 6946). $\lambda_a(d,b,E) = (h_a+h_r)\times d = (1.25+h_r)\times d$ where $h_r = h_{ro}/[(1\div E)-1+(2\div[1+\mathrm{sqrt}(1+[d^2\div b^2])-(d\div b)])]$ and $h_{ro} = 5.1$ (from Table A.1 of ISO 6946). e.g. if d=62.5mm, b=5mm and E=0.818 then $h_r = 5.1\div((1/0.818)-1+(2/(1+\mathrm{sqrt}(1+(62.5\times 62.5/(5\times 5)))-(62.5/5)))) = 2.377$, therefore $\lambda_a(62.5,5,0.818) = (1.25+2.377)*(62.5/1000) = 0.227$ W/m.K.

The following shows the equivalent thermal conductivities of air spaces for various cases.

Table 27: Thermal conductivities of air spaces for various cases in Example 2.

h_a	1.25	1.25	1.25	1.25
h_{ro}	5.1	5.1	5.1	5.1
d	62.5	175	175	10
b	5	5	10	65
E	0.818	0.818	0.818	0.818
d/b	12.500	35.000	17.500	0.154
d^2/b^2	156.250	1225.000	306.250	0.024
$A=\mathrm{sqrt}(1+d^2/b^2)$	12.540	35.014	17.529	1.012
1+A-d/b	1.040	1.014	1.029	1.858
2/(1+A-d/b)	1.923	1.972	1.944	1.076
1/E-1	0.222	0.222	0.222	0.222
h_r	2.377	2.324	2.354	3.926
λ_a	0.227	0.625	0.631	0.052

Thermal conductivity values are as follows:

Table 28: Thermal conductivity values for Example 2.

	Path 1 header, via 5 mm frog	Path 2 header, not frog	Path 3 stretcher, via frog, mortar in collar joint	Path 4 stretcher, not frog, mortar in collar joint	Path 5 stretcher, via frog, air in collar joint	Path 6 stretcher, not frog, air in collar joint	Path 7 bed joint	Path 8 perpend joint	Path 9 split header frog, mortar in collar joint	Path 10 split header, not frog, mortar in collar joint	Path 11 split header, frog, air in collar joint	Path 12 split header, not frog, air in collar joint	d, mm
Surface	-	-	-	-	-	-	-	-	-	-	-	-	0
Layer 1	0.57	0.57	0.57	0.57	0.57	0.57	0.57	0.57	0.57	0.57	0.57	0.57	22
Layer 2	0.74	0.74	0.74	0.74	0.74	0.74	0.49	0.49	0.74	0.74	0.74	0.74	20
Layer 3	0.625	0.74	0.227	0.74	0.227	0.74	0.49	0.6307	0.227	0.74	0.625	0.74	70
Layer 4	0.625	0.74	0.74	0.74	0.74	0.74	0.49	0.6307	0.49	0.74	0.625	0.74	20
Layer 5	0.625	0.74	0.49	0.49	0.052	0.052	0.49	0.6307	0.49	0.49	0.625	0.052	10
Layer 6	0.625	0.74	0.74	0.74	0.74	0.74	0.49	0.6307	0.49	0.74	0.625	0.74	20
Layer 7	0.625	0.74	0.227	0.74	0.227	0.74	0.49	0.6307	0.227	0.74	0.625	0.74	70
Layer 8	0.74	0.74	0.74	0.74	0.74	0.74	0.49	0.49	0.74	0.74	0.74	0.74	20
Surface	-	-	-	-	-	-	-	-	-	-	-	-	0
fraction	0.0112	0.2283	0.02422	0.3623	0.01038	0.1553	0.133333	0.0514	0.0008	0.0158	0.0003	0.0068	

Thermal resistance values are as follows:

Table 29: Thermal resistance values for Example 2

	Path 1 header, via 5 mm frog	Path 2 header, not frog	Path 3 stretcher, via frog, mortar in collar joint	Path 4 stretcher, not frog, mortar in collar joint	Path 5 stretcher, via frog, air in collar joint	Path 6 stretcher, not frog, air in collar joint	Path 7 bed joint	Path 8 perpend joint	Path 9 split header frog, mortar in collar joint	Path 10 split header, not frog, mortar in collar joint	Path 11 split header, frog, air in collar joint	Path 12 split header, not frog, air in collar joint	d, mm
Surface	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0
Layer 1	0.0386	0.0386	0.0386	0.0386	0.0386	0.0386	0.0386	0.0386	0.0386	0.0386	0.0386	0.0386	22
Layer 2	0.0270	0.0270	0.0270	0.0270	0.0270	0.0270	0.0408	0.0408	0.0270	0.0270	0.0270	0.0270	20
Layer 3	0.1120	0.0946	0.3084	0.0946	0.3084	0.0946	0.1429	0.1110	0.3084	0.0946	0.1120	0.0946	70
Layer 4	0.0320	0.0270	0.0270	0.0270	0.0270	0.0270	0.0408	0.0317	0.0408	0.0270	0.0320	0.0270	20
Layer 5	0.0160	0.0135	0.0204	0.0204	0.1923	0.1923	0.0204	0.0159	0.0204	0.0204	0.0160	0.1923	10
Layer 6	0.0320	0.0270	0.0270	0.0270	0.0270	0.0270	0.0408	0.0317	0.0408	0.0270	0.0320	0.0270	20
Layer 7	0.1120	0.0946	0.3084	0.0946	0.3084	0.0946	0.1429	0.1110	0.3084	0.0946	0.1120	0.0946	70
Layer 8	0.0270	0.0270	0.0270	0.0270	0.0270	0.0270	0.0408	0.0408	0.0270	0.0270	0.0270	0.0270	20
Surface	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0
TOTAL R	0.5667	0.5194	0.9539	0.5263	1.1258	0.6982	0.6780	0.5915	0.9814	0.5263	0.5667	0.6982	
fraction	0.0112	0.2283	0.02422	0.3623	0.01038	0.1553	0.133333	0.0514	0.0008	0.0158	0.0003	0.0068	
f/R	0.01977	0.43954	0.02539	0.68839	0.00922	0.22243	0.19666	0.08690	0.00082	0.03002	0.00053	0.00974	

The total of the “f/R” values is 1.72940 W/m²K, giving an upper limit of thermal resistance of 1 / 1.72940 = 0.5782 m²K/W.

The values of f/R are as follows:

Table 30: Values of f/R for Example 2.

	Path 1 header, via 5 mm frog	Path 2 header, not frog	Path 3 stretcher, via frog, mortar in collar joint	Path 4 stretcher, not frog, mortar in collar joint	Path 5 stretcher, via frog, air in collar joint	Path 6 stretcher, not frog, air in collar joint	Path 7 bed joint	Path 8 perpend joint	Path 9 split header frog, mortar in collar joint	Path 10 split header, not frog, mortar in collar joint	Path 11 split header, frog, air in collar joint	Path 12 split header, not frog, air in collar joint	d, mm
Surface	0.086	1.756	0.186	2.787	0.080	1.195	1.026	0.395	0.006	0.122	0.002	0.052	0
Layer 1	0.290	5.915	0.628	9.387	0.269	4.024	3.455	1.332	0.021	0.409	0.008	0.176	22
Layer 2	0.414	8.447	0.896	13.405	0.384	5.746	3.267	1.259	0.030	0.585	0.011	0.252	20
Layer 3	0.100	2.413	0.079	3.830	0.034	1.642	0.933	0.463	0.003	0.167	0.003	0.072	70
Layer 4	0.350	8.447	0.896	13.405	0.384	5.746	3.267	1.621	0.020	0.585	0.009	0.252	20
Layer 5	0.700	16.894	1.187	17.753	0.054	0.808	6.533	3.242	0.039	0.774	0.019	0.035	10
Layer 6	0.350	8.447	0.896	13.405	0.384	5.746	3.267	1.621	0.020	0.585	0.009	0.252	20
Layer 7	0.100	2.413	0.079	3.830	0.034	1.642	0.933	0.463	0.003	0.167	0.003	0.072	70
Layer 8	0.414	8.447	0.896	13.405	0.384	5.746	3.267	1.259	0.030	0.585	0.011	0.252	20
Surface	0.280	5.708	0.606	9.058	0.260	3.883	3.333	1.285	0.020	0.395	0.008	0.170	0
TOTAL R					0	0	0	0	0	0	0	0	-
f/R	0.0112	0.2283	0.02422	0.3623	0.01038	0.1553	0.133333	0.0514	0.0008	0.0158	0.0003	0.0068	

The following table shows the total value of f/R for each layer (i.e. the total of area fraction divided by thermal resistance for each of the 12 paths within a given layer).

Table 31: Total values of f/R for each layer in Example 2.

Layer	TOTAL of f/R	Rlayer
Surface	7.693	0.130
Layer 1	25.913	0.039
Layer 2	34.696	0.029
Layer 3	9.738	0.103
Layer 4	34.981	0.029
Layer 5	48.038	0.021
Layer 6	34.981	0.029
Layer 7	9.738	0.103
Layer 8	34.696	0.029
Surface	25.003	0.040
TOTAL		0.5496

This gives a lower limit of thermal resistance for the wall of 0.5496 m^2K/W.

The U-value of the wall is therefore 2 / (Rupper + Rlower), which is 2 / (0.5782+0.5496), or **1.77 W/m²K.** This is compared to the value of **2.1 W/m²K** calculated in Example 1 above.

At the level of a typical wall, including the fieldwork observations in the calculation process, as shown in Example 2, brings the theoretical values much closer to the typical measured values than the simpler calculation shown in Example 1. It therefore seems likely that much of the reason for the differences between the measured and calculated U-values for solid walls may derive from incorrect assumptions about the nature of the solid wall made in the calculations.

8 Theoretical calculated U-values for the fieldwork cases

As well as examining the differences between theoretical and calculated values at the level of a ‘typical’ wall, we are able to examine how well we can modify our assumptions at the level of each of the walls in our fieldwork sample, as described in Section 2 above.

It is clear from the research already presented, however, that achieving a match between measurement and theory may be difficult on a case-by-case basis. The research presented above has identified that significant variations can exist in moisture content and in the thermal conductivity of bricks of the same type, yet the field observations and retrieval of physical samples are generally from only a single location in each dwelling for practical reasons. We should, therefore, be realistic about how close a case-by-case level match will be, and expect that this may not be achieved. We should, nevertheless, hope that incorporating the general observations produces a better match between the *average* measured and *average* calculated values than was possible based on assumptions made prior to this research.

8.1 The default assumption for calculating U-values

The focus of this report is the findings from the 89 walls which had additional investigations (i.e. brick removals, moisture and density measurements etc.). In particular, it is of interest to know how the results from these investigations may improve the way we calculate U-values, and if the findings may help explain why the default assumptions for calculating solid walls may overstate the U-value.

To allow us to assess this in the clearest manner, the same quality filters as described in Section 2 above have been applied, and only ‘standard’ solid walls (i.e. brick built and of a single brick thickness, with wet plaster internal finish) have been examined. This provides a sample of 50 walls, which we can assess through this process.

In the absence of any additional evidence (of the type we have obtained through drilling and brick removal) the default assumption for calculating the U-value of a solid wall is to assume a thermal conductivity for the brick and mortar in a wall. Typically, this would assume a moisture content of 5% for brick and mortar (following CIBSE norms), and would not anticipate any air spaces within the structure. Usually the thickness of the wall (which can readily be obtained or estimated on site) would also be included in any calculation.

As the starting point of our assessment, to assist in the discussion of the refinement of the calculation procedure, this type of calculation has been undertaken for these 50 walls.

The mean and median calculated values are shown in Table 32 and have also been plotted against the measured values Figure 70 below.

Table 32 Measured values and calculated values under default assumptions for the 50 cases used for comparison

Wall type	Number of cases	Measured U-values: Mean and SD (W/m²K)	Measured U-values: Median (W/m²K)	Calculated U-values under default conditions: Mean (standard deviation) (W/m²K)	Calculated U-values under default conditions Median (W/m²K)
Standard solid wall (brick) – quality filters applied	50	1.74 +/- 0.05 SD = 0.18	1.72	*2.01* *(0.05)*	*2.00*

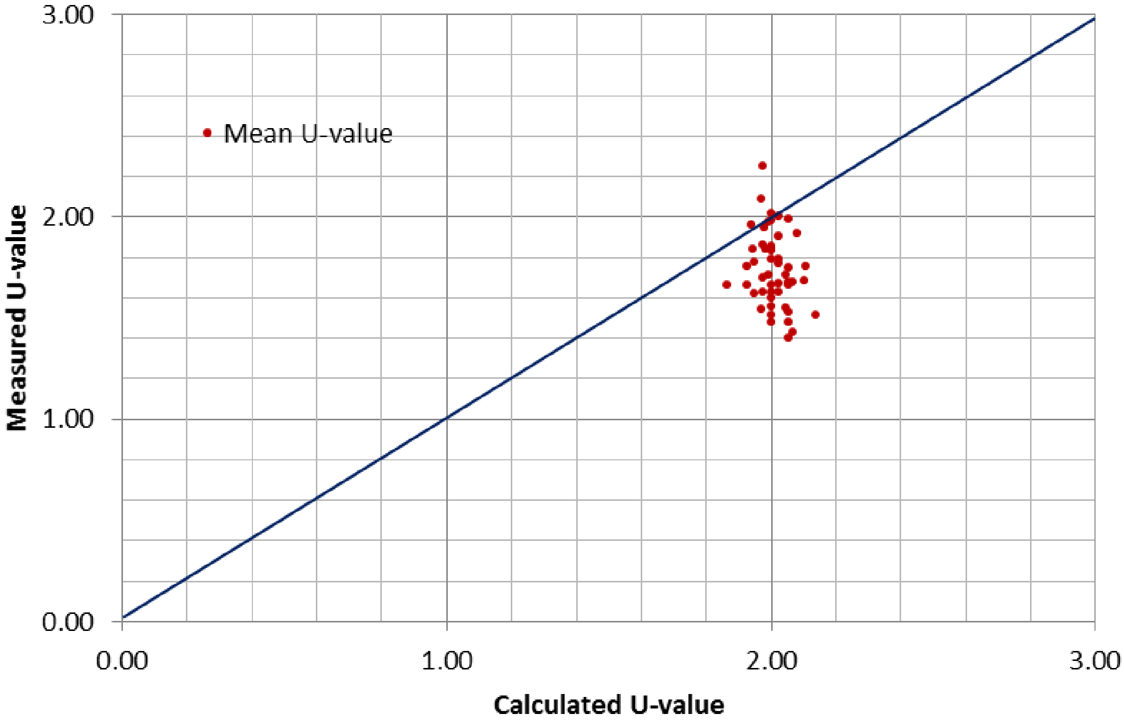

Figure 70 Measured and calculated values for the 50 cases used for comparison using the default calculation assumptions.

The results from this type of calculation show an average calculated value approximately 0.25 W/m^{2}K above the average measured value[6], and a strong clustering of all calculated values around single value (approximately 2.0). There is little or no variation between the different walls measured because of the absence of any additional data included in the calculation. Any variation observed is a result of the different wall thicknesses of the dwellings measured.

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[6] for these measurements we would recommend using the median as the best measure of central tendency – in practice, for these cases the mean and median are very close

It is apparent that this type of calculation procedure both overstates the U-value on average, and is unable to reflect the variation in measured U-values.

8.2 Inclusion of the observations

The process of removing a brick and investigating the wall, and the removal of a sample of brick, provided some additional data to refine our calculations. The next stage of this comparison is to include all of these observations in our calculations and to see how this affects the results.

The fieldwork results are described in detail in Section 2 above, although each case has different characteristics, a few general observations could be drawn:

a) The space between stretchers, known as the collar joint, was seldom fully filled with mortar. The median percentage of the exposed area estimated to be filled with mortar was 67%.

b) Perpends were also seldom fully filled with mortar. The median percentage of the exposed perpend area estimated to be filled with mortar was 70%.

c) Where a brick contained a frog, if it was found on the top face of the brick (brick laid “frog-up”) then it was almost always fully filled with mortar. If it was found on the bottom face of the brick (brick laid “frog-down”) it was very seldom filled with mortar.

d) Broken bricks, known as brick bats, and imperfect bricks forming part of the wall were relatively common. These type of bricks were revealed in approximately 9% cases. These generally resulted in additional air cavities.

e) Perforated bricks in walls of this type were very rare.

f) Bricks were generally very dry. The mean moisture content of brick samples and dust samples was ~0.7% by volume. Some bricks, however, were extremely wet with a median moisture content of >15%.

g) Mortar was slightly wetter than the brick samples, although generally also dry. The mean moisture content of mortar was ~2.8% by volume. Some mortar, however, was also extremely wet with a median moisture content of >15%.

h) The median dry density of bricks was higher to that generally assumed. The median measured density was approximately 1,805 kg/m^3 rather than the often assumed 1,750 kg/m^3.

In addition, we have derived a new relationship between brick density and thermal conductivity, and produced new estimates for mortar conductivity.

For these 50 walls we are able to include the additional data *specific* to each case and refine the U-values on a case-by-case basis. This makes the assumption that the data collected from, for example, the brick removed at each dwelling is representative of the area of wall in the same dwelling where the U-value is being directly measured. Much of the evidence presented earlier in this report, however, suggests that variation within a single wall may be large.

Firstly, there is the evidence on thermal conductivity of the Bedfordshire Red bricks, as measured by NPL in the guarded heat flow meter apparatus. As described above, the variation in thermal resistance (and conductivity) is relatively large (of the order 33% between the largest and smallest measurements). If this variation is common across all types of bricks of this age, we may expect that the single sample, as taken from the wall as part of our fieldwork, may not necessarily reflect the properties of the bricks in all locations. Similarly, the studies on moisture content across different façades of the same dwelling indicated that moisture could vary significantly across the extent of the building from <1% to > 15% moisture by volume. Given these findings, we should not expect to be able to obtain very strong correlations between the calculated U-value and the measured U-value. Where the differences between different wall types and brick types are larger than the variation within each wall, however, we might expect to see better levels of correlation.

Table 33 and Figure 71 show the effect of refining the calculation method by including all observations.

Table 33 Measured values and calculated values under revised assumptions informed by field observations from each case for the 50 cases used for comparison

Wall type	Number of cases	Measured U-values: Mean (standard deviation) (W/m²K)	Measured U-values: Median (W/m²K)	*Calculated U-values using all observed data: Mean (standard deviation) (W/m²K)*	*Calculated U-values using all observed data Median (W/m²K)*
Standard solid wall (brick) – quality filters applied	50	1.74 +/- 0.05 (0.21)	1.72	*1.81* *(0.22)*	*1.77*

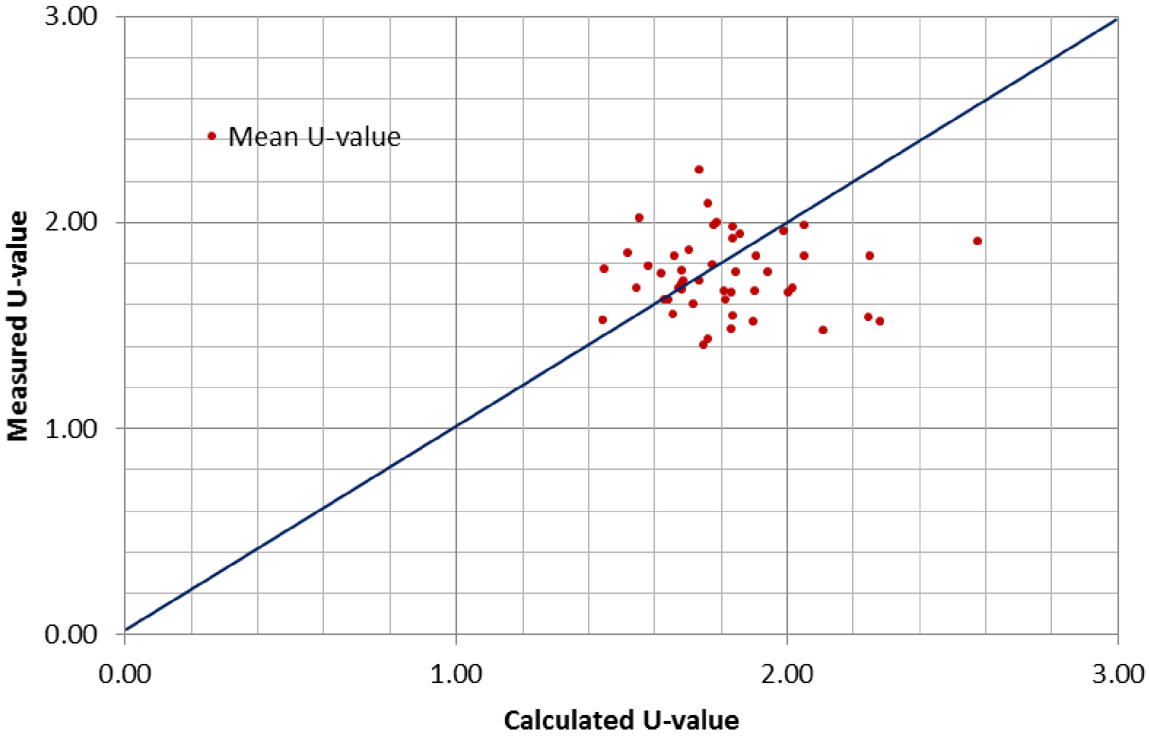

Figure 71 Measured and calculated values for the 50 cases used for comparison using the refined calculation assumptions.

As shown in the table, including all of these observations in the calculation has reduced the mean and median calculated U-value to much closer to the measured values (although above the measured value). The mean measured value is 1.74 +/- 0.05 W/m²K compared to a mean calculated value of 1.81 W/m²K. This is below the usual value used in SAP of 2.1 W/m²K.

The chart of measured against calculated values also shows a significantly increased scatter in the calculated U-values. Whereas the basic calculated values shown in Figure 70 show very little variation between cases, the variation in density, moisture content and the internal structure of the walls results in much more variation in calculated values shown in Figure 71.

The correlation for these 50 cases between the measured and calculated values remains relatively poor. That higher levels of correlation are achieved is not particularly surprising, given the experimental findings described above. The limited observations made may not be entirely typical of the exact locations where the U-value is being measured by the heat flux plates. For practical reasons, in particular the effect on the measurement itself, the removal of the brick and drillings could not take place in the same locality as the measurement. Instead another position on the wall was chosen and the results from this position, in this comparison, are extrapolated onto the measured location. The moisture content and extent and amount of mortar present in the wall are likely to vary significantly across the extent of the wall and there is no guarantee that the observations made at one point will in fact be representative of the measured U-value location. Even the density of bricks may vary significantly in walls which contain particularly heterogeneous bricks (such as are often found in hand made bricks of this age).

8.3 Extending the observations to all walls

The primary objective of the additional investigations is to understand the characteristics of all solid walls and to be able to refine the calculation assumptions where detailed observations of the type undertaken are not possible. The evidence from the walls in general seems sufficient to justify a revision to the defaults for calculating U-values of solid walls. The identification of air cavities within the wall structure, and lower than anticipated brick densities and moisture contents, provides evidence to revise the default assumptions used for walls of this type.

The final step in the improvement of the calculated values, therefore, is to extend the general findings to the data from the 23 walls which *did not* have any additional investigations. To allow us to do this we have applied median brick densities, moisture contents and findings relating to air gaps within the walls to the remaining cases where only the U-value was measured. As shown in Table 34 and Figure 72 below, this acts to reduce the calculated U-values. On average, the calculated U-values are now below the measured values, although closer to the measured values (~5% below) than under the original default assumptions (~13% above the mean measured values for this group).

The effect is to have shifted the distribution towards lower calculated U-values. It is important to recognise, however, this is not based simply on a perceived need to adjust the calculated values by a factor, but by the evidence on overall levels of moisture content, brick density and air spaces within the wall provided by the fieldwork.

Table 34: Measured values and calculated values under revised assumptions informed by field observations from each case for the 23 cases without any additional observations

Wall type	Number of cases	Measured U-values: Mean (standard deviation) (W/m²K)	Measured U-values: Median (W/m²K)	*Calculated U-values using all observed data: Mean (standard deviation) (W/m²K)*	*Calculated U-values using all observed data Median (W/m²K)*
Standard solid wall (brick) – quality filters applied	23	1.82 +/- 0.10 (0.24)	1.85	*1.75* *(0.05)*	*1.77*

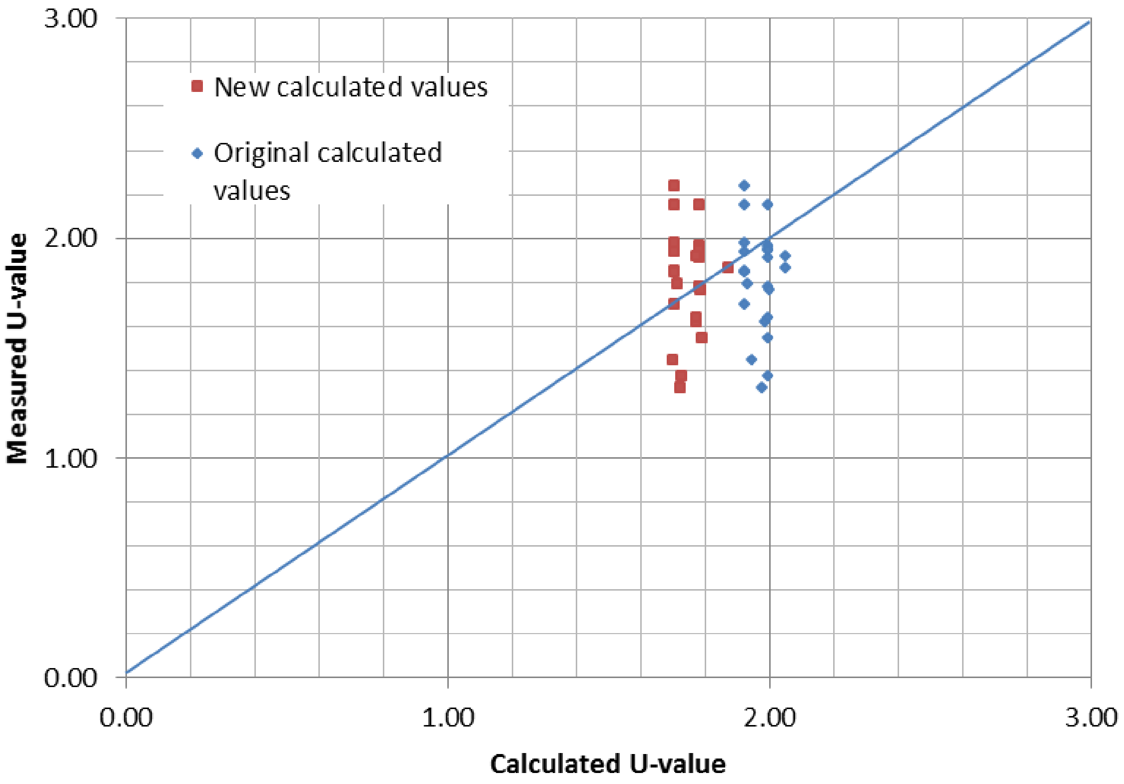

Figure 72: Comparison of measured and calculated values for the 23 cases which did not have additional observations under the original and revised calculations

9 Conclusions and discussion

9.1 Summary of findings

Previous work by BRE and others has identified that U-values of solid wall dwellings measured in situ are lower than the generally assumed value of 2.1 W/m²K. This research has provided evidence in support of a U-value of 1.75 W/m²K for solid walled dwellings.

This component of the solid wall insulation research project examined the nature of solid wall in situ. The work was intended to gather evidence which may justify a change to the usual theoretical assumptions which are made when attempting to calculate the U-value of a solid wall.

In order to investigate the likely reasons for this discrepancy, alongside an assessment of the in situ measurement methodology, BRE has undertaken an extensive programme of research into the thermal performance of solid walls.

This has taken the form of fieldwork, in which 137 dwellings were visited. In 89 of these, dust samples and/or brick samples were obtained in order to better understand the properties of the bricks and mortar used in the construction of the walls. Additional valuable information was obtained through a visual inspection of the internal structure of these walls following the removal of a brick. Other fieldwork visits, to three dwellings, obtained extensive dust drillings from all façades of the dwelling in order to ascertain how moisture content may vary over the extent of all walls.

A parallel series of laboratory investigations has also been undertaken. The first of these was the construction and testing of six solid walls in the hot-box at the National Physical Laboratory (NPL). This apparatus is able to measure the U-value of these walls directly, under controlled laboratory conditions. These tests included the construction of walls which aimed to mimic the observations from the fieldwork.

Alongside this, measurements of the thermal conductivity of 24 bricks were also made using the guarded heat flow meter apparatus at NPL. These have been supplemented by measurements of 33 bricks using the Hukseflux TP01 sensor.

The key findings from the fieldwork investigations in the 89 properties where bricks were removed and/or samples taken were:

a) The space between stretcher bricks, known as the collar joint, was seldom fully filled with mortar. The median percentage of the exposed area estimated to be filled with mortar was 67%.

b) Perpends were also seldom fully filled with mortar. The median percentage of the exposed perpend area estimated to be filled with mortar was 70%.

c) Where a brick contained a frog, if it was found on the top face of the brick (brick laid “frog-up”) then it was almost always fully filled with mortar. If it was found on the bottom face of the brick (brick laid “frog-down”) it was very seldom filled with mortar.

d) Broken bricks, known as brick bats, and imperfect bricks forming part of the wall were relatively common. These type of bricks were revealed in approximately 9% cases. These generally resulted in additional air cavities.

e) Bricks were generally very dry. The median moisture content of brick and dust samples by volume was 0.5%. Some bricks, however, were extremely wet with a median moisture content of >15%.

f) Mortar was slightly wetter, although generally also dry. The median moisture content of mortar by volume was ~2.7%. Some mortar, however, was also extremely wet with a median moisture content of >15%.

g) The median dry density of bricks was higher than generally assumed. The median measured density was approximately 1,805 kg/m^3 rather than the often assumed 1,750 kg/m^3.

The testing of the built walls in the hot-box provided laboratory derived U-values broadly in line with field observations.

The tests on brick thermal conductivity allowed the derivation of a new relationship between density of the samples and the brick thermal conductivity. There are considerable doubts over the validity of historic thermal conductivity measurements, and these new measurements revealed conductivity to be higher than many older measurements. This programme of work also revealed that, even within bricks from the same batch, thermal conductivity can vary substantially.

For the three dwellings where extensive dust drillings were taken, it was found that moisture content varied significantly across the extent of the walls from less than 1% in some areas to greater than 10% in others. Even in adjacent areas, the moisture content showed substantial variation.

The final part of this research has applied the findings of the work to the theoretical calculation of wall U-values, in an attempt to reconcile the measured and theoretical calculated values. The fieldwork has provided strong evidence to suggest refinements to the calculation of U-values to incorporate additional air cavities within the wall, and refined default moisture and density values. The effect of these changes has been to reduce the average (both mean and median) calculated values. The average calculated values following the revisions are closer to the average measured values.

At the individual case level, correlation between calculated and measured values increases following the use of the additional field data. Correlation is limited, however, which we can associate with the heterogeneity of the wall structure, and the known variation in moisture content and brick thermal conductivity as revealed by this work - i.e. the limited observations made may not represent the situation in the exact locations where the U-value is being measured by the heat flux plates.

9.2 Discussion

Correctly being able to define the thermal performance of an existing wall is important for numerous reasons. It is required if our estimates of the energy consumed by dwellings are to be as accurate as possible, to correctly size heating appliances, and to estimate savings from wall insulation.

The standard U-value assumed for solid walls, a value of 2.1 W/m^{2}K has been used since the initial definition of these quantities through calculation in the 1960s, ahead of the publication of the 1970 CIBSE Guide [3]. At this time the use of calculated U-values, rather than those derived through experiment, was promoted as it offers comparability across different materials, as well as the ability to adjust for different conditions of moisture (and other characteristics) as required. This value appears to have remained relatively unchallenged until recent experimental work to establish a baseline ahead of insulation work.

That the value remained unchallenged for so long is not surprising. Although the majority of the UK housing stock is old, the focus of recent studies in this area has been on the performance of other types of materials, in particular insulants, and more contemporary building materials used in modern construction, rather than ancient bricks found in historic buildings. It is only with the need to retrofit these older dwellings that the focus is placed upon the performance of the older existing stock, and only through the challenge to theoretical assumptions through fieldwork and experiment can we gain an insight into the true performance of the walls of these dwellings.

Our new research has provided strong evidence to support a revision to the assumed U-value for uninsulated solid walls, and supported our original findings measuring U-values in situ [10]. For solid walls, a U-value of approximately 1.75 W/m²K seems appropriate, and we would suggest that this value is taken forward as the default value in RdSAP. For other uses, boiler sizing for example, a higher value may be appropriate. The original value of 2.1 W/m²K is approximately two standard deviations above the new measured mean value and may be suitable to prevent undersizing of heating systems.

This lower average measured U-value seem likely to result from the following factors, which are supported by evidence from this research:

a) Additional air cavities within the wall. In particular, there is typically missing mortar between the stretcher bricks in the wall, and at the perpends. There are also often broken bricks and snapped header bricks forming part of the inner leaf of the wall.
b) Lower moisture contents than typically assumed. Rather than assuming 5% by volume as the moisture content, median values measured by this work were 0.8% for brick and 2.8% for mortar. This has the effect of significantly lowering the U-value of the wall.

This research has highlighted the continual need to challenge the ‘book values’ which are in use on a daily basis, and that our level of understanding as expressed through theory needs to be regularly validated with new experimental data. In particular, it suggests that many of the standard values for thermal performance may need revisiting. This research has focussed on only one particular type of wall, which is only one of many building elements. It has also primarily focussed on the performance of bricks. It seems likely that similar issues may exist with the standard assumptions employed across all other types of walls, as well as in roofs, floors and other building elements, and across the myriad of building materials in use. Although revisiting these multitude of default values is a daunting task, a rational approach could be taken based on the prevalence of each material or element and the confidence in the existing data as a starting point.

Additional work from this programme of research has suggested that the existing relationships between thermal conductivity and brick density may be based on data collected using techniques which are now considered inadequate. Our research proposes a new relationship, created using modern techniques and methods. This is a further example of where old assumptions have been revisited, leading to a new understanding of the performance of some basic building elements.

9.3 Further work

The research has raised a number of areas for further work and study. The six main areas where we recommend additional work is undertaken are:

1. Confirmation of the newly derived thermal conductivity-density relationship, and extension to other materials. This work has proposed a new relationship between thermal conductivity and density for bricks. It has highlighted the age of many of the basic ‘book values’ which are widely used, and the potential errors that may exist with these old measurements. We would recommend additional testing to both confirm the relationship which has been derived, and extend the research to new measurements of other basic building materials (including mortar), for which the book values may be equally historic.

2. Additional investigations of the effect of brick moisture. The measurements of brick moisture were from a single location, and from the back of the facing stretcher brick only. Moisture dust drillings have indicated the extent that moisture may vary across a wall, and it would be of great interest to understand how this may vary at different locations in different bricks. This would include the moisture content of the inner leaf.

3. Investigation of moisture correction. Numerous alternative methods of correcting for moisture exist – e.g. Jakob corrections, ISO10456, DIN 51692. The choice of correction will affect the final calculated U-value. As with the thermal conductivity-density relationship, much of the data on these corrections

is historic. We would recommend that new laboratory tests are designed undertaken to determine the most appropriate correction to use.

4. One area which has not been explored in detail in this work is the nature of the plasterwork. It was noted when plasterboard was present (and this is accounted for in the calculations) but types and thicknesses of plaster (except for the presence of plasterboard) were not measured for practical reasons of householder acceptance. Delamination of the plaster was also not accounted for.

5. The data on the distribution of different brick types within the housing stock is very limited. Additional knowledge of the types of bricks which are likely to be located in different locations may help to better define U-values at a local level. A survey could be designed to map the distribution of different brick types, which could be supplemented by laboratory (or in situ) measurements of the thermal performance of each different type.

6. Continuing investigation of the use of thermal probes for in situ measurements. Initial results from the use of a thermal needle probe are promising, with a good correlation between the measurements taken with the probe, and the measurements of thermal conductivity obtained in the laboratory. Further investigation of this technique is recommended, which ultimately may require the definition of a standard method for use of this equipment for the measurement of thermal conductivity in situ.

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Appendix A Wall weights for Hot Box test walls

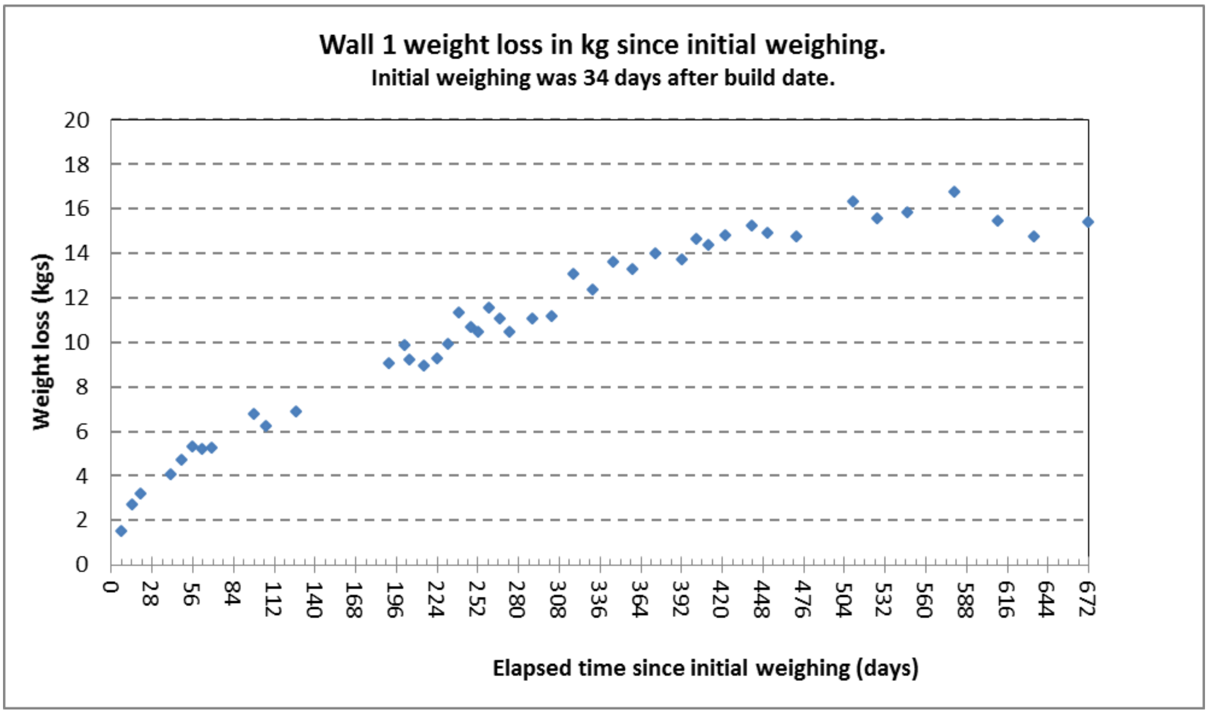

Figure A1: Wall weight loss for Wall 1.

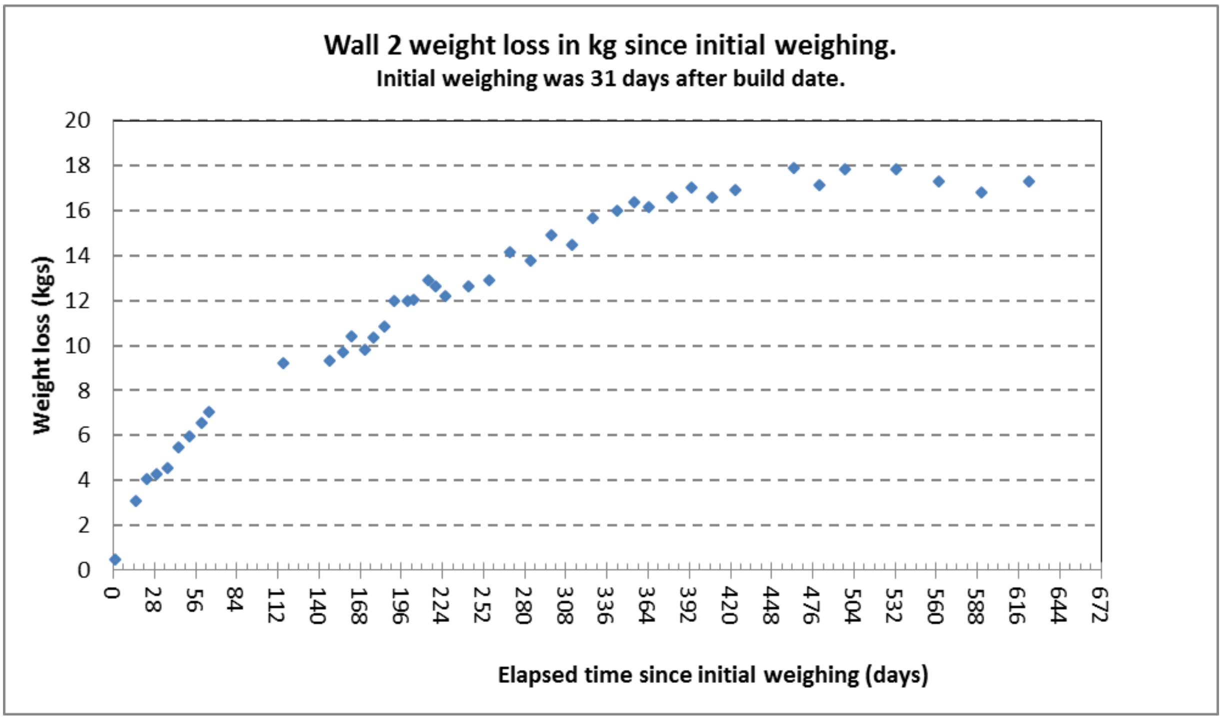

Figure A2: Wall weight loss for Wall 2.

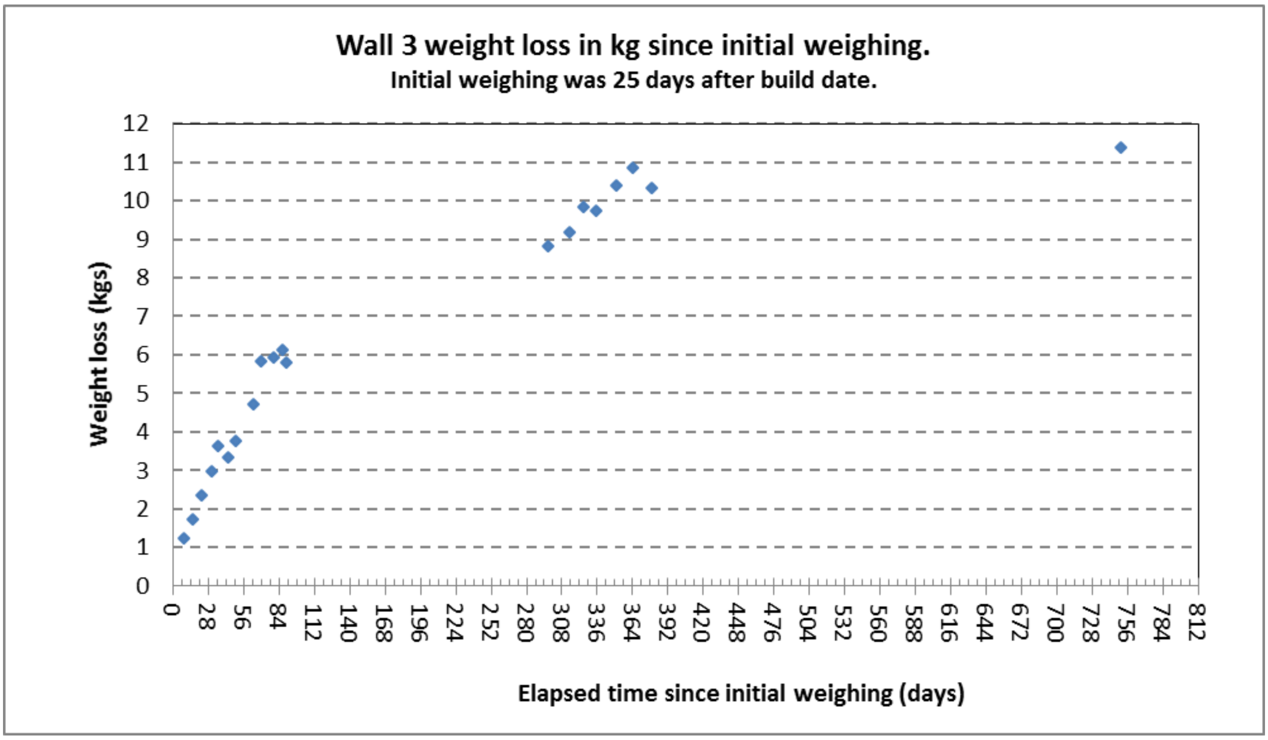

Figure A3: Wall weight loss for Wall 3.

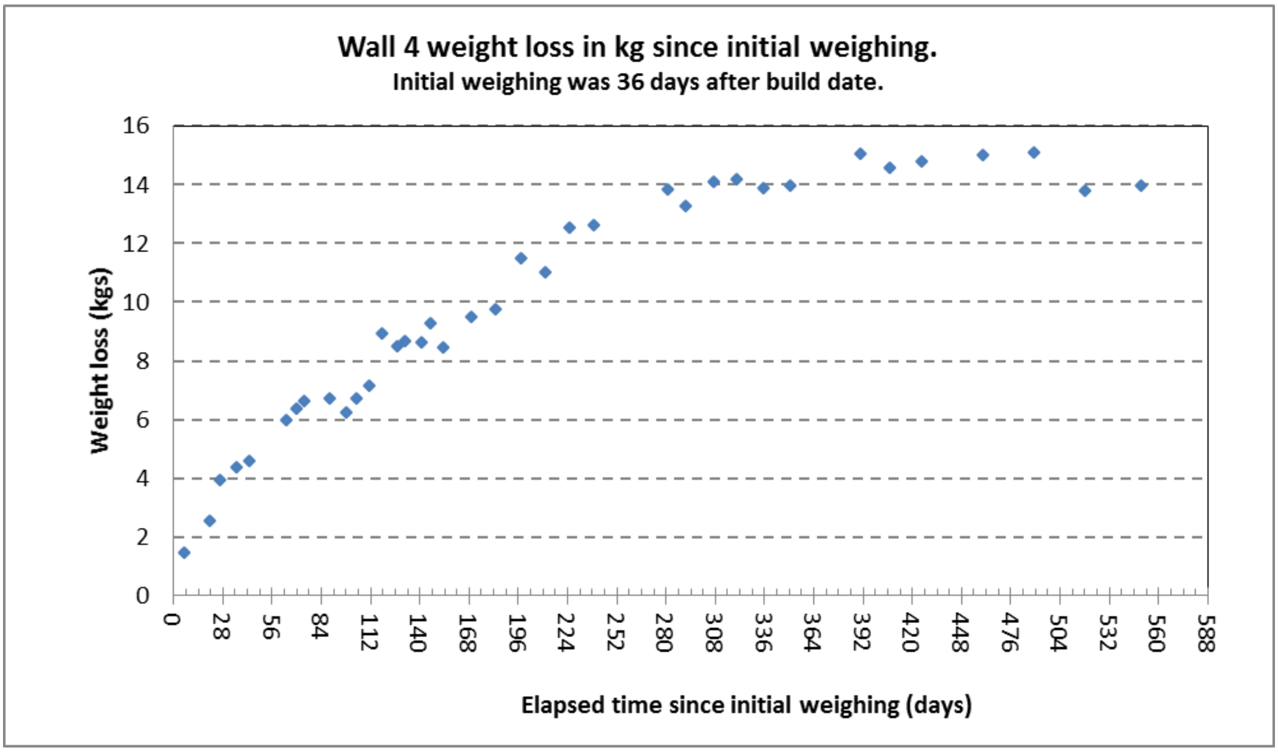

Figure A4: Wall weight loss for Wall 4.

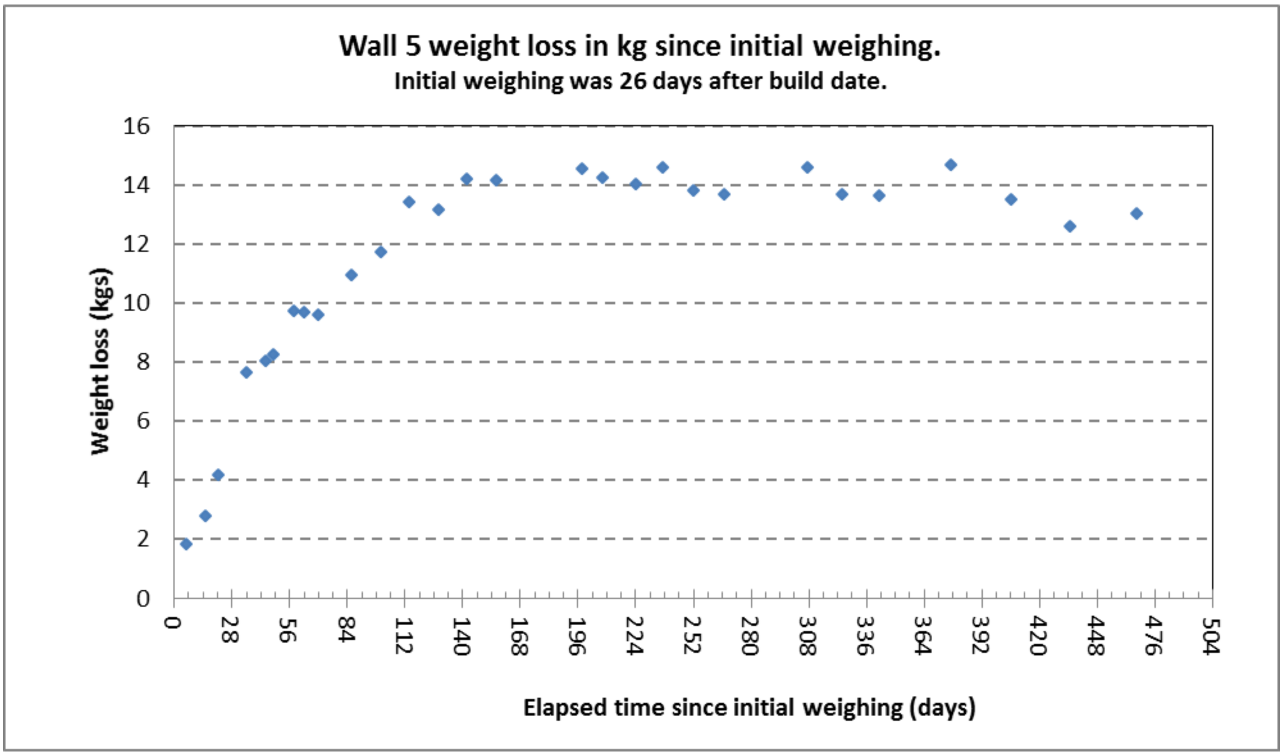

Figure A5: Wall weight loss for Wall 5.

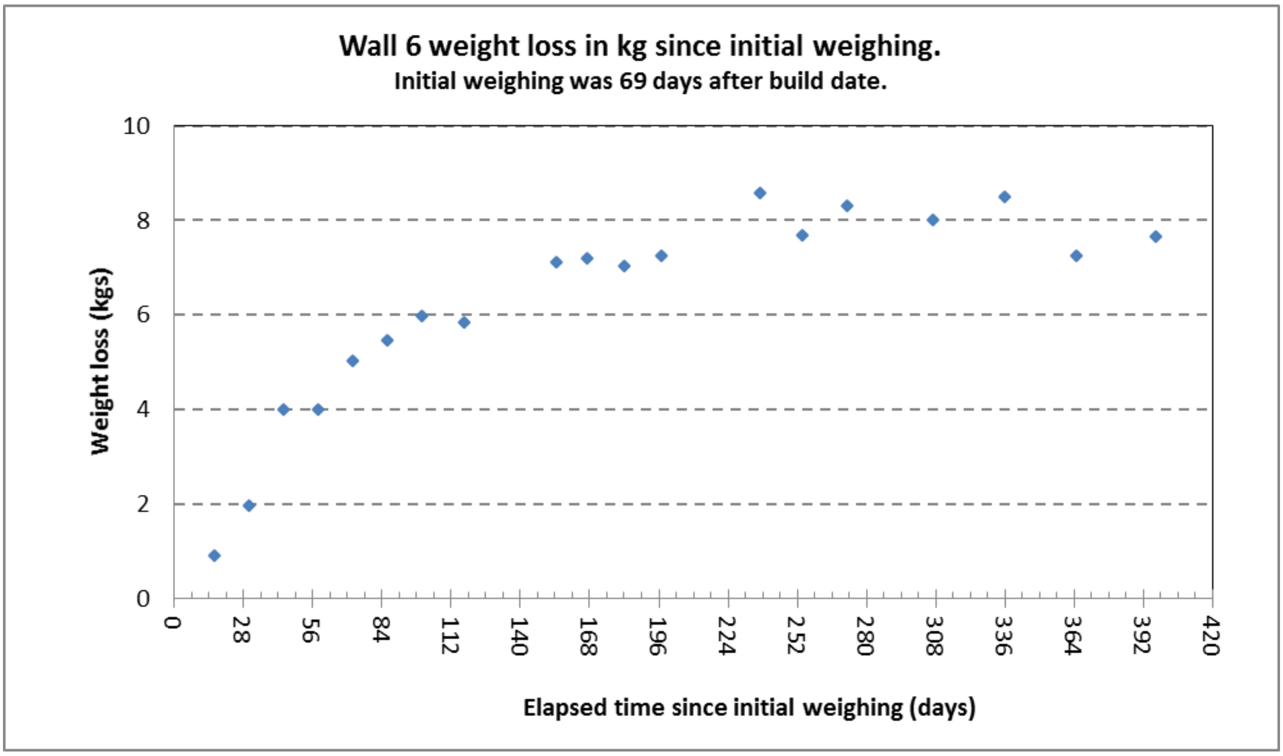

Figure A6: Wall weight loss for Wall 6.

Appendix B The Hukseflux TP01 Sensor

The TP01 measures thermal conductivity, and is usually used for the measurement of soil Thermal Conductivity. Its rated operating range is 0.3 to 4 W/(m·K).

The sensor inside TP01 is a temperature difference sensor consisting of 2 thermopiles. It measures the radial temperature difference around a heating wire with high sensitivity.

Both the heating wire and the sensor are incorporated in a very thin plastic foil. It can be connected directly to commonly used data logging systems. The low thermal mass of TP01 also makes it suitable for measuring the thermal diffusivity.

The thermal conductivity, λ, is calculated by dividing the TP01 sensitivity, S, by the sensor output, a small voltage difference ΔU which is a response to stepwise heating, and multiplying by the applied electrical power Q per meter heating wire.

The measurement function of TP01 is: $\lambda = S \cdot Q / U$. The factory-determined sensitivity S, as obtained under calibration reference conditions, is provided with TP01 on its product certificate.

The thermopile sensor generates a voltage output, as a reaction to the radial temperature difference around the heating wire. The heating wire generates a circular temperature field. After 180 s, the temperature difference around the sensor becomes stable.

The measurement principle of TP01 relies on measurement of the radial temperature difference around a heating wire. The temperature difference is measured by two thermopiles connected in series, generating a single output. Both the heater and the thermopile are incorporated in a thin plastic foil.

The thermal conductivity, λ, in W/(m·K), is calculated by dividing the TP01 sensitivity, S, by the output, a small voltage difference ΔU which is a response to stepwise heating, and multiplying by the applied electrical power Q per meter heating wire.

The measurement function of TP01 is:
$\lambda = S \cdot Q / \Delta U$

The voltage difference ΔU is determined by performing a measurement just before the heating starts and after heating for 180 s.

$\Delta U = U(180) - U(0)$

The factory-determined sensitivity S, as obtained under calibration reference conditions, is provided with TP01 on its product certificate. The heating power Q, in W/m, is determined from a voltage measurement across the heater and taking the heater length and electrical resistance into account.

Figure B1 below shows the TP01 sensor.

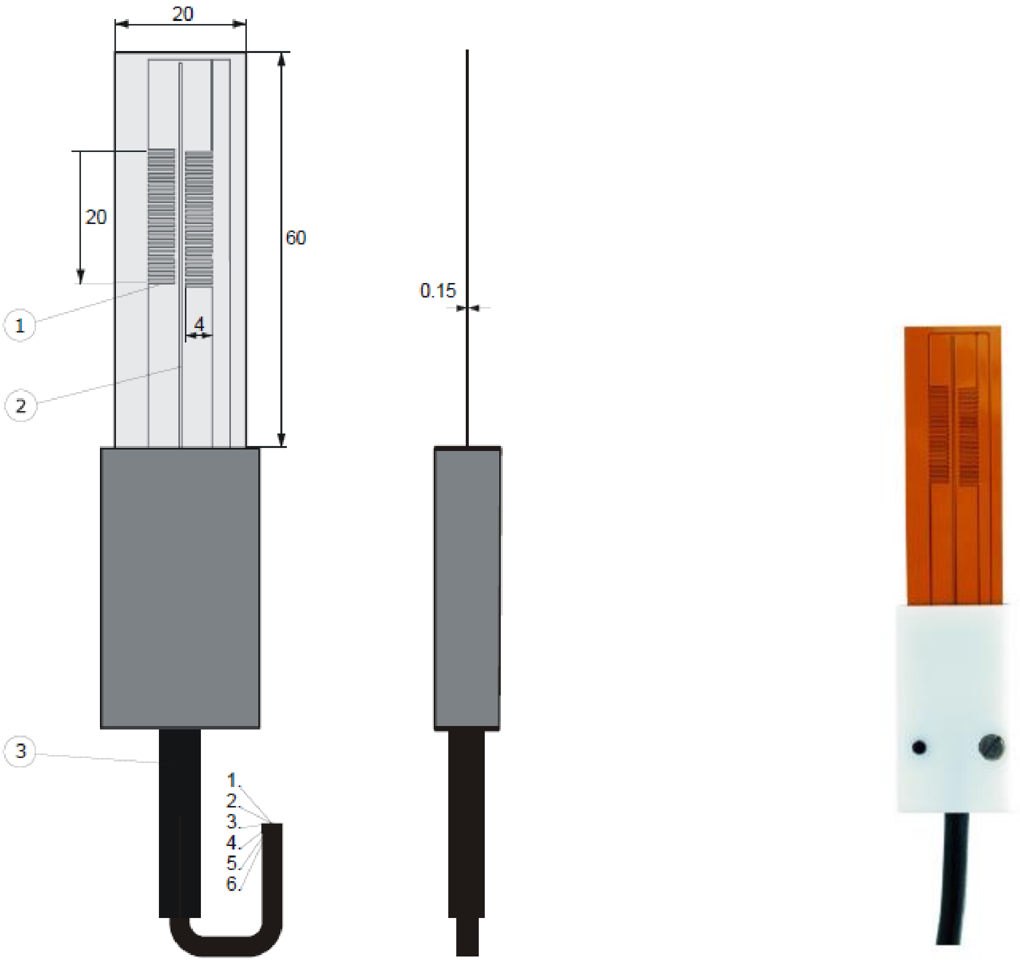

Figure B2: The TP01 Sensor.

1 = Thermopile, 2 = Heating wire, 3 = cable. Dimensions in 10^{-3}m.