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BRE Report

In-situ measurements of wall U-values in English housing

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Executive Summary

BRE has carried out in-situ measurements of wall U-values in approximately 300 domestic dwellings in England, together with more detailed investigations in a subsample of those walls. In addition, laboratory tests have been carried out in order to validate the method of measuring U-values. It is important to understand how the walls of homes in the UK are performing *in-situ* in order to provide realistic estimates of current energy consumption, and to quantify the potential for energy efficiency improvements such as wall insulation.

The fieldwork consisted of:

- A small supervised pilot study in late 2011.
- A main fieldwork component which collected measurements between January and March 2012 for a sample of approximately 300 walls of different types.
- Further investigation into the presence of insulation in 10 cavity wall dwellings, carried out in August 2012.
- Further investigation into the moisture content and density of bricks from 18 solid walls, alongside repeated U-value measurements, carried out in February and March 2013.

Alongside the measurements, theoretical U-values have been calculated using information from the field sheets and assumptions about the construction of the wall. Where additional information was available, as was the case in the walls which were examined more closely, the U-value calculations were refined to take this into account. It was found that consolidation of all field data is essential to identify the most appropriate inputs into the calculation process. In particular, reliance on a dwelling level classification of predominant wall type is insufficient due to the possibility of mis-classification by surveyors or measurements taking place on other (minor) wall types.

The average measured U-values returned by the survey for each wall type are shown in Table 1. Also shown are the average calculated U-values, current RdSAP conventional U-values, and the ratio the average measured and calculated / default RdSAP U-values.

The averages of the measured values for solid and uninsulated cavity walls are below the standard values used in the RdSAP methodology, and below the mean of the theoretical calculated U-value produced using observations about the wall. In contrast, the average of the measured values for insulated cavity walls is above the standard RdSAP value, and the mean calculated value.

Wide variations in U-values were observed for all wall types, 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 conducted in 2010, in that the measured U-values of solid walls are significantly below those calculated and assumed in RdSAP.

If the values measured are representative of those found nationally for these wall types, the effectiveness of national insulation programmes is likely to be less than might be expected using the usual (RdSAP) assumed U-values. This will also affect the distribution of households within each of the RdSAP based A to G bands used for Energy Performance Certificates (EPCs).

Table 1 - Summary of results and RdSAP values

Wall type	Number of cases	**Measured U-values: mean (standard deviation) W/m²K***	**Measured U-values: median W/m²K**	*Calculated U-values: mean (standard deviation), W/m²K*	*Calculated U-values: Median W/m²K*	**Typical RdSAP U-values[a] W/m²K**	Ratio of (Mean measured U-value) / (Mean calculated U-value)	Ratio of (Mean measured U-value) / (Typical RdSAP U-value)
Solid wall, standard[b]	85	**1.57 (0.32)**	**1.59**	*1.90 (0.20)*	*1.92*	**2.1**	*0.83*	*0.75*
Solid wall, non-standard[b]	33	**1.28 (0.42)**	**1.28**	*1.91 (0.49)*	*1.68*	**2.1**	*0.67*	*0.61*
Uninsulated cavity	50	**1.38 (0.30)**	**1.43**	*1.40 (0.11)*	*1.41*	**1.6**	*0.99*	*0.86*
Insulated cavity	109	**0.67 (0.23)**	**0.63**	*0.52 (0.08)*	*0.51*	**0.5**	*1.29*	*1.34*

Note a) From RdSAP Appendix S (v9.91) Table S6 - Solid wall standard & non-standard age bands A to D (Pre-1967), Uninsulated and insulated cavity age band D (1950-1966).
Note b) 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).

Nine of the ten cavity wall dwellings revisited, originally assumed to be uninsulated, were found to have insulation present. The insulation was found to be of variable quality and density, a situation which, if considered representative of all insulated cavity walls, can help to explain the wide variation in U-values seen in this group. For these nine cases, incorporating the observed data on presence of insulation resulted in a much better alignment of the calculated U-values with the measured U-values.

The data on brick density and moisture content from a further sample of solid walls acted to align calculated and measured values in some, but not all, cases examined. 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 observations). However, this assumption did not hold for all cases.

Attempts to investigate any temporal variation in U-value suggested that there may have been changes in the U-values of the walls between the two measurement periods (2011/12 and 2013), although the data is insufficient to conclude definitively that this is the case.

Additional work has been carried out under controlled laboratory conditions (using a hot-box to understand why measured U-values are often different to the theoretical calculated U-values). This has investigated the potential for systematic errors resulting from measurement system that is in use. The results suggest that a small error may indeed exist, which may result in measured U-values that are of the order 5% lower than the actual U-value of the wall. This is within the uncertainty of the equipment calibration, and no adjustment can be made to the values as measured with confidence in the absence of additional evidence (which is currently being gathered). It should be noted that the effect on the mean measured U-values of any systematic error of this type and scale will be very small (an increase of approximately 0.08 W/m²K in the mean value for solid wall dwellings).

Contents

1. Introduction

1.1 Background

There are approximately 22 million dwellings in England. Of these, approximately two-thirds are of cavity wall construction and one-third are of solid wall construction, including those built with solid brick, solid stone and concrete. It is important to understand how walls of all types are performing in practice in order to quantify the energy consumption of the housing stock accurately and to provide estimates of the potential for energy savings.

1.2 Summary of the project

BRE was commissioned by DECC to provide an assessment of the thermal performance of walls in a range of domestic dwellings in England, and to compare measured U-values with theoretical calculated values. Thermal performance is normally expressed in terms of a U-value ('thermal transmittance') which gives an indication of heat losses (or heat fluxes) through building elements such as walls. U-values were measured in approximately 300 solid wall, unfilled cavity wall and filled cavity wall dwellings, through the *in-situ* monitoring of heat flux and temperatures. Theoretical U-values were also calculated from the field observations. The measured and calculated values were then compared. Dwellings were selected for these measurements from those originally visited as part of the 2010/11 English Housing Survey (EHS).

Following the initial calculation of U-values, additional specific investigations were carried out on a subset of these walls to attempt to understand why some of the measured values differed from theoretical calculated values. These investigations included boroscopic inspections of cavity walls, and brick core and dust sampling from solid brick walls.

In order to investigate the possibility of systematic errors in the measurement apparatus, hot-box testing was also carried out under closely-controlled laboratory conditions. A test wall of a known U-value was constructed at National Physical Laboratory (NPL) and a number of the heat flux plates being used in the fieldwork were affixed to the wall. The wall and heat flux plates were then enclosed within a guarded hot box. The U-value of the wall measured by the heat flux plates was systematically compared with the U-value measured by the hot-box.

1.3 Heat flux and U-values

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).

1.4 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. Temperatures were also measured using thermistors, and in most cases 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 Figures 2 and 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/m^2.

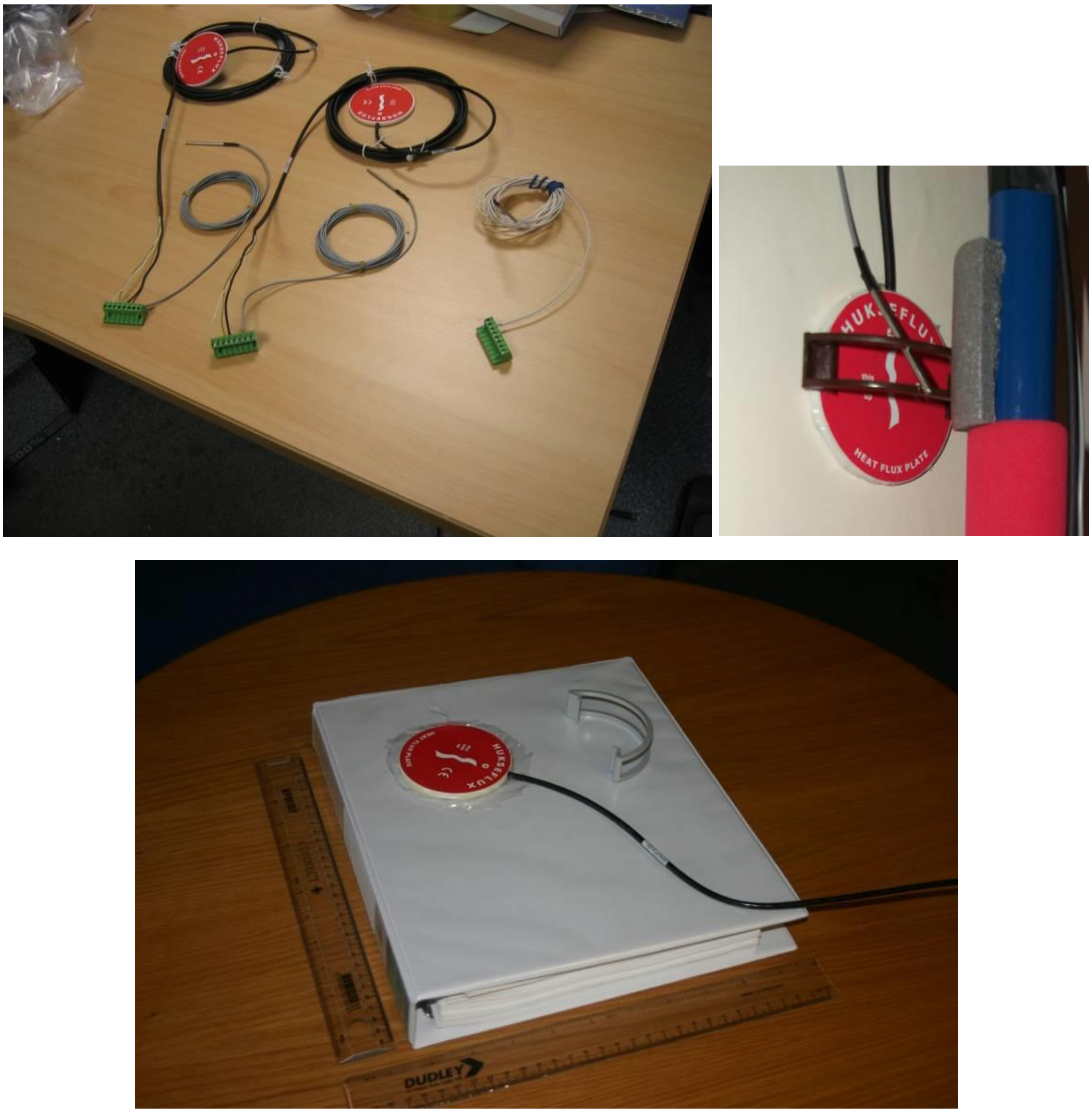

Figure 1 - The sensing equipment that was used for monitoring the heat flux and temperatures. The Hukseflux heat flux plates (circular plates) measure heat flux (in watts per square metre) and the thermistor sensors (silver tubes) measure temperature.

1.5 The pilot study

The project began with a pilot study, which was undertaken in November and December 2011.

The pilot study was essential for:

- Training of installation teams for conducting the *in situ* U-value measurements, and filling out the accompanying field sheets
- Testing the method of collection and collation of the monitoring data from a sample of housing involving a mixture of solid walls and cavity walls
- Preliminary analysis of the datasets

1.5.1 Training the staff for in-situ field measurements

A two-day training programme was held at BRE in December 2011 for staff that were to carry out the field measurements. This training included presentations on U-value measurements, discussions on data to be collected and practice in setting up equipment using BRE's test houses. Trainee staff then installed equipment in actual occupied housing, under observation to ensure that the installation was undertaken in a consistent manner according to the required procedures.

During the training session the staff were briefed on the following:

1. Use of field sheets for recording observations
2. Practical issues regarding the appropriate siting of monitoring equipment
3. The procedure for installing the equipment and activating the dataloggers
4. The procedure for retrieving data from the dataloggers
5. Liaison with householders
6. Use of thermal imaging cameras
7. Health and safety – driving, lone working, heights, safe working practices, ensuring safety of occupiers etc.

1.6 The data collected

The field sheet was designed to include the following:-

1. A unique house identifier (reference number)
2. Dates at which the property was visited
3. Measured wall thickness (for the section of wall where heat flux was measured)
4. Description of the wall construction, including internal and external finishes and other visible clues
5. Height of heat flux plates and internal temperature sensors above the floor
6. Distance to nearest windows, doors and corners (in order to provide an indication of the risk of errors arising from thermal bridging)
7. Type of room (e.g. bedroom, living room, kitchen etc.)
8. Serial number and calibration constant of each heat flux plate and serial number of each datalogger
9. Datalogger channels to which the heat flux plates and temperature sensors are attached
10. Compass directions in order to assess the potential for any effect of direct sunlight
11. The time that the dataloggers were started
12. Comments on exposure of the wall to wind and sunlight
13. The external wall surface (i.e. facing brick, stone or render)

14. The internal wall surface (i.e. hard plaster, soft plaster or plasterboard). Hard and soft plasters were indicated by how easily the investigator could use a safety pin or picture hook to penetrate the plaster (where permitted by the occupant). Plasterboard was identified by tapping the surface of the wall.

1.7 The main survey field visits, 2011/2012

Following the pilot study, the staff that were to carry out the field visits were divided into four teams and each team was tasked with installing and removing equipment according to the schedule in Table 2.

Mid-terraced houses were avoided as they often have a relatively small wall area and can be problematic for finding suitable measurement locations. Where possible, dry-lined walls were also avoided using data from the EHS on the presence of dry-lining. The base sampling frame consisted of cases from the 2010/11 EHS, which is randomly sampled from across England. Fieldwork for the follow-up U-value measurements was arranged to ensure that the follow-up visits were geographically spread across the country, using this sampling frame.

Table 2 - Fieldwork survey visit dates

Dates of installations 2012	**Dates of de-installations 2012**	**Number of properties visited per team**	**Total properties visited (approx.)**
3 Jan to 7 Jan	17 Jan to 21 Jan	20	80
23 Jan to 27 Jan	6 Feb to 10 Feb	20	80
13 Feb to 17 Feb	27 Feb to 2 Mar	20	80
5 Mar to 9 Mar	19 Mar to 23 Mar	15	60

1.8 Mounting the heat flux plates

The HFPs need to be placed firmly against the wall with a good thermal contact. It is possible to attach each HFP to a wall using a strong double-sided sticky tape in order to ensure good thermal contact. However, for this survey this was impractical, as this could cause damage to the paint or wallpaper which would not be acceptable to householders.

It was decided to affix the heat flux plates 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 [1,5,15,16]. 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 property to be monitored, it was decided that two heat flux plates would be used, in line with guidance in ISO 9869[2].

Internal air temperatures[a] were monitored adjacent to the HFPs using thermistors (one thermistor was used per HFP), attached at a distance of approximately 2cm 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.

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[a] Accurately recording internal and external temperatures is essential in U-value surveys. A discussion of the effect of temperatures is included in Appendix D.

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 outdoor temperature.

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

Figure 3 - 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)

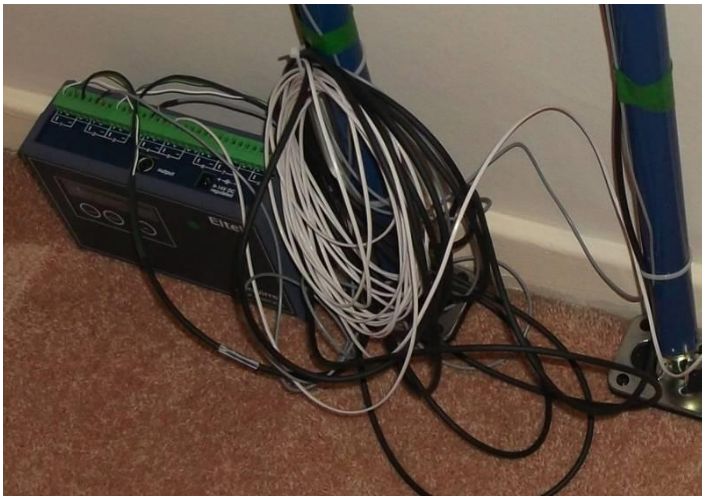


Figure 3 - An Eltek 851L datalogger, recording EMF and thermistor readings from the sensing equipment

1.8.1 Selecting a suitable location

Installations were made both upstairs and downstairs in a variety of rooms in the dwelling, 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 HFP. A thermal imaging camera was used for this purpose.

Figure 4 shows a thermal image of a particularly uneven wall which serves to highlight the importance of thermal imaging. Where an inhomogeneous wall was identified in this way, 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 IR indicated was at a temperature which represents the average of the wall as a whole.

Temperatures were measured at 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.

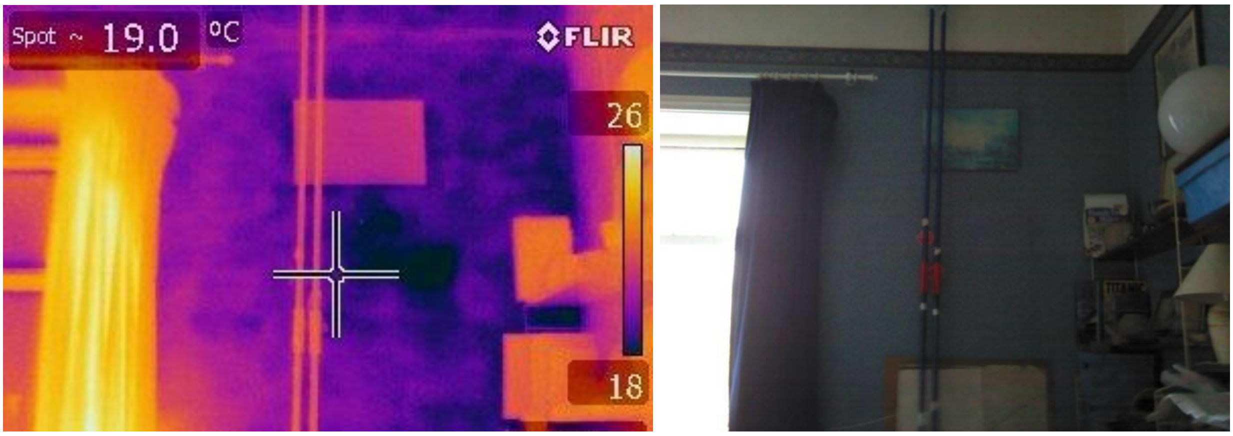


Figure 4 - A thermal image showing the equipment installed on a wall in a house. In this instance the thermal performance of the wall is unusually uneven and it was necessary to select a representative measurement point at approximately average temperature for the wall as a whole.

1.8.2 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 each 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.

1.8.3 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.

1.9 Additional investigations of 10 nominally uninsulated cavity walls

The results of the main U-value survey undertaken in 2011/12 indicated that some of the walls, described on the EHS as being in dwellings with predominantly uninsulated cavity walls, had surprisingly low U-values. It was suspected that these walls were, in fact, insulated. In order to investigate this further, 10 of these walls were revisited later in 2012 to carry out more intrusive investigations using a borescope.

For these walls, the presence and condition of any insulation present was noted and the width of each cavity was measured. In addition, for each wall, the thickness of the outer leaf was measured. As a result of these inspections and measurements it was possible, for each wall, to re-classify it as insulated (if appropriate) and to revise the theoretical U-value calculation which was compared with the measured U-value.

1.10 Additional investigations of 22 nominally solid brick walls

Further tests were also carried out on 22 nominally solid brick walls in February and March of 2013 with a view to verifying the U-values. The investigations primarily targeted those with large discrepancies between measured and calculated values. These further investigations also presented the opportunity to measure U-values of the same walls in two consecutive winters, and across a larger area of the wall.

The 'follow-on' investigations in nominally solid brick wall dwellings allowed:

1. <u>Confirmation of the classification of solid brick walls:</u> Drilling and coring of the solid brick walls was used to confirm the classification of the wall as solid.
2. <u>Investigation of brick densities and moisture content:</u> Taking core samples of brick from the outer stretchers and measuring the density and moisture content. Taking dust samples of both brick (at different depths) and mortar and measuring their moisture content
3. <u>Investigation of the presence of air cavities:</u> Following the removal of core samples, examining the region between inner and outer stretchers for significant air gaps and measuring their width if present.
4. <u>Investigation of spatial and temporal variation in U-values:</u> Re-measuring the U-value at four locations instead of two in order to verify the measured values and compare U-values from the same walls across two winters.

1.10.1 U-value measurements

The U-values were re-measured for all 22 walls, but the number of HFPs used was increased from 2 to 4 to allow the investigation of spatial variation. Using photographs from the original U-value measurements, two of the HFPs were placed as closely as possible to the original measured positions to allow comparison of U-values across two winters.

1.10.2 Drill and core samples

Samples of the brickwork were taken for laboratory testing. Where possible, brick core samples were taken in order to determine the density of the brick, although there were some dwellings where it was either not permissible to drill, or where the brick was too hard to permit a core sample to be taken. In addition to core samples, dust samples of brick at different depths and dust samples of mortar were also taken.

The drill samples were used to determine the moisture content of the wall. Two brick dust samples were taken: the first from the outermost 75 mm of an outer stretcher brick, and the second from between 75 mm and 150 mm of a header brick. These dust samples provided some information about the distribution of moisture at different depths. 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. The samples were weighed, both before and after oven-drying, and the change in weight was used to determine the moisture content.

The core samples were removed from outer stretchers, and taken to laboratories at BRE to be measured and weighed to determine the brick density. They were subsequently replaced in the walls and damage to the wall repaired. The removal of brick cores also allowed the examination of the interface between the outer stretchers and the corresponding inner stretchers. For each core sample, notes were taken regarding whether the space between the inner stretchers and outer stretchers was filled with air or with mortar and the distance between the inner and outer stretchers was noted. An example of a wall which a core sample has been taken from is shown in Figure 5.

Figure 5: An area where a core sample was taken. The gap between the inner and outer stretchers is just discernible as a shadow at the back of the bore hole.

1.11 Final categorisation of walls

Following all fieldwork, a key task prior to analysis was to confirm and categorise the type of wall actually measured by the U-values survey. The starting point for the categorisation of all walls is the assessment of the predominant wall type of the dwelling made by the EHS surveyor at the time of the original survey in 2010/11.

Using the EHS data, the predominant wall type of the dwelling was initially subdivided into the following categories:

1. Insulated cavity walls
2. Uninsulated cavity walls
3. Standard solid walls
4. Non-standard solid walls (all other solid walls)

Solid walls are classified in the EHS according to their construction material and thickness. ‘Standard’ refers to solid brick built walls that are approximately one header brick thick (two stretcher bricks). These walls are generally around 9” thick, plus any additional thickness due to rendering, plastering or other internal or external wall finishes. For this work, all brick walls with a total wall thickness below 330mm are classified as “standard”. Non-standard solid walls are any other types of solid wall including stone, concrete or thicker types of brick construction.

In most cases the EHS wall type will be the same as the actual wall measured in the U-values survey, but in some cases the EHS surveyor could have mis-classified the wall or the U-value measurements were, for practical reasons, undertaken on a wall of different construction to the predominant wall type. To identify where this may be the case all of the information collected was examined to make the most appropriate classification of the wall, modifying the EHS classification as necessary. This included data from the boroscopy, drilling and coring for the sub-sample of walls, as well as photographs, thermal images and all field observations for all cases. The reclassification process is described in greater detail in Appendix C.

1.12 Analysis of the measured U-values data

The field measurements used dataloggers to collect the data on heat flow and temperatures used to determine the measured U-values of the walls. These data were analysed by BRE in order to determine the measured U-value of the wall. The process for analysing the data is outlined in Appendix A.

1.13 Theoretical calculated U-values

Alongside the measured U-values, theoretical calculations of the wall U-values were also made based on field data. 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 or cavity), the measured wall thickness, the nature of the internal and external wall surface and any other data from the fieldwork (including the boroscopy, drilling and coring)[b].

For the four wall types examined in the study, various constants were assumed in the calculations. These were the thermal conductivities of generic materials, thicknesses of wall finishes, the thermal resistance of cavities and surface thermal resistances. These constants were, as far as possible, consistent with those assumed in the calculation of U-values using BR443, and used in assessment methodologies such as SAP. The various default values are given in Table 3. Where additional data on brick density, moisture content or cavity thickness were measured through the brick dust drillings, brick coring or boroscopic investigations these values were used in place of the default values in all calculations. The thermal conductivities of the bricks were determined from densities and moisture content using the algorithm in BS EN ISO 10456. In the final calculations, presented here, it was further assumed for the calculations of U-values of *all* solid walls that there was a 10mm gap between stretcher bricks which was filled with air rather than mortar[c]. Additional follow-up work, currently being undertaken on behalf of DECC, is investigating the effect of this assumption on calculated U-values.

The thickness of the masonry element of the wall used in the calculation of the estimated U-value is equal to the measured wall thickness minus the assumed thicknesses of the noted internal wall finishes (e.g. internal plaster) minus the assumed thickness of any external render.

[b] No adjustment to calculated values was made based on the hardness of the brick, as it was unclear whether those that could not be drilled were hard throughout the extent of the brick, or just at a thin surface layer.

[c] This assumption is based on the observations made in solid wall dwellings described in Section 1.10. It should be noted that this assumption is based on the investigation of these limited number of cases, and may not reflect the nature of all solid walls in the stock. The relatively small number of cases investigated in this process did not allow investigation of any patterns in the thickness of any air gap etc.

Table 3 - Assumptions used in the theoretical U-value calculations for the various wall types measured. Additional measured data on brick density, moisture content or cavity thickness were used in place of these values where available.

Wall element		Thickness (mm)	Thermal conductivity (W/mK)	Thermal resistance (m²K/W)
Internal surface		-	-	0.130
External surface		-	-	0.040
Plasterboard		13	0.21	0.062
Plaster (hard)		13	0.57	0.023
Plaster (soft)		13	0.18	0.072
Dry-lining Cavity		15	-	0.15
Cavity of cavity wall construction		60	-	0.18
Assumed gap between stretchers in solid walls		10	-	0.15
Mortar[1]		10	0.94	0.01
Render		20	1.00	0.02
Stone		-	2.0	-
Brick (protected)[2]		-	0.56	-
Brick (exposed)[3]		-	0.77	-
Inner leaf of cavity wall		100	0.56	0.18
Cavity fill insulation		60	0.04	1.500
Wall thickness could not be measured	Solid stone wall	487		
	Solid brick wall	220		
	Cavity wall	265		

[1]It should be noted that many of the oldest properties may have lime mortar of slightly lower conductivity. The effect of this is being investigated in on-going work for DECC. [2]Bricks are considered to be protected if they form the inner leaf of a cavity wall. [3]Bricks are considered to be exposed if they form a solid wall (whether rendered or un-rendered) or the outer leaf of a cavity wall (whether rendered or un-rendered). The difference in thermal conductivity relates to the different moisture contents.

1.14 Additional laboratory investigations to investigate the heat flux measurement methodology

Additional work has been carried out under controlled laboratory conditions (using a hot-box to understand why measured U-values are often different to the theoretical calculated U-values). This has investigated the potential for systematic errors resulting from measurement system that is in use. Full details of this work are described in Appendix E.

2. Results

2.1 U-value measurements made during the winter of 2011/12

Following the field data collection undertaken between December 2011 and March 2012, analysis was carried out and measured U-values obtained. In total 297 properties were visited. Twenty of these cases have been excluded because of aspects of the data returned which suggests that results may be unreliable (e.g. wide discrepancies between the two U-value measurements (>=0.5W/m^{2}K)). These outliers may indicate a problem or additional uncertainty within the measurements, or may also indicate real variation across the extent of the wall itself. Additional analysis of these data points, possibly in conjunction with further site investigations, may assist in understanding why the values vary so widely. At present this has not been carried out, but the need for this type of additional work to investigate outliers is recommended for future U-value measurements of this type.

2.1.1 Summary of results

Table 4 summarises the results of the U-value measurements and calculations, with the results for all cases included in the Table in Appendix F. The calculated U-values include data from the subsequent intrusive investigations, and assume for *all* solid brick walls (not solid stone walls) in the sample that there is air between inner and outer stretchers (based on the results from the subsequent investigations).

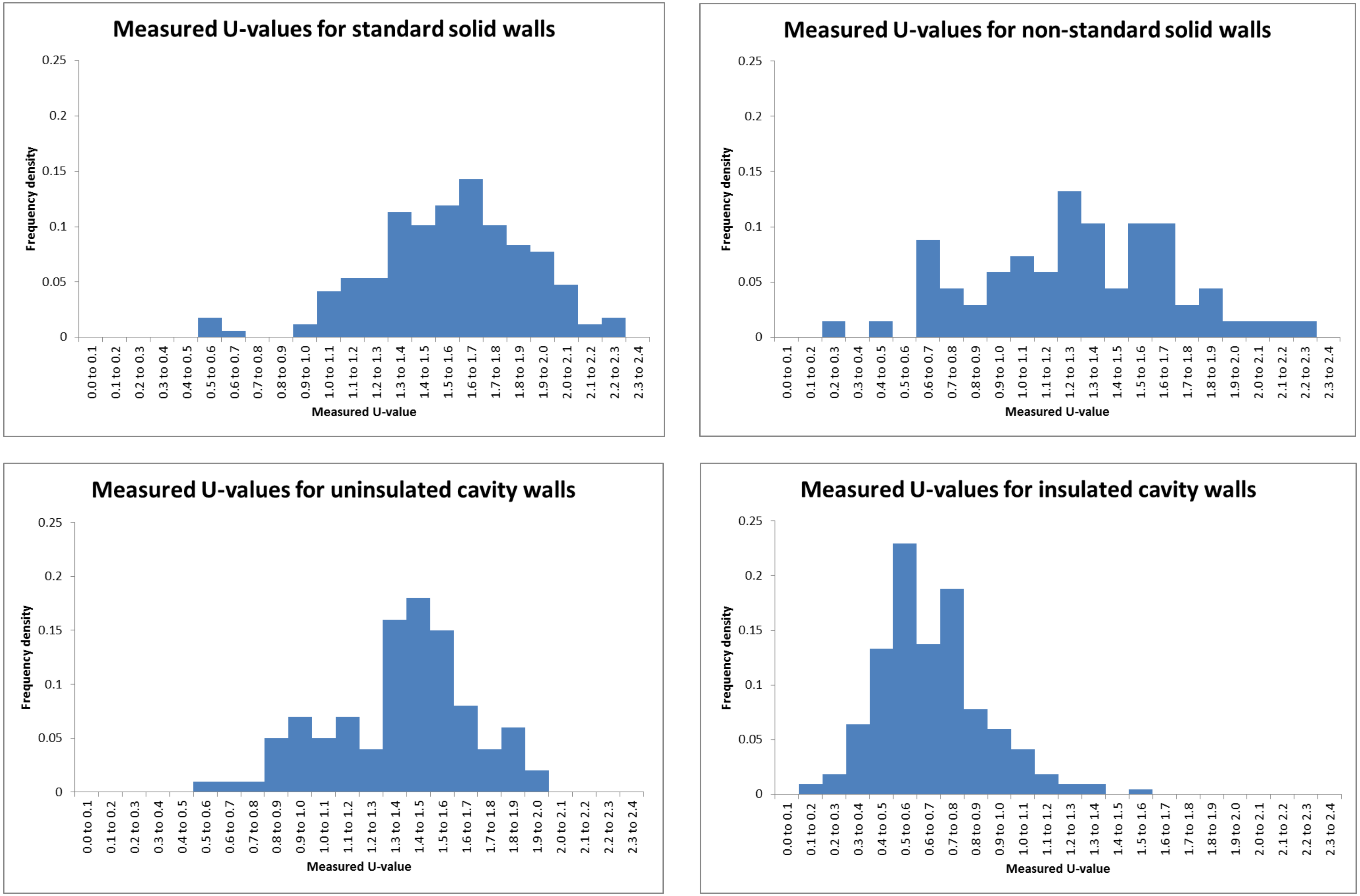
Figures 6 to 9 show the frequency density plots for all U-values measured, for each type of wall. These allow the comparison of the spread of results for each type of wall.

A subsequent recalibration of five heat-flux plates and detailed comparison with a hot-box at the National Physical Laboratory (NPL) was undertaken to identify any systematic error in measured values that may be occurring as a result of the measurement process (see Appendix E). The results suggest that a small error may indeed exist, which may result in measured U-values that are of the order 5% lower than the actual U-value of the wall. This is within the uncertainty of the equipment calibration, and no adjustment can be made to the values as measured with confidence in the absence of additional evidence (which is currently being gathered). It should be noted that the effect on the mean measured U-values of any systematic error of this type and scale will be very small (an increase of approximately 0.08 W/m^{2}K in the mean value for solid wall dwellings). See Appendix E for more details of this work.

Table 4 - Summary of results. Classification of wall and calculation of U-values is based on all available data (including boroscopic investigations, mortar and brick dust drillings and coring). Results only included where U-values from both HFPs consistent to <=0.5 W/m².

Wall type	Number of cases	**Measured U-values: mean (standard deviation) W/m²K***	**Measured U-values: median W/m²K**	*Calculated U-values: mean (standard deviation), W/m²K*	*Calculated U-values: Median W/m²K*	**Typical RdSAP U-values[a] W/m²K**	Ratio of (Mean measured U-value) / (Mean calculated U-value)	Ratio of (Mean measured U-value) / (Typical RdSAP U-value)
Solid wall, standard [b)]	85	**1.57 (0.32)**	**1.59**	*1.90 (0.20)*	*1.92*	**2.1**	*0.83*	*0.75*
Solid wall, non-standard [b)]	33	**1.28 (0.42)**	**1.28**	*1.91 (0.49)*	*1.68*	**2.1**	*0.67*	*0.61*
Uninsulated cavity	50	**1.38 (0.30)**	**1.43**	*1.40 (0.11)*	*1.41*	**1.6**	*0.99*	*0.86*
Insulated cavity	109	**0.67 (0.23)**	**0.63**	*0.52 (0.08)*	*0.51*	**0.5**	*1.29*	*1.34*

Note a) From RdSAP Appendix S (v9.91) Table S6 - Solid wall standard & non-standard age bands A to D (Pre-1967), Uninsulated and insulated cavity age band D (1950-1966).
Note b) 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 (including stone and concrete). Due to the relatively small sample size, no further disaggregation of the sold wall non-standard types is possible.



Figures 6 to 9: Frequency density distributions of measured U-values for all measured points, for each type of wall measured.

2.1.2 Discussion of results

It is apparent from the results in Table 4 that a significant discrepancy exists between the average measured U-values (both mean and median) and the calculated wall U-values for both types of solid walls, and for insulated cavity walls. Solid wall measured U-values are below the calculated values (i.e. these walls appear to be performing better than the theoretical calculation suggests), whereas insulated cavity walls measured U-values are above the calculated values (i.e. these walls appear to be performing worse than the theoretical calculation suggests). Uninsulated cavity walls, however, are measured as performing (on average) very close to the calculated values (although rather lower than the standard RdSAP value) as discussed below.

Figures 6 to 9 (and the standard deviations in Table 4) show the relative spread of the measured values for each wall type. It can be seen that all wall types exhibit a considerable spread in the measured values. These are likely to result from actual differences in the walls measured (some of which are taken into account in the calculations - as discussed later under Section 2.2), as well as uncertainty introduced by the measurement process itself. The limited drilling and coring work undertaken on a subsample of walls has confirmed that different bricks will have different densities, porosities and moisture content. This will affect the different U-values that are measured, and contribute to this spread, as in most cases these factors are unknown and unable to be included in the calculation of theoretical U-values. Other factors which will affect the U-value include presence or absence of frogs in bricks (and whether they are filled with mortar), the thickness of mortar beds and the presence of mortar within the various joints within the wall. Additional variations are introduced by the placement of the HFPs on different elements of wall structure. For example, we might expect a slightly different result were an HFP to be placed on a header brick, as opposed to on a stretcher or on a mortar junction. The non-standard solid wall group shows a particularly wide spread in measured U-values. This reflects the diversity of wall types covered by this group. In this analysis, because of the relatively few cases within this group, no attempt to disaggregate this group into subsets (e.g. stone, concrete etc.) has been made.

A number of outliers can also be seen in the frequency density plots for many of the wall types. Some, but not all of the outliers can be explained by further investigation of the underlying field data (these are discussed in greater detail in Section 2.2 of this report). A number of these may, however, be the product of measurement error of some sort. This may include failure to maintain the HFP in good contact with the wall (leading to lower U-values), inadequate avoidance of thermal bypasses (leading to higher than expected U-values) or problems in accurately recording internal or external temperatures. Ideally these properties would be revisited to confirm the measured values, and this need is noted in lessons for future work of this sort.

The medians of the measured U-values shown in Table 4 are generally close to the mean U-values. They are however, very slightly higher for standard solid walls and for the uninsulated cavity walls. This can be associated with a few outliers with low measured U-values for these wall types which reduce the mean. For the insulated cavity walls, the reverse is true with a median value slightly lower than the mean. For this wall type there are a few outliers which increase the mean. These outliers are discussed in greater detail, and can be seen on the scatter plots (Figure 15 to Figure 20) in Section 2.2.

It can also been seen in Table 4 that the mean of the calculated values for the solid wall types, are below the generally assumed RdSAP values. This is due to a number of factors, including that the walls were measured to be thicker than assumed for the standard value in RdSAP, and that based on the results from the coring of the solid walls (see below) it was assumed for the calculations of U-values that the gap between stretcher bricks was filled with air rather than mortar.

The means of the measured U-values for insulated and uninsulated cavity walls (0.67 W/m²K and 1.38 W/m²K respectively) are very close to those measured in earlier work produced by BRE for EST in 2008[8]

(0.65 W/m²K and 1.3 W/m²K respectively). The consistency between these two surveys provides some additional confidence in the results for these wall types. We can associate the discrepancy between the measured and calculated values for cavity insulated walls with variable quality of cavity fill which is a known and recognised phenomenon. The mean measured U-value of this wall type is, however, below the mean calculated value which may suggest that the assumed thermal conductivity used in the calculations (0.4 W/mK – a value that is widely used in calculations of this type) is not representative of the stock as a whole (i.e. it assumes a higher level of performance than is found on average). As the thermal conductivity value of 0.4 W/mK assumes that the wall is well insulated throughout, in order to achieve alignment with the value measured, the HFP would need to be placed over an area of high quality insulation. Where cavity wall fill is patchy, thermal conductivity will vary across a range of values. To account for this some additional analysis has considered the effect of moving the default thermal conductivity from 0.4 to 0.6 W/mK[d] for all insulated walls in the wider sample (this is equivalent to assuming that "patchy" insulation is the usual situation). This has the effect of raising the mean calculated U-value for insulated cavity walls from 0.52 to 0.67 aligning the mean measured and mean calculated values. It should be noted that this correction, while aligning the mean values across all types of wall, will not always bring individual measured and calculated values closer together for any particular HFP. Across the extent of the wall with "patchy" insulation the quality of insulation will vary, and a plate could be placed on an area of good, moderate or poor insulation depending on the location chosen (which may not be visible through the IR inspection).

Less well understood than the discrepancy between measured and calculated values for cavity walls, is why a discrepancy should exist for solid walls. The mean of the measured U-values for solid walls is approximately 1.6 W/m²K for standard solid walls and 1.3 W/m²K for non-standard solid walls. These values are significantly below both the mean of the calculated values, approximately 1.9 W/m²K and 1.7 W/m²K respectively, and the appropriate RdSAP default values of approximately 2.1 W/m²K for both types. These results confirm the findings of other investigations of solid walls of this type (e.g. Ward, T (1993) [13], Rye, C & Scott, C, 2010 [11]; Baker, P (2011) [12]; Rhee-Duverne, S & Baker, P, 2013 [10], EST/BSRIA Solid Wall Insulation Trials, 2012[1]).

To try to understand the reasons why solid walls may be performing better than expected, BRE are undertaking additional work on behalf of DECC between 2013 and 2015 which will investigate these walls in detail.

Possible reasons for lower than expected measured U-values of solid walls include:

1. Presence of voids within a nominally solid wall
2. Rubble or soft material within a nominally solid wall
3. Alterations to a solid wall – e.g. lightweight concrete blocks inserted as part of a refurbishment
4. Different moisture contents of bricks to those used in the calculations
5. Different brick densities to the assumed density used in the calculation

These aspects of wall construction are unknown for the majority of the sample owing to the non-intrusive approach taken when visiting the majority of the properties.

To help with the comparison between measured and calculated U-values in solid walls, consideration of possible wall configurations provides an indication of the possible levels of uncertainty in the calculated U-values that arise from unknown physical properties of the measured wall.

Table 5 and Table 6 give, for a typical 'Standard' construction (for each wall type), the ΔUs that might arise from the uncertainty in a number of known (Table 5) and unknown (Table 6) parameters.

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[d] A value of 0.6 W/mK for patchy insulation is an assumption and would require additional measurements in the field or laboratory to confirm.

There are additional uncertainties not included in Table 6 that will affect the U-value of the measured walls. For example, the unknown moisture content of the masonry at the time of the measurement. This is likely to be more marked in the calculation of the U-value for the solid and unfilled cavity walls and less so in the filled cavity walls where the insulation will dominate the thermal performance. For the unfilled cavity walls another possible uncertainty in the calculated U-value is the degree to which the cavity may be unintentionally vented. For example, the calculated U-value would normally assume an unventilated cavity. However, if the cavity were partially ventilated this could result in an increase in U-value (and hence the calculated U-value) of around 0.22 W/m^2K.

Table 5: 'Standard' calculated U-values (W/m^{2}K) for each wall construction showing the effect of adding known parameters of the construction

Known parameters:			1		2		1 + 2	
	Wall Type	**Base U-value**	**Render**	**ΔU**	**Dry-lining**	**ΔU**	**Render + Dry-lining**	**ΔU**
1	Stone	2.28	-		1.47	-0.81		
2	Solid Brick	2.16	1.72	-0.44	1.42	-0.74	1.21	-0.95
3	Cavity	1.45	1.32	-0.13	1.07	-0.38	1.00	-0.45
4	Filled cavity	0.5	0.48	-0.02	0.44	-0.06	0.43	-0.07

Table 6: 'Standard' calculated U-values (W/m^{2}K) for each wall construction showing the effect of unknown parameters of the construction

Unknown parameters:			1		2		3		4		1 + 2		3 + 4	
	Wall Type	**Base U-value**	**5 mm air gap**	**ΔU**	**Reduced masonry cond.**	**ΔU**	**Reduced width of cavity**	**ΔU**	**Increased insulant cond.**	**ΔU**		**ΔU**		**ΔU**
1	Stone	2.28	1.82	-0.46	1.92	-0.36	-	-	-	-	1.59	-0.69	-	-
2	Solid Brick	2.16	1.75	-0.41	1.9	-0.26	-	-	-	-	1.57	-0.59	-	-
3	Cavity	1.45	-	-	1.3	-0.15	-	-	-	-	-	-	-	-
4	Filled cavity	0.5	-	-	-	-	0.57	0.07	0.66	0.16	-		0.74	0.24

Notes:

a) Masonry (stone) conductivity reduced from 2.0 to 1.5 W/mK

b) Masonry brick (protected) reduced from 0.56 to 0.45; Brick (exposed) reduced from 0.77 to 0.62 W/mK

c) Cavity width reduced from 60 mm to 50 mm

d) Insulant conductivity increased from 0.04 to 0.06 W/mK

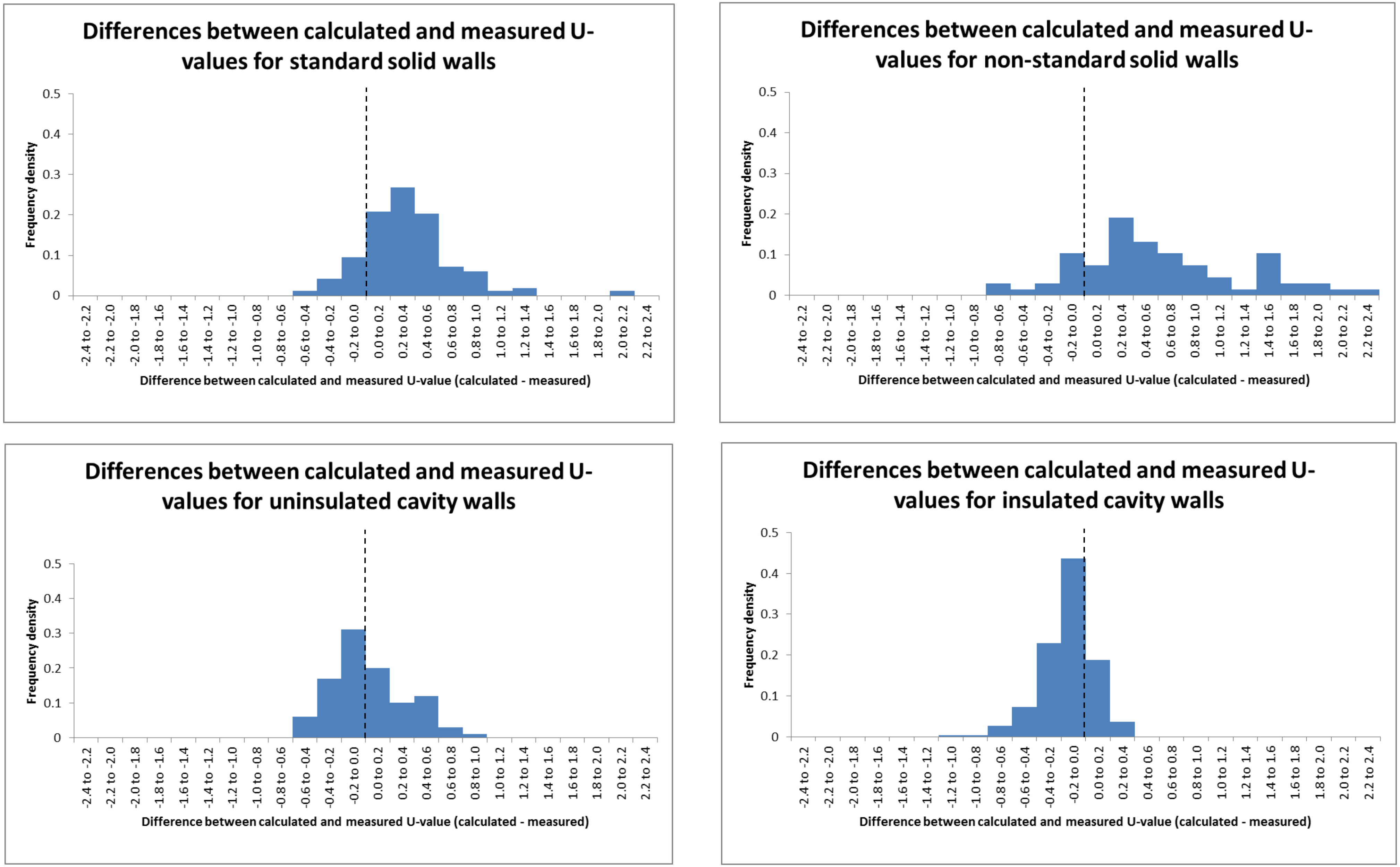
2.2 Comparison of measured and calculated values.

One of the objectives of this work is to examine the differences between the U-values measured, and those calculated theoretically based on field observations. The differences have been expressed in two main ways below: frequency density distributions of the differences between calculated and measured values and scatterplots. Both types of chart use the final classification of wall types. A comparison of the results using the original EHS classification of walls are shown in Appendix C, which the reader is referred to in order to highlight the importance of appropriately identifying the type of wall being measured.

The frequency density plots show the differences between measured and calculated values for all wall types. These are shown in Figures 10 to 14 below. These plots are useful in examining the spread of the differences for each of the different wall types.

It can be seen in the frequency density charts that, for both types of solid walls, calculated values are generally higher than measured values (i.e. calculated values minus measured values are positive). For uninsulated cavity walls there is an approximately even spread of cases where calculated values are above and below corresponding measured values, and for insulated cavity walls, calculated values tend to be lower than measured values. This supports the data on mean values shown in Table 4. Also apparent is that the spread of differences is considerably greater in the non-standard solid wall group. This indicates the diverse nature of this group, and the difficulty of calculating U-values for many of these cases without additional field data on, for example, wall construction.

The second method of displaying the difference between calculated and measured values is by the creation of scatterplots which show measured U-values versus calculated U-values. For each wall, two points are shown, indicating the measured U-values at the two HFPs. Figure 15 shows the results for all walls in the sample. Plots for each individual wall type are shown in Figure 16 to Figure 20.



Figures 10 to 13: Frequency density distributions of differences between calculated and measured U-value for all measured points, for each type of wall measured. Dashed line shows position of zero difference.

2.2.1 Comparison of measured and calculated values for all wall types.

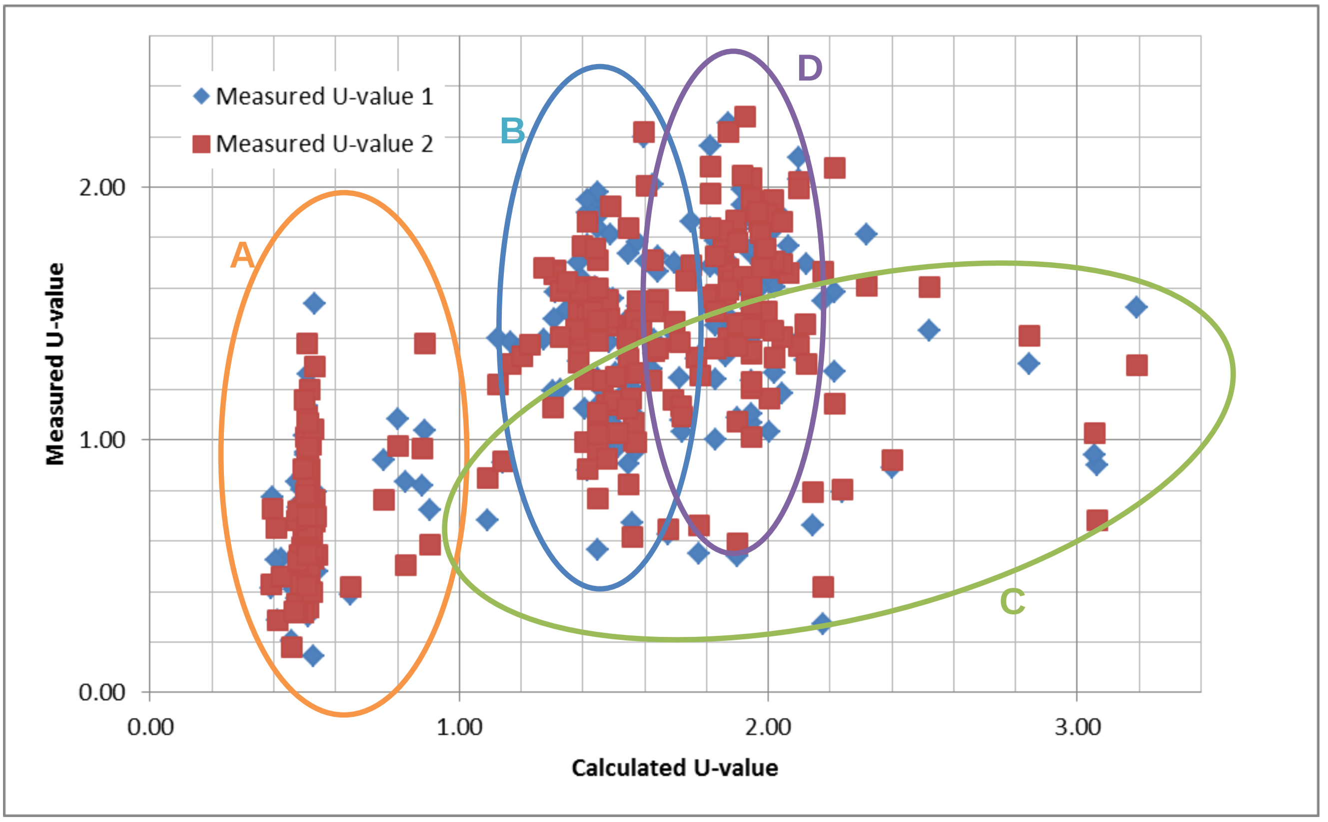


Figure 14: A comparison between measured U-values and calculated U-values (all wall types are shown together. In the calculation of U-values for solid brick walls it is assumed that the vertical joints between stretcher bricks are filled with air).

In general:

- insulated cavity walls can be found in the area marked as “A”,
- uninsulated cavity walls in the area marked as “B”,
- non-standard solid walls in the broad region marked as “C”,
- standard solid walls marked as “D”.

The R^2 coefficient (a measure of correlation between the calculated and measured value) for all walls, as plotted in Figure 14, is approximately 0.6. This indicates that approximately 60% of the variation in measured values can be explained by the variation in calculated values for all walls.

For plots of individual wall types (such as those in Figure 15 to Figure 19) the R^2 coefficients are close to zero. This indicates that within each particular type of wall there is a high level of variation in the measured U-value which is unexplained by the calculated U-value. This may be because the values of key variables, which are required to accurately calculate the U-values for a particular wall type, are in most specific cases unknown and default values are used. These include the moisture content of the wall, the density of the brick (or stone/concrete) and plaster (all of which have considerable variability), and information on air gaps within the structure of the wall.

2.2.2 Comparison of measured and calculated values for standard solid walls

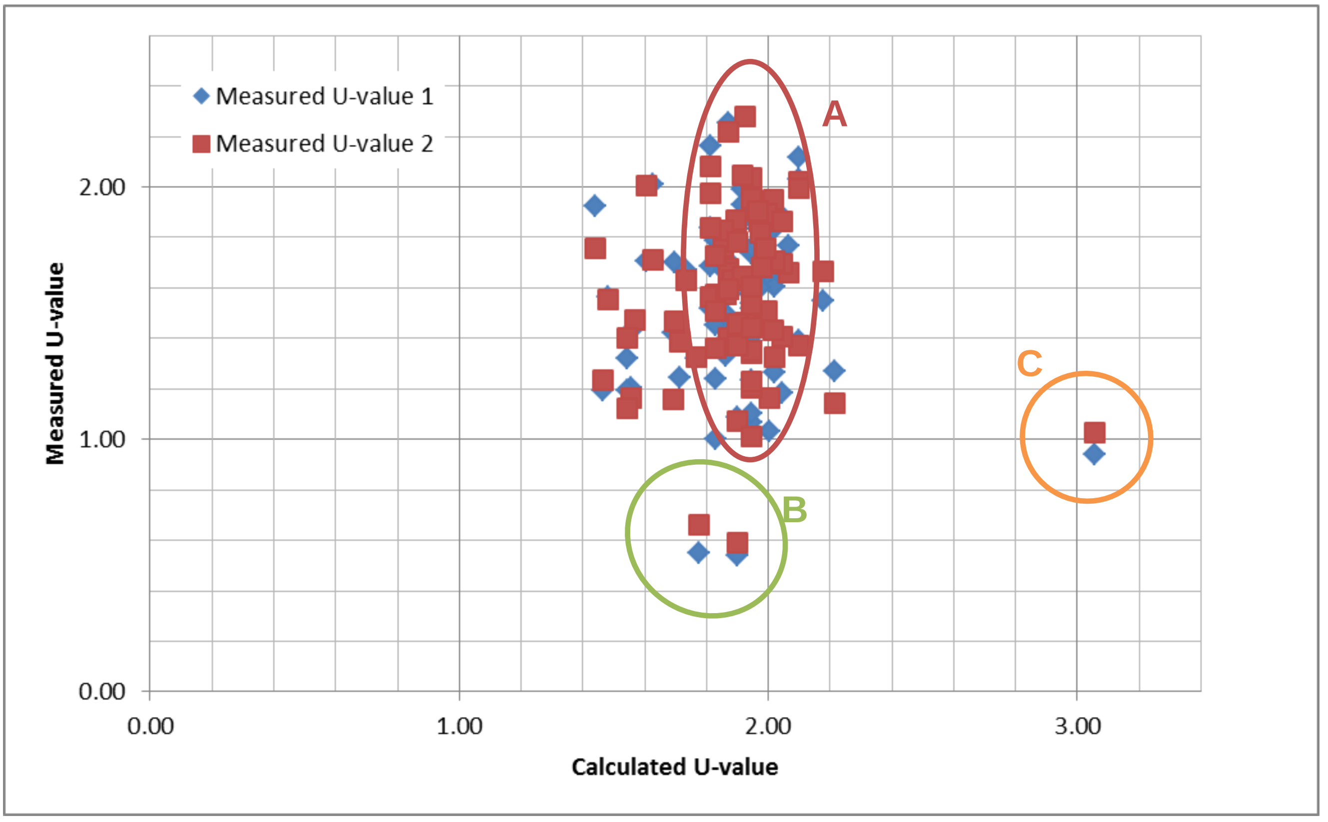


Figure 15: Standard solid walls. A comparison between measured U-values and calculated U-values; the latter taking into account all data from fieldsheets, dust drilling and coring. The outliers in areas B & C are described below.

The standard solid wall type includes all brick walls with a total wall thickness (including render and plaster) below 330mm. In general, the standard solid wall type exhibits a clustering of data around the mean measured value of approximately 1.6, and mean calculated value of 1.9. There is a clear tendency for points to be below a line of y=x, indicating that measured U-values tend to be lower than calculated values. There are a cluster of cases around a calculated value of 1.9-2.1 (area A). The measured values for these cases, however, are distributed in a range of roughly 1.0 to 2.3 indicating that there are features of the walls in these dwellings that are not being taken account of in the calculation of U-values.

The two outliers marked in area B are:

- A thatched pre-1850 cottage. This cottage has a standard brick exterior, and there is no reason to suspect that the measurement was done in an extension or minor wall type. Due to the age of the property, the walls may be of an unusual type (e.g. not brick) but there is no evidence to change the wall classification without additional intrusive investigations
- Measurements were undertaken in an area covered in thick ivy, which was clearly acting to affect the temperature of the wall in some way (the effect of this was visible on the IR camera).

The outlier marked in area C is a case where additional data, from the revisit, on moisture indicated a very wet wall. As a result the calculated value is increased considerably from the default. The large difference between the calculated value and measured value may indicate that this measured moisture content was not indicative of the area where the U-value was measured, however, additional field data would be required to confirm this.

2.2.3 Comparison of measured and calculated values for non-standard solid walls.

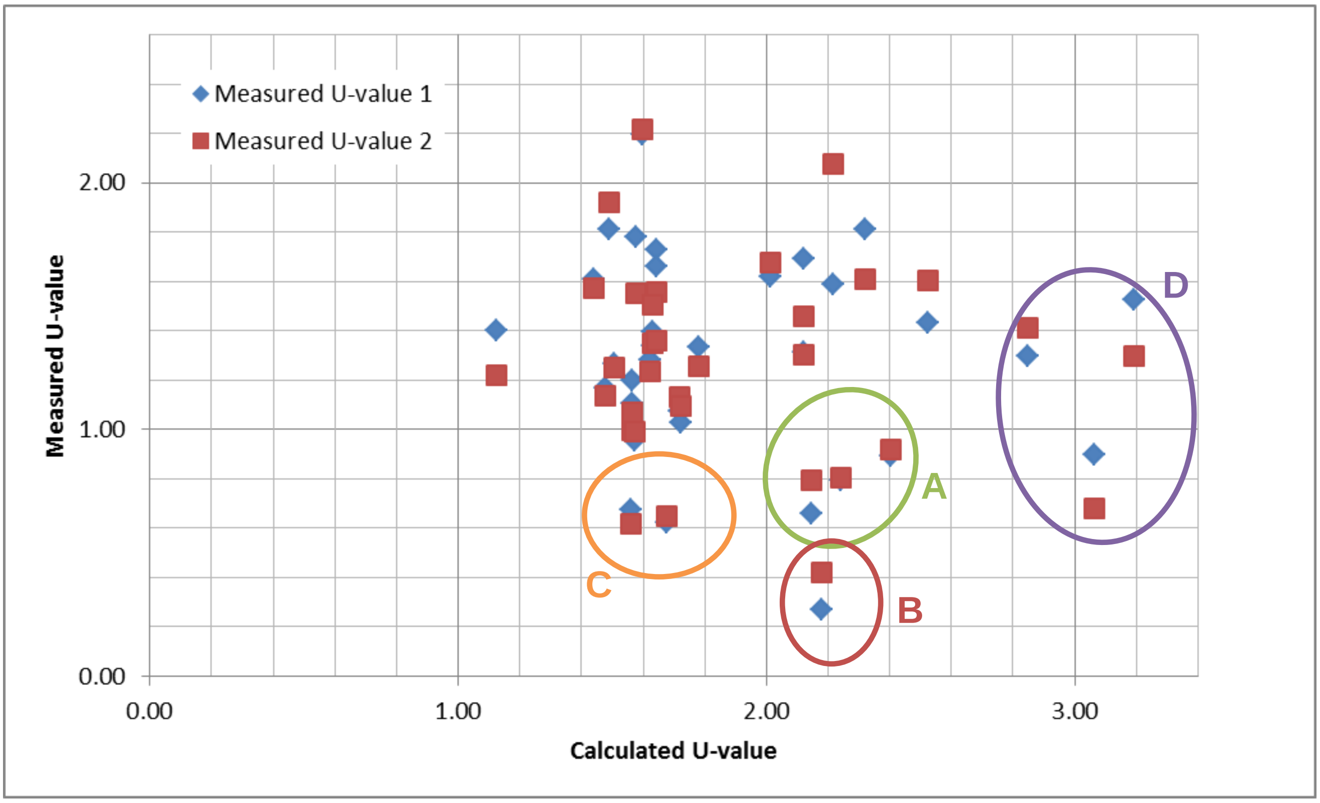


Figure 16: Non-standard solid walls. A comparison between measured U-values and calculated U-values; the latter taking into account all data from fieldsheets. Outliers in groups A, B, C and D are discussed below.

In general the non-standard solid wall type exhibits a more scattered distribution than other wall types. This group is particularly diverse, including concrete walls, stone walls and thick (>=330mm) brick-built walls. There is a degree of clustering around the mean measured U-value of 1.3, but a considerable number of outliers. As regards the calculated U-value, much of the data required for these types of wall are unknown, such as the type of concrete construction or the presence of cavities within rubble stone walls. A large spread is therefore to be expected within this group. It is clear from Figure 16, and the frequency density distribution in Figure 11 above, that current calculation methods, based on non-intrusive data, are limited for these types of walls which can be very diverse in nature.

Four groups of outliers which demonstrate the diversity of the group have been identified and are marked as A, B, C and D in Figure 16.

- Group A includes two very thick (>500mm) stone walls which may be, for example, solid stone blocks or rubble stone construction, and one wall which appeared to be a composite construction of stone faced with a blockwork inner leaf which was visible on the infra-red images.
- Group B includes a 17th Century Barn conversion, of mixed wall types and complex history, and a property with nominally stone walls faced with a brick skin.

- Group C includes a flat in a block with rendered walls which appears to be of concrete / non-traditional construction, and a thick sandstone wall of unknown type. Without further investigation of these walls there is insufficient data to refine the U-value calculation beyond the standard values used for these wall types.
- Group D are all stone built properties of modest thickness (<300mm). The assumed thermal conductivity for stone walls used in calculations is high (2.0 W/mK) as indicated in Table 3. This results in high calculated U-values for relatively thin walls. Unknown features within walls of this type (e.g. internal cavities, alternative materials behind stone facing) may, in reality, considerably reduce this conductivity and corresponding U-values. It is possible that these outliers are stone walls containing these features which act to reduce the measured U-values. Confirming this, however, is not possible without further investigations.

2.2.4 Comparison of measured and calculated values for uninsulated cavity walls.

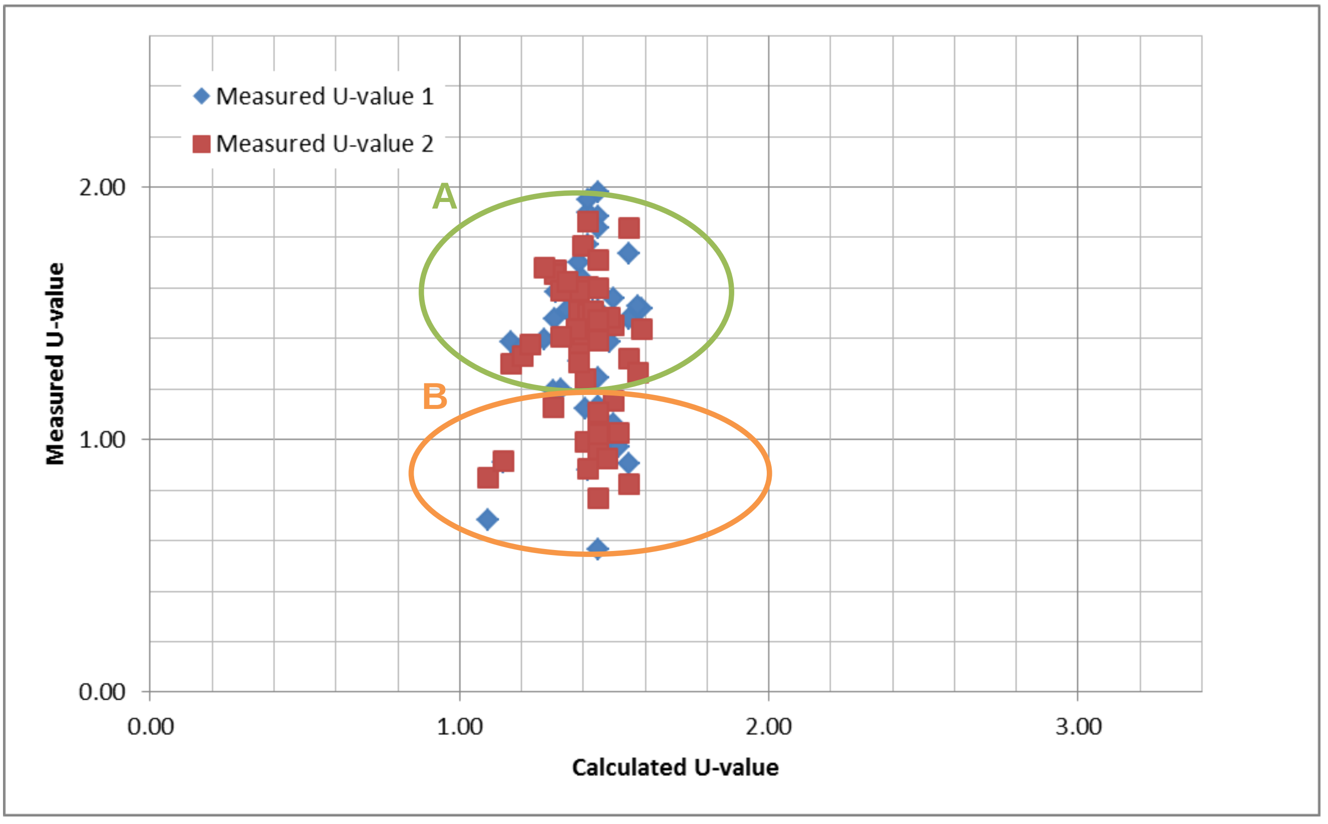


Figure 17: Uninsulated cavity walls: A comparison between measured U-values and calculated U-values; the latter taking into account all data from fieldsheets and boroscopic investigations. Groups A and B are discussed in the paragraph below.

In this figure, comparing measured and calculated values for uninsulated cavity walls, there are two fairly tight clusters of data, one corresponding to a measured U-value of around 1.0 W/m²K and one corresponding to a measured U-value in the region of 1.5 W/m²K. In the cluster marked “A” the measured U-value agrees closely with the calculated U-value, but in the cluster marked “B”, the measured U-values are lower than the calculated U-value. One possible reason is that for this second group the inner leaf of masonry could be composed of low density blockwork (known as a brick-block wall) rather than an internal leaf of brick (a brick-brick wall) as is assumed in the calculation.

The presence of blockwork can sometimes be identified using Infra-Red (IR) imagery. However, this was not explicitly surveyed by the installers of the U-value monitoring equipment and it is not visible on all images in group B. One of the recommendations of this work for future surveys is that all surveys explicitly use IR imagery, and look for evidence in key locations, to try to determine the presence of blockwork.

In the absence of comprehensive IR or other data on the presence of a blockwork inner leaf, an alternative is to look for any relationship between measured U-value and age of dwelling for this type of wall. As building practices changed over time, in part driven by increasingly stringent building regulations, brick-block construction became more prevalent. We would, therefore, expect increased levels of brick-block construction, and lower measured U-values in more modern walls. Although there are some exceptions, this can be seen for most of the data points in Figure 18 below. In general, older properties tend to have higher measured U-values and more recent properties tend to have lower measured U-values, albeit with a high degree of overlap between the groups.

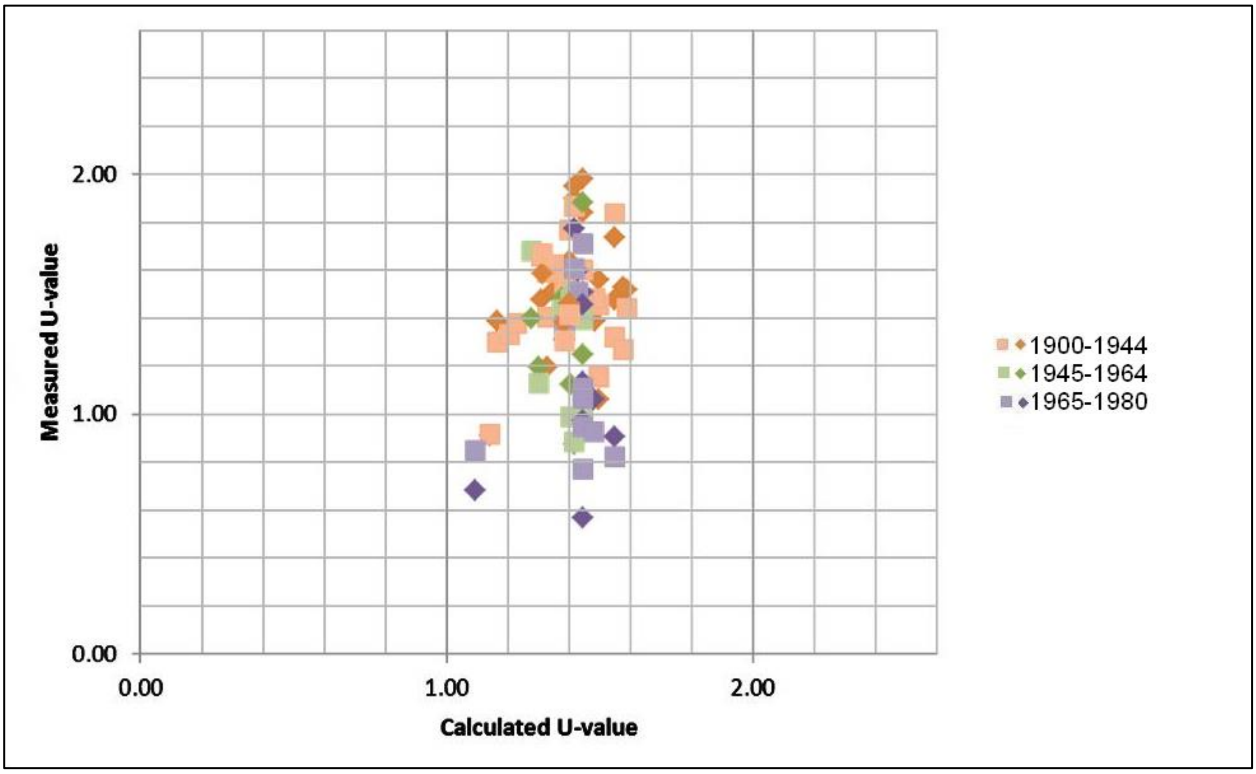


Figure 18: Uninsulated cavity walls marked by age of dwelling (dwellings built between 1900 and 1980): A comparison between measured U-values and calculated U-values; the latter taking into account all data from fieldsheets and boroscopic investigations.

2.2.5 Comparison of measured and calculated values for insulated cavity walls types.

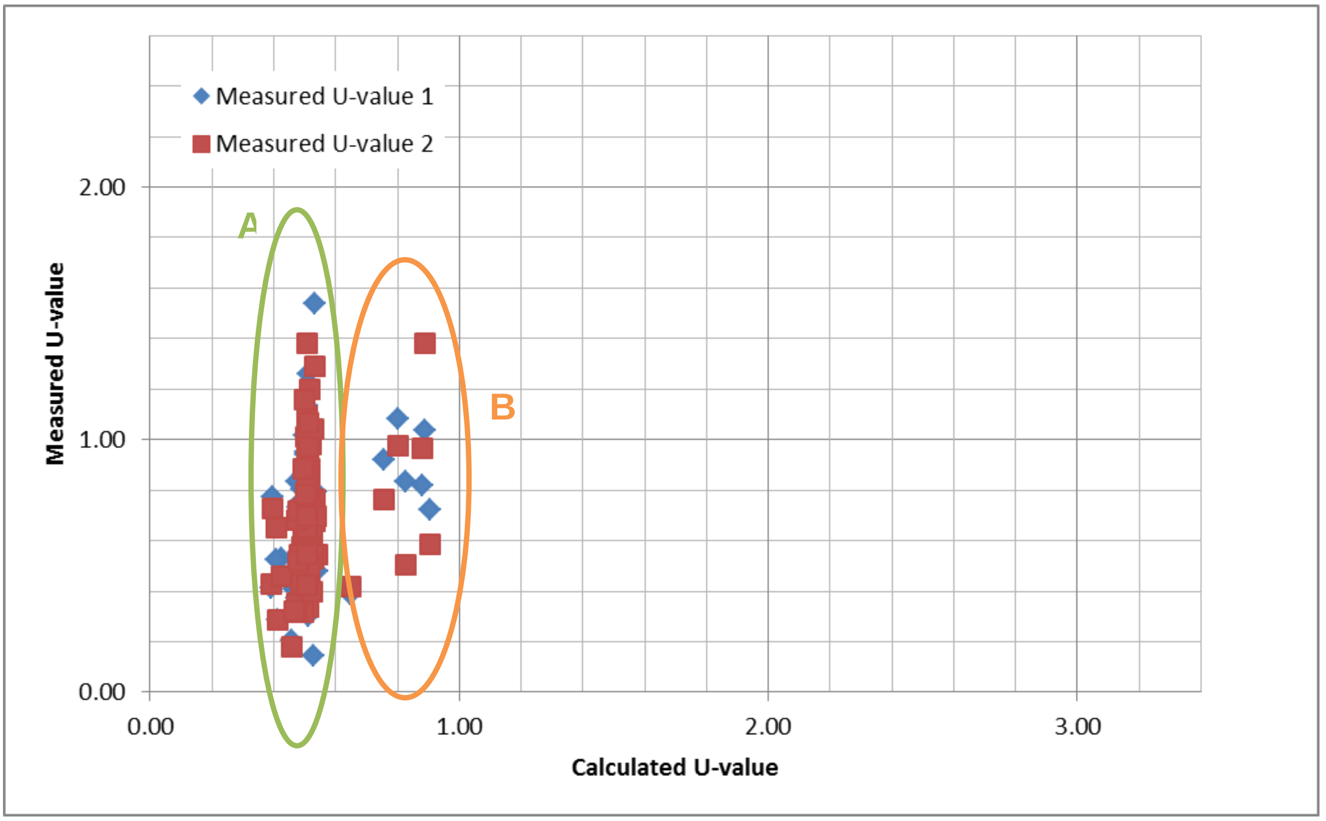


Figure 19: Insulated cavity walls. A comparison between measured U-values and calculated U-values; the latter taking into account all data from fieldsheets and boroscopic investigations. Groups A and B are discussed in the paragraph below.

The dominant factor in the calculation of U -values of insulated cavity walls is the performance of the insulation itself. This results in the linear clustering of calculated U-values seen in Figure 19. Two clusters of data, marked as A and B, are visible on this chart. Cluster A, with a calculated value of approximately 0.5 W/m²K, are walls where no information is available on the performance of the insulation (the majority of cavity walls), or where the boroscopic investigation of the wall showed the insulation to be in good condition (the standard assumption, with a thermal conductivity of 0.04 W/mK, results in a U-value of approximately 0.5 W/m²K). The boroscopy in some cavity walls, however, indicated the presence of 'patchy' insulation. The assumed thermal conductivities of the insulation in these cases have been adjusted in the calculation of U-values to a more appropriate value (see Table 7 below for details). Altering these assumptions leads to the formation of cluster B.

The measured values for this wall type show a much wider range. This can be associated with the variable performance of cavity wall insulation *in-situ*.

Comparing the measured and calculated values against a y=x line, it can be seen that the majority of cases show a worse thermal performance than is indicated by the calculated U-values. This is particularly the case for group A where the thermal conductivity has not been adjusted to allow for 'patchy' insulation.

2.3 Results of uninsulated cavity wall boroscopic investigations

Following the main U-values monitoring, a total of 10 cavity walls, originally marked as uninsulated, but which exhibited particularly low U-values were inspected using a borescope[e]. It was suspected that some or all of these may, in fact, have insulation present. Table 7 shows the results for each dwelling investigated. Nine of the ten walls inspected were found to have some insulation present, despite originally being classified as uninsulated. One of these nine appeared to have insulation by virtue of insulation straying from a neighbouring property. The observed condition of the cavity insulation and assumed thermal conductivity are shown in the table. The thermal conductivity of the cavity insulation was estimated on the basis of the observed completeness of fill.

Table 7 Cavity wall insulation in previously designated uninsulated walls

Case ID	Observations using the borescope	Assumed thermal conductivity of insulation (W/mK)	Measured width of cavity (mm)	Measured thickness of outer leaf (mm)
U256	Wall is insulated and in good condition	0.04	60	102
U026	Wall is insulated and in good condition, UF foam type insulation	0.03	60	130
U154	Wall is insulated, but insulation is very patchy	0.08	60	115
U102	Wall is insulated, but insulation is very patchy	0.08	50	105
U055	Some insulation appears to have strayed from neighbour's property (very patchy)	0.08	50	110
U172	No insulation observed in cavity	No insulation	60	101
U291	Wall is insulated, and insulation is in good condition	0.04	90	118
U089	Wall is insulated, but insulation is patchy	0.06	50	118
U247	Wall is insulated, but some voids noted (patchy insulation)	0.06	60	118
U072	Wall is insulated. Insulation seems to be of low density, but few actual voids observed.	0.04	80	111

[e] It should be noted that the results in sections 2.1 and 2.2 of this report have been adjusted to account of these further investigations.

In nine of the ten cases examined insulation was found to be present, despite the original EHS data indicating that the walls were uninsulated. The presence of insulation explains why these cases have low measured U-values. There was one instance (U172), however, where the cavity was found to have no insulation despite the low measured U-value. It is possible that the inner leaf could consist of a low density material such as aircrete, or that some other property of the wall is unknown to us, but this could not be confirmed either by the boroscopy or by examining the thermal images.

The data in Table 7 were used to re-calculate the U-values for these cases to confirm that a better match between measured and calculated U-values is obtained when the presence of insulation is included in the calculations. Table 8 below summarises the results.

The table shows the following:

1. The mean of the two measured U-values obtained during the winter of 2011/12.
2. The result of the original U-value calculation, based on the original assumptions prior to the boroscopic examination
3. The re-calculated U-value, taking into account the observed condition of the insulation, the observed cavity width and the observed thickness of the outer leaf.

Table 8 – Comparison of original and re-calculated U-values

Case ID	Mean measured U-value	Original calculated U-value	Re-calculated U-value
	W/m²K	W/m²K	W/m²K
U256	0.54	1.38	0.51
U026	0.58	1.33	0.41
U154	1.02	1.41	0.80
U102	0.65	1.55	0.91
U055	1.02[1]	1.45	0.89
U172	0.76	1.15	1.15
U291	0.42	1.55	0.52
U089	0.83	1.45	0.76
U247	0.40	1.38	0.67
U072	0.29	1.27	0.41
Mean	0.61	1.39	0.70
R^2 (compared to mean measured results)	-	0.0003	0.3836

[1]In Case ID U055, only one U-value measurement was available due to one HFP becoming detached from the wall

There is much better agreement between the measured and calculated U-values following the change to the calculation to account for the new observations. Many of the differences between the measured U-value and the initial calculated U-value can, therefore, be attributed to the presence and condition of the insulation and cavity width being unknown. The collection of more detailed information about these features led to better agreement.

The misclassification of walls by surveyors undertaking non-intrusive surveys is a known problem. To minimise misclassifications, EHS surveyors are asked to look for evidence of cavity wall insulation in multiple locations, including drill holes in walls, evidence from insulation around breaks in the walls (e.g. meter boxes or air bricks) and from insulation spilling into the roof space under the eaves, as well as asking householders whether their walls are insulated. Despite these checks, in nine of the ten cases revisited here the insulation was not identified by the EHS surveyor. In some of these cases it was noted at the revisit that the wall had been carefully repointed after it had been insulated and any drill hole pattern was not visible. In other cases the drill holes were noted to be very far apart or indistinct. These factors are likely to have led to the initial misclassification by the EHS surveyor which was only resolved after the boroscopy had been carried out.

The overall extent of misclassification by the EHS and other non-intrusive surveys is unknown. These few cases were specifically selected for further investigation as they were suspected of being insulated because of their low U-values, and are therefore non-representative of the EHS as a whole. To obtain an indication of the prevalence of misclassification in non-intrusive surveys, a more representative sample would need to be selected for boroscopy.

2.4 Results of the dust drilling and coring of revisited solid brick walls

Following the main U-value survey, further tests were carried out on 22 brick walls, originally identified as being of solid construction according to the EHS classifications[f]. The walls were primarily those which exhibited large differences between measured and calculated values based on the original U-values survey.

The ‘follow-on’ investigations in nominally solid brick walled dwellings allowed:

5. Confirmation of the classification of solid brick walls: Drilling and coring of the solid brick walls was used to confirm the classification of the wall as solid brick.
6. Investigation of brick densities and moisture content: Taking core samples of brick from the outer stretchers and measuring the density and moisture content. Taking dust samples of stretcher and header bricks (at different depths), and mortar and measuring their moisture content
7. Investigation of the presence of air cavities: Following the removal of core samples, examining the region between inner and outer stretchers for significant air gaps and measuring their width if present.
8. Investigation of spatial and temporal variation in U-values: Re-measuring the U-value at four locations instead of two in order to verify the measured values and compare U-values from the same walls across two winters.

2.4.1 Confirming the classification of the walls

Of the 22 dwellings, 19 were confirmed as having solid brick walls and 3 were cavity walls that had been mis-classified.

[f] It should be noted that the results in sections 2.1 and 2.2 of this report have been adjusted to account of these further investigations.

2.4.2 Densities and moisture content of the bricks, and the presence of air cavities

Core samples were taken in order to determine brick density and investigate the presence of air gaps between stretchers. The moisture contents of the walls were determined by taking drill dust samples. In total, densities were measured for 15 of the 19 solid brick walls[9] and moisture content in 18 of the 19 solid walls. Table 9 shows the densities and moisture contents, and derived thermal conductivities, for all solid wall cases.

Table 9 – Measured densities, moisture contents and derived thermal conductivities of bricks in the 19 revisited solid brick walls.

Ref	Dry density kg/m³	Moisture content from outer 75mm of brick (%ge of original wet mass)	Moisture content B from inner 75mm of brick (%ge of original wet mass)	Derived thermal conductivity of bricks (W/mK)	Observed gap between stretcher bricks (mm)
U098	1647	0.8%	0.5%	0.47	10
U195	-	-	-	-	10
U057	1728	4.5%	3.5%	0.86	10
U121	1520	0.3%	0.5%	0.41	10
U225	1789	0.6%	0.5%	0.53	10
U251	1636	0.3%	0.3%	0.45	10
U071	1710	2.5%	2.4%	0.69	10
U238	1636	0.4%	-	0.45	10
U105	1740	0.3%	0.3%	0.49	10
U222	1887	8.3%	7.8%	2.59	10
U009	-	0.3%	0.2%	-	10
U217	1964	4.1%	3.6%	1.16	5
U129	1781	0.2%	0.2%	0.50	10
U258	1863	0.2%	0.2%	0.54	5
U223	-	1.2%	0.8%	-	10
U248	1973	0.6%	2.0%	0.83	10
U036	-	0.0%	-	-	10
U296	1636	0.4%	0.2%	0.44	10
U017	1918	0.2%	0.3%	0.56	5
Mean	1761	1.4%	1.5%	0.73	9.2

The mean dry density (i.e. after the brick core samples were oven-dried) was found to be 1761 kg/m³. The mean moisture content, by weight, (expressed as a proportion of the pre-dried weight of the dust sample) was found to be 1.4%. Density was found to vary on a case-by-case basis from the least dense

[9] Samples were not taken from those dwellings found to be cavity walled, rather than solid.

sample of 1520 kg/m^3 to the densest sample of 1973 kg/m^3. Moisture content was found to vary to an even greater degree from 0% to 8.3%, although the 13 of the 18 cases had moisture content below 1%.

The moisture content was measured separately for the outermost 75 mm of the brick material and for the brick material at a depth of between 75 mm and 150 mm. It was found that the moisture content was similar at these two depths. The mean moisture content was found to be 1.4% for the outermost 75 mm and 1.5% for depths in the range 75 mm to 150 mm.

The mean thermal conductivity for the bricks where core samples were available (i.e. for 15 cases) was calculated to be 0.73 W/mK based on the observed densities and moisture contents.

The mean gap between the inner and outer stretchers of solid walls, which tended to be mainly air, was 9.2 mm. The most frequently-occurring air gap was 10 mm.

It should be noted that this sample of walls is statistically-biased, as the majority of walls were selected on the basis of having unexpectedly low U-values. Therefore, little inference can be made about the national average density and/or moisture content of bricks, or the overall probability of mis-classification[h]. However, a few preliminary observations can be made even on this limited data:

The fact that the brick dust samples from both 75mm and 150mm had, on average, similar moisture contents supports convention of using the same moisture content for an inner and outer stretcher given in section 3.3.5 of the CIBSE A3 Guide (1999 Edition)[6] and in Arnold, P J Thermal Conductivity of Masonry Materials [7]. The mean derived thermal conductivity, is close to the standard thermal conductivity of exposed brick of 0.77 W/mK quoted in BR443, although the derived conductivity varies widely (from 0.41 to 2.59). However, the non-representative nature of the sample does not allow us to be able to draw any firm conclusions on these issues.

On a case by case basis there was no consistent correlation between the observed densities and the observed moisture content, although it is interesting to note that the two samples with the highest moisture contents (U057 and U222) are also two of the three samples with the highest densities (1887 and 1964 kg/m^3 respectively).

2.4.3 Recalculated U-values for revisited solid wall dwellings, based on all observations.

The derived thermal conductivities of the bricks were used in recalculations of the U-values for the 19 solid walls revisited for further sit investigations, to investigate whether this additional information could explain the gap between measured and calculated U-values for these walls.

The observations made at site, when drilling was carried out, strongly suggested that air spaces are present in many of the vertical joints between bricks. The corresponding U-value calculations for these walls, therefore, took this into account and three calculations were carried out for each wall, with the gap between inner and outer stretchers (a) fully filled with air (b) partially filled with air (c) fully filled with mortar.

Table 10 shows the discrepancies between the U-values as measured during the Winter of 2011-12, those of Feb-Mar 2013 and the calculated U-values in each year, taking account of measured density and

[h] Work currently being undertaken is investigating density and moisture contents in a wider sample of brick walls. Additional revisits to a subsample of walls would be required to understand the probability of mis-classification by the EHS or other similar surveys (this work is proposed in the future work section below).

measured moisture content. The discrepancies are expressed as the calculated U-value minus the measured U-value.

The data on brick density and moisture content acted to align calculated and measured values in some, but not all, cases examined. The best alignment, on average, 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 observations). However, this assumption did not hold for all cases. Some cases (e.g. U296 and U251) show the best correlation under the assumption that the gap between stretchers is filled with 100% mortar, whereas others (e.g. U036) and U105) show the best match when it is assumed that there is 50% mortar and 50% air.

In addition, a number of cases continue to show a large discrepancy between measured and calculated values under all assumptions. The calculated U-values for Cases U222, U009 and U217 are around 1 W/m^2K above the measured values, (even assuming 100% air between stretchers). Case U009 is explicable in that, in this case, it appears thick ivy appears to be acting to affect the temperature of the wall (see outliers described in section 2.2.2 above). Cases U222 and U217 are harder to explain. They are notable for being relatively wet and dense walls (see Table 9 and Section 2.4.2). However, these factors should already be accounted for in the calculation process, and should act to raise rather than lower the U-value. This may indicate a problem with the measurements, or some other unknown property of the wall which is affecting the U-value.

Table 10 - Discrepancies between measured and calculated U-values in 2012 and 2013 data for the 19 revisited solid wall cases.

	Winter 2011-2012 data			2013 data						
	Measured U-value	Calculated U-value (not taking into account observation from drilling)	Differences between calculated & measured U-values (calculated – measured)	Measured U-value	Calculated U-values			Differences between calculated & measured U-values (calculated – measured)		
Wall ID	Mean of two measure-ments 2012	Original 2012 calculated values	Original 2012 difference	Mean of four measure-ments 2013	100% air between stretchers	100% mortar between stretchers	50% air / 50% mortar between stretchers	100% air between stretchers	100% mortar between stretchers	50% air / 50% mortar between stretchers
U098	1.17	2.00	0.83	1.30	1.35	1.67	1.57	0.05	0.37	0.27
U195	1.09	1.59	0.50	1.07	1.65	2.14	1.99	0.58	1.07	0.92
U057	1.39	1.45	0.06	1.69	1.71	2.24	2.08	0.02	0.55	0.39
U121	1.20	2.00	0.80	1.27	1.28	1.55	1.47	0.01	0.28	0.2
U225	1.29	1.37	0.07	1.02	1.43	1.78	1.67	0.41	0.76	0.65
U251	1.15	2.02	0.88	1.66	1.32	1.63	1.54	-0.34	-0.03	-0.12
U071	1.30	1.90	0.59	1.96	1.59	2.04	1.9	-0.37	0.08	-0.06
U238	1.34	2.01	0.67	1.38	1.34	1.64	1.55	-0.04	0.26	0.17
U105	1.82	2.02	0.20	1.68	1.37	1.7	1.6	-0.31	0.33	-0.1
U222	0.97	2.11	1.13	1.22	2.26	3.32	2.99	1.04	2.1	1.77
U009	0.56	1.95	1.39	0.66	1.65	2.14	1.99	0.99	1.48	1.33
U217	1.05	1.41	0.36	0.87	2.00	2.54	2.38	1.13	1.67	1.51
U129	1.27	2.11	0.83	1.45	1.39	1.72	1.62	-0.06	0.27	0.17
U258	1.44	1.90	0.46	1.59	1.52	1.81	1.72	-0.07	0.22	0.13
U223	1.36	1.90	0.54	1.82	1.65	2.14	1.99	-0.17	0.32	0.17
U248	1.09	2.00	0.91	1.20	1.69	2.21	2.05	0.49	1.01	0.85
U036	1.09	1.69	0.60	1.38	1.27	1.54	1.46	-0.11	0.16	0.08
U296	1.53	1.96	0.42	1.56	1.3	1.59	1.51	-0.26	0.03	-0.05
U017	1.82	1.92	0.10	1.58	1.53	1.81	1.74	-0.05	0.28	-0.07
Mean	1.26	1.86	0.60	1.39	1.54	1.96	1.83	0.15	0.59	0.43
R^2	-	0.004	-	-	0.084	0.075	0.076	-	-	-

The differences and the residual discrepancies that remain for many cases under all assumptions suggest that additional data is needed as inputs into the calculation to more accurately predict the U-value. Relevant details of these walls are not sufficiently understood for us to be able to calculate the U-values appropriately. For example, this may include the presence of an insulating plaster or other item which could not be detected by the installation teams.

2.4.4 Temporal and spatial variation in measured U-values

The revisits to 22 dwellings also provided the possibility of examining whether measured U-values changed between two subsequent heating seasons, and whether U-values varied across the wall at four measurement positions.

2.4.4.1 Temporal variation in U-values: observed changes to the U-values in different years

Table 11 summarises the U-values that were measured in both the original survey (2011/12) and the follow-up (2013). For each house, a total of six U-value measurements were carried out - two U-value measurements during the winter of 2011-12 and four U-value measurements during February and March 2013.

Table 11 - Measured U-values in the 22 revisited cases (19 solid walls and 3 cavity walls marked *)

Case ID	Measured U-value winter 2011-12 (average of two measurements) (W/m²K) $U_{m,2011\text{-}12}$	Measured U-value, Feb-Mar 2013 (average of four measurements) (W/m²K) $U_{m,2013}$	Difference between measurements years (W/m²K) $U_{m,2013} - U_{m,2011\text{-}12}$
U098	1.17	1.30	0.13
U195	1.09	1.02	-0.07
U057	1.39	1.69	0.30
U121	1.20	1.27	0.07
U225	1.29	1.02	-0.27
U251	1.15	1.66	0.51
U071	1.30	1.84	0.54
U238	1.34	1.38	0.04
U105	1.82	1.68	-0.14
U222	0.97	1.22	0.25
U009	0.56	0.66	0.10
U277*	0.61	0.68	0.07
U170*	1.33	1.33	0.00
U217	1.05	0.83	-0.22
U129	1.27	1.45	0.18
U083*	1.60	1.49	-0.11
U258	1.44	1.59	0.15
U223	1.36	1.82	0.46
U248	1.09	1.20	0.11
U036	1.09	1.38	0.29
U296	1.53	1.61	0.08
U017	1.82	1.58	-0.24
Mean	1.25	1.35	0.10

It can be seen that, using all measured data, between the winter of 2011-12 and the spring of 2013, the mean measured U-value from all measurements rose slightly, from 1.25 to 1.35. However, at an individual case level changes can be seen of different magnitudes and direction, with many cases exhibiting a drop in average U-value.

Additional insight can be gained by analysis of the data using the measurements from only those positions very close to those originally measured. Where possible, two of the measurement locations in the second set of measurements (2013) corresponded closely to the two positions used in the first set of measure[i]ments (2011/12). These are referred to as positions 1 and 2.

In total, there were 33 measurements where the positions in the 2013 measurements were considered to be within 100mm of the two positions used in the original 2011/12 measurements. Figure 20 shows the change in U-value that was observed between the two periods of measurement, for each case. Although the mean U-values from these positions rose (by an average of approximately 0.7 W/m²K) between 2011-12 and 2013, the pattern at the individual case level was mixed. In 15 of the 33 measurements, the U-value fell rather than rose between the first winter and the second.

Of particular note, however, is that the direction of change (i.e. whether a rise or fall in U-value is observed) is in the same direction in 12 of the 14 cases where data is available from both positions – i.e. where one position shows a rise in U-value the other position generally does too (and vice-versa with falls).

The observed changes in U-values between the two winters may be due to real changes in the wall (such as walls becoming wetter or drier between the two measurement periods), differences introduced by the slightly different position measured, or some other error in the measurement process for these walls. If changes in U-value result from random uncertainty within the measurement process or through different positions on the wall we might expect that the direction of change would show no particular pattern. That the direction of change is generally uniform for each case suggests that some difference in the property of the wall may indeed be behind the change in U-value. The most likely variation is in the moisture content of the walls between the two measurements periods. The differences in U-values may reflect a variation in the wall between the two winters as a whole, or, as measurements were not carried out in the same month in each winter, may reflect shorter term variation in the properties of a wall through the course of any particular winter.

Confirming this explanation, however, is not possible using the data collected. In particular, the lack of moisture content data from the original measurement period and inability to reproduce the measured position precisely makes it difficult to draw firm conclusions. It should further be noted that the majority of dwellings visited for follow-up were selected because their initial U-values were unexpectedly low. There is, therefore, also an increased likelihood that any temporal change in measured U-values actually results from a problem with the original measurement rather than any real change.

In future work to investigate temporal change it is recommended that U-values are measured across several winters (rather than just two), that the position of the HFPs is recorded very precisely in anticipation of a revisit to allow for exact replication of the measurement and that a representative sample is used. Measurements of moisture content would also be required for all winters measured, and

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[i] The follow-up measurements in 2013 were a later addition to the original 2011-12 programme of measurements, and the requirement to repeat measurements precisely at the same location in dwellings was not foreseen during the initial programme of work. As a result, at the follow-up visit, the positions of the HFPs could only be approximated and could not be replicated exactly. Ideally a much closer match to the original position would have been sought, however, to within 100mm was the closest that could be achieved practically. It should be noted that this introduces additional uncertainty into this comparison as, for example, a HFP could be placed over a header brick in one measurement and a stretcher in the other.

measurements taken at approximately the same date during the winter (although this would not necessarily guarantee similar weather conditions).

Figure 20 - Change in U-values between winter 2011-12 and 2013 at approximately equivalent positions.

2.4.4.2 Spatial variation in measured U-values: Variation between measurement points.

The measurement of four U-values in 2013 allows for a limited consideration of spatial variation in U-values. To do this, the degree of variation in measured U-value, from one position on the wall to the next, is expressed as a range.

These are shown in Table 12. It should be noted that the range is based on only four observations per case, and as such cannot be considered as a comprehensive indication of the range of possible values. Variations across the extent of a wall may result from actual differences or uncertainty introduced by the measurement process itself. We might expect a slightly different measured heat flux if an HFP is placed on a header brick, as opposed to on a stretcher or on a mortar junction. In addition, any particular group of bricks within a wall are likely to exhibit differences in density, porosity and water absorption and this will be reflected in different U-values that are measured. Possible errors introduced by the measurement process include the calibration accuracy of the HFPs themselves (and thermistors, loggers etc.) as well as differences in the installation process such as the amount of petroleum jelly applied to the plate and the level of thermal contact achieved with the wall at each location.

The calculated ranges are typically 0.1 to 0.4 W/m^{2}K. Some measured results, however, were more varied. Case U248 showed the greatest variation in U-value with a range of 0.88 W/m^{2}K. This indicates that this wall is particularly thermally inhomogeneous for some reason. There is some evidence of this from the IR thermographic images, shown in Figure 21 below, which shows a significant variation in temperature across the internal wall surface. This case helps to highlight why Infra-Red Thermography is an essential source of additional data when interpreting *in-situ* U-value measurements.

Table 12. Range of U-values measured in 2013.

Case ID	Mean of the four measured U-values (2013) (W/m^{2}K)	Range of four measured U-values (2013) (W/m^{2}K)
U098	1.30	0.17
U195	1.02	0.12
U057	1.69	0.26
U121	1.27	0.30
U225	1.02	0.18
U251	1.66	0.19
U071	1.84	0.20
U238	1.38	0.36
U105	1.68	0.07
U222	1.22	0.13
U009	0.66	0.07
U277*	0.68	0.34
U170*	1.33	0.19
U217	0.83	0.14
U129	1.45	0.35
U083*	1.49	0.33
U258	1.59	0.23
U223	1.82	0.24
U248	1.20	0.88
U036	1.38	0.40
U296	1.61	0.24
U017	1.58	0.41
Mean	1.35	0.26

Cases marked with * are cavity walls, all others are solid walls.

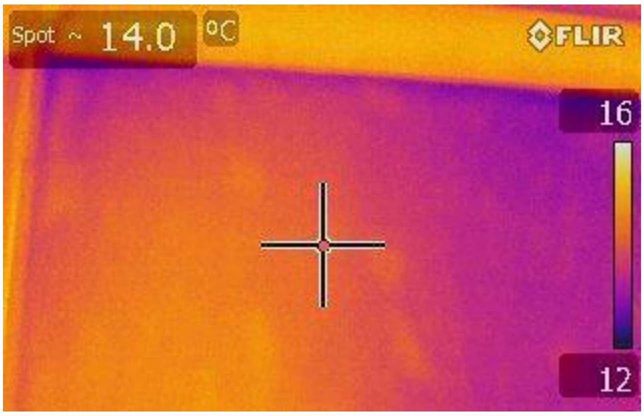

Figure 21: Inhomogeneous wall temperatures (shown by the variation in colours) in case U248, revealed by IR thermography.

3. Conclusions

3.1 Summary of findings

A total of 297 properties were visited and had wall U-value measurements taken, of which 277 provided data for analysis. The average measured and calculated U-values for each wall type, alongside typical RdSAP values for walls of these types, are shown in Table 13 below:

Table 13 - Summary of results and RdSAP values

Wall type	Number of cases	**Measured U-values: mean (standard deviation) W/m²K***	**Measured U-values: median W/m²K**	*Calculated U-values: mean (standard deviation), W/m²K*	*Calculated U-values: Median W/m²K*	**RdSAP U-values[a] W/m²K**	Ratio of (Mean measured U-value) / (Mean calculated U-value)	Ratio of (Mean measured U-value) / (Typical RdSAP U-value)
Solid wall, standard[b]	85	**1.57 (0.32)**	**1.59**	*1.90 (0.20)*	*1.92*	**2.1**	*0.83*	*0.75*
Solid wall, non-standard[b]	33	**1.28 (0.42)**	**1.28**	*1.91 (0.49)*	*1.68*	**2.1**	*0.67*	*0.61*
Uninsulated cavity	50	**1.38 (0.30)**	**1.43**	*1.40 (0.11)*	*1.41*	**1.6**	*0.99*	*0.86*
Insulated cavity	109	**0.67 (0.23)**	**0.63**	*0.52 (0.08)*	*0.51*	**0.5**	*1.29*	*1.34*

Note a) From RdSAP Appendix S (v9.91) Table S6 - Solid wall standard & non-standard age bands A to D (Pre-1967), Uninsulated and insulated cavity age band D (1950-1966).
Note b) 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 (including stone and concrete). Due to the relatively small sample size, no further disaggregation of the sold wall non-standard types is possible.

Alongside the measurements, theoretical U-values have been calculated using information from the field sheets and assumptions about the construction of the wall. Where additional information was available, as was the case in the walls which were examined more closely, the U-value calculations were refined to take the additional information into account. It was found that consolidation of all field data is essential to identify the most appropriate inputs into the calculation process. In particular, reliance on a dwelling level classification of predominant wall type is insufficient due to the possibility of mis-classification by surveyors or measurements taking place on other (minor) wall types. As a result, inappropriate classification of the wall being measured can lead to significant errors and distortion of distributions and mean results.

A small subsample of properties was revisited to conduct further investigations. These investigations were to provide additional data to inform the theoretical calculations, and allowed the revision of wall type classifications if required. Nine cavity wall dwellings, originally assumed to be uninsulated, were found to have insulation present. This resulted in a much better alignment of the calculated U-values with the measured U-values for these cases.

Additional data on brick density and moisture content from a further sample of solid brick walls acted to align calculated and measured values in some, but not all, cases examined. The best alignment, on average, 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 observations). However, this assumption did not hold for all cases.

Attempts to investigate any temporal variation in U-value suggested that there may have been changes in the U-values of the walls between the two measurement periods, although the data is insufficient to conclude definitively that this is the case. It is recommended that any future work where temporal variation is to be investigated should aim to measure the position of HFPs as precisely as possible, and that brick moisture content data will be required for all winters examined (rather than only a single winter as in this case).

Initial laboratory testing has also taken place on the measurement methodology (outlined in Appendix E). This has suggested that any systematic bias in the method, should it exist, is likely to be small. Some possible sources of inaccuracy (e.g. thermal bridging effects near junctions and openings), however, could not be directly investigated as part of this work and are suggested for further work below.

3.2 Discussion and implications

It is important to understand how the walls of homes in the UK are performing *in-situ* in order to provide realistic estimates of current energy consumption, and to quantify the potential for energy efficiency improvements such as wall insulation. The average measured values are below the standard values used in the RdSAP methodology and elsewhere, with the exception of the average measured value in insulated cavity walls which is above the standard values. Therefore, the results suggest that uninsulated walls perform better, and insulated walls perform worse, than currently assumed.

The average U-value for a solid wall, for example, for the properties in this sample was found to be less than the default RdSAP value of 2.1 W/m²K that is typically used in modelling for this type of wall. Reducing the U-value of solid walls from 2.1 to approximately 1.6 could significantly alter the assumed energy performance of solid-walled properties. Consequently, if the measured values represent the actual U-value for this type of wall, the effectiveness of Government-supported insulation programmes on solid walls is likely to be less than had previously been thought. A similar effect would be seen for cavity walls, with an un-insulated U-value below what is assumed in RdSAP and an insulated U-value above what is assumed. Government programmes such as ECO and Green Deal already make allowance for these effects through the use of “In Use Factors”, which reduce the modelled savings in line with those determined from the large-scale statistical analysis under DECC’s NEED programme.

Preliminary analysis has been conducted using the EHS 2011 dataset, however, to provide an indication of the potential impact of revising the assumed U-values in RdSAP. The alterations to the U-value assumptions have been applied according to Table 14. The analysis suggests that if the mean U-values observed by this study are used in place of the RdSAP values, the average SAP of the stock could increase by approximately one SAP point (from a published value of 56.7 in 2011).

EPC band F and G rated dwellings; particularly those in the private rented sectors, are of particular policy interest currently. The preliminary analysis suggests that if the U-value assumptions were altered, the number of F and G rated properties could decrease by around 500,000 dwellings. This is a drop of about 27% of all F and G rated dwellings. The corresponding figure for private rented dwellings only is around 100,000 (around 24% of F and G rated rented dwellings). It should be noted that these figures have been heavily rounded because of the preliminary nature of the analysis.

Table 14 Assumptions used in initial modelling of the effect of alternative U-values

Wall type	RdSAP based assumed U-value	Revised estimate of U-value
Solid walls built before 1976	2.1	1.57
Uninsulated cavity walls built before 1976	1.6	1.38
Insulated cavity walls built before 1976	0.5	0.67

3.3 Lessons learned and future work

The main aims of this project were to provide an assessment of the thermal performance of walls in domestic dwellings in England through the in-situ measurement of U-values, and to compare how close theoretical calculated values were to those measured. It has been an iterative process during which recommendations have emerged from each stage that have informed which direction could be taken for the next stage. This section summarises the main lessons that future projects should learn from this work; both in terms of the way data are collected and the way they are analysed.

The data showed that measured U-values were consistently lower than calculated for solid and uninsulated cavity walls and higher for insulated cavity walls. We can hypothesise that the main reason for this is the limitations of the assumptions used in the calculation of theoretical U-values but it is also possible that some systematic bias exists in the chosen measurement method (HFPs). This can be addressed by the following procedures, which have been, or are due to be completed as part of the current investigation of solid wall performance. Indeed item one is complete and is summarised in Appendix E.

1. Installing heat flux plates within a hot-box using a sample section of known U-value and comparing the results of the two methods. This should enable us to see whether the heat flux plates are an acceptable field alternative to the hot-box method. It should be noted, however, that factors which may affect the measurements on site (e.g. edge effects, local thermal bridging, radiant heat sources) are not tested by this method.

2. Carrying out laboratory tests at BRE examining the sensitivity of the experimental method to a variety of experimental factors (e.g. surface roughness, wall curvature, thermistor position, fixings etc.).

3. Examining the difference between the measured internal air temperatures and the internal surface temperatures in order to gain a better understanding of the error in the U-value measurements.

Future work should also seek to answer questions about the assumptions used in the calculation of U-values and how these could be improved. This includes maximising the collection and interpretation of useful information on non-intrusive surveys but also requires research to gain a better understanding of the nature and composition of brick walls in the UK. In particular, the research areas below would go some way to improving this understanding.

1. Additional fieldwork to carry out more intrusive inspections in brick, and other types, of solid walls. This would look for micro-cavities measure moisture content, etc. in order to understand some of the U-values measured as part of this project. This would be carried out across all solid wall types (brick, stone, concrete etc.) examined in this study. This item would assist greatly in the understanding of *why* the U-values differ from those calculated theoretically. Further work of this type in solid walls could investigate the presence of mortar gaps in wall joints, the prevalence of frogs within bricks (and how they are laid).
2. In cavity walls there is a need to investigate the condition of insulation in a more systematic way. This would also require additional intrusive investigations, ideally across the extent of the wall, to investigate how in-situ insulation is performing.
3. There are some uncertainties about the dependence of the thermal conductivity of brick upon density and moisture content. For example, sources such as CIBSE Guide A3[6] and Arnold, P J [7] provide different mechanisms for accounting for moisture content. It would be advisable, at some point in the future, to conduct a systematic measurement of the density, moisture content and thermal conductivity of brick samples.
4. Examination and deconstruction (under laboratory conditions) of nominally solid walls, taken from dwellings scheduled for demolition, to identify inhomogeneities such as very thin cavities, loose rubble, earth or other soft materials.
5. More drilling of insulated cavity walls to identify the type and condition of insulation in a wide range of properties with CWI installed at a range of different times. This should be combined with U-value measurements and supplemented with infra-red surveys (at appropriate times of day and weather conditions). This should provide data on whether older insulation can and should be modelled differently, and provide an indication of the number of properties which may require re-insulation.
6. Thermal modelling of edge effects, the effect of radiant heat sources and other local factors on heat flux measurements would be valuable in refining the measurement methodology in support of the hot-box tests already being undertaken.
7. Additional statistical analysis of the data collected by this survey (and others, such as that collected by EST/BSRIA[1]) may be able to provide additional insight into both the measurement system, and the actual condition and performance of walls of all types.

It can be assumed that the majority of surveys of existing dwellings, such as Green Deal assessments, will remain non-intrusive. The techniques described above can be used in research projects to provide a statistical evidence base for guidance on the assumptions to make when using non-intrusive survey data to establish U-values. These studies would ultimately need to be large enough for the outcomes to have statistical validity. There should also be lessons learned about how data are recorded and analysed in non-intrusive surveys. This would include:

1. Investigating the possibility and potential use of identifying blockwork in cavity wall dwellings. This might be using Infra-Red Thermography or looking for visual evidence in the loft, garage or services boxes. This would not require any more intrusive techniques than those used currently.
2. Quantifying the level of undercount of insulation in cavity walls on surveys like the EHS. This would be achieved by drilling a larger sample of EHS cavity wall dwellings and where retro-fit could not reasonably be identified and whether there are any training implications arising but also looking at the specific group of dwellings built during a time period when CWI may or may not have been included in the original construction.
3. Using all visible clues to maximise the likelihood of correct wall type identification. This would incorporate lessons learned from the re-classification process undertaken as a desk exercise as part of this project in order to create the most accurate dataset possible. Visual clues include

measurement of wall thickness at reveals, identification of brick bonding patterns, cavity wall drill holes, evidence of insulation spilling out through breaks in the wall and IR thermography.

Future work should anticipate the need to revisit outliers and cases where unexpected U-values are returned. To assist in this, improved recording of the original placement of the HFPs should be kept (to allow measurement in the same location). A further area identified by this project as requiring further research in the future is the broad and varied 'non-standard' solid wall group. It is estimated by Hulme and Beaumont (2008) [14] that this may represent approximately 1/3rd of all solid walls. This group includes brick walls that are greater than one brick thick, stone walls and the many varieties of concrete and metal frame non-traditional constructions. These wall types each have different characteristics and challenges associated with their energy efficient refurbishment. The non-cavity stock is dominated by brick walls but other types should not be overlooked because a standard approach to improvement for brick walls is unlikely to be applicable to many of these other types of wall.

The data showed that HFPs that were measuring different areas of the same wall at the same time could give different measurements of heat flux and therefore U-value. There were also variations in the heat fluxes measured by heat flux plates in the same location in two different heating seasons. These observations suggest that either the thermal conductivity varies either spatially or temporally, or that there were some inconsistencies in the way the equipment was used.

There are a number of plausible reasons for real differences in U-values to exist. Spatial differences may exist because of inhomogeneities in the wall, or varying measurement conditions in the vicinity of each HFP (e.g. one HFP is closer to a radiant heat source or sink than another HFP). Temporal differences may exist if weather conditions or fabric repair issues mean that the wall contains more moisture on one occasion than another.

Additional fieldwork designed to investigate these issues in greater detail could be undertaken. Understanding and controlling for relevant factors is important for any future studies. Two phases of fieldwork were not envisaged at the start of this project and therefore the requirement to precisely record the location of every heat flux plate was unknown, and moisture content was not initially measured. This need can be anticipated in future studies and fieldsheets developed accordingly.

4. References

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Appendix A: The analysis of the heat flow data

The format of the field data

The fieldwork phase of the project has led to the provision of datafiles 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, however U-values are still subject to revision.

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:

$U = (\Sigma_k q_k / n) / [(\Sigma_k T_{i,k} / n) – (\Sigma_k T_{e,k} / n)]$ Equation A1

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 HFP, 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:

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

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

$U´ (t_1, t_n) = (1 / C) (\Sigma_k \varepsilon´_k / n) / [(\Sigma_k T´_{i,k} / n) – (\Sigma_k T´_{e,k} / n)]$

Thermal mass

The above equation (*Equation A1*) 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. 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. The thermal resistance measured must therefore be corrected to account for the effect of the Hukseflux heat flux plate and the Vaseline (petroleum jelly) substrate. These corrections are summarised in Table A1 below.

Table A1 Correction applied to thermal resistance

	Thickness	Thermal conductivity	Thermal resistance
	mm	W/mK	m²K/W
Hukseflux coverings	0.2	0.2	0.0010
Hukseflux central portion	5	1.0	0.0050
Vaseline	1	0.18	0.0056
TOTAL	6.2	-	0.0116

For the purposes of considering heat flux, let q´ be the heat flux at the internal surface of a wall in the absence of a heat flux meter and let q be the corresponding heat flux in the presence of a heat flux meter and substrate of combined thermal resistance R_{HFP}.

The measured U-value is corrected for the total thermal resistance of the heat flux plate and Vaseline, by

$U_{corrected} = 1 / [\ 1/U_{uncorrected} - 0.0116\ m^2K/W]$

Appendix B: Theoretical impact of moisture content, density and air gaps on U-values of solid walls.

Theoretical effect of moisture content

In existing U-value calculation procedures, moisture content of brick is considered to be affected by the degree of exposure of brick to external conditions. Some information is given by CIBSE Guide A3[6] and by Arnold[7]. In conventional U-value calculations, exposed brick is considered to have a moisture content of 5%, and this includes the bricks forming a solid wall, whether rendered or not. Protected brick, such as the brick forming the inner leaf of a cavity wall, is considered to have a moisture content of only 1%. It is possible that the moisture content could be influenced by a number of other factors, including the level of driving rain, the presence of hygroscopic salts, temperature and humidity.

According to Section 7.1 of ISO 10456:2006, the thermal conductivity of brick, λ_L, may be expressed as:

$$\lambda_L = \lambda_{L_0}(\rho)\ F_T\ F_m\ F_a$$

Where $\lambda_{L_0}(\rho)$ is the thermal conductivity at standard conditions, F_T is a temperature conversion factor (very small according to section 7.2 of ISO 10456:2006, but nevertheless given in Table A.11 of ISO 10456), F_m is a moisture conversion factor (information is given in Table 4 of ISO 10456, under 'fired clay') and F_a is an ageing conversion factor. λ_{L_0} is a function of the dry density, ρ, of the brick.

$$F_m = \exp(f_\Psi(\Psi - \Psi_0))$$

Where f_Ψ is the moisture conversion coefficient for brick, Ψ_0 is the standard moisture content (corresponding to λ_{L_0}) and Ψ is the actual moisture content (by volume rather than by mass).

For fired clay, results are given in Table 6.4.25 on page 41 of the Thermal Values report 1999[9]. The moisture conversion coefficient, f_Ψ, when moisture content is by volume, for brick, is 10.0 (according to Table 4 of ISO 10456). This f_Ψ-value of 10.0 corresponds to a correction factor of 9.5% per % (volume by volume).

Theoretical effect of density

The dependence of thermal conductivity on density, ρ, under dry conditions, according to Graph 25, in Appendix 4, of the Thermal Values report[9], is

$$\lambda_{L_0}(\rho) = (0.00038017\ \mathrm{W.m^2/kg.K} \times \rho) - 0.19617\ \mathrm{W/mK}$$

where the density, ρ, is normally expressed in kg per cubic metre.

Theoretical effect of air gaps

For the purposes of understanding the impact of air gaps, Table B1 below shows the thermal resistance that is assigned from theory against an air gap, versus the width of the air gap. The thermal resistance of air gaps tends to level off at gaps above 15 mm.

Table B1 – Theoretical effect of air gaps between stretcher bricks in solid walls.

Width of air gap (in the dimension parallel to direction of heat flow)	Thermal resistance of air gap	Equivalent thermal conductivity of air gap
5 mm	0.11 m²K/W	0.05 W/mK
10 mm	0.15 m²K/W	0.07 W/mK
15 mm	0.17 m²K/W	0.09 W/mK
20 mm	0.18 m²K/W	0.11 W/mK
50 mm	0.18 m²K/W	0.38 W/mK

In instances where the air space is bridged by all of the connecting headers, then it is still appropriate to consider the wall as a 'solid' wall. In instances where there are no headers bridging the air space, it is more appropriate to consider the wall as a 'cavity' wall.

Air gaps in the middle of a solid brick wall could be interconnected to some extent which may affect the U-values. Moving air currents within these structures are likely to increase U-values with still air likely to reduce U-values. No estimates of the effect of interconnected air gaps have been made in this study.

Combined theoretical effect on U-values of solid walls

The following tables show the expected effect of density and moisture content on the U-value of a typical solid wall. In the case of the first table, Table B2 , the predicted U-values correspond to a solid Flemish-Bonded brick wall where the inter-stretcher spaces are completely filled with mortar. In the case of the second table, Table B3, the predicted U-values correspond to the same situation but where the inter-stretcher spaces are completely filled with air. In both cases, the perpend spaces and bed joints are considered to be completely filled with mortar.

The U-values in both tables are based on a solid brick wall where the bricks measure 215 mm long, 102.5 mm wide and 65 mm high, arranged in a Flemish Bond with 10 mm spaces for mortar. The mortar is assumed to have a thermal conductivity of 0.94 (although it is recognised that many of the oldest properties may have lime mortar of a lower conductivity of approximately 0.7). The internal finish is assumed to be 13 mm of plaster of thermal conductivity 0.57. The bricks are assumed to have no frogs.

It can be seen that for low density bricks, or dry walls, the U-value can be expected to be significantly lower than higher density walls and wetter walls. These variations alone, however, seem insufficient in themselves to explain the difference in U-value between that measured, and that calculated outlined in the main body of this report.

The results in the two tables also suggest that the standard CIBSE A3 thermal conductivity of 0.77 W/mK, for exposed brick, corresponds to a density of close to 1750 kg/m3 and a volume-by-volume moisture content of close to 5%.

Table B2 - Predicted U-values, assuming mortar joints are fully filled

Density of brick core after oven-drying, ρ´	Actual density of brick core, immediately after it has been removed from wall, ρ	Moisture content, mass by mass, u=(ρ–ρ´)/ρ	Moisture content, volume by volume, Ψ=(ρ–ρ´)/ρ$_{water}$	Predicted thermal conductivity, λ, BS EN ISO 10456	Predicted U-value of typical solid wall
kg/m³	kg/m³	%	%	W/mK	W/m²K
1500	1500	0.0%	0.0%	0.374	1.561
1500	1510	0.7%	1.0%	0.413	1.639
1500	1520	1.3%	2.0%	0.457	1.720
1500	1550	3.2%	5.0%	0.617	1.985
1700	1700	0.0%	0.0%	0.450	1.708
1700	1710	0.6%	1.0%	0.497	1.792
1700	1720	1.2%	2.0%	0.550	1.880
1700	1750	2.9%	5.0%	0.742	2.163
1900	1900	0.0%	0.0%	0.526	1.841
1900	1910	0.5%	1.0%	0.581	1.931
1900	1920	1.0%	2.0%	0.643	2.024
1900	1950	2.6%	5.0%	0.867	2.320

Table B3 Predicted U-values, assuming air between inner and outer stretchers (10mm gap)

Density of brick core after oven-drying, ρ´	Actual density of brick core, immediately after it has been removed from wall, ρ	Moisture content, mass by mass, u=(ρ–ρ´)/ρ	Moisture content, volume by volume, Ψ=(ρ–ρ´)/ρ$_{water}$	Predicted thermal conductivity, λ, BS EN ISO 10456	Predicted U-value of typical solid wall
kg/m³	kg/m³	%	%	W/mK	W/m²K
1500	1500	0.0%	0.0%	0.374	1.498
1500	1510	0.7%	1.0%	0.413	1.567
1500	1520	1.3%	2.0%	0.457	1.638
1500	1550	3.2%	5.0%	0.617	1.869
1700	1700	0.0%	0.0%	0.450	1.627
1700	1710	0.6%	1.0%	0.497	1.702
1700	1720	1.2%	2.0%	0.550	1.778
1700	1750	2.9%	5.0%	0.742	2.022
1900	1900	0.0%	0.0%	0.526	1.744
1900	1910	0.5%	1.0%	0.581	1.822
1900	1920	1.0%	2.0%	0.643	1.903
1900	1950	2.6%	5.0%	0.867	2.154

Appendix C: Original EHS classification of walls

During the data analysis phase of this project it was recognised that the EHS classification of walls is limited in its usefulness when it is being used for analysis of individual dwellings. The EHS is a sample stock survey which reports results at an appropriate level of aggregation for statistical validity. A follow-up study on single dwellings of the type described in this report requires greater resolution on the wall actually being measured than is available from the EHS. This is for a number of reasons, including:

a) The EHS classification is of the predominant type of wall in the dwelling, whereas the measurement may have been made in a part of the dwelling which is of a different (minor) wall type. For example the U-value measurement may have been in an extension which is constructed in a different manner to the main wall of the dwelling or the part of the wall used for U-value measurement may be uninsulated whereas the majority of the dwelling is insulated (for example, an area of cavity wall above a conservatory is likely to remain uninsulated).

b) The EHS surveyor may have misclassified the wall. In particular, insulated cavity walls may be misclassified as uninsulated where drill holes are not readily visible to the surveyor. This could occur when drill holes are made good particularly well or when the walls have subsequently been painted or even rendered. The EHS survey form guides the surveyor through an evidence gathering process so that the chances of them identifying the presence of CWI are maximised however it is sometimes simply not possible to tell from a non-intrusive survey. The other cause of this kind of mis-classification is the uncertainty about whether CWI would have been installed at the time of construction for dwellings built in the time period around the 1990s. It is less likely that there will be visual evidence and when creating a wall type classification it is necessary to use assumptions based on construction date that will not be correct in every case.

In the wall classification used in the main body of this report, the type of wall measured has been defined by consolidation of data from various sources including the U-values survey fieldsheet data, visible and IR photographs taken by the installer of the monitoring equipment, data on wall construction, extensions and evidence of wall insulation from the EHS and data from the follow-up drilling investigations. Data has also been filtered to exclude houses which displayed large differences (>=0.5 W/m^2K) between the U-values returned by the HFPs and or between the monitored temperatures (> 2°C). Differences of this magnitude are considered likely to indicate a problem with the measurement process. Such problems could include the introduction of an additional radiant heat source close to one of the HFPs or the accidental or deliberate interference with the equipment by householders.

In order to demonstrate the effect of reclassification, filtering and inclusion of additional data, Tables C1 and C2, and Figures C1 to C8 below gives results using the original and reclassified data. These results highlight the necessity of accurately classifying the type and characteristics of the wall that is actually being measured in U-value surveys.

The main changes, aside from the reclassifications resulting from the drilling and boroscopic investigations were:

- Transfer of standard solid wall cases into uninsulated and insulated cavity wall cases. This is primarily the result of monitoring being undertaken where the predominant wall type was solid, but other data indicating that the wall actually measured was in a cavity wall extension.
- Transfer of standard solid wall cases into non-standard solid wall. This may be due to walls being measured as thicker than is feasible for a standard solid wall (EHS surveyors in 2010/11 did not measure wall thickness directly), or other data such as U-value installer field data or photographs indicating a misclassification of the wall.

- Transfer of uninsulated cavity walls into insulated cavity walls. This is when other data, such as the U-values installer data or photographs, indicates evidence of retrofitted insulation (such as drill holes) and that a wall has been mis-classified.

The inspection of additional photographic data for the reclassification process also provided additional data for improving the calculation assumptions. This included confirmation of the wall material (brick, stone etc.), and finish (render, masonry pointing). As a result, a number of the calculated values for walls changed following the reclassification, even if the classification of the wall type itself remained the same.

Table C1: Example of unfiltered results which use only the EHS predominant wall type classification (not adjusting for any other field data).

Wall type	Number of cases	**Measured U-values: mean (standard deviation) W/m²K**	*Calculated U-values: mean (standard deviation), W/m²K*
Solid wall, standard	115	1.46 (0.42)	1.75 (0.38)
Solid wall, non-standard	29	1.26 (0.44)	1.58 (0.59)
Uninsulated cavity	53	1.07 (0.47)	1.32 (0.31)
Insulated cavity	97	0.77 (0.32)	0.53 (0.21)

Table C2: The final survey results, following reclassification of walls, additional filtering of data for low temperature differentials etc. and inclusion of additional field data.

Wall type	Number of cases	**Measured U-values: mean (standard deviation) W/m²K***	*Calculated U-values: mean (standard deviation), W/m²K*
Solid wall, standard	85	1.57 (0.32)	*1.90 (0.20)*
Solid wall, non-standard	33	1.28 (0.42)	*1.91 (0.49)*
Uninsulated cavity	50	1.38 (0.30)	*1.40 (0.11)*
Insulated cavity	109	0.67 (0.23)	*0.52 (0.08)*

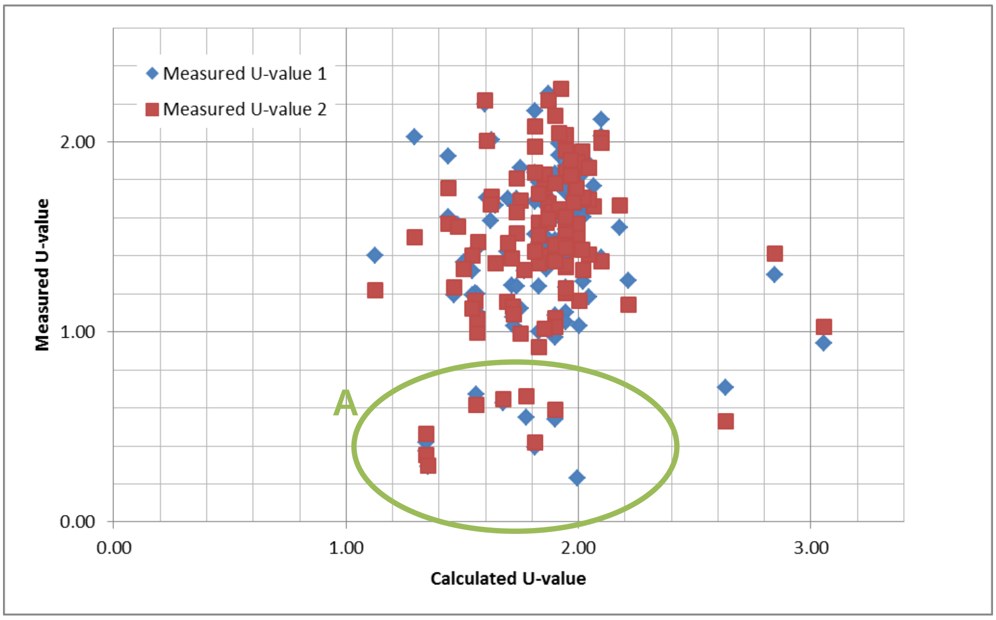

Figure C1: Scatterplot of measured against calculated U-values using the EHS predominant wall type classification of standard solid walls and prior to the filtering of data for low temperature differentials etc. Group A indicates properties which are predominantly standard solid walls, but where the measurement has taken place in an insulated cavity wall extension.

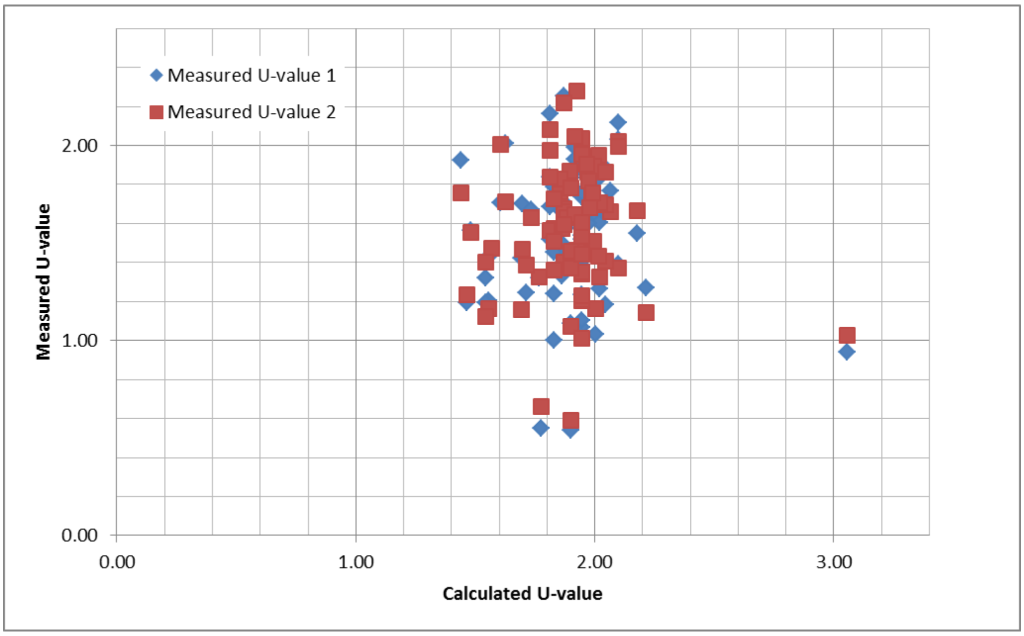

Figure C2: Scatterplot of measured against calculated U-values of standard solid walls using the final wall type classification and filtering data for low temperature differentials etc. Note that the majority of outliers visible in Group A of Figure C1 have now been now reclassified as having been in insulated cavity walls.

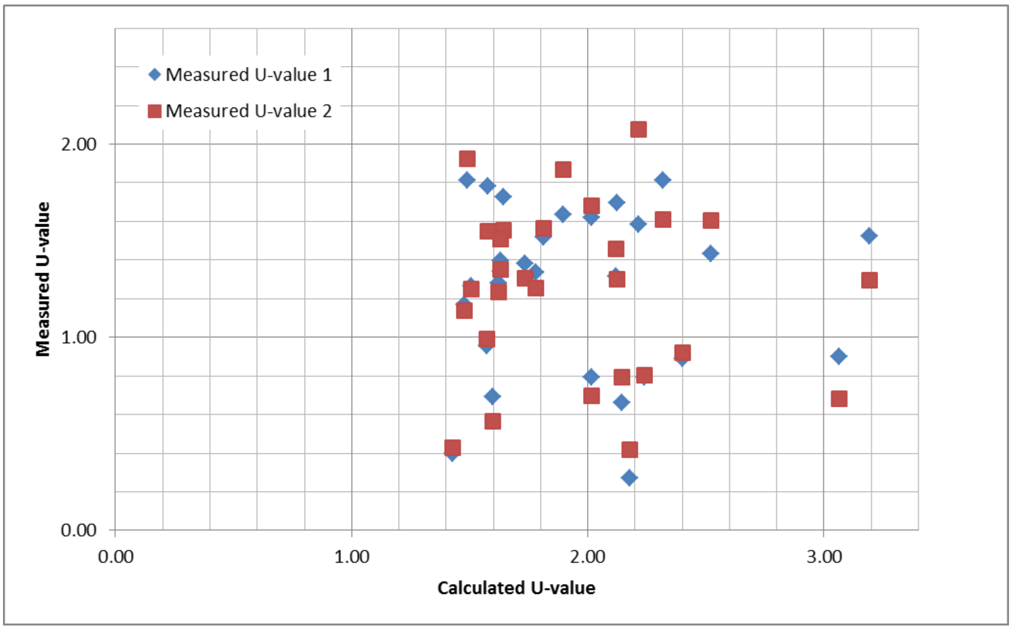

Figure C3: Scatterplot of measured against calculated U-values using the EHS predominant wall type classification of non-standard solid walls and prior to filtering of data for low temperature differentials etc. Some of these properties required reclassification or other adjustments to calculations based on the field data collected by the U-values equipment installer.

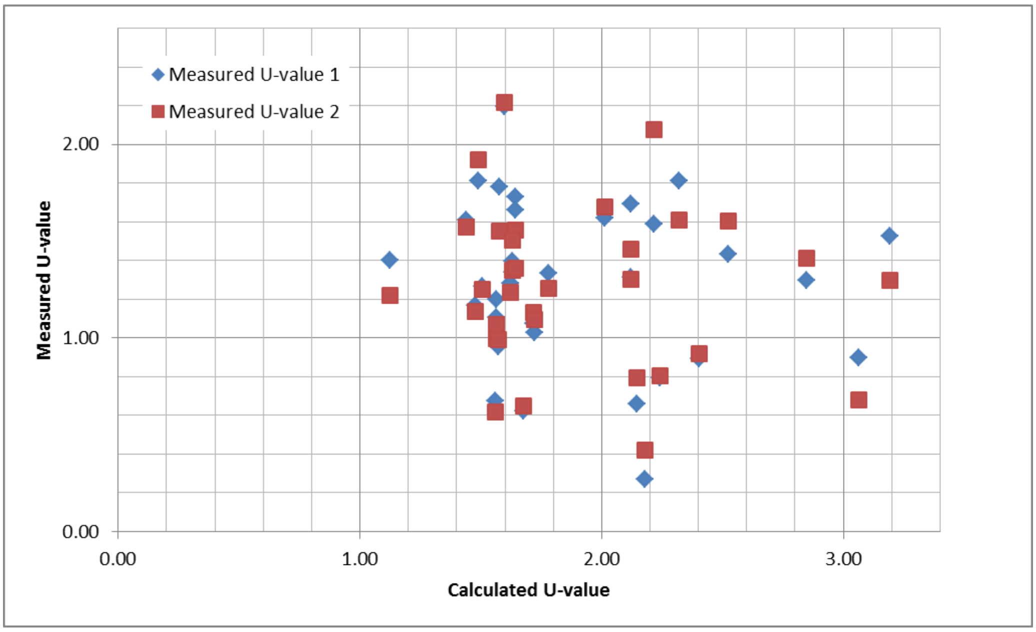

Figure C4: Scatterplot of measured against calculated U-values for non-standard solid walls using the final wall type classification and filtering data for low temperature differentials etc.

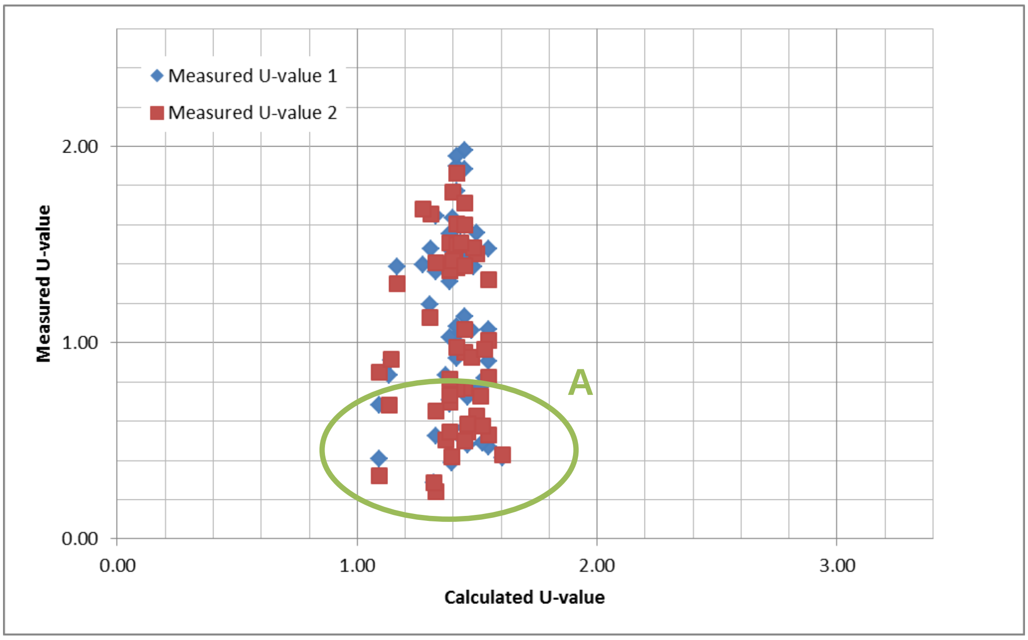

Figure C5: Scatterplot of measured against calculated U-values using the EHS predominant wall type classification of un-insulated cavity walls and prior to the filtering of data for low temperature differentials etc. Several of the properties in group A were re-classified as insulated cavity walls based on additional evidence (e.g. field notes that measurement was in newer extension or boroscopic investigations).

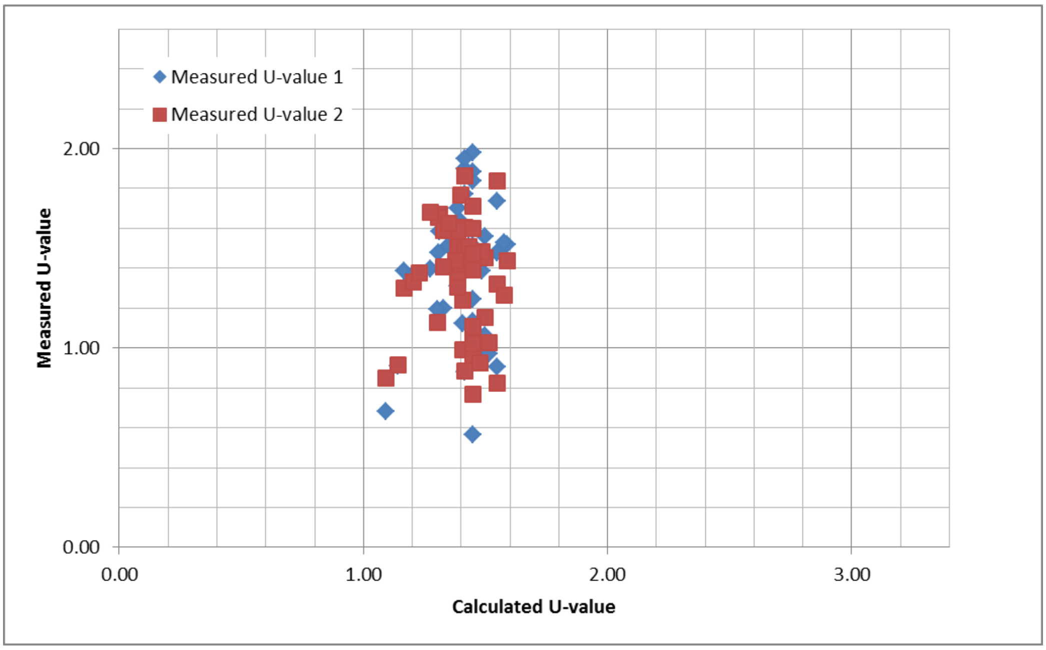

Figure C6: Scatterplot of measured against calculated U-values of un-insulated cavity walls using the final wall type classification and filtering data for low temperature differentials etc. Note the removal of several properties identified in group A of Figure C5 from this group.

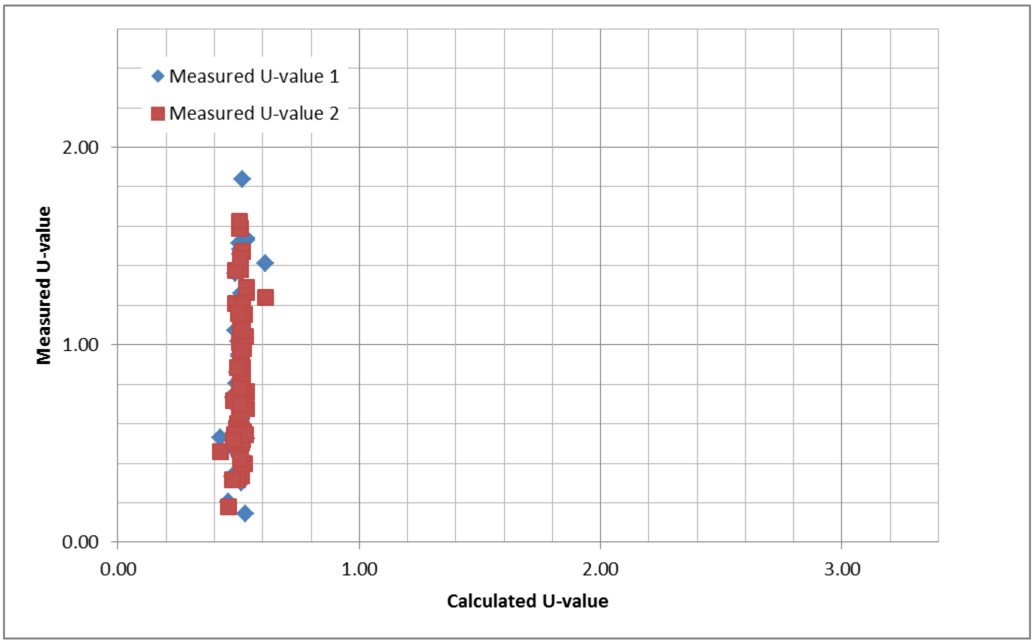

Figure C7: Scatterplot of measured against calculated U-values using the EHS predominant wall type classification of insulated cavity walls and prior to the filtering of data for low temperature differentials etc. These data do not also include the adjustments to the calculations made based on the boroscopic investigation these properties.

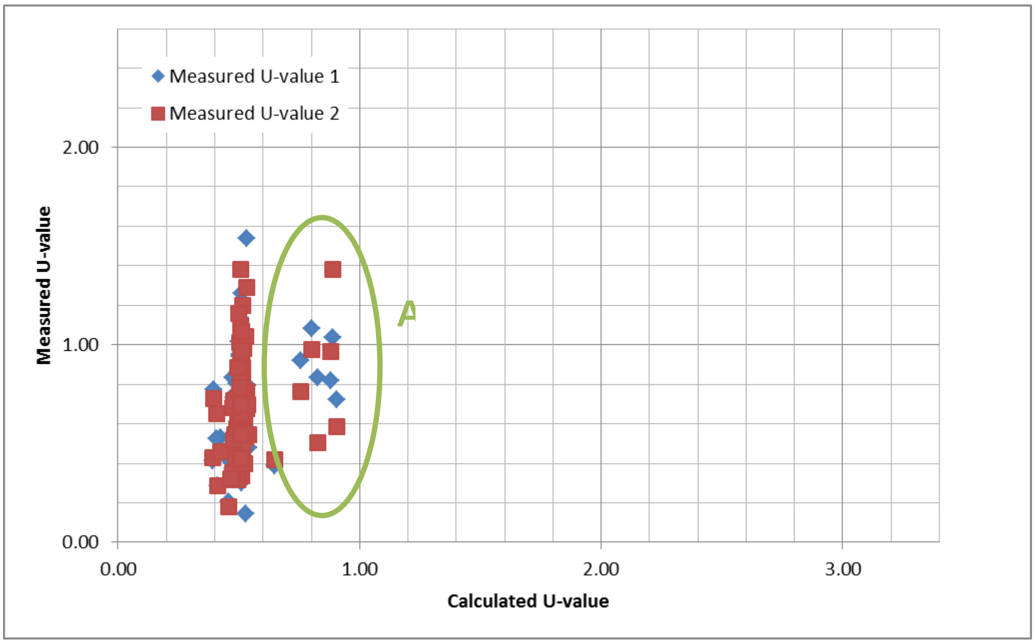

Figure C8: Scatterplot of measured against calculated U-values of un-insulated cavity walls using the final wall type classification and filtering data for low temperature differentials etc. Note the adjusted calculated values informed by the boroscopic investigations in the area marked A.

Appendix D: Discussion of temperature measurements used in U-values surveys

Air temperatures, radiant temperatures and surface temperatures

The temperature of a solid object, such as a temperature probe or a heat flux plate, will be influenced by both the temperature of the air that it is in contact with and the local radiant temperature. Local radiant temperature, in turn, depends upon the temperatures and emissivities of other objects as well as any sources of heat radiation, such as lights or radiators. In the external environment, radiant temperature is also influenced by sunlight and by the night sky, where the latter acts as a radiant heat sink. Radiant effects will generally lead to a surface or a temperature probe having a slightly different temperature to the air adjacent to it.

The net exchange of radiant energy between two objects depends upon their temperatures and emissivities. As a result, if there are sources of heat nearby then the radiant temperature may be much higher than the air temperature and in addition, objects of higher emissivity could differ in temperature from objects of lower emissivity. This may lead to a heat flux plate having a slightly different temperature from the surface of the wall next to it, thereby generating potential inaccuracies in U-value measurements. In order to avoid this problem, the HFPs and their associated temperature sensors were sited away from sources of heat such as radiators, TVs and lamps.

At present, it is not understood whether the temperature of the air within a few centimetres of the inside surface of a wall is significantly lower than the temperature of the air at the centre of the room. If indeed there is a significant ‘boundary layer’ next to the inside surface of external walls in a typical occupied house, then the temperature sensors could be underestimating indoor temperatures, thereby slightly overestimating U-values. Monitoring indoor temperatures at a range of distances from the inside surface of a wall, under typical domestic conditions, could provide some information on the potential errors in measured U-values that could arise from this.

An alternative approach, which has not been used in this work, is to monitor the temperature of the surface of a wall rather than the air adjacent to the wall. This would then not include internal surface thermal resistance in the measured U-value. If this is done, distortions caused by the difference between air and radiant temperatures could have less impact upon the U-value measurement. BRE plans to carry out further tests during the winter of 2013/14 to gain a better understanding of how the above phenomena may affect U-value measurements. This will include the monitoring of surface wall temperatures alongside air temperatures adjacent to the wall.

Fluctuating temperatures and thermal storage

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. The necessary period of time depends upon the accuracy in U-value that is required, the thermal mass of the wall and the degree to which temperatures fluctuate. For example, under laboratory conditions where temperatures are tightly controlled, an accurate U-value can be obtained in a matter of days, whereas in occupied housing, where temperatures vary, the period of monitoring usually needs to be at least two weeks. In this study, heat flux was monitored for a minimum of two weeks for all cases.

Appendix E: Verification of the *in-situ* methodology: Summary of the hot box tests at the National Physical Laboratory (NPL), April-June 2013

In order to test the method of measuring U-values which has been used in occupied housing, the National Physical Laboratory (NPL) were commissioned to carry out a series of laboratory tests. These tests involved the following:

1. Construction of a test panel (with a U-value of approximately 1.4 W/m²K).
2. Measurement of the U-value of the test panel using a guarded hot-box.
3. Measurement of the U-value of the test panel using the same apparatus, i.e. heat flow meter (or heat flux plate) and (as closely as possible) the same fixing arrangement used in occupied housing.
4. Comparison between the hot box results and the results using the heat flux plates used in occupied housing.

Five heat flux plates (manufactured by Hukseflux) were affixed to the surface of the test panel by BRE staff and then moved into NPL's hot box. The aim of the tests was to evaluate the performance of the arrangement used in the field, i.e. the pressure-fixing of the Hukseflux heat flux plates to the inside surface of the wall under test.

4.1 Construction of the test panel

A test panel, measuring 1.23 m wide by 1.48 m high, was specifically constructed for the measurements. It comprised a 13 mm thick sheet of high density expanded polystyrene sandwiched between two sheets of 12.5 mm thick plasterboard. The EPS was bonded to the plasterboard using PVA wood glue with additional clamping being provided by nine nylon bolts (6 mm in diameter).

Initially the surface of the test wall was smooth, but at a later stage in the tests a layer of embossed wallpaper was applied to the wall.

4.2 The hot-box

The measurements were conducted at the NPL Rotatable Wall Guarded Hot Box, described in NPL Report CBTLM 25. Where relevant, the equipment and measurement procedures were in accordance with the requirements of BS EN ISO 8990:1996. The main features of the equipment are summarised below:

1. The interior dimensions of the hot box were 2.4 m × 2.4 m
2. All surfaces 'seen' by the test element were matt black
3. There were twenty-five air temperature sensors, 75 mm from the baffle faces, (and well away from the boundary layer). They were positioned at the centres of squares of equal areas in front of the specimen in both the hot and cold boxes.
4. Tests were carried out with the test element held vertically (i.e. the principal direction of heat flow was horizontal).

The normal hot box outputs were used to derive the thermal transmittance of the test element in the steady state

4.3 The method of affixing the heat flux plates

The five heat flux plates (also known as heat flux meters) were clamped to the warm surface of the wall using a method that was as close as possible to the method that had been used in the field. This is shown in figure E1 below.

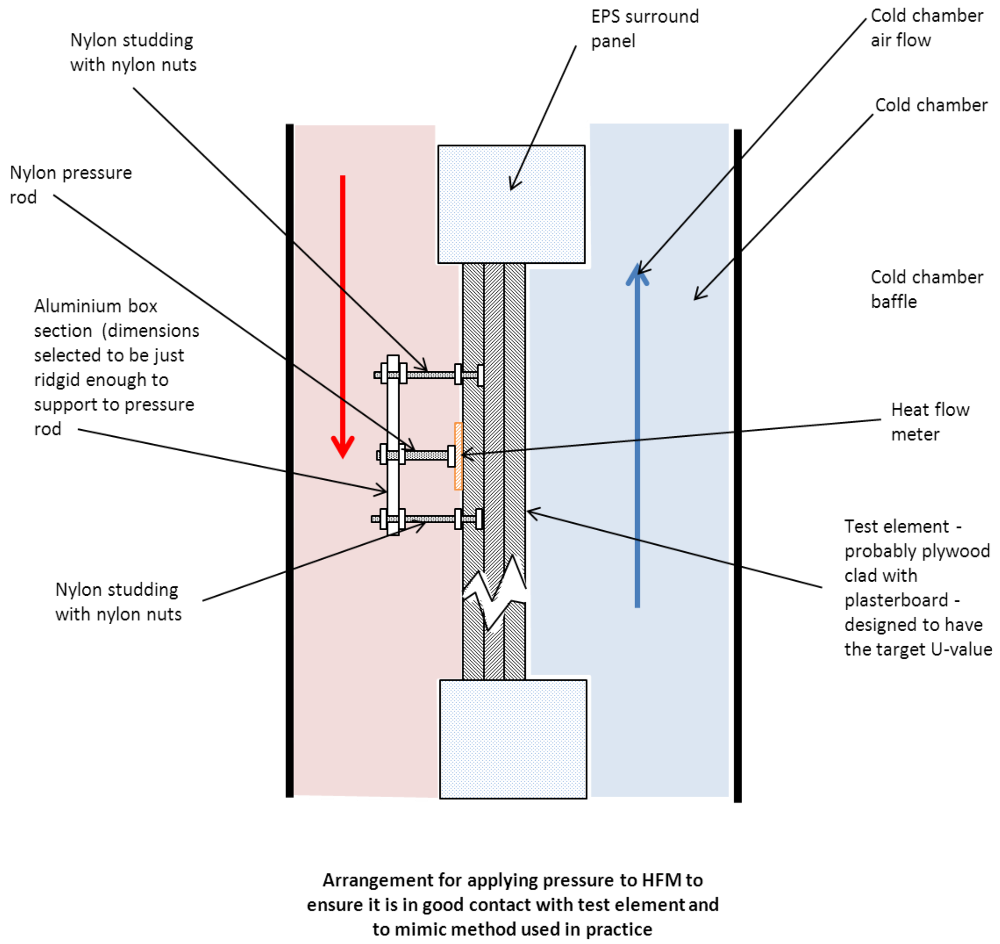

Figure E1 the hot box arrangement, and the method of pressure-fixing the Hukseflux heat flux plates

Each Hukseflux heat flux plate was pressure-fixed to the surface of the test panel using a nylon rod as shown. Each nylon rod was supported by an aluminium box section which was, in turn, supported by nylon studding and nylon nuts. This arrangement was intended to provide a similar pressure to that provided in the field (by means of a teleprop and flexible plastic clamp. Each heat flux plate had a substrate applied to it, just as would be done in the field, comprising a layer of petroleum jelly ('Vaseline'), approximately 1 mm thick, and a thin layer of polythene ('cling film').

A photograph of the equipment *in-situ* in the laboratory is shown in Figure E2 below.

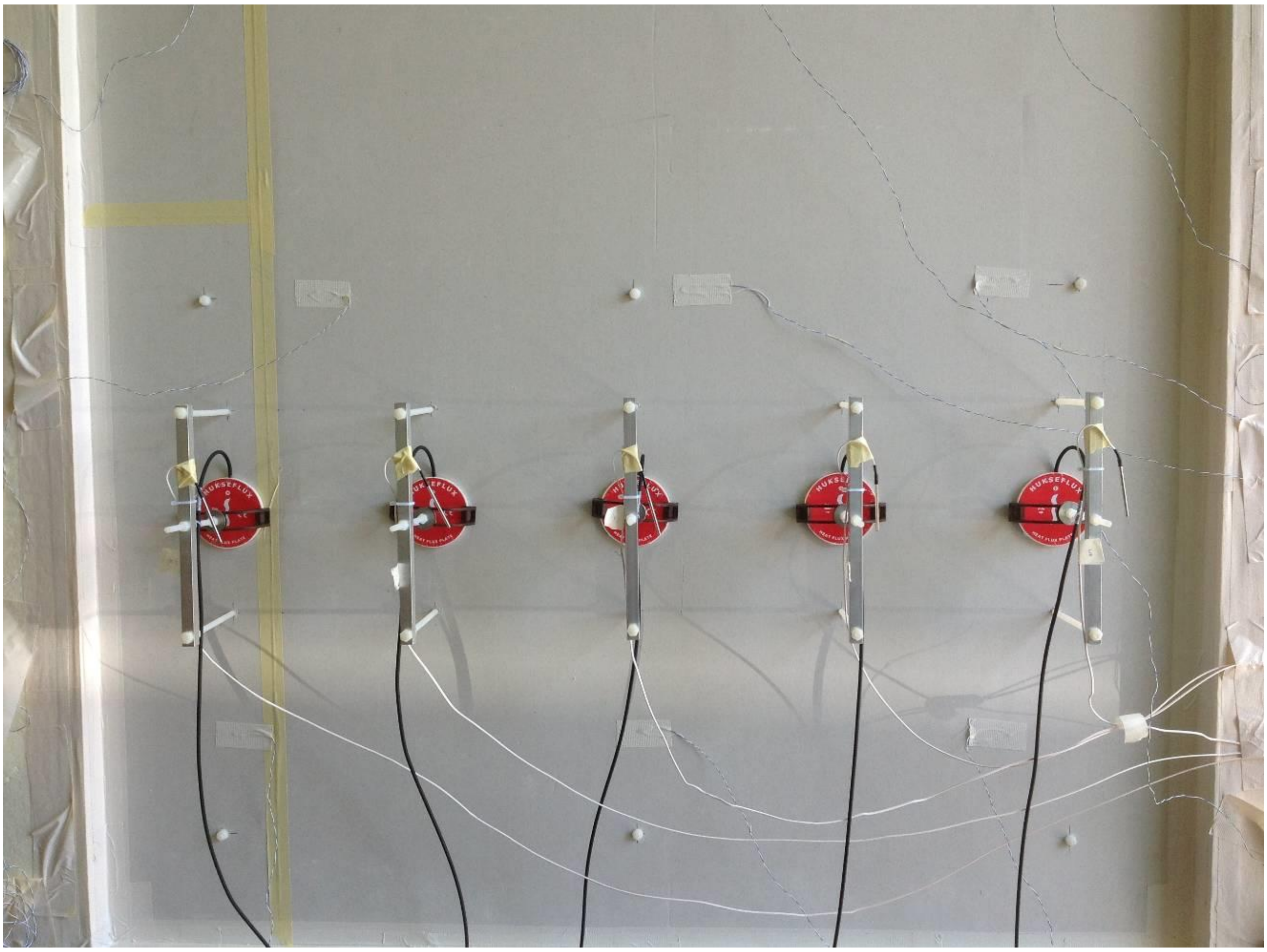

Figure E2 – photograph of in-situ setup of equipment fixed to test panel

4.4 The experimental runs

The experimental runs were carried out at National Physical Laboratories between 11 May 2013 and 17 June 2013.

The hot box arrangement and mounting arrangement, as well as the construction of the test panel, was carried out by NPL but with full consultation with BRE throughout the duration of the work. NPL provided interim results for each of the runs to permit BRE to consider and comment prior to the next run being started.

Preparation of the HFP's and their final installation within the hot box was carried out by BRE staff. They were mounted on the test panel using a layer of petroleum jelly and cling film. For all measurements the HFPs were affixed to the test panel surface by BRE staff. HFPs were installed equal distances apart, across the width of the test wall, at the same vertical height.

The testing programme involved five sets of measurements, these being as follows:

Run 1: The hot-box was run to measure the U-value of the test panel without any HFPs in place,

Run 2: As Run 1, but with the 5 HFPs installed and pressure fixed to the plasterboard at the warm side surface of the test panel. In addition, five thermistor temperature sensors (as used *in-situ* and provided by BRE) were installed, where for each of the five HFP locations the thermistor was located in the air on the hot-side approximately 10 to 20 mm from the surface of each heat flux plate. These thermistor temperatures were logged on loggers (provided by BRE) and compared to the various temperatures as measured by thermocouples located and provided by NPL.

Run 3: As Run 2 but with one positional rotation of the 4 HFPs rotated either side of the central 5th HFP (which remained in place undisturbed throughout subsequent runs) and with the thermistor temperature sensors moved to 75 mm from the surface of the HFP where these were in the plane of the NPL thermocouple sensors.

Run 4: As Run 3, but with the hot-side surface papered with embossed wall-paper and the thermistor temperature sensors removed.

Run 5: As in Run 4 but with one positional rotation of the 4 HFPs rotated either side of the central 5th HFP.

In Runs 2 to 5, the EMF outputs from the five HFPs were logged every 10 minutes through the hot box instrumentation. The heat flux (in W/m²) measured by the HFPs was compared with the heat flux measured by the hot box instrumentation. For Runs 2 and 3, the outputs from the thermistors were logged using the same Eltek dataloggers used in the field work.

All five heat flux plates were recalibrated by the manufacturer immediately following these tests, and the revised calibration constants have been used in the calculation of the heat flows measured using these particular Heat flux plates. .

4.5 The surface finishes used

In Runs 2 and 3, the HFPs and their substrates were in contact with the plasterboard. The substrates consisted of a thin layer of petroleum jelly (‘Vaseline’) to accommodate undulations in the surface, and a very thin layer of polythene (‘cling film’) to prevent petroleum jelly from seeping into the plasterboard. Prior to runs 4 and 5, embossed wallpaper was added to the test panel surface, by BRE staff, in order to test the effect of surface roughness.

4.6 The level of agreement achieved

The hot box apparatus was used to measure the U-value from the ‘environmental’ temperature difference, the test element area and the power (in watts) through the test element. The environmental temperature was calculated from the temperature of the surfaces in radiant exchange with the test element, the air temperature, the test element surface temperature and the density of heat flow rate through the test element. Thermocouples were mounted on the hot and cold surfaces of the test element, in the free air stream and on the baffle surfaces which were 150 mm away from the surface of the surround panel to facilitate calculation of the environmental temperatures, as specified in BS EN ISO 8990.

The power (in watts) through the test element was calculated by deducting the power through the surround panel from the hot box total power. The power through the surround panel was calculated from its thermal conductivity and the surface temperature difference across it. The thermal conductivity of the expanded polystyrene (EPS) material was measured in the NPL guarded hot plate facility.

The steady-state thermal transmittance values quoted are the mean of five sets of readings taken at two-hourly intervals. Equilibrium was assumed when the maximum difference between the five thermal transmittance values was less than approximately 1%.

4.7 Results

There was some variation in temperatures between HFP locations, both on the hot-side and on the cold side of the test panel and the better temperature difference (between the hot side and cold side) to use was that of the surface temperatures. Thus the thermal conductance of the test panel (i.e. excluding surface resistances) was used in comparing the thermal performance of the test panel determined by the HFPs and that determined from the hot-box.

Results indicate that the error in thermal conductance of the test panel determined by the HFPs is low. The mean U-value measured using the HFPs is approximately 5% less than that determined by the hot-box. The measured error is within the estimated calibration error of the HFPs and the hot-box itself and as such, in the absence of additional evidence (which is being gathered), no adjustment can be made at this stage to the values as measured with confidence. The effect on the mean measured U-values of any systematic error of this type will be very small (an increase of approximately 0.08 W/m²K in the mean value for solid wall dwellings) but it should be recognised, that actual U-values may be slightly higher than values measured and reported on in the main body of this document.

Appendix F: Tabulated data from survey

Case identifier	Dwelling type	Dwelling age	Wall type (of wall measured after reclassification)	Calculated U-value	Measured U-value @HFP1	Measured U-value @HFP2
U001	semi detached	1850 to 1899	Standard solid wall	2.10	2.12	2.00
U002	semi detached	1945 to 1964	Filled cavity wall	0.51	0.66	0.54
U004	end terrace	1900 to 1918	Standard solid wall	2.22	1.27	1.14
U005	detached	1919 to 1944	Standard solid wall	1.93	2.01	2.28
U006	semi detached	1945 to 1964	Filled cavity wall	0.52	0.50	0.50
U007	end terrace	1945 to 1964	Filled cavity wall	0.50	0.68	0.78
U008	semi detached	pre 1850	Non-standard solid wall	1.78	1.34	1.26
U009	detached	pre 1850	Standard solid wall	1.90	0.54	0.59
U010	semi detached	1919 to 1944	Standard solid wall	1.83	1.79	1.72
U011	detached	1965 to 1974	Unfilled cavity wall	1.43	1.60	1.51
U012	semi detached	1919 to 1944	Standard solid wall	1.95	1.76	1.60
U013	detached	1945 to 1964	Filled cavity wall	0.51	1.00	0.90
U014	detached	pre 1850	Non-standard solid wall	1.57	1.10	1.07
U015	semi detached	1945 to 1964	Filled cavity wall	0.42	0.53	0.46
U016	semi detached	1850 to 1899	Non-standard solid wall	2.24	0.80	0.80
U017	semi detached	1850 to 1899	Standard solid wall	1.63	2.01	1.71
U018	semi detached	1919 to 1944	Filled cavity wall	0.51	0.72	0.63

U019	semi detached	1965 to 1974	Filled cavity wall	0.53	1.02	1.04
U020	semi detached	1945 to 1964	Unfilled cavity wall	1.41	1.44	1.50
U021	detached	1965 to 1974	Filled cavity wall	0.48	0.47	0.52
U022	semi detached	1919 to 1944	Standard solid wall	1.97	1.93	1.92
U023	end terrace	1900 to 1918	Filled cavity wall	0.47	0.41	0.32
U024	end terrace	pre 1850	Non-standard solid wall	2.32	1.81	1.61
U025	semi detached	1900 to 1918	Standard solid wall	1.95	1.34	1.35
U026	detached	1945 to 1964	Filled cavity wall	0.41	0.52	0.65
U027	semi detached	1919 to 1944	Filled cavity wall	0.51	0.68	0.73
U028	bungalow	1975 to 1980	Filled cavity wall	0.51	0.43	0.42
U029	detached	1945 to 1964	Unfilled cavity wall	1.41	1.40	1.47
U030	semi detached	1919 to 1944	Standard solid wall	1.99	1.75	1.76
U031	semi detached	1850 to 1899	Non-standard solid wall	1.62	1.28	1.23
U032	end terrace	1919 to 1944	Non-standard solid wall	1.60	2.20	2.22
U033	detached	1965 to 1974	Filled cavity wall	0.53	0.78	0.76
U034	semi detached	1850 to 1899	Non-standard solid wall	1.63	1.40	1.35
U035	semi detached	1850 to 1899	Standard solid wall	1.71	1.24	1.38
U036	end terrace	1919 to 1944	Non-standard solid wall	1.72	1.08	1.13
U037	bungalow	1919 to 1944	Unfilled cavity wall	1.33	1.20	1.59
U039	semi detached	1919 to 1944	Unfilled cavity wall	1.17	1.39	1.30
U040	semi detached	1945 to 1964	Filled cavity wall	0.51	1.13	1.09

U041	end terrace	1945 to 1964	Non-standard solid wall	2.01	1.62	1.68
U042	semi detached	1919 to 1944	Standard solid wall	1.83	1.45	1.51
U044	detached	1945 to 1964	Filled cavity wall	0.52	0.85	0.83
U045	semi detached	1919 to 1944	Standard solid wall	1.95	1.54	1.34
U046	semi detached	1965 to 1974	Filled cavity wall	0.52	0.80	0.82
U047	end terrace	1945 to 1964	Filled cavity wall	0.51	0.63	0.55
U048	detached	1965 to 1974	Filled cavity wall	0.51	0.58	0.53
U049	semi detached	1850 to 1899	Non-standard solid wall	1.51	1.27	1.25
U050	bungalow	1945 to 1964	Filled cavity wall	0.51	0.59	0.70
U051	semi detached	1919 to 1944	Unfilled cavity wall	1.14	0.91	0.91
U052	detached	1850 to 1899	Unfilled cavity wall	1.38	1.70	1.52
U053	semi detached	1919 to 1944	Unfilled cavity wall	1.59	1.52	1.44
U054	detached	1965 to 1974	Filled cavity wall	0.51	0.55	0.56
U055	end terrace	1919 to 1944	Filled cavity wall	0.89	1.03	1.38
U056	semi detached	1945 to 1964	Filled cavity wall	0.52	0.71	0.72
U057	semi detached	1919 to 1944	Standard solid wall	1.83	1.24	1.57
U058	detached	1975 to 1980	Filled cavity wall	0.52	0.56	0.53
U059	detached	1975 to 1980	Filled cavity wall	0.88	0.82	0.97
U060	detached	1965 to 1974	Unfilled cavity wall	1.45	0.57	0.77
U061	end terrace	1945 to 1964	Filled cavity wall	0.51	0.85	0.73
U062	detached	1850 to 1899	Non-standard solid wall	2.18	0.27	0.42

U064	detached	1900 to 1918	Filled cavity wall	0.51	0.58	0.53
U065	purpose built flat, low rise	1975 to 1980	Filled cavity wall	0.51	0.74	1.07
U066	detached	1919 to 1944	Unfilled cavity wall	1.58	1.53	1.27
U067	semi detached	1919 to 1944	Unfilled cavity wall	1.38	1.38	1.37
U068	semi detached	1919 to 1944	Standard solid wall	1.87	1.49	1.60
U069	detached	1850 to 1899	Standard solid wall	1.75	1.87	1.69
U070	end terrace	1945 to 1964	Filled cavity wall	0.51	1.16	0.78
U071	semi detached	1900 to 1918	Standard solid wall	1.77	1.32	1.33
U072	end terrace	1965 to 1974	Filled cavity wall	0.41	0.29	0.29
U073	purpose built flat, low rise	1919 to 1944	Standard solid wall	1.97	1.72	1.87
U074	semi detached	1919 to 1944	Filled cavity wall	0.51	0.57	0.49
U075	bungalow	1945 to 1964	Filled cavity wall	0.51	0.91	0.85
U076	detached	1919 to 1944	Filled cavity wall	0.51	0.71	0.94
U077	purpose built flat, low rise	1945 to 1964	Filled cavity wall	0.50	0.48	0.61
U078	detached	1919 to 1944	Filled cavity wall	0.52	0.68	0.74
U080	semi detached	1919 to 1944	Standard solid wall	1.70	1.70	1.47
U081	bungalow	1919 to 1944	Unfilled cavity wall	1.45	1.98	1.60
U082	semi detached	1850 to 1899	Standard solid wall	1.96	1.72	1.91
U083	semi detached	1900 to 1918	Unfilled cavity wall	1.31	1.59	1.67

U085	semi detached	1965 to 1974	Filled cavity wall	0.49	0.76	0.57
U086	semi detached	1919 to 1944	Unfilled cavity wall	1.35	1.51	1.62
U087	detached	1945 to 1964	Filled cavity wall	0.51	0.49	0.40
U088	semi detached	1919 to 1944	Unfilled cavity wall	1.40	1.64	1.77
U089	detached	1965 to 1974	Filled cavity wall	0.76	0.92	0.76
U090	bungalow	1965 to 1974	Filled cavity wall	0.50	0.62	0.71
U091	semi detached	1919 to 1944	Standard solid wall	1.94	1.57	1.64
U092	purpose built flat, low rise	1919 to 1944	Non-standard solid wall	1.48	1.17	1.14
U093	semi detached	1850 to 1899	Standard solid wall	1.95	1.23	1.23
U094	semi detached	1919 to 1944	Filled cavity wall	0.51	0.53	0.54
U095	bungalow	1945 to 1964	Filled cavity wall	0.50	0.67	0.79
U096	semi detached	1945 to 1964	Unfilled cavity wall	1.45	1.88	1.39
U097	end terrace	1945 to 1964	Filled cavity wall	0.51	1.00	1.38
U098	semi detached	1900 to 1918	Standard solid wall	1.56	1.21	1.16
U099	semi detached	1945 to 1964	Unfilled cavity wall	1.41	1.41	1.24
U100	semi detached	1919 to 1944	Filled cavity wall	0.51	0.60	0.55
U101	semi detached	1945 to 1964	Standard solid wall	2.01	1.63	1.43
U102	bungalow	1945 to 1964	Filled cavity wall	0.91	0.72	0.59
U103	semi detached	1919 to 1944	Standard solid wall	1.90	1.83	1.78
U104	semi detached	1919 to 1944	Standard solid wall	1.95	1.43	1.54

U105	semi detached	1919 to 1944	Standard solid wall	1.60	1.70	2.01
U106	semi detached	1919 to 1944	Unfilled cavity wall	1.50	1.56	1.45
U107	purpose built flat, low rise	1975 to 1980	Filled cavity wall	0.51	0.62	0.74
U109	detached	1919 to 1944	Filled cavity wall	0.46	0.21	0.18
U110	semi detached	1945 to 1964	Filled cavity wall	0.53	1.54	1.29
U111	detached	1965 to 1974	Filled cavity wall	0.51	0.35	0.45
U112	semi detached	1945 to 1964	Non-standard solid wall	1.64	1.73	1.56
U113	end terrace	1919 to 1944	Filled cavity wall	0.52	0.74	0.62
U114	semi detached	1850 to 1899	Unfilled cavity wall	1.45	1.51	1.42
U115	detached	1919 to 1944	Standard solid wall	2.01	1.65	1.92
U116	end terrace	1900 to 1918	Standard solid wall	1.90	1.62	1.37
U117	semi detached	1919 to 1944	Unfilled cavity wall	1.45	1.84	1.47
U118	semi detached	1965 to 1974	Filled cavity wall	0.51	0.76	0.56
U119	semi detached	1945 to 1964	Filled cavity wall	0.54	0.79	0.70
U120	end terrace	1850 to 1899	Standard solid wall	2.07	1.77	1.66
U121	detached	1850 to 1899	Standard solid wall	1.46	1.19	1.24
U122	end terrace	1945 to 1964	Filled cavity wall	0.48	0.73	0.72
U123	semi detached	1900 to 1918	Standard solid wall	1.90	1.09	1.07
U124	semi detached	1919 to 1944	Standard solid wall	1.87	2.26	2.22
U125	semi detached	1850 to 1899	Filled cavity wall	0.83	0.83	0.50

U126	bungalow	1850 to 1899	Filled cavity wall	0.50	1.01	1.16
U127	detached	1945 to 1964	Unfilled cavity wall	1.38	1.48	1.44
U128	end terrace	1919 to 1944	Filled cavity wall	0.47	0.42	0.35
U129	semi detached	1900 to 1918	Standard solid wall	1.69	1.42	1.16
U130	detached	1919 to 1944	Unfilled cavity wall	1.49	1.39	1.48
U131	end terrace	1919 to 1944	Standard solid wall	1.95	1.74	2.04
U132	end terrace	1919 to 1944	Unfilled cavity wall	1.33	1.64	1.41
U133	end terrace	1850 to 1899	Standard solid wall	2.05	1.66	1.86
U134	end terrace	1945 to 1964	Unfilled cavity wall	1.41	0.88	0.89
U135	end terrace	1919 to 1944	Standard solid wall	1.86	1.37	1.76
U136	detached	1919 to 1944	Standard solid wall	1.74	1.67	1.63
U137	semi detached	1850 to 1899	Standard solid wall	1.81	2.16	2.08
U138	bungalow	1975 to 1980	Non-standard solid wall	2.85	1.30	1.41
U139	end terrace	1945 to 1964	Filled cavity wall	0.51	0.54	0.57
U140	semi detached	1900 to 1918	Standard solid wall	1.95	1.36	1.21
U141	semi detached	1919 to 1944	Standard solid wall	1.92	1.93	2.05
U142	detached	1965 to 1974	Unfilled cavity wall	1.48	1.06	0.92
U143	semi detached	1919 to 1944	Unfilled cavity wall	1.55	1.74	1.84
U144	detached	1850 to 1899	Non-standard solid wall	1.57	0.95	0.99
U145	detached	1965 to 1974	Filled cavity wall	0.47	0.33	0.32
U146	semi detached	1919 to 1944	Standard solid wall	1.92	1.99	1.65

U147	semi detached	1900 to 1918	Unfilled cavity wall	1.40	1.46	1.41
U148	semi detached	1945 to 1964	Filled cavity wall	0.51	1.03	0.81
U149	bungalow	1900 to 1918	Standard solid wall	1.77	0.55	0.66
U150	semi detached	1919 to 1944	Unfilled cavity wall	1.31	1.48	1.66
U151	semi detached	1945 to 1964	Filled cavity wall	0.51	0.42	0.50
U152	semi detached	1919 to 1944	Standard solid wall	1.87	1.71	1.67
U153	detached	1919 to 1944	Filled cavity wall	0.51	0.61	0.57
U154	semi detached	1919 to 1944	Filled cavity wall	0.80	1.08	0.98
U155	semi detached	1919 to 1944	Unfilled cavity wall	1.38	1.56	1.51
U156	semi detached	1945 to 1964	Filled cavity wall	0.52	0.91	0.89
U157	detached	1975 to 1980	Filled cavity wall	0.49	0.40	0.43
U158	semi detached	1945 to 1964	Filled cavity wall	0.51	0.57	0.64
U159	semi detached	1919 to 1944	Filled cavity wall	0.51	0.63	0.80
U160	semi detached	1919 to 1944	Standard solid wall	1.98	1.45	1.68
U161	semi detached	1965 to 1974	Filled cavity wall	0.50	0.95	1.01
U162	semi detached	1945 to 1964	Filled cavity wall	0.51	0.63	0.71
U163	semi detached	1919 to 1944	Standard solid wall	1.95	1.45	1.45
U164	end terrace	1919 to 1944	Standard solid wall	1.95	1.52	1.95
U166	purpose built flat, low rise	1945 to 1964	Non-standard solid wall	1.44	1.61	1.57
U167	end terrace	1945 to 1964	Non-standard solid wall	1.63	1.34	1.51

U168	semi detached	1850 to 1899	Non-standard solid wall	3.06	0.90	0.68
U169	detached	1965 to 1974	Unfilled cavity wall	1.45	1.51	1.71
U170	semi detached	1919 to 1944	Unfilled cavity wall	1.20	1.37	1.33
U171	semi detached	1919 to 1944	Standard solid wall	1.81	1.68	1.98
U172	purpose built flat, low rise	1975 to 1980	Unfilled cavity wall	1.09	0.68	0.85
U173	detached	1919 to 1944	Standard solid wall	1.90	1.65	1.46
U174	semi detached	1919 to 1944	Standard solid wall	1.87	1.71	1.66
U175	semi detached	1919 to 1944	Standard solid wall	2.01	1.83	1.95
U176	semi detached	1919 to 1944	Unfilled cavity wall	1.50	1.06	1.15
U177	detached	1919 to 1944	Filled cavity wall	0.52	0.39	0.42
U178	end terrace	1945 to 1964	Non-standard solid wall	2.12	1.31	1.46
U181	detached	1945 to 1964	Filled cavity wall	0.54	0.48	0.55
U182	end terrace	1900 to 1918	Standard solid wall	1.95	1.07	1.01
U183	detached	1919 to 1944	Unfilled cavity wall	1.55	1.48	1.32
U184	end terrace	1945 to 1964	Unfilled cavity wall	1.28	1.40	1.68
U185	detached	1965 to 1974	Filled cavity wall	0.52	0.77	0.72
U186	detached	1945 to 1964	Filled cavity wall	0.40	0.78	0.73
U187	semi detached	1945 to 1964	Filled cavity wall	0.50	0.61	0.60
U188	end terrace	1850 to 1899	Standard solid wall	1.86	1.33	1.58
U189	semi detached	1919 to 1944	Standard solid wall	2.05	1.88	1.70

U190	semi detached	1850 to 1899	Standard solid wall	1.81	1.52	1.57
U191	end terrace	1919 to 1944	Non-standard solid wall	1.68	0.62	0.65
U193	end terrace	1965 to 1974	Filled cavity wall	0.53	0.47	0.53
U194	end terrace	1945 to 1964	Unfilled cavity wall	1.30	1.19	1.13
U195	purpose built flat, low rise	1919 to 1944	Non-standard solid wall	1.57	1.20	1.00
U196	semi detached	1919 to 1944	Filled cavity wall	0.50	0.94	0.67
U197	end terrace	1975 to 1980	Filled cavity wall	0.52	0.75	0.98
U198	semi detached	1919 to 1944	Unfilled cavity wall	1.38	1.46	1.59
U199	semi detached	1945 to 1964	Unfilled cavity wall	1.45	1.25	1.02
U200	semi detached	pre 1850	Standard solid wall	1.95	1.10	1.44
U201	detached	1965 to 1974	Filled cavity wall	0.52	0.57	0.40
U202	detached	1975 to 1980	Filled cavity wall	0.52	0.66	0.72
U204	semi detached	1919 to 1944	Filled cavity wall	0.51	0.51	0.58
U205	semi detached	1919 to 1944	Standard solid wall	1.88	1.46	1.63
U206	bungalow	1945 to 1964	Filled cavity wall	0.49	0.80	0.51
U207	detached	pre 1850	Non-standard solid wall	3.19	1.52	1.30
U208	detached	1900 to 1918	Non-standard solid wall	2.52	1.43	1.60
U209	semi detached	pre 1850	Non-standard solid wall	2.22	1.59	2.07
U210	semi detached	1919 to 1944	Standard solid wall	1.95	1.39	1.20
U212	semi detached	1945 to 1964	Standard solid wall	1.99	1.50	1.90

U214	semi detached	1919 to 1944	Standard solid wall	2.02	1.61	1.71
U215	detached	1945 to 1964	Filled cavity wall	0.51	0.66	0.88
U217	end terrace	1900 to 1918	Non-standard solid wall	1.72	1.03	1.09
U218	end terrace	pre 1850	Non-standard solid wall	2.40	0.89	0.92
U219	converted flat	1850 to 1899	Standard solid wall	1.87	1.58	1.60
U220	semi detached	1919 to 1944	Standard solid wall	2.10	2.03	2.02
U221	detached	1850 to 1899	Unfilled cavity wall	1.51	0.97	1.02
U222	end terrace	1850 to 1899	Standard solid wall	3.05	0.94	1.03
U224	detached	1919 to 1944	Standard solid wall	1.87	1.40	1.40
U225	end terrace	1900 to 1918	Non-standard solid wall	1.12	1.40	1.22
U226	detached	pre 1850	Non-standard solid wall	2.12	1.69	1.30
U227	semi detached	1900 to 1918	Filled cavity wall	0.50	0.44	0.47
U228	detached	1975 to 1980	Filled cavity wall	0.48	0.51	0.55
U229	semi detached	1945 to 1964	Non-standard solid wall	1.58	1.78	1.55
U230	semi detached	1850 to 1899	Standard solid wall	1.99	1.69	1.51
U231	semi detached	1900 to 1918	Standard solid wall	1.44	1.92	1.76
U232	end terrace	1919 to 1944	Standard solid wall	1.83	1.00	1.36
U233	detached	1919 to 1944	Unfilled cavity wall	1.41	1.95	1.86
U234	semi detached	1919 to 1944	Filled cavity wall	0.51	1.26	0.97
U235	semi detached	1919 to 1944	Filled cavity wall	0.47	0.37	0.47
U236	detached	1975 to 1980	Unfilled cavity wall	1.38	1.31	1.37

U237	detached	1945 to 1964	Filled cavity wall	0.51	0.64	0.73
U238	detached	1945 to 1964	Standard solid wall	1.54	1.32	1.40
U239	detached	1975 to 1980	Filled cavity wall	0.51	0.49	0.52
U240	end terrace	1919 to 1944	Filled cavity wall	0.50	0.36	0.32
U241	semi detached	1945 to 1964	Filled cavity wall	0.52	0.57	0.56
U242	end terrace	1900 to 1918	Unfilled cavity wall	1.38	1.38	1.31
U243	semi detached	1900 to 1918	Standard solid wall	1.89	1.63	1.87
U244	end terrace	1850 to 1899	Non-standard solid wall	2.14	0.66	0.79
U247	end terrace	1965 to 1974	Filled cavity wall	0.65	0.39	0.42
U248	semi detached	1850 to 1899	Standard solid wall	2.00	1.03	1.17
U249	detached	1965 to 1974	Unfilled cavity wall	1.45	1.13	0.95
U250	semi detached	1919 to 1944	Standard solid wall	2.02	1.27	1.33
U251	detached	1850 to 1899	Standard solid wall	1.54	1.19	1.12
U252	detached	1919 to 1944	Standard solid wall	1.95	1.87	1.98
U253	end terrace	1945 to 1964	Filled cavity wall	0.50	0.86	0.73
U254	semi detached	1945 to 1964	Filled cavity wall	0.51	0.74	0.77
U255	semi detached	1965 to 1974	Filled cavity wall	0.50	0.68	0.57
U256	detached	1975 to 1980	Filled cavity wall	0.51	0.54	0.55
U257	detached	1900 to 1918	Filled cavity wall	0.51	0.30	0.34
U258	semi detached	1919 to 1944	Standard solid wall	1.57	1.44	1.47
U259	semi detached	1919 to 1944	Filled cavity wall	0.51	0.71	0.70

U260	semi detached	1945 to 1964	Standard solid wall	2.10	1.39	1.37
U261	semi detached	1965 to 1974	Filled cavity wall	0.51	0.57	0.61
U263	end terrace	1919 to 1944	Standard solid wall	2.18	1.55	1.66
U264	semi detached	1900 to 1918	Standard solid wall	1.92	1.63	1.46
U265	detached	1945 to 1964	Filled cavity wall	0.51	0.83	0.90
U266	detached	1965 to 1974	Unfilled cavity wall	1.45	0.97	1.11
U267	end terrace	1945 to 1964	Filled cavity wall	0.53	0.52	0.68
U268	semi detached	1900 to 1918	Standard solid wall	1.95	1.58	1.54
U269	end terrace	1919 to 1944	Standard solid wall	1.99	1.81	1.74
U270	semi detached	1945 to 1964	Filled cavity wall	0.52	0.50	0.52
U271	semi detached	1945 to 1964	Unfilled cavity wall	1.41	1.13	0.99
U272	detached	pre 1850	Non-standard solid wall	1.56	0.67	0.62
U273	semi detached	1919 to 1944	Unfilled cavity wall	1.41	1.90	1.87
U274	semi detached	1900 to 1918	Standard solid wall	1.86	1.67	1.83
U275	purpose built flat, low rise	1965 to 1974	Unfilled cavity wall	1.55	0.90	0.82
U276	semi detached	1919 to 1944	Unfilled cavity wall	1.23	1.36	1.38
U277	semi detached	1850 to 1899	Filled cavity wall	0.53	0.71	0.53
U278	detached	1850 to 1899	Filled cavity wall	0.51	0.61	0.71
U279	semi detached	1900 to 1918	Standard solid wall	2.05	1.18	1.41
U280	semi detached	1945 to 1964	Filled cavity wall	0.53	0.15	0.55

U281	bungalow	1945 to 1964	Filled cavity wall	0.51	0.84	0.70
U282	semi detached	1850 to 1899	Non-standard solid wall	1.64	1.66	1.36
U283	semi detached	1945 to 1964	Filled cavity wall	0.49	0.74	0.88
U284	bungalow	1975 to 1980	Filled cavity wall	0.47	0.84	0.68
U285	semi detached	1945 to 1964	Non-standard solid wall	1.49	1.81	1.92
U286	semi detached	1900 to 1918	Standard solid wall	1.81	1.84	1.84
U287	semi detached	1919 to 1944	Standard solid wall	1.97	1.85	1.94
U288	detached	1975 to 1980	Unfilled cavity wall	1.45	1.46	1.07
U289	detached	1945 to 1964	Filled cavity wall	0.50	0.52	0.58
U290	semi detached	1965 to 1974	Unfilled cavity wall	1.41	1.77	1.61
U291	detached	1919 to 1944	Filled cavity wall	0.39	0.41	0.43
U292	detached	1945 to 1964	Filled cavity wall	0.51	0.43	0.48
U293	semi detached	1945 to 1964	Filled cavity wall	0.51	0.57	0.56
U294	semi detached	1919 to 1944	Standard solid wall	1.97	1.60	1.82
U295	semi detached	1945 to 1964	Filled cavity wall	0.52	0.91	1.20
U296	semi detached	1900 to 1918	Standard solid wall	1.48	1.56	1.55

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