

The thermal performance solid wall homes in England

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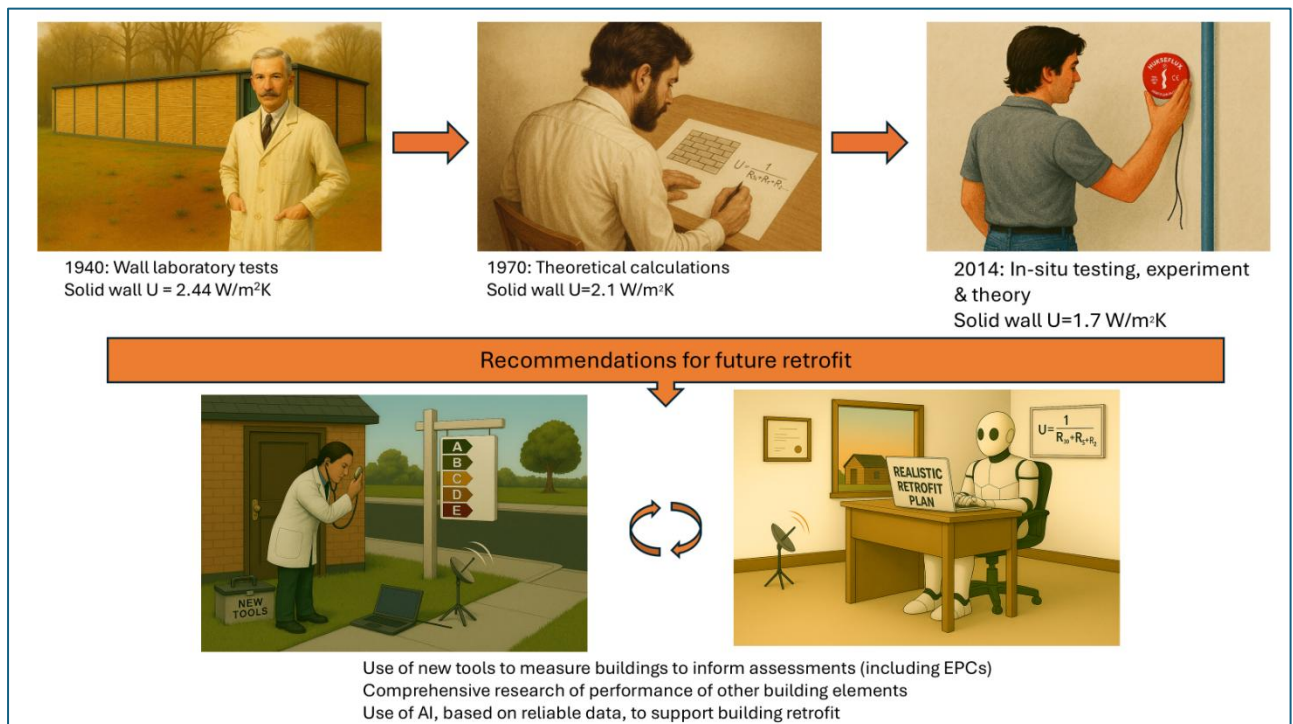
The thermal performance of solid wall homes in England

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Graphical Abstract



Abstract

Work on defining the first standard coefficients for thermal transmittance began with experimental work in the 1920s and 1930s, with standardised coefficients published by the Institute of Heating and Ventilating Engineers (IHVE) in 1940 in the *IHVE Guide to Current Practice*. For a plastered 9" thick (220mm) solid wall, the U-value published in the 1940 *Guide* was equivalent to $2.44 \text{ W/m}^2\text{K}$. This value was not revised until the 1970 version of the *IHVE Guide*. Rather than rely solely on experimental values from full thickness walls, a theoretical calculation was used for this revision. The U-value published in the 1970 *Guide* was equivalent to $2.10 \text{ W/m}^2\text{K}$.

In the 2010s my work measured the U-values of over 300 solid walls *in-situ*. Fieldwork was accompanied by a wide-ranging set of other measurements including:

- Hot-box tests
- Moisture tests
- Thermal conductivity measurements of bricks and mortar

- Comparison of revised theoretical and measured U-values
- Consideration of the implications of findings for theoretical U-value calculations of a typical wall

These results supported U-values which were significantly lower than in use at that time (originally proposed in the 1970 IHVE *Guide*). This could be attributed to a lower moisture content, and the presence of air gaps within the wall.

Based on these results, the standard U-value coefficient to be used for Energy Performance Certificates (EPCs) for 9" (220mm) thick solid wall was changed to 1.7W/m²K. This represents the most significant revision to solid wall U-value assumptions since 1970. The body of work I present here represents a substantial original contribution to knowledge. The findings have had direct impact on Government policies and current practices and changed the way millions of homes energy ratings are assessed. The research has been cited in government consultations, academic literature, and industry guidance, and has significantly influenced the direction of retrofit policy.

My research also highlighted the variability in the U-value of solid walls due to differences in construction, materials and moisture contents. As energy ratings become increasingly used for regulatory and other policies it is important that new and developing *in-situ* techniques for measuring U-values are incorporated.

A programme of research, similar to that conducted for solid walls, is also needed for other core building elements, including other wall types, roofs and floors. Many of the assumed standard coefficients for these elements are unlikely to have been challenged in many decades.

There is also a major opportunity to apply machine learning and AI techniques to enhance the assessment and recommendation of retrofit solutions, complementing data from surveys and measurements. The benefits of these techniques, however, are unlikely to be achieved unless the models can be trained on new reliable base data across a range of building elements.

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Appendices (Published works)

The four published works which form the core of this thesis are attached as Appendices A to D.

Appendix A (Report 1):

Hulme, J. and Doran, S. (2014) *In-situ measurements of wall U-values in English housing*. Garston: Building Research Establishment.

Appendix B (Report 2):

Hulme, J. (2016) *Solid wall heat losses and the potential for energy saving: The nature of solid walls in situ*. Garston: Building Research Establishment.

Appendix C (Report 3):

BRE (2016) *Review of default U-values for existing buildings in SAP. Consultation paper CONSP:16*. Garston: Building Research Establishment.

Appendix D (Report 4):

Hulme, J. (2015) 'Energy use and home temperatures in English housing: results from the energy follow-up survey', in *Proceedings of ECEEE Summer Study 2015*. Stockholm: European Council for an Energy Efficient Economy.

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The work is dedicated to the householders who gave so much time (and in many cases gave parts of their walls) in support of this work and our ongoing efforts to find solutions to the climate challenges of our time, and without whom this research would not have been possible.

Declaration

I declare that all the material contained in this thesis is my own work.

Introduction

This thesis is about the walls of a house. It is specifically about the 9-inch (220mm) solid brick wall, seemingly the simplest of all wall types. It tells a story of how these walls are much more diverse and complicated than first impressions suggest, and how this affects their ability to prevent heat loss.

Defining the thermal performance of the walls of a home is not just an academic exercise. The values given to thermal performance are inputs into the calculation of estimates of the energy use of a home. These estimates are put to a large number of uses, including for national carbon accounting, and are relied upon to allocate of billions of pounds of public and private investment in retrofit. If thermal performance is incorrectly estimated there are a number of implications: heating systems such as heat pumps may be mis-sized, insulation savings may be overstated, and ultimately householders may lose trust in the promises of policymakers to save them energy and money. This thesis demonstrates that assumed values for thermal performance were indeed wrong for an extended period of time. It explores the context of how the performance of walls were originally defined and subsequently revised, and discusses the consequences of uncertainty in the standard coefficients used for solid walls, and other similar quantities.

This work draws on my research completed in the 2010s, but the findings continue to have great relevance today. The UK's housing stock remains among the least energy efficient in Europe, and there is an increasingly urgent need to make progress in energy efficiency improvements if we are to meet national and international targets. Numerous policies have been recently launched, or are due to be launched shortly. This includes support for heat pump installations and wall insulation, and penalties for homes deemed energy inefficient on their Energy

Performance Certificate (EPC). But for these types of measures to be successful it is *essential* that existing performance of the building is understood. Only then can building performance be properly rated through items such as the EPC and the benefits of intervention stated with any confidence, and technical risks (for example of mis-sizing heat-pumps) avoided.

The research context has also expanded significantly since the original fieldwork was undertaken in 2011-2012. At that time, the primary concern was reducing carbon emissions from (primarily) gas-heated homes through fabric improvements. Today, the policy landscape has expanded to include the mass rollout of heat pumps, where accurate U-values are essential for correct sizing. Summer overheating, where wall thermal mass affects indoor temperatures, is also of increasing concern. And the expansion of EPCs for regulatory enforcement rather than as simple information tools makes confidence in energy performance essential. The findings of this research are, therefore, increasingly relevant today.

More generally, without improved understanding of the basic elements of energy performance there is a significant risk of eroding trust in the assurances of policymakers and advocates of energy efficiency. Households with poorly performing technologies will not be advocates of change to other households. And if promised benefits do not materialise at a large scale because of outdated or oversimplified assumptions then this (by undermining trust) risks the success of the policy. It also has direct implications for the household concerned who have undertaken work at cost and inconvenience, but not seen any benefit in terms of reduced fuel bills. These issues were highlighted through my work and, although some action has been taken to address them, much more can and should be done.

U-values of solid walls

The UK has the highest proportion of homes built before the second world-war in Europe (Piddington et al., 2017; Corlett and Judge, 2024). These homes represent 30% of the housing stock in England (DLUHC 2025), but represents 38% of the total carbon emissions from the

housing stock for space heating, water heating and lighting. (DLUHC 2024). These older homes are typically built with solid (rather than cavity) walls. Homes with solid walls currently account for 28% of the housing stock in England (DLUHC 2024).

The energy use of homes, and the associated carbon emissions, are products of the energy performance of the building 'fabric' (i.e. the nature of the building materials), the building technologies (e.g. space and water heating system), the behaviour of the occupants, and external weather and environmental conditions. These different aspects of the energy use of a home are not independent. The sizing and subsequent performance of heating systems, for example, is dependent on having a good understanding of fabric heat losses. If a home is assumed to lose more heat than it does in reality then a heating system may be oversized and run inefficiently. Likewise, the way that an occupant interacts with their home can be affected by its fabric performance. A home that loses a lot of heat (perhaps being expensive to run) may be heated in a very different way to a well insulated home. Even the weather and fabric performance are inter-related. Damp walls transmit more heat than dry walls, and exposed conditions can lead to draughts and a loss of thermal comfort. In this way such aspects which come together to define the energy use of a home can lead to sometime unexpected or counter-intuitive results. The influence of weather conditions on measured and modelled performance can be accounted for in several ways. The Heat Flow Meter method used throughout this work averages readings over a period of at least two weeks, so that day-to-day variation in temperature and solar gain is smoothed, and measurement is undertaken in mid-winter when the temperature difference across the wall is greatest and most stable. For the modelling of retrofit solutions, weather is more usefully treated not as a source of error to be removed but as a variable in its own right which needs to be accounted for by performing calculations across a distribution of possible scenarios and paying attention to likely 'worst case' scenarios for each circumstance.

This thesis reflects on my work which has aimed to understand in detail the thermal performance of the most common type of wall found in pre-war homes, the 9" (220mm) solid wall, and the quantity known as the U-value. In particular, I place my work in the historical context of research into the thermal performance of these types of walls and the development of standardised U-value coefficients. Much of this original work took place at a time when these types of walls were still commonly being built in the UK, and I reflect on how understanding has progressed, and what lessons can be learned from the various revisions and re-revisions as our understanding develops.

The coefficient "U" (for U-values) was first proposed in 1868 by Thomas Box in his '*A Practical Treatise on Heat, as Applied to the Useful Arts*' (Box, 1868). Considering the heat lost at a single exposed wall, Box produced a series of coefficients which could be used to estimate heat losses. He proposed that this take '*the value of U, or the loss in Units per square foot per hour*'. Box's original work importantly included the combination of all relevant types of heat transfer, and specifically the inclusion of radiative processes alongside convective and conductive heat transfer.

Since this proposition, '*U-values*' have become invaluable tools in estimating heat losses from building elements, and are ubiquitous in the field of building thermal performance. They are used for estimates of heat losses and subsequently feed into calculations of heating and cooling requirements. These are then used to appropriately size heating and cooling equipment. More widely they have uses within estimates of thermal comfort, and condensation risk. Minimum U-values which should be achieved are set within regulations, including England's Building Regulations Part L (MHCLG, 2021), and are used within composite indicators of building performance including BREEAM (BRE, 2025) and the UK Net Zero Buildings Standard (NZCBS, 2025).

Conduction heat losses through building elements are typically calculated using a steady state equation shown in Equation 1 below (Loudon, 1968):

Equation 1:

$$\frac{q}{A} = U(t_i - t_o)$$

Where q/A = rate of heat loss per unit area; U = thermal transmittance of the structure (the U-value) and t_i and t_o are the inside and outside temperatures.

U-values of simple walls are typically calculated as the reciprocal of the sum of thermal resistances shown in Equation 2 below (Loudon, 1968):

Equation 2:

$$U = 1/(R_{si} + R_1 + R_2 + \dots + R_{so})$$

Where R_{si} and R_{so} are the inside and outside surface resistances and R_1 , R_2 etc. are the thermal resistances of the structural components. For a slab of material of thickness l and thermal conductivity k , $R = l/k$. The internal and surface resistances, which are calculated as equal to $1/h_r + h_c$ where E is the longwave Emissivity and h_r and h_c are the radiation and convection coefficients (Loudon, 1968).

U-values are used in calculations of a steady state temperature condition (i.e. the calculation is made disregarding fluctuating temperature conditions and as if temperatures are maintained at fixed temperatures on either side of the wall). These types of calculations do not reflect the dynamic situation of changing temperatures, absorption and re-emission of heat within a real building. In solid brick walls (and in other heavyweight construction types) the thermal mass of the bricks means that heat is absorbed during warm periods and released during cooler periods. This effect is not captured by a steady-state quantity like a U-value. Alternative approaches exist but are more complex to include in standard calculations, but can be

incorporated into dynamic thermal simulation using tools such as *EnergyPlus* or *IES-VE*. These include using time-varying parameters such as the periodic thermal transmittance (Y-value) (described in ISO 13786:2017). The increasing availability of computational power has made these dynamic approaches more accessible, however, though they require additional input data including specific heat capacity and density which are typically not available for existing buildings. For these reasons, U-values remain central to the calculation of energy performance of existing homes. Despite this, dynamic approaches are recognised (given the correct input data) to provide more accurate results in many circumstance and could potentially be made better use of today and in the future. These opportunities include by looking for to complete dynamic calculations and incorporate periodic thermal transmittance (Y-value) and specific heat capacity of the construction where these values are already available rather than simply defaulting to U-value. In particular, density and thermal conductivity, provide the input data that such methods require and may be available in some circumstances even for existing homes (e.g. for newer homes, if details of the materials used remain available). Dynamic methods do not need to be applied universally, but can be reserved for the cases where it matters most, such as the assessment of heat retention effects in heavyweight construction or specific geographical locations. When dynamic assessment is likely to add particular value to an assessment it may be valuable to collect the necessary input data (including using some of the new and emerging measurement techniques described in this thesis). This thesis forms a reflection on four published works which collectively help to define a U-value for solid walled buildings in England. The works include measurement of wall U-value taken *in-situ* in several hundred homes. These were then considered in the context of the observed construction of the wall, and additional measurements including of the thermal conductivity of bricks and mortar, and air spaces, which make up this type of wall. Further assessment was made the moisture content of the walls, and considers how moisture content affects conductivity. Large scale reproductions of historic walls were also made and tested at the National Physical Laboratory

(NPL). The works bring together extensive and comprehensive fieldwork, small and large scale laboratory experiment, and theoretical calculations to propose a new set of coefficients to be used when assessing the important quantity of wall U-value. Collectively these works form a body of research which has been used to redefine the U-values of walls of historic homes, and in particular solid wall homes. This research forms the latest chapter in the understanding of thermal performance for these types of home, and has been used to redefine these standard coefficients used when it is necessary to understand heat losses. The results of my work have also been used to help explain, at least part of, the 'performance gap' which is observed between the expected and observed energy performance of solid wall homes. This thesis places my published works in this context and provides implications of the findings and recommendations for further work.

Summary of published works

Table 1: Summary of published works attached to this thesis (Appendices A to D):

ID	Title	Date	Attached as Appendix
1	In-situ measurements of wall U-values in English housing	July 2014	Appendix A
2	Solid wall heat losses and the potential for energy saving: The nature of solid walls in situ	November 2016	Appendix B
3	Review of default U-values for existing buildings in SAP (Consultation paper CONSP:16)	June 2016	Appendix C
4	Energy use and home temperatures in English housing: results from the energy follow-up survey (ECEEE 2015)	June 2015	Appendix D

These publications represent a unique contribution to knowledge. They are novel both as sets of single measurements and in combination together – i.e. by explaining a measured discrepancy, validating it under controlled conditions, and carrying it into the coefficients used nationally for the production of EPCs. These works are distinctive in combining large-scale field measurement of U-values with the detailed physical investigation of wall construction, laboratory validation, thermal conductivity testing, and moisture analysis. Each publication addressed a specific gap in knowledge. In *Report 1* the scale of the discrepancy between the existing standard coefficients and *in-situ* measurements was established through large scale fieldwork. In *Report 2* I completed additional fieldwork and laboratory work and explained why this discrepancy exists. In *Report 3* I translated the technical findings into the national calculation methodology used for Energy Performance Certificates. Finally, in *Report 4* I

considered how these findings may be affecting the performance gap between predicted and observed energy use.

The four published works which form the basis of this thesis were produced within a collaborative research environment at BRE, and in partnership with the National Physical Laboratory (NPL). The scale of the fieldwork and laboratory programmes was such that they necessarily relied on teams of technicians, field operatives and laboratory staff. This section also sets out my own contribution to each work, and distinguishes it from the contributions of colleagues and collaborators. While many individuals supported the delivery of these projects, the design of the investigations, the analysis and interpretation of the results, and the translation of the findings into revised standard coefficients, were led by me.

My contribution is focussed on the conception and direction of an integrated programme of research. I established the scale of the discrepancy, explained its physical and historical causes, validated the measurement method, and was able to then incorporate the revised value into the national methodology. What constitutes this as a coherent and independent doctoral contribution is the bringing together of fieldwork, laboratory validation, construction history and policy translation into a single, coherent reinterpretation of the thermal performance of solid walls.

Report 1: In-situ measurements of wall U-values in English housing (July 2014)

This report describes a large-scale field study undertaken in the winter of 2011/2012, which measured the U-values of 300 homes across in both solid wall and cavity wall construction, as well as a limited number of follow-up measurements and investigations of moisture content of walls and presence of insulation in 2012 and 2013. This report indicated a significant difference between the *in-situ* measured U-values of all wall types and both the standard coefficients used for Energy Performance Certificates (and listed in the RdSAP document from that time), and

theoretical calculated U-values. This work confirmed some of the findings of earlier fieldwork undertaken in 2011 (BSRIA/EST 2011). It also began the process of considering how differences in items such as material thermal conductivity, moisture content and air gaps within walls may act to reduce the U-values. Crucially, however, the work did not collect enough data to adequately explain *why* the U-values, especially of solid walls, were different and a much deeper and more targeted investigation was identified as being required.

The novel contribution of this work is in its scale and that it is nationally representative data. Whereas the earlier BSRIA/EST fieldwork had indicated that solid walls might perform better than the standard coefficient, that finding rested on a small sample. By measuring approximately 300 walls drawn from the English Housing Survey frame, this work established the scale of the discrepancy across the stock, and, in particular, first demonstrated the extent of the variation between walls of nominally the same construction.

I was the lead author of this report and responsible for all drafting and the majority of accompanying analysis. I designed the field study, including the approach to sampling from the English Housing Survey (EHS) frame and application of the in-situ Heat Flow Meter (HFM) protocol used to measure each wall, as well as follow-up borescope investigations on cavity walls. I conducted fieldwork within one of the four fieldwork teams. My colleague Dr. Sean Doran established the data analysis excel model based on previous work he had undertaken used to process the heat-flux and temperature records, but I modified and improved these to automate features and enhance data quality. The interpretation of the differences between the measured, calculated and RdSAP values, together with the assessment of possible systematic measurement error arising from the hot-box verification, were also my responsibility and were led by me. I led all analysis and comparison with English Housing Survey data, designed the follow-up fieldwork which would be taken forward in Report 2. I was responsible for all drafting

of the final report, and the presentation of the results to the Department of Energy and Climate Change (DECC). This report was internally peer-reviewed at BRE by relevant experts. These included Dr. Brian Anderson at BRE (an international expert on U-value calculations), and Dr. Les Shorrock (an expert on energy performance). It was also subject to external peer review in line with DECC Science policy by academic reviewers, with comments provided back to me via DECC. Although the comments were anonymised before being presented to me, I understood that the panel of researchers used for this task included experts at University College London, Loughborough University and Leeds Beckett University.

Report 2: Solid wall heat losses and the potential for energy saving: The nature of solid walls in situ (November 2016)

This work formed the follow-on detailed assessment of a large sample of solid wall brick homes, and the materials used to construct these homes, to help understand why U-values in these types of homes were lower than the standard coefficients and standard calculations. The work is multi-faceted and comprises of an extensive and wide-ranging programme of fieldwork, laboratory and experimental studies, and subsequent revisions to calculation methods which can be compared to observations. Specifically:

Fieldwork: A programme of fieldwork where U-value measurements were taken in 137 dwellings, accompanied by an examination of the interior of the wall and the removal of samples in 87 homes. This included inspection the interior of the wall (see Figure 1), and removal of a sample of brick and mortar for density and moisture testing.



Figure 1: An example of the space revealed inside a solid wall following the removal of a 'stretcher' brick, from Report 2. The joint between the two stretcher bricks (known as the 'collar joint') shows little evidence of mortar; the lack of staining across most of its surface indicates that no mortar was present in this space. This air space is likely to significantly increase the thermal resistance, and reduce the Wall U-value.

Laboratory hot-box tests: Six two-by-two metre square sections of solid walls of different configurations were built in the laboratory at the National Physical Laboratory (NPL) and tested in their guarded hot-box apparatus (see Figure 2). These tests used historic bricks and materials were designed to identify, in a laboratory environment, the effect on U-values of the fieldwork observations. These tests also were designed to investigate any differences between the in-situ (heat flow meter) measuring techniques and the results from the hot box.



Figure 2: The NPL hot-box experiments in Report 2. From upper left. (1) Two sections of solid wall inside testing frames. (2) Me installing heat flow meters on the plastered (warm side) of the wall to allow direct comparison with hot box measurements (3) The external (cold side) of a wall, surrounded by insulant to minimise heat losses (4) A view of the open hot box. Warm side coloured red, cold side coloured blue. Various thermocouples used in monitoring test are attached to the apparatus.

Moisture tests: Extensive moisture tests at three dwellings were undertaken to determine the extent that moisture may vary across different facades of the same solid wall building. Drillings taken at several depths and locations on each facade showed that moisture content varies significantly, not only between the different facades of a dwelling but across a single facade, with both brick and mortar affected. Local features including run-off and rising damp, together with the orientation of the wall relative to prevailing winds, may account for much of this variation. The principal implication is that a single measurement cannot be taken as representative of a wall as a whole, which reinforces the case for characterising these walls through distributions rather than single assumed values. This variation, and its effect on U-values, is discussed further in Part 1.

Laboratory thermal conductivity measurements: Brick

samples returned from the fieldwork were tested for thermal conductivity at NPL and BRE. A revised relationship between brick density and thermal conductivity was proposed based on these findings.

In situ thermal conductivity measurements: A thermal needle probe (a ‘transient heat flow method’) was tested in the field to assess whether thermal conductivity could be readily assessed in situ.

Consideration of the implications of findings for theoretical U-value calculations of a typical wall: The assumptions made in the theoretical calculation of U-values for a typical wall were reassessed in light of the fieldwork and laboratory findings. The effect on the calculated U-values was considered and new thermal paths through this type of wall were proposed.

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

This large programme of work resulted in a significantly enhanced understanding and confidence in why U-values in these types of wall were lower than anticipated, and provided a theoretical basis, grounded in observation, which supported lower U-values for this wall type.

The novel contribution of this work is that it explains the lower-than-assumed performance of the solid wall. The construction at NPL of large-scale reproductions of historic walls, built to include the partially filled joints and brick bats observed in the field, allowed the effect of these features to be tested under controlled conditions, and provided a validated physical basis for the revised coefficient. The reconciliation of this evidence with a recalculated theoretical U-value, based on how the walls were actually built rather than as assumed, constitutes the central original contribution of this thesis.

I am the author of this report, and the investigation was designed by me. The research combined fieldwork in 137 dwellings, with internal inspection and sampling of the wall undertaken in 87 of these, alongside hot-box testing at NPL, thermal conductivity measurement of brick and mortar, and a programme of moisture analysis. The decision to construct the NPL test walls so as to reproduce the defects observed in the field, in particular the partially filled joints and the use of brick bats, was mine, and was made deliberately so that the laboratory could test whether these features did in fact produce the reductions in U-value expected. I attended the laboratory daily and supervised and oversaw the construction of the walls, measurement of heat flux within the NPL hot box, and led the analysis which reconciled the measured U-values with a recalculated theoretical value. I also completed measurements of thermal conductivity of brick samples. The explanation for why these walls perform better than the historic assumption, drawing on the omission of collar-joint mortar, the use of brick bats, and the irregularity of locally-fired brick, was developed by me from the building-history literature. As with the *Report 1*, this report was internally peer-reviewed by a number of internal BRE experts on U-values and energy performance including Dr. Sean Doran, Dr. Paul Davidson, Dr. Les. Shorrocks and Dr. Brian Anderson at BRE. It was also subject to external peer review in line with DECC Science policy by academic reviewers, with comments provided back to me via DECC with the same panel of reviewers as noted for *Report 1* above.

Report 3: Review of default U-values for existing buildings in SAP (Consultation paper CONSP:16) (June 2016)

As the results of the large study of solid wall performance became finalised, I worked together with the RdSAP and SAP development teams to produce a recommendation for a revised U-values to be used in RdSAP. This paper, which was a formal public consultation paper produced for the RdSAP revision which would ultimately take forward these changes into RdSAP and require their use for all EPCs produced in the future. As well as changes to the U-values of uninsulated solid walls, changes were also proposed for insulated and uninsulated cavity walls (based on *Report 1* above) as well and for insulated solid walls. Following the publication of this

paper, a revised RdSAP specification was produced including these changes to U-values. These values therefore, through the new RdSAP specification, went forward into the calculation of EPCs for existing homes from this point forward.

The novel contribution of this work is the translation of the measured and validated findings into the national methodology. It proposed the first revision of the standard solid wall coefficient since Loudon in 1970, from 2.1 to 1.7 W/m²K. This has consequences at national scale including for carbon accounting, the appraisal of retrofit, and for the regulatory use of the Energy Performance Certificate.

This work was published as a BRE consultation paper, rather than under individual authorship. I was a supporting author to the lead RdSAP and SAP development teams, who were responsible for the implementation of the changes within the RdSAP specification, and responsible for translating the findings of Reports 1 and 2 into the proposed revisions to the standard coefficients: for solid walls from 2.1 to 1.7 W/m²K, together with the associated revisions to the cavity wall values. The proposed values, and the evidence base supporting them, were mine. Internal peer review of this paper was completed by Dr. Paul Davidson and Dr. Brian Anderson at BRE. External peer review for this report took place in the form of a public consultation (and subsequent incorporation of any material changes identified by this consultation).

Report 4: Energy use and home temperatures in English housing: results from the energy follow-up survey (ECEEE 2015) (June 2015)

This report presents some of the implications of this work, and was presented as a peer-reviewed paper at the ECEEE conference in France in 2015. It presents broad results from a large study of energy efficiency and energy performance undertaken in 2011, prior to the solid wall insulation project. This report considers the pattern of predicted consumption (shown by the SAP rating) and observed energy use (shown by fuel spend). It can be seen that households

with low SAP ratings (which include most solid wall homes) are not spending as much on energy as predicted by SAP. This difference is likely to be behind at least part of the 'performance gap', whereby energy savings from retrofit fall short of predictions (Gupta and Gregg, 2016; Maby and Owen, 2015). My findings provide part of the explanation for this gap, i.e. if the base assumption of wall performance is too poor then predicted savings after insulation will be overstated (the savings were never there in the first place). These findings also reflect and help explain the 'prebound effect' identified by Sunikka-Blank and Galvin (2012) which identifies how relatively inefficient dwellings consume less than predicted.

This report is single-authored, and was subject to conventional peer review as part of the ECEEE Summer Study process. I completed the analysis of the Energy Follow-Up Survey (EFUS) data, identified and quantified the prebound effect within the UK sample, and connected the pattern of whole-dwelling underspend to the wall-performance findings of the other reports.

The novel contribution of this work is that it connects the single wall-level finding to a pattern observable across the whole stock. In identifying and quantifying the prebound effect within the English housing data, it provides independent, whole-dwelling evidence consistent with the conclusion that these dwellings lose less heat than the standard assumption predicts.

Validation of work

The work was validated through several independent means. Each report was subject to technical scrutiny by BRE experts in U-value calculation and energy performance, and Reports 1 and 2 additionally underwent external academic review through the Department of Energy and Climate Change, with reviewers from University College London, Loughborough University and Leeds Beckett University. Report 3 was tested through formal public consultation, and Report 4 through peer review for the ECEEE Summer Study. The findings were confirmed experimentally at the National Physical Laboratory, where historic wall sections tested in the guarded hot box

provided controlled corroboration of the reductions measured in the field. Most significantly, the revised coefficients were adopted into the RdSAP specification and have been used in the production of Energy Performance Certificates ever since. Subsequent independent research, in the United Kingdom and internationally, has further supported the findings, as discussed in Part 1.

Structure of this thesis

This thesis is structured in two parts. Part 1 places my published research in its historical context. This section describes the development of U-value measurements and establishment of the first accepted coefficients from the 1920s to the present day. Part 2 discusses the implications of these findings and sets out conclusions for policy, research and practice.

Part 1.

Developing and revising U-values for solid walls

*“Thou wall, O wall, O sweet and lovely wall,
Show me thy chink to blink through with mine
eyne.”*

The establishment and development of standardised U-value coefficients

My work represents the most recent major iteration of research which has been undertaken to define standardised U-value coefficients, also known as ‘design U-values’. These are values that are accepted and typically used in the variety of calculations used to assess energy performance. This includes the RdSAP methodology used to produce Energy Performance Certificates (BRE, 2024) and the assessment of heat losses used to size radiators, boilers and cooling systems (e.g. CIBSE, 2021). These values were first established in the first half of the 20th century as new knowledge and measurement techniques became available, and when homes with these types of walls were still being built in large numbers. This was followed further revisions, initially in the early 1970s and subsequently with my work in the mid 2010s. These revisions coincided with an increased need to consider the thermal performance of these types of homes, for example in response to new regulatory requirements or enhanced policy ambitions for these homes.

This thesis focuses on solid wall homes in England, but the findings are relevant in other nations. The 9-inch (220mm) solid brick wall is a construction type found across Northern Europe, North America, and former British colonies. Similar discrepancies between assumed and measured U-values have been identified in Luxembourg (Merzkirch, 2015), Italy (Lucchi, 2017), Cyprus (Xeni, 2015) and are also likely to be found elsewhere. Even where construction practices differ, many of the findings from my research may also be applicable in these countries, or provide clues to help guide further research in these cases.

Table 1 below shows the different standardised coefficients in place at different points in time. The first publication of standard values was in the 1940 Institution of Heating and Ventilating Engineers (IHVE) guide. These were then first revised for the 1970 version of the IHVE guide. The original version of the Reduced Data SAP calculation method was introduced in 2006 and

contained default values for use in existing buildings. This value was updated in 2017 based on my work.

Year	1940	1970	2006	2017
U-value for plastered solid walls (W/m²K)*	2.44	2.10	2.1	1.7
Source	IHVE Guide	IHVE Guide	RdSAP (v9.80)	RdSAP (v9.93)
Based on:	<i>Dufton (1940)</i>	<i>Loudon (1968)</i>	<i>Loudon (1968)</i>	<i>Hulme and Doran (2016)</i>

* n.b. older references will typically use Imperial units BTU/ ft²/°F/h. These have been converted to W/m²K in this table.

Understanding how building elements lose heat is an essential pre-requisite to designing efficient and effective heating and cooling systems. U-values are central to this and have been key elements of the heating engineers toolkit for over a century. In this part of my thesis, reflecting on my published works, I consider how the values in Table 1 developed, and how these have been influenced by a changing research and policy background. My work was the source of updates to these values made in 2017, as part of this timeline of continual development of understanding and knowledge.

The first standardised U-value coefficients

The late 19th century and beginning of the 20th century marked a period of increased scientific study of buildings, and the dawn of many aspects of modern building sciences. This was accompanied by the establishment of various professional institutions, including many which are still in existence today. For example, in the USA, the American Society of Heating and Ventilating Engineers (ASHVE) was established in 1894, which was later amalgamated with the American Society of Refrigeration Engineers (ASRE), to become ASHRAE. In the UK, the Institution of Heating and Ventilating Engineers (IHVE) was established in 1897. This Institution

would later become the modern-day Chartered Institute of Building Services Engineers (CIBSE). IVHE's core membership were engineers responsible for performance of heating and ventilation systems. Therefore, having a good understanding of heat losses from buildings was central to their needs. Early work of the Institution included work on standardisation of processes and values (Hodges, 1996). Dufton (1939) notes that a motion of the Institution was passed at a summer meeting in Leamington in 1915:

"That it is desirable that the Institution take immediate steps to fix certain standards for the use of the trade generally, and the members of the Institution in particular, and that steps be taken to make it known to architects, consulting engineers, municipal engineers and others that the Institution of Heating and Ventilating Engineers has proved and adopted the said standards for general use"

Dufton further notes that the first item on the list for standardisation was:

"Coefficients for heat-losses from glass, walls, ceilings, floors, air-changes - etc."

Notwithstanding this recommendation in 1915, it would take another 25 years before agreed and recognised coefficients for thermal performance were achieved. To do this would require primary research, which would take place in the period after the First World War.

Early work and drivers of research – laboratory based testing

During the period following the First World War there was an increased recognition of the poor health of the population, which had been highlighted through the military conscription process, and the relationship between living conditions and health. Immediately following the armistice, the Prime Minister, David Lloyd George, promised an ambitious programme to build "*homes fit for heroes*", and made this mission central to the general election campaign which had also been called at that time. There then rapidly followed by the "Addison Act" (Housing, Town Planning, &c. Act 1919) and the establishment of a programme of research into buildings and

building performance in support of this mission . This included the establishment of the Building Research Board (BRB) in 1920 to “*consider and direct the conduct of research and building materials and methods of construction*”. This body, and the subsequently established Building Research Station (BRS), are the predecessors to the modern private sector consultancy the Building Research Establishment (BRE) (Lea, 1971).

Among the handful of initial reports published by the nascent BRB, three related to the thermal properties of buildings and building elements. (BRB, 1921; Griffiths, 1923; Fishenden and Dufton, 1929). These reports outlined the findings from new and recent work, including work undertaken during the final years of WW1 and some other studies that had taken place internationally. Through a process of experiment there began to develop an understanding of the performance of basic building elements under laboratory conditions. Reflecting on my own work, it is interesting to note that some of this early work was undertaken in collaboration with the National Physical Laboratory (NPL) (e.g. Griffiths 1923), as was some of my own experimental work 90 years later. Indeed, many aspects of my work aligned with the processes and experiments originally undertaken at this time albeit with greatly enhanced technological and measurement capabilities. What is notable is that the work of this period was focussed on defining performance based on experiment and observation. As outlined below, as research and work in this area continued there would be a move away from reliance on experimental data, and towards values based on theoretical methods which would provide more flexibility.

Continued experimental work in the inter-war period – the BRS “wall laboratory”

This very earliest experimental work was principally based upon experiments which had taken place under laboratory conditions (e.g. Griffiths, 1923), but was this recognised to have limitations, principally that the walls were not subject to realistic conditions of weather and heating (Dufton, 1942). The newly established BRS began a process of additional

experimentation in the 1930s, including the construction of a large scale laboratories. Initially, this work was carried out in a specially built “experimental house” (also known informally as ‘Fishenden House’ after the notable scientist in this field, Margaret Fishenden). This is shown in Figure 3, (Dufton, 1933) which allowed for some initial tests on walls to be completed alongside other experiments. The experimental house produced some of the first BRS estimates of solid wall U-value were produced (Marley, 1935) reporting a U-value of between 1.5 and 1.8 W/m²K. However, there was recognition that a bespoke facility to understand wall heat losses was required which would allow for greater flexibility in experiment under realistic conditions. In 1936 the “BRS wall laboratory”, also shown in Figure 3, was constructed at Garston specifically to consider the thermal performance of walls exposed to realistic conditions. The laboratory consisted of six chambers, one side of which faced north and could be replaced with walls of different constructions, with all other surfaces insulated and monitored. By heating each chamber, and measuring the temperatures within the chamber alongside the various losses and the external air temperature, the heat transmission through each wall section could be determined. The results were initially published sporadically in the *Journal of The Institution of Heating and Ventilating Engineers* (e.g. Dufton & Sheard, 1937; Sheard 1937; Sheard 1938; Dufton, 1942; Parsons, 1949; Parsons & Burnand, 1951), and are collated alongside other measurements over several decades in this facility by Pratt (1969).

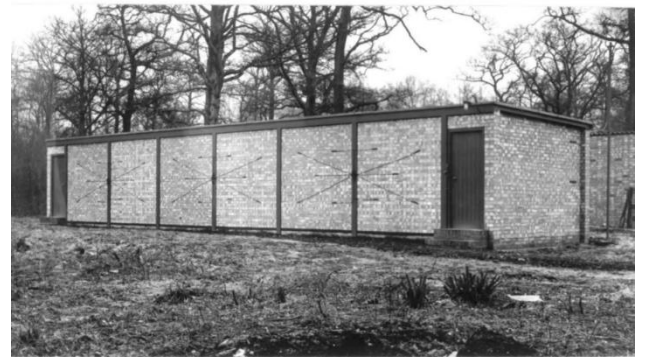


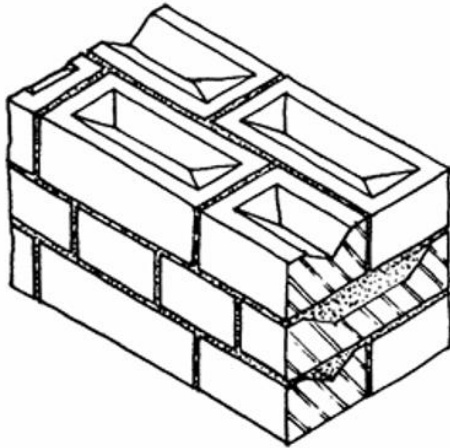
Figure 3: The BRS experimental house (left), informally known as ‘Fishenden House’, and the BRS wall laboratory (right) used to provide initial data which formed the first established U-value coefficients. Initial results were provided from the experimental house, with the wall laboratory established to undertake more comprehensive experiments (from Dufton, 1933 and Dufton, 1941). More detailed description of the wall laboratory can be found in Pratt, 1981.

Pratt provided detailed sketches of the construction of the walls that were tested (Pratt 1969).

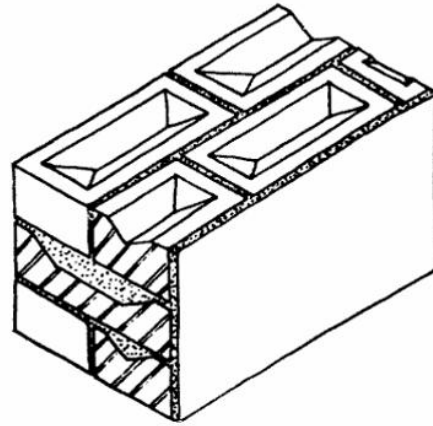
These are reproduced in Figure 4 below. These sketches provide important details which provide clues to why the U-values measured by these walls may have been higher than those measured in my work on these types of walls. One difference was the placement of the indentations within the bricks known as ‘frogs’. The BRS bricks were set in a cement mortar with frogs (the indentations on the bricks) on one side of the bricks placed upwards and fully filled with mortar. Whereas in my fieldwork, one of the key observations was placement of ‘frogs’ down. This could create air pockets, increasing thermal resistance and decreasing the U-value. The diagrams of the original BRS experiments also indicate mortar in all brick joints. Compare this to key findings from my work, which highlight the effect of the numerous airgaps commonly seen in the *in-situ* walls, with some examples shown below in Figure 5. For example, in the walls I studied it was rare for the collar joint (the joint between two side-on ‘stretcher’ bricks) to be fully filled with mortar.

Panel No. 1
Single-leaf wall of solid brickwork, 9 in. thick, constructed in 1936 when the laboratory was built. Fletton bricks set in cement mortar.

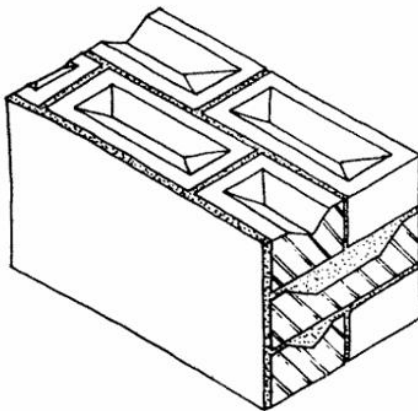
Three similar walls were built at this time and the first set of results are the mean for all three. One wall (in room 5) was retained unchanged until 1949.



Panel No. 2
Single-leaf wall of solid brickwork, 9 in. thick, constructed in 1936. Fletton bricks set in cement mortar. Plastered inside in early February 1937.



Panel No. 3
Single-leaf wall of Fletton bricks, 9 in. thick, built in 1936. Rendered on outside early February 1937.



Panel No. 4
Single-leaf wall of Fletton bricks, 9 in. thick, built in 1946. Rendered on outside, strapped and plastered on laths inside. Total thickness 11 in.

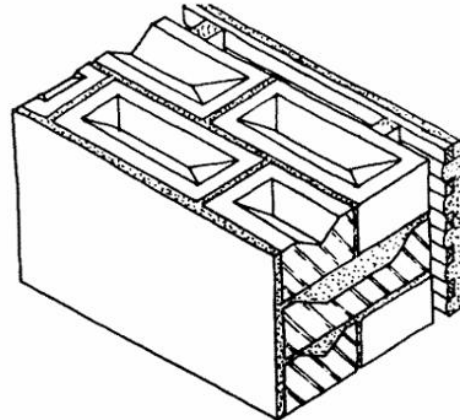


Figure 4: Sketches of the solid wall panels tested in the BRS wall laboratory. The sketches show 'frog-up' bricks with indentations on the top face of the bricks, the type of bonding ('English bond') and filled cement mortar beds (Pratt, 1969).

The walls examined in the BRS laboratory were also at a notably higher moisture content than that in my fieldwork, although the variable moisture content across different parts of the solid walls is commented on (Dufton, 1942). Solid walls tested in the BRS wall laboratory were observed to have much higher moisture contents in the outer quarter thickness of the brick

(corresponding to 1¾ inches, approx. 44mm, of wall) than the inner quarter thickness. The outer portion had a moisture content of 5%, but inner sections ranged from 0.6% to 1.8%. The choice and suitability of a methodology for moisture correction was explored through my work, and the lack of moisture within the bricks (on average) is one of the key differences between theoretical U-values which formed the basis of earlier design values, and the actual values which were measured subsequently.



Figure 5: Examples of air gaps within the walls visited as part of the Report 2 fieldwork, created by the use of broken bricks ('brick bats'). A single lengthways 'stretcher' brick was removed from the wall and the internal condition of the wall was examined. On the left the use of broken bricks in the inner leaf can be seen clearly. The photograph on the right shows the use of a 'snapped header' - i.e. one which appears to be a header (end on) brick but which in fact has been snapped and is only half the original length, generating an additional joint and air gap.

In 1939, based on the wall laboratory results, Dufton makes a renewed case at a meeting of the IVHE for publication of agreed standardised coefficients (Dufton, 1939). He further requests that standardised calculation methods to allow for the calculation of estimates of transmission where experimental data were not available stating '*It is surely preferable that such computations should be on a consistent basis*'. This need for calculation methods, which are informed by and complement the results of experimentation are a key theme reflected through my published work. A significant portion of the work is dedicated to understanding the experimental results, and then reconciling these with the theoretical thermal performance of these walls.

In 1940, a year after Dufton's call for publication of an accepted standard, the IHVE published the first edition of their "*Guide to current practice*" (IHVE, 1940), which was later extracted into a specific focussed pamphlet on heating and ventilation requirements called *Recommendations for the computation of heat requirements for buildings* (IHVE, 1942). These guides included tables listing coefficients of for thermal transmittance (i.e. U-values). Originally, published in the IHVE journal (Dufton, 1940) for unplastered 9" (220mm) thick solid walls these provide a value of 0.47 BTU/ ft²/°F/h reducing to a value of 0.43 BTU/ ft²/°F/h for plastered walls. These are equivalent to a U-value of 2.67 W/m²K and 2.44 W/m²K in modern SI units. These values are significantly higher (i.e. represent greater levels of heat loss) than those used today. In the preface to the *Recommendations* the IHVE state that publication was produced:

" . .with a view to unifying practice and in response to the wide demand from many quarters for authoritative data regarding heat-transmission coefficients . . "

This need to provide an authoritative set of heat loss coefficients to support consistency of practice was, and remains, a core need of designers and heating engineers. As a result, these coefficients became rapidly propagated and referenced. This includes within official guidance produced during the Second World War, produced to address the "*urgent need for the conservation of fuel*" from the Ministry of Fuel and Power (Ministry of Fuel and Power, Fuel Efficiency Bulletin no. 12, 1943) on the Thermal Insulation of Buildings. In this guide the values were published in the context of the need to provide additional insulation, a need that mirrors the background to the publication of my reports.

This theme was continued after the end of the war. The 'Egerton report' from 1945 (Egerton, 1945), which formed part of the *Post-War Building Studies* series of reports produced immediately after the war continues to emphasise the need to consider heat losses:

"The design of buildings with a view to reducing heat loss is, I consider, of equal or even greater importance than actual efficiency of the heating appliances ... in this country there are millions

of detached and semi-detached houses of very low standards of insulation and leaky to air and heat. ... The extra cost of insulation in new housing is negligible compared with the value of the advantage gained over the years”

And a post-war Ministry of Works “practical guide to good building” pamphlet, entitled “*It all depends on U*” (Ministry of Works, 1949) aimed at the builders and specifiers also used figures from the IHVE guide to demonstrate good practice and high performing types of construction.

Through these types of documents, these coefficients for the performance of solid walls became firmly established, and would remain in common usage until the 1970s.

The 1940 “*Guide to current practice*”, containing these coefficients, was to be republished and updated and would become the standard reference guide for engineers today. Today, it has developed into the CIBSE Guides, which provides the recognised standard data used by modern day specifiers of heating and cooling systems in the UK.

The post-war years: attention moves away from older wall types

In the 1950s and 1960s, attention moved away from traditional solid wall construction and towards more modern construction techniques. Pratt (Pratt 1969 and 1981) lists a wealth of concrete, prefabricated and cavity walls as having been tested in the BRS wall laboratory in this period, however, the testing of 9” (220mm) solid wall construction is noted to have stopped in 1949 as research interest and attention moved towards the new post-war construction techniques of that period. At this time progress was also made towards techniques to measure U-values *in-situ* (i.e. in the walls of existing housing). BRS initially developed of a large in-situ ‘hotbox’ which was tested on free-standing walls at the BRS Scottish Laboratories at Thorntonhall near Glasgow (Pratt & Hendry, 1958). These results included assessment of two solid brick walls, which showed significantly higher U-values (i.e. higher thermal transmittance) than measured in the BRS wall laboratory. Pratt and Hendry considered this most likely due to

high levels of moisture in the exposed free-standing walls and in the generally wetter environment of Western Scotland. Outside of BRS, work on thermal transmittance of cavity walls was also undertaken by the London Brick Company, using a variation on the guarded hot-box constructed at Stewartby in Bedfordshire (Dinnie et. al, 1959) although this work did not include any further assessment of solid walls.

The 1970s : Wall laboratory measurements are challenged and a move towards calculated values.

The next stage in the evolution of standard design values for this type of wall was a concerted effort to review and update U-value coefficients which were to be included in the 1970 edition of the IHVE *'Guide to common practice'*. This was significant update, which would establish a new U-value for historic wall types. This U-value would remain in place for over 40 years for these types of walls, until my work was completed which provided the data needed to update these values. Unlike the earlier editions of the guide, which had presented work based on experimental results, the updates to the 1970 Guide were principally based upon theoretical performance of walls. Loudon (1968) argued that a firm theoretical basis for calculations were required in order to allow for flexibility, and the assessment of multiple different wall types. Loudon produced and published a series of calculations and estimates of U-values for walls, including solid masonry walls. These were then placed in context and compared against existing experimental data to provide validation of the results. The BRS wall laboratory results were the key pieces of experimental data which Loudon validated his own estimates against, noting that generally the BRS wall laboratory measurements were around 12% higher than the theoretical values. Of these measurements, however, Loudon noted several deficiencies and additional observations. In particular, of the original results from the 1930s he noted:

"U-values of masonry walls slowly decreased as moisture dried out, and changed noticeably when the walls were left in place for a second or third heating season. Most of the

measurements were made during the first year after erection and the U-values were higher than for typical walls.”

He also considered some of the experimental issues encountered by the laboratory may have resulted in these higher U-values. This included unrecorded edge losses and possible additional heat losses to the corridor guard space. Finally, he questioned whether some of the temperature measurements had been correctly applied. Loudon proposed revised calculated values were used, rather than those based solely in experiment:

“...[Calculated values] have advantages over measured values in that they are more comprehensive and can be assessed for typical average conditions of moisture, airspace ventilation and the like. They can be modified if desired for particularly wet conditions or for particularly windy conditions. They are not subject to the particular moisture contents, edge loss conditions, etc., in test laboratories.”

Loudon’s work was supported by a review of the appropriateness of the moisture content which is applied (via a correction factor) when calculating U-values (Arnold, 1969), and a variety of studies which compiled estimates of thermal conductivities (e.g. Ball, 1968, Pratt and Ball, 1956, Arnold, 1969). Taken together these pieces of work constituted a substantive and comprehensive review of the state of the art at that time, and providing a solid base of data to make revisions.

My own work, undertaken 40 years later, repeated many of these elements used by Loudon in drawing his conclusion. Whereas Loudon was restricted to reviewing older existing data from the BRS Wall Laboratory, measured on newly constructed walls, I was able to ground my work in a large study of *in-situ* wall performance not available at that time (based on the technique established by Anderson in the 1980s (Anderson, 1985)). These observations would also provide important observational information as well as quantitative data. As well as the measurement of walls, I also completed extensive measurements of the thermal conductivity of

brick samples, and of mortar samples, replicating some of the work that Arnold had based her work on for the 1970 IHVE *Guide to common practice* (Arnold, 1969). Examples of samples tested by NPL in this way are shown in Figure 6 below.



Figure 6: Brick and mortar samples tested for Thermal Conductivity at the National Physical Laboratory.

I considered and reviewed the appropriateness of moisture levels and moisture corrections and produced revised calculations of wall U-values to consider how well these matched observation, again mirroring the considerations of Arnold (Arnold, 1969).

My work, however, was able to be focussed on just one or two types of wall. Compare this to the work of Loudon who was attempting to produce a comprehensive reassessment across all building elements including roofs and floors, as well as walls. As a result, I was able to undertake much more in depth assessment of the nature of the walls, as they are found *in-situ*.

Loudon, and the IHVE Committee which was drafting the new 1970 *Guide to common practice*, were satisfied that there was sufficient correlation between his theoretical calculations and that this fell within the bounds of uncertainty of the earlier experimental work. In 1969, BRS Digest 108 “*Standardised Thermal Transmittance*” was published based on Loudon’s calculation method including the U-value for a solid wall of 2.1 W/m²K (BRS, 1968b). This value was then included in the 1970 IHVE *Guide to common practice*, the standard reference guide of the time, based on Loudon’s calculations and these assumptions (IHVE, 1970).

The 1970 IHVE *Guide to common practice* values, while closer to the values proposed and finally adopted following my work, are based on various assumptions which do not match those I used in my analysis or the observations made for solid walls. In particular, the assumed moisture content of the walls (5% for exposed walls in Loudon’s work) was significantly higher than observed in my field studies (my work suggested below 1% on average). These original values were based on the work of Arnold (1969) who openly acknowledges limitations of these data which she states as based on “*sparse*” information available at that time on *in-situ* moisture content. Indeed, as noted above, the solid walls tested in the BRS wall laboratory showed a wide range of moisture contents across the breadth of the wall, as low as 0.6% at the inner portion of brick.

For solid wall moisture contents, queries over a moisture content below 5% is also acknowledged by Pratt in published discussion of U-value measurements undertaken by the London Brick Company (Dinnie et al, 1959)). The moisture content, measured in 1938 was 4.9% by volume, but Pratt acknowledges that this value decreased over time:

“*The U-value of a 9-in. solid Fletton brick wall built in 1936, decreased from 0.45 to 0.40 [BTU ft²/°F/h] over a period of about 12 years. It is believed that this change was due to the drying out of the brickwork, for the technique of measurement did not change.*”

Beard & Dinnie of The London Brick Company undertaking work in the late 1960s (Beard & Dinnie, 1974) also note the lack of information relating to *in-situ* moisture testing stating:

“Although the I.H.V.E Guide gives many conductivities and moisture contents for building and insulating materials there is an acute lack of information on the moisture content attained by the materials in use. . . . we probably have little idea of the of the actual moisture contents in practice and one is unable to make estimates of values which are likely to be realistic. This is clearly an area for further research.”

Notwithstanding these concerns, the work of Loudon certainly represented the state of the art and presents the best available estimates at that time, as he states:

“Although there are still many unanswered questions, the procedure set out in 1970 Guide attempts to provide the best information obtainable in the present state of knowledge.”

Despite this recognition of the uncertainty in these estimates, for solid walls little further work on the fundamentals were made to challenge these original assessments was made for several decades and the standard U-value for a plastered solid wall of 2.1 W/m²K remained largely unchallenged until the 2000s. Solid wall building had ceased to be built in the first half of the twentieth century. It was not until a need arose to consider how best to make energy efficiency improvements to these types of buildings, that interest was rekindled as the importance of the performance of these wall types was recognised.

Energy crises, fuel poverty, and energy conservation

After the ‘*urgent need to need for the conservation of fuel*’ identified in the wartime publications referred to above (Ministry of Fuel and Power 1943), further geopolitical events of the 1970s marked a period of renewed emphasis and interest in energy security. This included a desire to understand options to reduce energy consumption, including for fuel needed to power our buildings. The Energy Crisis of 1973 was caused by an oil embargo in response to the 1973 Yom

Kippur war (Mallaburn and Eyre, 2013). The West saw oil prices raised from \$3 per barrel to over \$12 as members of OPEC raised prices and imposed an embargo on the USA. In the UK serious fuel shortages were encountered and exacerbated by miners and rail workers strikes. In December 1974, a 'three day week' was imposed to ration electricity use. This was followed by a further energy prices shock in response to the Iranian Revolution in 1979. These events acted to highlighted the West's dependence on imported energy, and a renewed emphasis was placed on the need not to waste energy. This included energy for heating homes and other buildings.

The 1970s also saw some of the initial interest in concepts which we now recognise as fuel poverty or affordable warmth. 1978 saw the publication of the fuel poverty research book "*Old and Cold*" (Wicks, 1978). This further emphasised the need to enhanced energy efficiency in the context of enhanced health outcomes and concepts of social justice.

Against this background, the 1970s saw a significant raft of energy efficiency plans established and implemented. The amendments to the Building Regulations which came into force in January 1975 dramatically reduced the maximum U-values for an external wall in a new home from 1.7 W/m²K to 1.0 W/m²K (Building (Second Amendment) Regulations, 1974). This was to begin a process of efforts to increase levels of energy efficiency in new homes which continues to this day. As required U-values in the walls of new homes fell, the effects of clay bricks and mortar in new buildings became reduced relative to other elements of the wall (such as wall cavities, insulating blockwork and other insulants). As a result, research interest continued to move away from the masonry elements of the wall performance. In a note from 1975, which considers priorities for further work on U-values, Loudon recognises the contemporaneous view that the performance of brick materials which make up a wall are of decreasing importance:

"... values assigned to damp masonry . . . have become less critical than before, since they contribute proportionately less to the overall thermal resistance." (Loudon, 1975)

Any mention of the performance solid masonry walls is also missing from official guidance from this period. The 1971 Department of Environment guide to “Thermal Insulation of buildings” (Handyside, 1971) includes a wide range of different construction types, but simple solid wall masonry construction is not among them. This type of wall was simply no longer being built at this time, and this was reflected in reduced research interest and laboratory time which could be provided to these now redundant types of construction.

Energy conservation had started as a recognition of the benefits to energy security and productivity in the 1970s. In the 1980s and 1990s this need was reinforced by increasing recognition of the concepts of global warming and climate change, coupled with formalisation of the concept of fuel poverty by Brenda Boardman in her book “*Fuel Poverty*” (Boardman, 1991).

Alongside this interest in energy conservation in general, in the period between the 1970s and the early 2010s, there was the recognition of the potential for energy savings to be achieved through retrofitting existing homes, including the oldest solid wall houses.

Following the energy crises and subsequently, BRE and others considered a number of options for enhancing the thermal performance of solid wall homes, including cost-effectiveness of measures (e.g. Nash and Muckley, 1976; Southern & Milbank, 1980). The BRE Energy Conservation Unit (BRECSU, established in 1978), also undertook ‘Energy Conservation Demonstration Projects’ (ECDP) and measurements and studies of the performance of solid wall insulation in properties in Tewksbury, Gloucestershire and Harrow, North London (Uglow, 1983) and other examples in Liverpool (Trim, 1991). BRESCU also published case study guidance on how these types of properties can be improved (Trim, 1991). BRECSU’s successor, the Energy Efficiency Best Practice in Housing programme (EEBPH) put out numerous ‘Good Practice’ and other guides to how solid wall insulation could potentially offer increased levels of energy efficiency and reduced bills (e.g. EST, 2004). These studies, however, did not attempt to

review or revise the now long-established U-value for uninsulated solid walls, as established by Loudon and published in the 1970 IHVE '*Guide to common practice*'.

The principal focus in this period was on the potential that existed through measures such as cavity wall and loft insulation. These methods were much more cost-effective and simpler to install than solid wall insulation installed in older homes. We can consider this in the context of other options for enhancing energy efficiency at the time, among which dealing with hard-to-treat solid wall housing was an unattractive option. Some major studies, for example, the 40% house project (Boardman et al, 2005) proposed that it may be more appropriate to undertake demolition of some of these types of properties rather than undertake complicated renovation work.

The BRS wall laboratory ceased operating in 1961 (Pratt, 1981). Although a new 'rotatable' laboratory was constructed no known results relating to wall transmission from this facility were ever published (Pratt, 1981) with the laboratory being glazed and converted for use in air conditioning studies in 1968 (BRE, 1968a).

Rather than laboratory techniques, attention turned to the development of a number of in-situ measurement techniques which allow the assessment of U-values in real walls. These included guarded hot-boxes, thermographic techniques and the establishment of the Heat Flow Meter (HFM) method of measuring transmittance. Laboratory techniques require large apparatus, which could not readily be used in existing buildings. But the technique of using small Heat Flow Meters (HFM), formalised by Brian Anderson in the 1980s (Anderson, 1985), allowed much more ready measurements of wall performance (albeit measurements were needed over an extended two week period). Using these techniques, BRE staff undertook some U-value measurements of a variety of wall types in the 1980s (Ward, 1993). For solid walls, these findings presented some initial indications that the performance of these types of walls may be better than assumed in the standard coefficients (i.e. a lower thermal transmittance); findings

which would later be confirmed in the 2010s when I also used the HFM method to measure a much larger sample of solid walls.

The 2010s and renewed interest in older homes

It was not until the 2010s however, that focus, and crucially funding, began to switch in any major way towards insulating solid wall homes. The UK Government's ambitious Green Deal programme, and the associated Energy Company Obligation, had solid wall insulation as a major measure which was required to meet climate change targets. Both of these Government schemes were predicated on producing an estimate of how much energy had been saved by an insulation scheme. This needed accurate estimates of the performance of the wall both before and after insulation had been applied. In support of these objectives, the Building Services Research and Information Association (BSRIA) and Energy Saving Trust (EST) had begun work on a solid wall insulation field trial on behalf of the UK Government Department of Energy and Climate Change (DECC). This included an assessment of the pre- and post- insulation performance of the walls (BSRIA/EST, 2011; Li et al, 2015). Measurements taken as part of this work identified that uninsulated performance of solid walls may be significantly better than expected (i.e. the U-values in the uninsulated position would be lower than expected). As a result, the effectiveness of solid wall insulation would be reduced on these types of buildings.

Other results from this time began to emerge showing similar patterns. These included on reports produced on heritage buildings by the Society for the Protection of Ancient Buildings (SPAB) (Rye and Scott, 2011) and English Heritage (Rhee Duverne and Baker, 2013). Similar findings for historic buildings were also observed internationally, for example in buildings in Luxembourg (Merzkirch et al, 2015), Italy (Lucchi, 2017) and Cyprus (Xeni, 2015).

These findings also provided a possible explanation for the 'performance gap' between predicted and actual energy savings as a result of retrofit measures. If the baseline performance of walls was better than assumed then the savings attributable to insulation would be smaller

than predicted. Furthermore, it had been postulated that incorrect base assumptions on energy performance of building elements may help explain the phenomenon of the ‘prebound’ effect in older buildings (Sunikka-Blank and Galvin, 2012). The term ‘prebound’ was coined to describe the phenomenon of relatively high energy dwellings, such as those historic dwellings with solid walls, consuming less than predicted by standard models (as opposed to the ‘rebound’ effect for low-energy dwellings which consume more than predicted). In the UK, various studies showed this pattern, including work presented in my portfolio of published work (*Report 4 – Hulme, 2015*), and others (e.g. Kelly 2011).

The findings in the UK were of importance to national policy objectives. Solid wall insulation savings were considered essential components of meeting legally binding carbon budget targets set under the UK’s Climate Change Act and identified as such the Committee on Climate Change (CCC, 2010). If these savings were less than originally assumed, because the walls were performing better in the first place, this was important to take into account as it would impact the ability and trajectory for hitting these targets. On the back of this core question BRE was commissioned to undertake a wide ranging field trial, and subsequent set of measurements which form the core papers in support of my thesis. After a gap of almost 40 years since the previous 1970 revisions to standard U-value assumptions, understanding the performance of uninsulated solid wall had become a necessity.

Summary of impact of published works.

The published works which form the basis of this thesis are summarised in Table 1 above.

These works comprise a thorough and multi-faceted assessment of the thermal performance of solid wall dwellings in England. The historical context outlined above describes how the original standardised coefficients for wall performance evolved, initially based on experiment and then pivoting to be based principally on theoretical calculation in 1970. It also outlines the background to the commissioning of this work in the 2010s. My work represents the latest

iteration in the body of research to understand the thermal performance of solid wall homes.

My work combined both theoretical and experimental approaches, aiming to reconcile the results of experiment and field work within a theoretical framework. This provides the flexibility provided by calculated methods to adjust and predict levels of performance, as highlighted by Loudon in 1968, with the additional confidence provided by measurement. The work provides a robust answer to the questions posed by the commissioners of the work in Government on the thermal performance of these types of walls, and crucially addressed both the measured performance as well as providing an explanation of what characteristics of the walls lead to this performance. The confidence provided by the results was sufficiently high to allow changes to be made the national tools used to assess the performance of walls, including Energy Performance Certificates (EPCs).

In the UK, EPCs are legally required to be available for the sale or rent of dwellings (HMSO, 2012 Energy Performance of Buildings (England) Regs). A wide variety of measures and metrics are displayed on EPCS, but it is commonplace for focus to be on the main EPC rating. This rating, which runs on a scale from A (best) to G (worst) is based on a calculation of the running cost of the dwelling, under standardised conditions and fuel prices. Initially introduced as an information tool for prospective occupants and owners, EPCs in England have more recently been used to determine legal compliance against another set of regulations called Minimum Energy Efficiency Standards (MEES). These standards make rental of dwellings with an EPC rating below a certain value illegal. Current standards preclude the rental of a property with an EPC rating below EPC Band E, although there are also current proposals to tighten these standards so that rental is only allowed in properties with a Band C rating or better (DESNZ,2025). EPCs are also widely used, outside of regulation, within organisations Environmental and Social Governance (ESG) targets. For example, many large landlords may specify that all of their stock needs to achieve a particular EPC rating. Another use of EPC

ratings within the private sector is in determining eligibility for 'Green Mortgages' where a preferential lending rate may be tied to achieving an improvement in EPC rating.

EPCs are currently produced using a procedure called the Standard Assessment Procedure for the Energy Rating of Dwellings (typically shortened to the acronym 'SAP'). SAP was originally developed by BRE and is based on a version of the BRE Domestic Energy Model (BREDEM) (Anderson et al., 1985). SAP and BREDEM are based up a simplified heat transfer calculation and can be used for new dwellings (for which SAP is a key part of the Building Regulations compliance process) as well as for existing dwellings. However, for existing buildings, it is recognised that detailed performance data on, for example, wall construction is unlikely to be readily available to the person trying to perform the calculation. For this reason, a set of predefined assumptions and conventions were created for existing dwellings. This is called Reduced Data SAP (shortened to RdSAP). In this way RdSAP, and the assumptions within it, underpin the whole of the EPC process and are fundamental to both regulatory (e.g. MEES) and non-regulatory (e.g. Green Mortgages) uses of EPCs.

The original assumptions for the U-value of solid wall dwellings in England within RdSAP were produced in 2005 and stated that the U-value to be used in the calculation for solid wall dwellings was $2.1 \text{ W/m}^2\text{K}$. As outlined in detail above, this value was originally developed in the late 1960s (Loudon, 1968). It was based on theoretical calculation of wall performance and validated against some experimental data from the 1930s.

Following the challenges to this value, initially identified by BSRIA/EST field survey (see above) a key objective of my work was to challenge and propose revision this value. My first published work attached to this thesis (*Report 1: Hulme and Doran, 2014*) presents the results of a large field study of over 300 dwellings. The objective of this work was to provide a sufficiently large and representative sample, collected in a short period of time required by Government, with a key aim being to provide additional data to confirm or challenge findings emerging form the

BSRIA/EST trial that suggested U-values of uninsulated solid walls were lower than expected. It was designed as a large, but (for reasons of speed) necessarily shallow, study which aimed to measure a large number of walls across England, but not to conduct significant deeper investigation into the nature of these walls or any reasons for observations. The work also considered other wall types. Of the 300 walls around half were cavity walled dwellings (both filled with insulation and unfilled), with the aim to consider if similar concerns may exist for cavity wall dwellings. Indeed, for cavity wall dwellings the project included some extra measurements, including inspections made using a borescope to view the condition of the insulation. For solid walls, the results from this study broadly confirmed the findings from BSRIA/EST, i.e. these types of walls were performing significantly better than standard calculations might assume. It did not, however, provide sufficient data to explain *why* this was the case. It remained unclear what it was about the walls, the measurement method or the calculation method which do not bring them into better alignment. This left the results open to significant challenge. Although, as outlined above, the HFM method of measuring walls had been developed for several decades there had been little systematic verification. Some initial work considering experimental uncertainty and error was completed as part of *Report 1*, but primarily my second published work (*Report 2*: Hulme, 2016) provided this type of additional verification.

Report 2 represents a thorough examination not just of the walls but also of the methodology for measuring walls combining extensive in-depth field studies, experimental work at the National Physical Laboratory (NPL) and at BRE and additional calculation methods to build a picture of why these walls may be performing better than expected.

This impact of *Reports 1* and *2* are reflected in the public consultation document presented as *Report 3* (BRE, 2016). This paper proposes a change to the default/standard U-values within RdSAP from 2.1 W/m²K (the previous value originally developed by Loudon for the IHVE 1970

Guide to common practice and taken into the initial version of RdSAP in 2005), to 1.7 W/m²K, the value based on my research. It also highlighted the variability in U-values for walls of this type as shown in Figure 7 below, a phenomenon that had also been observed by other studies of both solid and other walls (e.g. BSRIA/EST, 2011; Stamatiou, 1991).

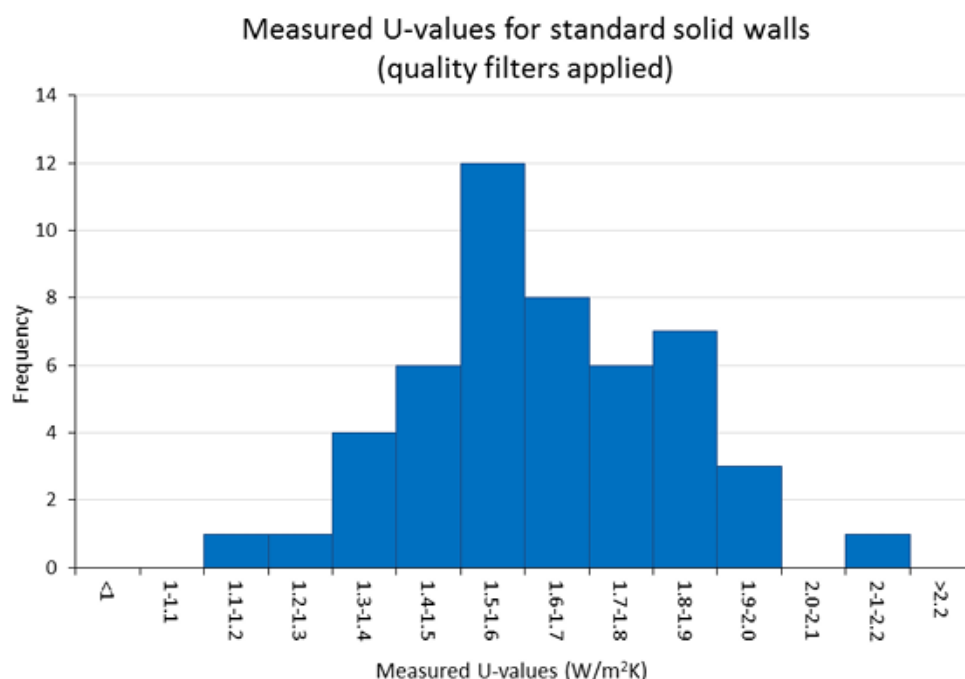


Figure 7: Measured solid wall U-values as recorded in Report 2, showing distribution of U-values and variability in performance.

The change from 2.1 to 1.7 W/m²K is a significant and impactful change. Analysis presented in *Report 1* indicated changing the U-value of solid wall dwellings may remove as many as 500,000 dwellings from the F&G bands (27% of dwellings in this band). This would mean they would no longer be affected by the Minimum Energy Efficiency Standards regulations of that time. In this way, adjustment to what can sometimes seem a somewhat esoteric single value has a real-world effect which impacts half a million homes and would allow them to become rentable, whereas previously they were not. Other changes were also proposed within *Report 3* which affected cavity wall dwellings. Based on the measured results from *Report 1*, and the cavity wall observations, the standard U-value coefficient for uninsulated cavity wall dwellings was

proposed to be changed to 1.5 W/m²K (from 1.6 W/m²K) and insulated cavity walls to 0.7 W/m²K (from 0.5 W/m²K). This change in insulated cavity wall performance, which performed worse than originally calculated, was identified as being due to imperfect coverage of insulants injected into cavity walls, as observed via borescope in the *Report 1* fieldwork. The change to uninsulated cavity wall performance were of smaller magnitude to those for solid walls, but similarly based on experimental data obtained in the *Report 1* field study, providing confidence in these changes.

The proposals consulted on within *Report 3* were implemented, following a public consultation, in RdSAP version 9.93 published in 2017. These changes, based on my work, represented the first major change in the accepted coefficients since 1970 and from this point had a significant effect on the official EPC rating, including regulatory compliance for millions of homes in England.

Report 4 (Hulme, 2015) presents results highlighting the ‘prebound effect’ in the UK, a term coined by Sunikka-Blank & Galvin in 2012. This is where dwellings with poor energy efficiency use less energy (at the whole dwelling level) than standard models predict. At least some of this effect is explained by the assumed performance of the walls of these dwellings identified in *Reports 1 to 3*. If these types of dwellings lose less heat than expected under the traditional assumptions of a U-value of 2.1 W/m²K, there should be a corresponding level of underconsumption at a whole building level (called ‘underspend’ in *Report 4*). Recognising and quantifying the prebound effect in the UK, and providing some evidence which can help explain it in the form of data on wall performance, has a direct impact on policy development in the UK. The consequence of the results in *Report 4*, taken together with those in the other papers, is that energy savings from solid wall insulation are likely to be much lower than simple model comparisons may initially predict. Initial results from these publications were presented to Government in 2012 and 2013. A policy response then began to manifest itself through changes

that were made to the main energy efficiency improvement scheme in the UK in the 2010s, called the Energy Company Obligation. The original version of this scheme (ECO1) had originally heavily promoted solid wall insulation, but changes made for the next iteration of the scheme (ECO2, which ran from 2015 to 2017) dramatically reduced the expected number of installations (Platt & Rosenow, 2014). These changes were made in the context of achieving cost savings from this policy, but it is notable that the principal target for such savings were from reducing the number of solid wall insulations. Indeed, the uncertainty around solid wall U-values originally raised by the original EST work (and at that time being confirmed by emerging results from *Reports 1 and 2*) are recognised by Platt & Rosenow in their IPPR paper from 2014 raising concerns over the changes to the ECO scheme:

“... it is true that estimates about the energy savings achieved by solid wall insulation have been downgraded by about half in recent years on the basis of measured evidence from in-situ installations. This downgrading has reinforced the fact that solid wall insulation is an expensive way to achieve carbon emission reductions or bill savings from the housing stock, compared with other energy efficiency measures.”

The next iteration of the scheme (ECO3) went further. The expected number of solid wall homes to be treated were reduced further, and further options to achieve equivalent cost savings in these homes other than via solid wall insulation were added (BEIS, 2018).

The 2010s represented a challenging policy background for energy efficiency for a number of reasons, in particular cuts to public spending. Other measures also saw large falls in installations in this period, and the choice to reduce targets and ambition for solid wall installations cannot be put down to changes in the U-value and subsequent reduction in cost-effectiveness alone. The evidence provided directly to policy makers in *Reports 1 to 4*, however, was contemporary with these decisions being taken and would have influenced what actions were taken.

Placing the results in the context of historic buildings and building techniques

My research had indicated a number of reasons for U-values of solid walls being lower than previously assumed. This included relatively high prevalence of internal gaps and cavities within these walls. These findings should be considered both in the context of building techniques used in the construction of these homes, and diversity and variability within the materials in use at the time these types of buildings were common place.

For example, solid walls are generally built using a technique known as ‘backing up’ or ‘backing in’ (Lynch, 1994; Collinson, 2012). This technique installs the facing bricks (i.e. those visible from outside) first but only applies the backing bricks (i.e. those that are not visible from the outside of the wall) once all facing bricks on a course have been laid. The consequence of this process, however, may be a lack of mortar in the ‘collar joints’, which are the joints between two ‘stretcher bricks’ (i.e. two bricks laid next to each other lengthways along the length of wall a solid, as opposed to ‘header bricks’ which cross the length of the wall). During the process of backing in, mortar is generally not buttered onto the face of the backing brick when it is pushed against the facing brick as this risks pushing the facing brick out of position. Instead, mortar is pushed up from the mortar bed to allow it to fill the collar as the brick is laid, or mortar should be pushed down between the joint from above. This process, therefore, relies on sufficient mortar in the mortar bed being squeezed up into this joint, and/or mortar being placed sufficiently from above. This is a very imprecise process and seems almost certain to lead to some unintended air gaps where this mortar has not been able to penetrate the joint. Lynch (Lynch, 1994) also notes other techniques which can lead to imperfect fill of joints, including that of ‘shoving’, in which squeezed mortar from the horizontal mortar bed is immediately retrieved by the bricklayer and placed on the vertical (perpend) joint. Lynch notes that in many

instances there is insufficient mortar to fill the vertical joint, which will lead to the creation of air cavities. An example from *Report 2* of incomplete fill in vertical joints is shown in Figure 8 below.



Figure 8: Example of missing mortar in perpend joints. Looking upwards at exposed bricks in the upper course at the top of the void, the extent of mortar in the perpend joints can be seen. In this example, the perpends can be estimated to be approximately 50% filled.

Other clues to why there may be areas of missing mortar can be found in technical guides and books from the late nineteenth and early twentieth century, when many of these homes which survive today were constructed. Two bricklaying guides from the beginning of the twentieth century (Richards, 1901; Forbes, 1926) outline poor practices which were in use to save time and mortar. These include the techniques of ‘grouting’ and ‘larrying’ where very thin mixes which were sometimes produced and poured onto the laid (but unjointed) bricks, rather than each course of bricks being buttered. Although there are some legitimate reasons for using this type of technique in some circumstances, Richards (Richards, 1901) states that it could lead to poor adhesion but save time, mortar and ultimately money. An 1899 guide (Hammond, 1899) outlines how for thinly jointed walls there may be no mortar at all laid directly onto the

horizontal bed joints, instead relying on mortar buttered onto the back and front of the bricks. These techniques are likely to result in gaps in mortar, and a wall that is less solid than it might appear at first glance. The missing mortar in all joints was replicated in the laboratory test walls (tested in the NPL hot box apparatus) which were built as part of the work described in *Report 2*. This is shown in Figure 9 below.



Figure 9: Partially filled joints were deliberately included in some of the test walls which were built for testing in the NPL hot-box apparatus.

My work also identified the extensive use of broken bricks (known as ‘brick bats’) within solid walls. While some legitimate structural reasons exist for using brick bats (e.g. around corner ‘quoins’), it seems likely that use in the middle of a solid wall resulted from a desire to use as many of the available bricks as possible, even the broken ones. Lynch (Lynch, 1994) describes how “*careless bricklayers*” building Flemish bonded walls (which have alternate stretcher and header bricks) would use brick bats instead of full header bricks across the width of the wall where they had allowed the inside gauge of the brickwork to run out of sync with the external work. In these cases, the outer and inner work of the same course did not correspond in height and bonding across the wall using a proper header was often only possible in the relatively unusual situations where the courses fell even. Lynch further goes on to describe how these

walls had been known to split in two along their lengths (i.e. delaminate). This is also an issue for Flemish bonded walls noted in a BRE produced newsletter 'Defect news' on observed defects (BRE, 1983).

The nature of the bricks themselves as used in the construction of solid wall homes is also very different to modern bricks, which are manufactured with factory precision. When many solid wall homes were built, it would be common for bricks to be sourced locally (Hounsell, 2022). Hand cutting and imprecise firing of bricks led to significant variation in the materials, which can help explain the variability in thermal performance and the potential for internal cavities to be created. Shown below in Figure 10 are some examples of sections of bricks from solid walls the early twentieth century showing internal gaps and inclusions, inconsistent baking of clay and other internal structures.



Figure 10: Three sections of bricks from solid wall homes. Left: London stock brick showing internal clinker and other inclusions, gaps and extensive cavities. Centre: Red brick demonstrating concentric discolouration. Right: Stock brick showing significant differences in internal structure and colouration around harder and more uniform margin, likely to indicate incomplete firing.

Sources from the early twentieth century also comment on the disposal of poor quality bricks by erecting 'workmen's houses in populous districts' (Searle, 1931). Taken together, these

factors will all lead to variable thermal performance; and perhaps counterintuitively an improved level of thermal performance as gaps and irregularities are created in the walls. The moisture content of these walls is a further source of variability, and it too varies across a single dwelling rather than only between one building and another. Dust drillings taken at three depths and at nine locations on each facade of the sampled dwellings showed that the moisture content of both brick and mortar varied significantly within the same building. Brick moisture content by volume ranged from 0.21 per cent to 6.98 per cent, and mortar from 0.10 per cent to 18.24 per cent. Local features such as run-off from downpipes and sills, or localised rising damp, may account for some of this variation, and samples taken from the upper elevations were generally drier than those nearer ground level. Orientation is a further factor. The prevailing winds in the United Kingdom are south-westerly. Therefore, north-facing walls may be drier than those facing south and west. The principal implication is that a single measurement of moisture cannot be taken as representative of a wall. This reinforces the case for characterising the performance of these walls through distributions rather than through single assumed values.

Walls may also have changed over the course of their lifetime to affect their thermal performance. For example, pointing and repointing of mortar joints may have introduced mortars of different composition and thermal conductivity. Other processes, such as settlement and / or structural movement can create or close air gaps within the wall structure or the installation of damp-proof courses, insertion of services, or repairs may have affected the internal structure of the wall. The walls measured in my fieldwork were around 100 years old. In this period the walls have been modified, repaired and weathered.

The contemporary research background

Since these works have been published, there has been a renewed interest in both the definition and measurement of wall U-values, including of historic buildings.

International work including from Luxembourg (Merzkirch, 2015), Italy (Lucchi, 2017) and Cyprus (Xeni, 2015) provided similar results for historic buildings in those countries as had been observed in *Reports 1 and 2* in England, i.e. that the calculated U-values were generally higher than the measured U-values. In the UK, independent estimates have also calculated the effect of revised U-values on the efficacy of solid wall insulation measures (Loucari et al., 2016; Seifhashemi et al. 2020).

My work was based on the most common and most established method of measurement (described in BS ISO 9869-1:2014), using heat flow meters which need to be in place over a two week period during the heating season. Significant recent work both in the UK and internationally, however, has been done on alternative techniques which may provide the opportunity to measure U-values more quickly and/or with less disruption to households. These efforts results in the standardisation of the next most commonly employed technique which is based on Infra-Red thermography, in the form of ISO 9869-2:2018. The main drawback for this measurement is the complexity introduced by building materials of high heat capacities. The ISO 9869-2:2018 standard is, therefore, restricted to materials with a heat capacity of less than $30\text{kJ/m}^2\text{K}$

A full review of techniques for measuring U-values was produced by Teni (Teni, 2019) which characterised the following main methods:

- Heat Flow Meter (HFM) Method
- Infra-Red Thermography (IRT) Method
- Temperature Based Method (TBM)
- Natural convection and Radiation (NCaR) Method
- Simple Hot-Box Heat Flow Meter (SB-HFM) Method

As outlined in my recommendations in Part 2 of this thesis, I outline that the inherent uncertainty and variation in U-values requires the development of a way of better characterising

wall U-values. In particular, work completed on using thermography shows potential and is relatively widespread – although concerns exist over whether it is able to overcome some of the inherent difficulties associated with thermal storage (i.e. heat retention) by heavyweight masonry walls and the need for a relatively large temperature gradient. I expand on the need for further work and development on U-value measurements techniques in Part 2 below.

The thermal characteristics of solid walls are also relevant to cooling strategies, an increasingly important consideration as climate change increases the frequency of extreme heat events in the UK. The thermal mass of solid brick walls can provide passive cooling benefits by absorbing heat during the day and releasing it at night, moderating peak indoor temperatures. However, realising these benefits requires appropriate ventilation strategies, particularly night-time purge ventilation, which may conflict with security concerns or noise from external sources.

Understanding the thermal mass characteristics of solid walls, alongside their U-values, is essential for developing appropriate guidance on managing overheating in these buildings.

Many historic buildings may be particularly suitable for installation of passive cooling technologies rather than air conditioning. Design guides for these types of system such as Ford et al. (Ford et al., 2010) note the need for cooling designs to take direct account of U-values.

This represents an area where the detailed characterisation of wall properties undertaken in my research has applications beyond winter heating.

Part 2:

Discussion and Conclusions

*“O wicked wall, through whom I see no bliss,
Cursed be thy stones for thus deceiving me!”*

Discussion

This section discusses a number of key issues raised by my research, placing them in the context of current use of wall U-values.

The relative importance of U-value accuracy

Energy use in buildings is the product of multiple factors, each of which has its own level of uncertainty. These include fabric losses, ventilation losses, infiltration losses, and the building's heating system. Each of these contributes to total energy use, and each carries its own uncertainty. Fabric losses depend on the U-values of the individual elements and, as this thesis has shown, these are themselves subject to both systematic bias and considerable variation. Ventilation and infiltration losses depend on the airtightness of the dwelling and on occupant behaviour such as window opening, and are rarely measured directly in the assessment of existing homes. The efficiency of the heating system, and the way it is controlled and used, introduces further variation, as does the pattern of demand set by the occupants themselves, including the temperatures to which rooms are heated and the hours of occupation. The relative weight of these factors differs from dwelling to dwelling, which is why an apparent underspend against prediction, of the kind identified in Report 4, cannot be attributed to fabric performance alone. The contribution of this thesis is to reduce the uncertainty attaching to one significant and previously mis-estimated term, the solid wall U-value, while recognising that it sits among several different inter-related uncertain aspects that combine to define a home's energy performance. Uncertainties in defining one element such as the U-value, may not make a significant difference given the overall level of uncertainty across all elements, or the relative magnitude of heat losses through walls compared to other sources of loss. This raises the question of whether it is actually important and beneficial to define term such as a U-value accurately.

The uncertainties in U-values, however, represent a systematic bias that affects all dwellings of similar construction type in the same direction. The overestimation of solid wall U-values led to a consistent overestimation of heat losses and, therefore, an overestimation of potential energy savings from insulation. The size of the discrepancy in U-value is also substantial (approximately 19%). For a typical solid wall dwelling, wall heat losses account for 30% or more of total fabric losses. As such, the case for defining wall U-values accurately is strong.

The limitations and appropriate uses of RdSAP

Reduced Data Standard Assessment Procedure (RdSAP) was developed for the production of Energy Performance Certificates (EPCs) using a simplified survey process. This recognised that detailed information about existing buildings would not be readily available to surveyors.

Missing data was therefore imputed using standardised assumptions and default values.

However, EPCs are now put to much broader use. These include being used for legal compliance under Minimum Energy Efficiency Standards (MEES), eligibility for grant schemes, and qualifying for preferential mortgage rates. These uses need a level of accuracy that the RdSAP methodology was never intended to provide.

My research has highlighted the core pieces of data which underpin the calculation of EPCs are subject to large uncertainties. In particular, it highlighted that there is significant variation between walls of nominally the same type. For standard (9-inch/220mm) solid walls, the measured U-values ranged from 1.1 W/m²K to 2.2 W/m²K. This range can have a potentially significant effects on the EPC rating. For a typical home of this type, the difference between the

lowest and highest U-value in this range corresponds to a SAP rating difference of four points¹.

This discrepancy is large given the size of the EPC bands. A difference of four points representing uncertainty in the U-value of the wall is able to move dwellings (even those relatively far from the EPC band boundary) across the threshold between complying with regulations and failing them.

Given the nature of these regulations, the real world effects of this uncertainty are significant. A landlord may be prevented from letting their property because of an EPC rating of F, but in reality their property may perform better (and use less energy) than a similar property achieving a Band E. This same landlord may also be persuaded of the need to insulate the walls of their home to increase their EPC band, with other aspects of the EPC process providing estimates of energy, cost and carbon savings they may achieve. But in reality because their walls are performing much better than the standardised assumptions and better outcomes (more carbon or money saved) may have been achieved by using their funds to, for example, replace their heating system.

These data uncertainties are exacerbated by additional errors introduced by variation in surveyor assessments. Crawley (Crawley et al., 2019) estimated that uncertainties associated with surveyor variability could lead to high levels of incorrect EPC bands, for example estimating that 24% of band D homes are rated as band C. Earlier work on the SAP process by Jake Chapman (one of the original developers of SAP) (Chapman, 1991) also highlighted this conflict between enhanced complexity in building energy modelling and the additional uncertainties that may be introduced by issues such as input error. Chapman recognised that increased complexity providing a theoretical improvement in accuracy of 2% would not be achieved if it required an additional 10 inputs due to the likelihood of data errors. Likewise, the original field

¹ Based on a mains gas home with 16,200kWh total annual energy use for space heating, where 30% of heat loss can be attributed to fabric losses through walls.

trials of RdSAP (BRE & FAERO, 2004) highlighted the large variation that was likely to occur within these types of survey. BRE and FAERO's work indicated that RdSAP inspectors were only able to achieve desired results within 10 SAP points in 70% of cases.

Policy responses to update EPCs have been focused on two areas, neither of which directly address these uncertainties. The first is a wish to update the metrics that are calculated to better align with policy objectives (MHCLG, 2024). The second is the need to overhaul the fundamentals of the SAP methodology, including additional calculation complexity to address, for example, short period changes in energy demand (CIBSE, 2021). This is the major ongoing project to produce the Home Energy Model (HEM).

There has been little progress to date, however, on how to collect better underlying data for existing homes to populate the models. As I argue above, U-values are important quantities to define and represent a significant element of heat loss. As with all modelling work, enhancing the precision of a model (e.g. through the HEM project) is unable to lead to more accurate outputs without also addressing the uncertainty in the inputs and any uncertainty in the inputs are propagated to the outputs. I argue below for sustained efforts to fill these important data gaps, which need to be in parity to the efforts to produce more accurate modelling methods.

Current context: climate adaptation and the changing demands on historic buildings

The context for understanding the thermal performance of solid wall homes in 2025 has developed from the 2010s, when I produced the published works which are the subject of this thesis. At that time, the main policy objectives for understanding solid walls were associated with supporting solid wall insulation programmes that reduced heat losses (and associated carbon emissions). Today, there is increased recognition of the need for climate adaptation, and in particular the need for mitigation of overheating risks. The summers of 2022 and 2023

demonstrated that the UK housing stock is vulnerable to extreme heat events. Solid wall buildings can retain heat over successive hot days. This has the potential to cause overheating. Understanding U-values of solid walls is, therefore, essential to understanding risk of overheating and appropriate interventions.

Flooding represents a further climate-related risk to solid wall buildings. The moisture behaviour of solid walls following flooding events, and the implications for thermal performance during and after drying out, requires better understanding. The relationship between moisture content and thermal conductivity identified in this research has direct relevance to understanding the recovery of thermal performance following flooding.

These emerging challenges reinforce one of the central findings of this research. This is that standardised assumptions about building performance are not well understood or validated and as such may be insufficient to direct policy and interventions effectively.

Implications for machine learning and artificial intelligence models

The need for enhanced confidence in input data is made more urgent by the current rapid advances in machine learning and artificial intelligence (AI) models. The accessibility and availability of computing power which is able to undertake complex modelling offers great potential for identifying and specifying retrofit opportunities. Successful outcomes will only be achieved, however, alongside equal efforts to ensure that these calculations are based on reliable data. Research has indicated that AI models are subject to collapse through continual recursively generated data (Shumailov et al, 2024); the need for new and reliable data sources is central to the success of these types of models. This data collection needs be directed by human researchers (see Figure 11, Bosammani et al, 2022).

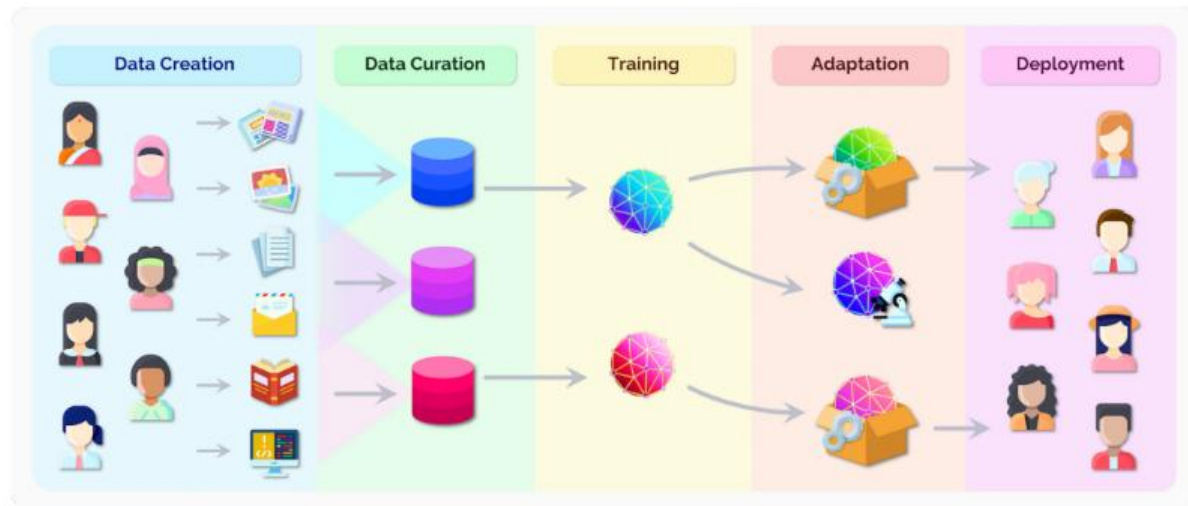


Figure 11 (After Bosammani et al, 2022). AI 'foundation' models. Highlighting the need for human led data collection to train and populate models.

If these uncertainties are overlooked AI models are unlikely to provide reliable results. Artificial intelligence models are no different to other models in this regard. No matter how advanced the modelling, the uncertainty in the basic assumptions must be addressed as a high priority to deliver useful outputs. These techniques are therefore best understood as complementary to, rather than a replacement for, physical measurement. A model of the kind described would draw on characteristics such as construction type, age, and observed features of a dwelling to estimate its likely U-value, but it can only do so reliably where it has been trained on a body of measured data of the type produced by the in-situ and laboratory work described in this thesis. In particular, the material and in-situ testing provides both the initial training data and the means of ongoing validation against which such a model's estimates must continue to be checked. The role of the model is to extend the reach of a limited set of physical measurements rather than to substitute for the collection of new data.

Once populated by reliable data, however, the ability of these techniques to analyse and derive relationships between datasets holds great potential for supporting retrofit of existing buildings. It may be possible to develop a tool to determine revised U-values based on, for example, images of buildings, smart meter data and a dataset of measurements from similar walls. The

full potential of these techniques to provide appropriate recommendations for retrofit is likely to be a fruitful area for future research.

Achieving change

Achieving changes to policy in these areas will require well targeted and informed policies and incentives, supported by numerous aspects of industry as well as the occupants and owners of the homes themselves. To achieve this will require collaboration between research, policy and industry stakeholders.

The stakeholders are summarised in the Figure 12 below:

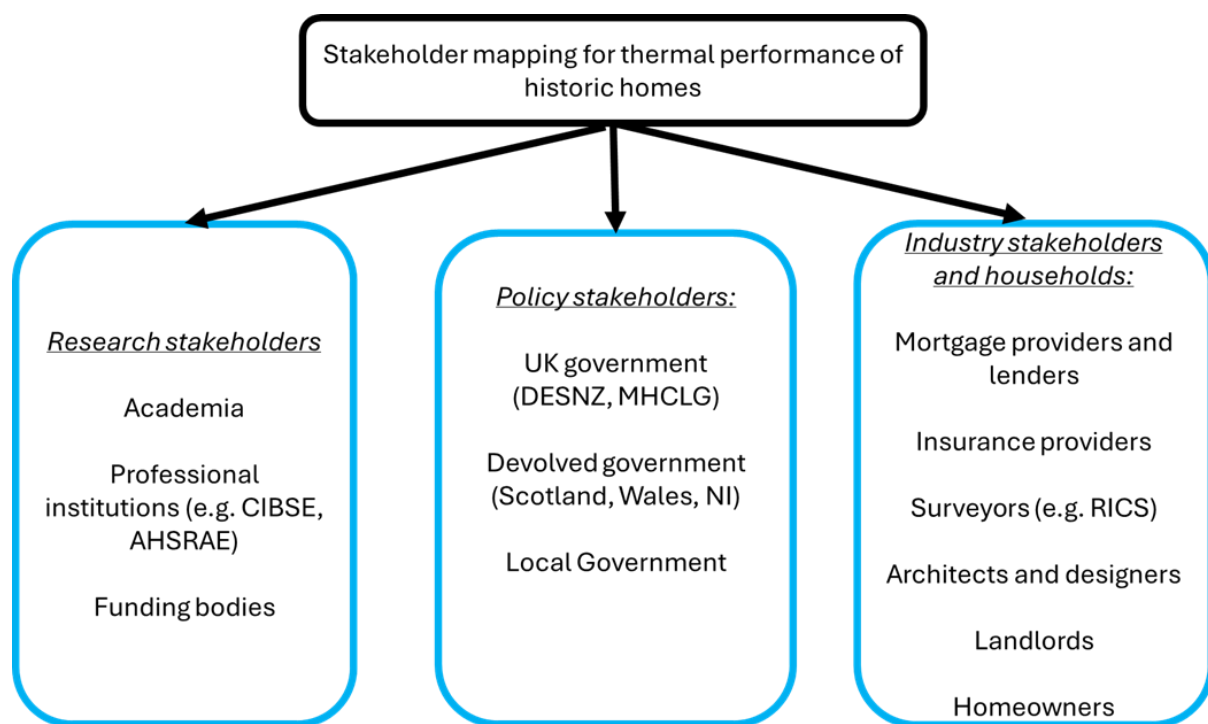


Figure 12: Stakeholders for the thermal performance of historic homes.

Stakeholders have been split into three broad groups: research stakeholders, policy stakeholders, and industry stakeholders including households.

Within the household category, the implications differ significantly between owner-occupiers, private landlords, social housing providers, and tenants. Owner-occupiers face decisions about investing in their own properties. Private landlords face regulatory requirements under MEES

and must balance compliance costs against rental income. Social housing providers manage large portfolios where small errors in U-value assumptions aggregate to significant budget implications. Tenants, while not making investment decisions, bear the consequences of incorrect assessments through energy bills and thermal comfort.

The industry category also includes architects and building services engineers who specify retrofit solutions, surveyors who assess buildings for EPCs, installers who deliver retrofit measures, and the supply chain for insulation materials and heating systems.

My research raises some key questions for researchers, and identifies a number of areas where additional investigation and research is needed. This includes questions on funding for large fieldwork studies, and associated infrastructure.

The research also questions the validity some of the key policy levers, in particular EPCs, which rely on accurate data about historic homes. Addressing these questions is a high priority for policy officials in central government across all nations in the UK, and for local Government officials who also rely on EPCs. Impacts on EPCs are also of relevance to landlords and homeowners affected by EPC based regulation, or who are relying on EPC recommendations to take decisions on improving their homes.

More broadly the research is of relevance to providers of mortgages or other lending, as well as insurance companies, who are keen to ensure that their investments are protected and that benefits for energy efficiency are realised in practice.

Cross-cutting themes and challenges

The research highlights a number of cross-cutting issues which are necessary to support the successful retrofit of new homes. These are shown in the table below:

Cross cutting issues which support successful retrofit			
Need to recognise and reduce uncertainty in data inputs used in defining retrofit	Need to take account of the complexity and diversity of older homes being retrofitted	Multi-disciplinary approach required to understand existing homes	Consideration of existing homes in the context of their history and design intent

Achieving these aims faces significant obstacles. Unless these challenges are addressed, retrofit and other policies are unlikely to be wholly successful. Examples of these challenges are discussed in greater detail in the recommendation section below.

Challenges to achieving these aims				
Difficulties in establishing and maintaining infrastructure for large scale research	Difficulties in identifying and challenging long held assumptions about existing buildings	Challenges of collaboration between specialists across different disciplines	Inertia of pre-existing policies and regulations	Challenges in maintaining focus on new and regular data collection over extended timeframe.

Conclusions

My published works redefined the thermal performance of solid wall homes in England and represents the latest in a series of U-value coefficients which have been defined since the 1940s. These works have been summarised and placed in context by this thesis.

The principal conclusions are:

- 1) **The thermal performance of solid walls is significantly better than previously assumed.** The average measured U-value was $1.7 \text{ W/m}^2\text{K}$, rather than the previously assumed $2.1 \text{ W/m}^2\text{K}$ (a value that had been in use since 1970). Data collected from wall inspections and laboratory tests indicated that this difference in U-value was due to lower moisture contents than previously assumed, and the presence of air gaps within walls.

- 2) **There is substantial variation and uncertainty in the thermal performance of solid walls .** The measured U-values ranged from 1.1 W/m²K to 2.2 W/m²K, and is likely to reflect differences in construction materials, techniques, and conditions.
- 3) **An implication of these results is that the current EPC system may not suitable for regulatory uses beyond a basic information tool (its original purpose).** EPCs were designed as information tools for homebuyers, but are now used for a wide variety of other uses including legal compliance against the Minimum Energy Efficiency Standard (MEES) regulations, grant eligibility, and by mortgage providers to offer improved lending terms. High levels of uncertainty in the basic data inputs, such as U-values, will result in a correspondingly high level of uncertainty in the outputs. As a result, it may be inappropriate for there to be significant financial or legal consequences attached to the ratings unless these uncertainties can be addressed.
- 4) **New measurement techniques must be incorporated into assessment processes.** The Heat Flow Meter methodology used in this research, while accurate, is too slow and intrusive for routine use in an assessment process. Emerging techniques including rapid thermal imaging and smart meter analysis, possibly coupled with machine learning and AI techniques, offer the potential for practical assessment of individual building performance. These techniques, however, require a process to support validation and formal incorporation into assessment protocols.
- 5) **There is the need for a comprehensive programme of research into the thermal performance of other building elements .** My research examined only one building element of one construction type. Similar uncertainties almost certainly exist for other wall types, roofs, floors and windows. Although some work has been done on these elements (e.g. Pelsmakers et al, 2017 for floors), many of the standardised coefficients for these elements are based on limited data which, like for solid walls, are many decades old and/or based on very small and limited datasets.

- 6) **Research into the thermal performance of walls is increasingly important for cooling and climate mitigation, in addition to understanding and reducing heat losses.** Any policies to reduce winter heat losses need to account for other effects of climate change, such as summer overheating and flooding risks.
- 7) **New tools, including AI and machine learning techniques, offer the ability to transform how we assess building performance. But these techniques require high quality input data to achieve their potential.** Advanced analytical techniques (including AI, machine learning etc.) offer the potential to manipulate, process and analyse data and provide new insights into building performance. This may allow for better identification of many factors including wall U-values. These techniques, however, require reliable ‘training data’ to be able to provide these insights. Unless reliable new data can be collected, there is the risk that these techniques will propagate and (and potentially amplify) existing errors or create the impression of accuracy in areas where there is extensive underlying uncertainty.

Recommended actions

There are several actions recommended for policymakers and researchers:

1. **Policymakers should consider the suitability of using EPC ratings for an expanded policy purpose.** There is a high level of uncertainty within the calculation of an EPC which results from inherent uncertainty in the inputs. It may be inappropriate to attach Minimum Energy Efficiency Standard (MEES) policies, and other regulations, to EPC bands without acknowledging and accounting for these uncertainties. Not doing this risks unfairly penalising some households while unfairly rewarding others. This situation will undermine the policy objectives and is likely to decrease public confidence in the regulations.

2. **New tools and techniques for the thermal assessment of walls should be reviewed and developed, and incorporated into the EPC assessment process.** A number of commercial tools for rapid thermal assessment already exist, and other tools are in use by academics and in development. The Government and research bodies should review these tools and techniques in a structured way and establish a route and process which allows them to be validated and incorporated into EPC and other energy assessments.
3. **There is a need to develop and fund regular large-scale fieldwork programmes to confirm the fundamental performance of building elements.** The type of comprehensive field measurement undertaken in my research is not regularly undertaken and requires sustained and specific funding to be made available. This type of fieldwork requires significant resource, and requires specialist teams to, for example, manage the logistics of arranging appointments with households and multiple teams of technicians and field operatives. This type is often not well aligned with traditional PhD funding routes, or the research and publication priorities of academic institutions. To collect this type of essential data, research institutions and funders need to recognise its importance and prioritise its collection

For the UK to achieve statutory targets on climate change it is necessary to understand the baseline performance of the housing stock in its current state. This allows us to accurately estimate the energy savings from retrofit measures and optimise the use of limited resources for energy efficiency improvements. My research has demonstrated that basic assumptions around wall thermal performance were incorrect for one major building element. It would be complacent to assume that other assumptions are correct. The evidence base for retrofit policy must be strengthened through continued empirical research. Additional work of this type represents good value by avoiding inappropriate investment of many billions of pounds in interventions that fail to deliver their promised benefits.

*“Thus have I, Wall, my part dischargèd so,
And, being done, thus Wall away doth go.”*

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Report 1: Hulme, J. and Doran, S. (2014) *In-situ measurements of wall U-values in English housing.* Garston: Building Research Establishment.

Report 2: Hulme, J. (2016) *Solid wall heat losses and the potential for energy saving: The nature of solid walls in situ.* Garston: Building Research Establishment.

Report 3: BRE (2016) *Review of default U-values for existing buildings in SAP. Consultation paper CONSP:16.* Garston: Building Research Establishment.

Report 4: Hulme, J. (2015) 'Energy use and home temperatures in English housing: results from the energy follow-up survey', in *Proceedings of ECEEE Summer Study 2015.* Stockholm: European Council for an Energy Efficient Economy.

Appendix A

Report 1: Hulme, J. and Doran, S. (2014) In-situ measurements of wall U-values in English housing

BRE Report

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

Prepared for: Alex Boss, DECC

Date: 4th July 2014

Output Number: 290-102



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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/m ² K	Measured U-values: median W/m ² K	Calculated U-values: mean (standard deviation), W/m ² K	Calculated U-values: Median W/m ² K	Typical RdSAP U-values ^a W/m ² K	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).

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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/m².

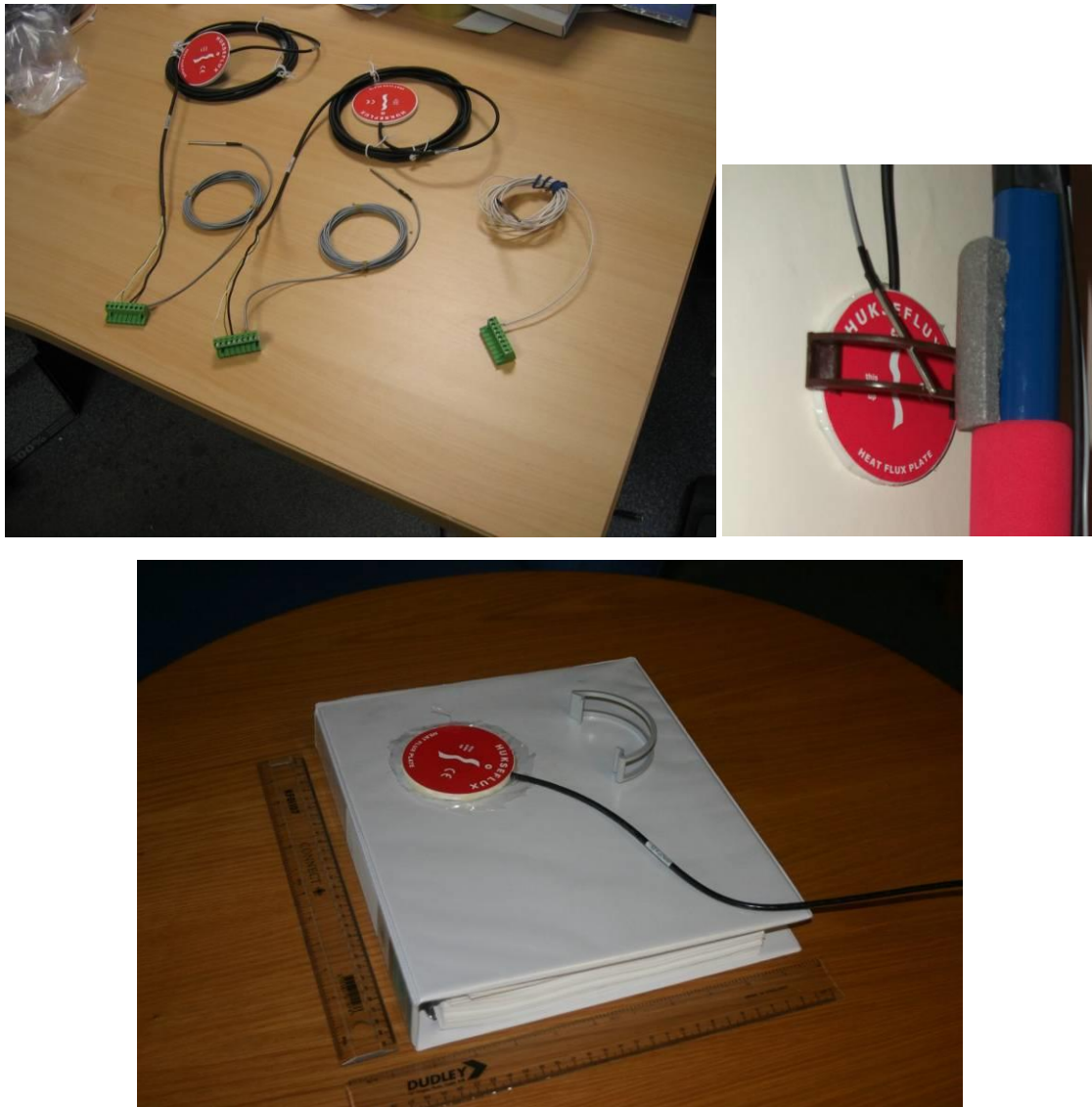


Figure 1 - The sensing equipment that was used for monitoring the heat flux and temperatures. The Hukseflux heat flux plates (circular plates) measure heat flux (in watts per square metre) and the thermistor sensors (silver tubes) measure temperature.

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.

^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.

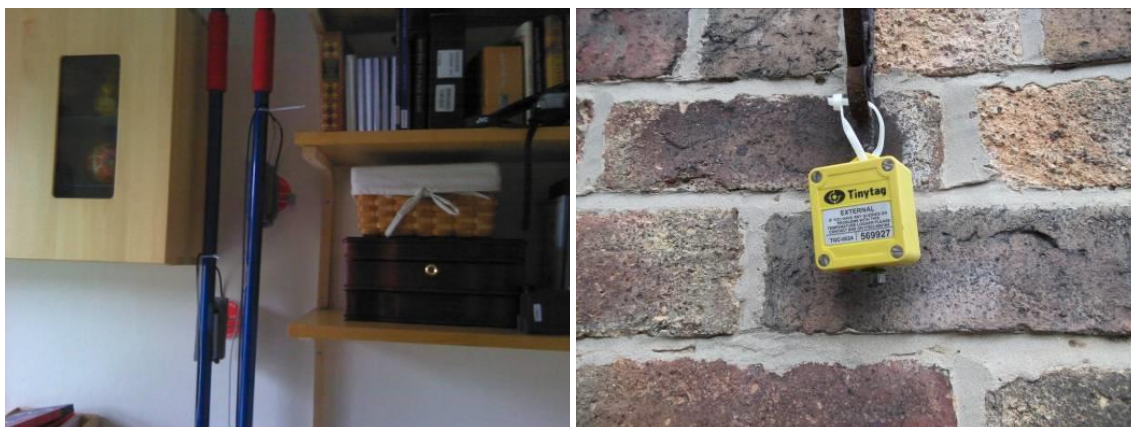


Figure 3 - The equipment installed in an occupied dwelling (left hand picture) showing the heat flux plates (red discs) and indoor temperature sensors supported by teleprops (blue poles) and clamps. Also shown is a Tinytag datalogger (right hand picture) attached to the outside wall (in a location out of direct sunlight)

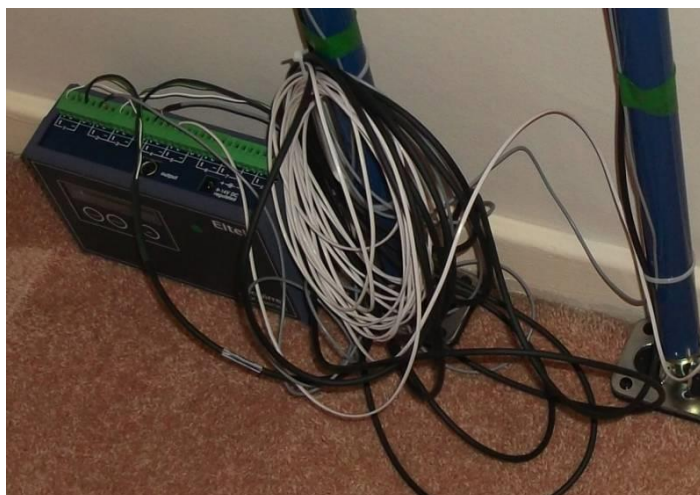


Figure 3 - An Eltek 851L datalogger, recording EMF and thermistor readings from the sensing equipment

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.

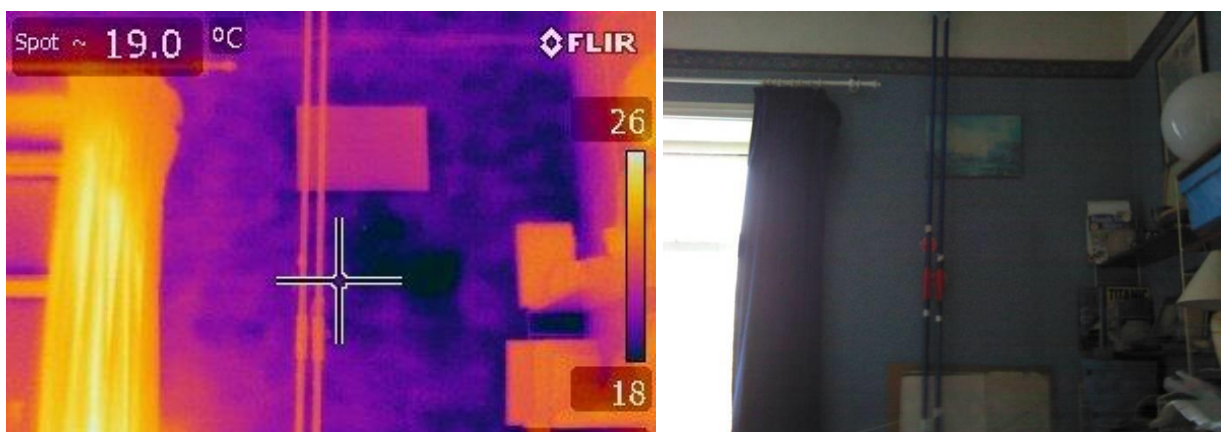


Figure 4 - A thermal image showing the equipment installed on a wall in a house. In this instance the thermal performance of the wall is unusually uneven and it was necessary to select a representative measurement point at approximately average temperature for the wall as a whole.

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. 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.
2. 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 both brick (at different depths) and mortar and measuring their moisture content
3. 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.
4. 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.

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 (m ² K/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 ($\geq 0.5 \text{ W/m}^2\text{K}$)). 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.

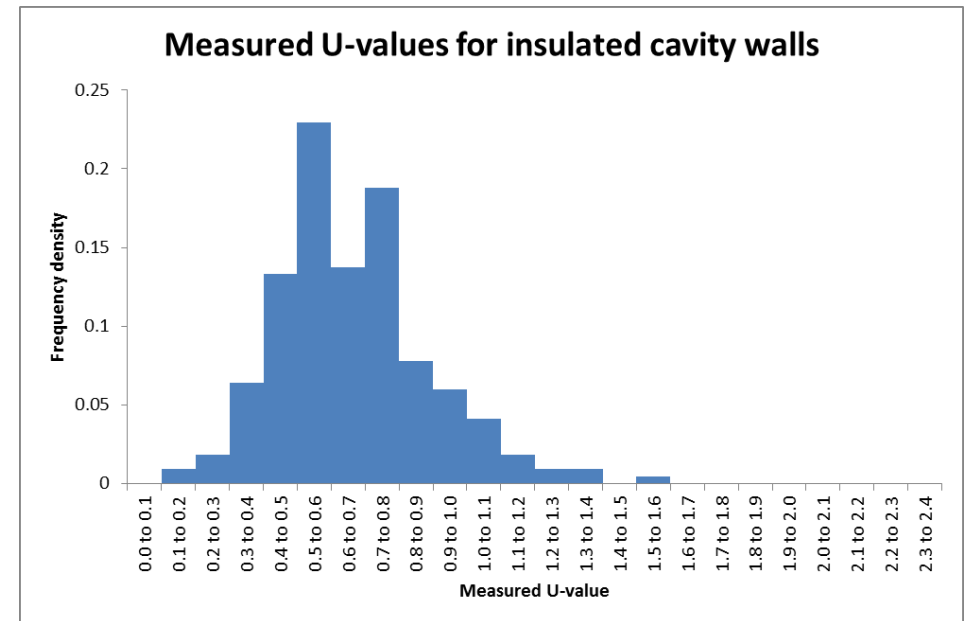
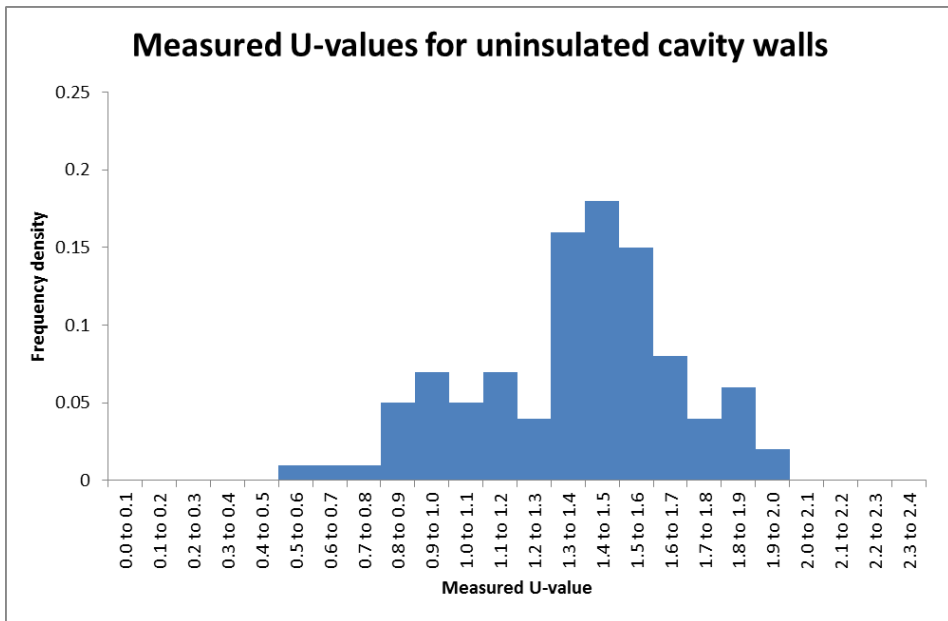
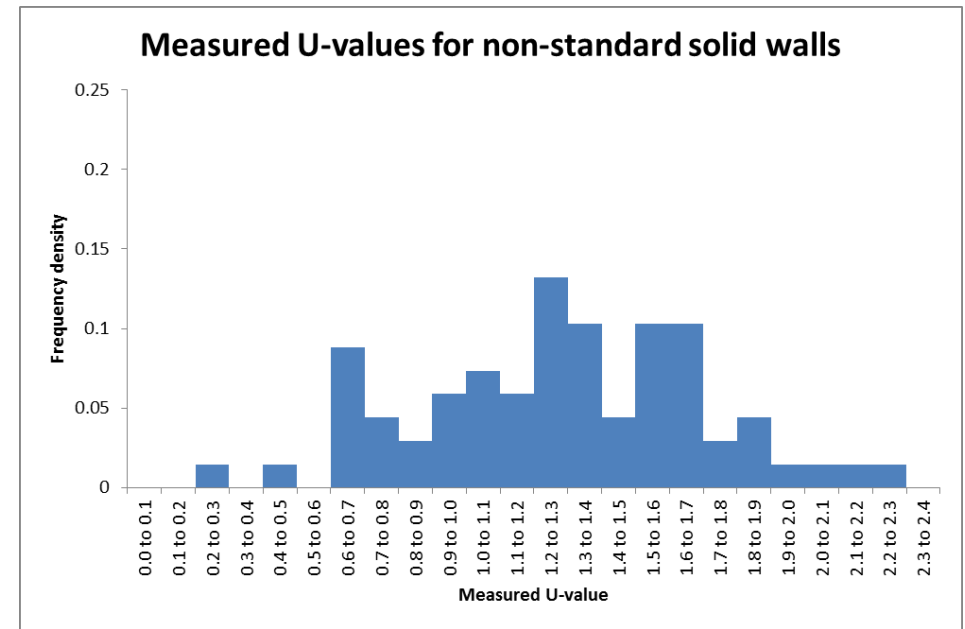
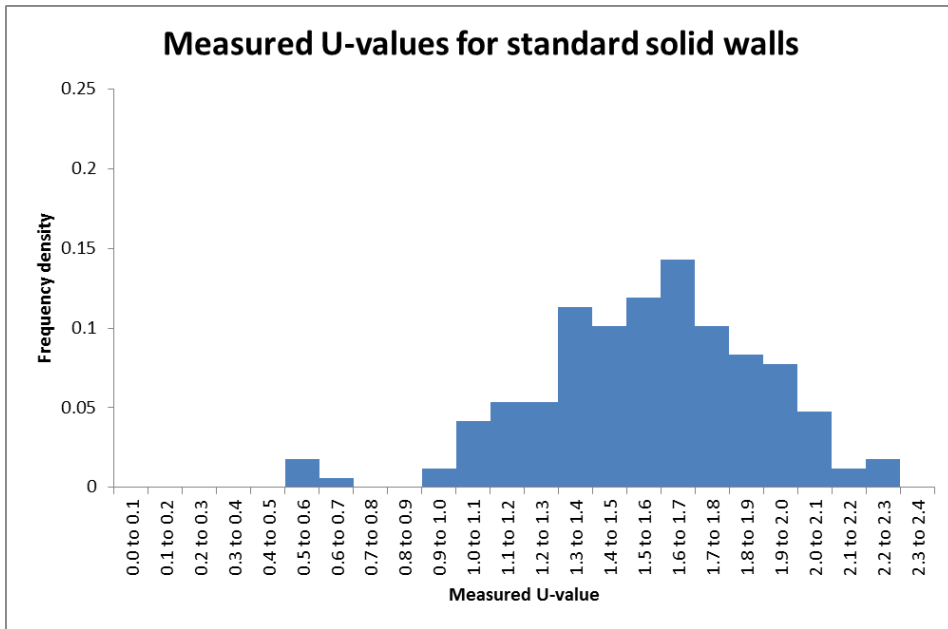
A subsequent recalibration of five heat-flux plates and detailed comparison with a hot-box at the National Physical Laboratory (NPL) was undertaken to identify any systematic error in measured values that may be occurring as a result of the measurement process (see Appendix E). The results suggest that 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 $0.08 \text{ W/m}^2\text{K}$ 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 $\leq 0.5 \text{ W/m}^2$.

Wall type	Number of cases	Measured U-values: mean (standard deviation) $\text{W/m}^2\text{K}$	Measured U-values: median $\text{W/m}^2\text{K}$	Calculated U-values: mean (standard deviation), $\text{W/m}^2\text{K}$	Calculated U-values: Median $\text{W/m}^2\text{K}$	Typical RdSAP U-values ^a $\text{W/m}^2\text{K}$	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 $\geq 330\text{mm}$ 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 solid 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 be 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 ΔU s that might arise from the uncertainty in a number of known (Table 5) and unknown (Table 6) parameters.

^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/m²K.

Table 5: 'Standard' calculated U-values ($\text{W/m}^2\text{K}$) 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 ($\text{W/m}^2\text{K}$) 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

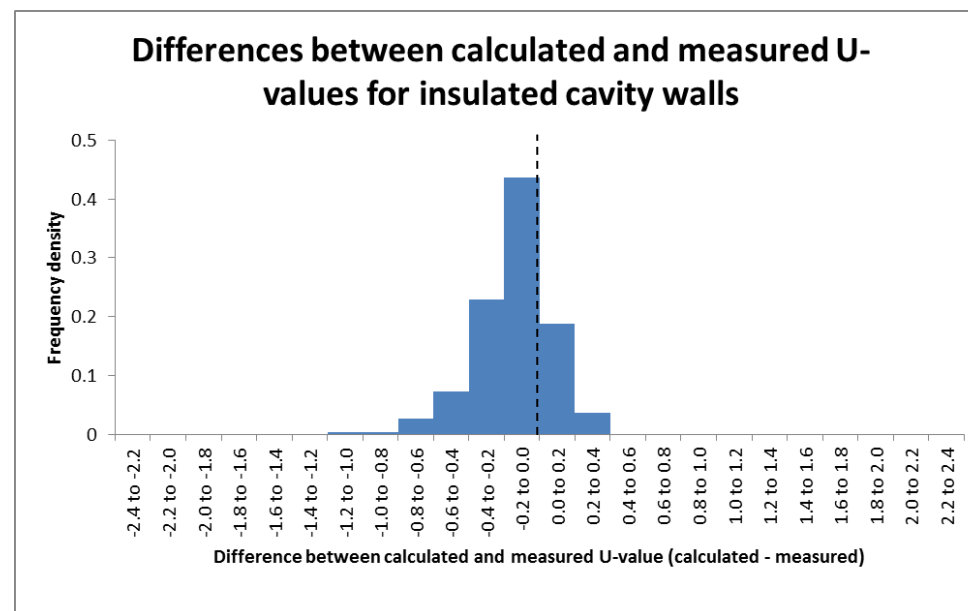
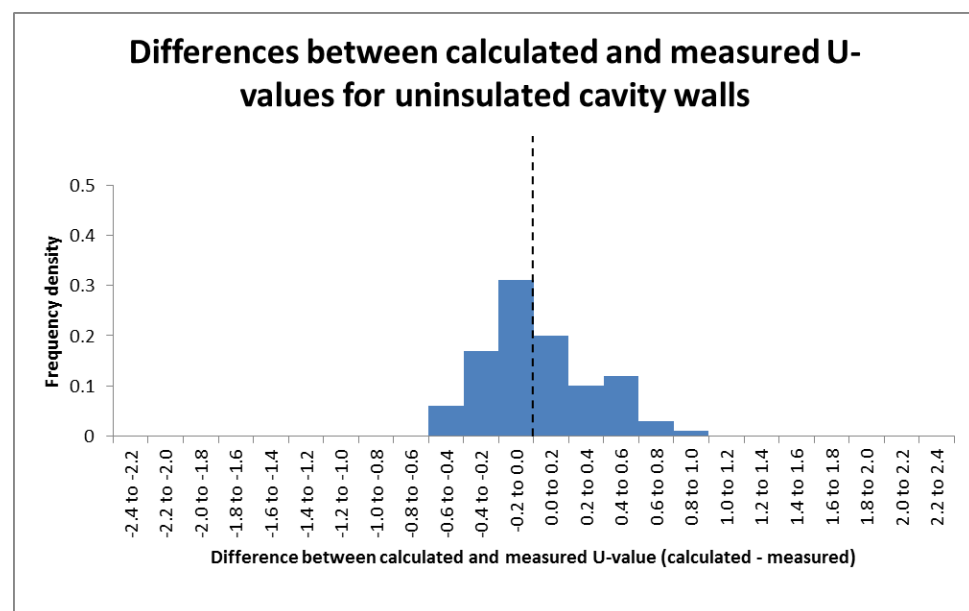
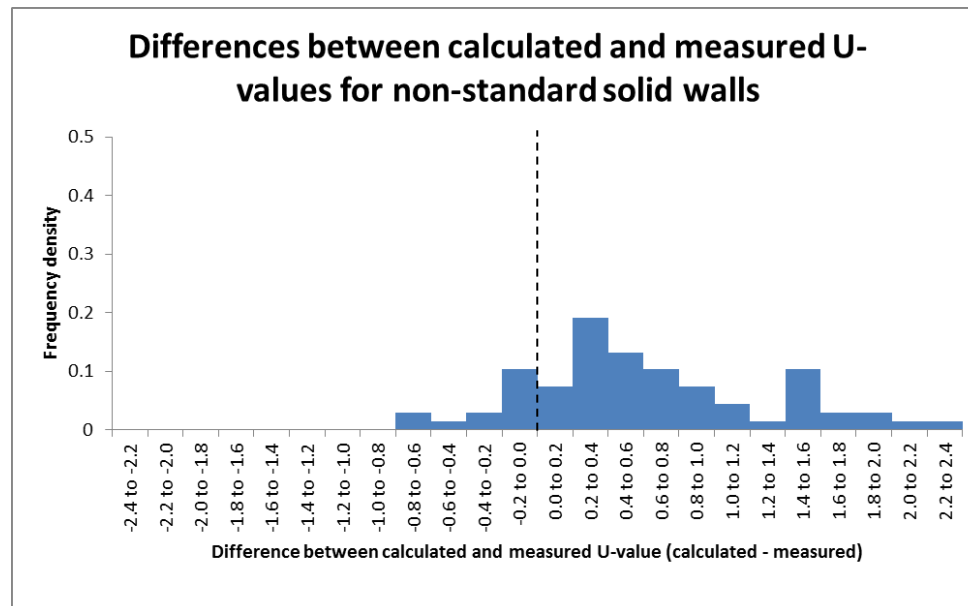
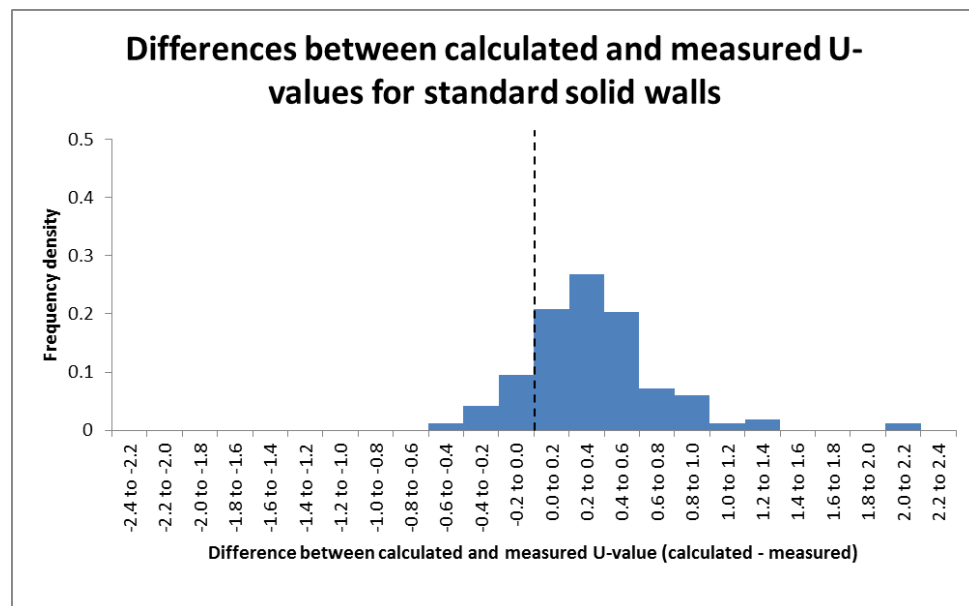
2.2 Comparison of measured and calculated values.

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.

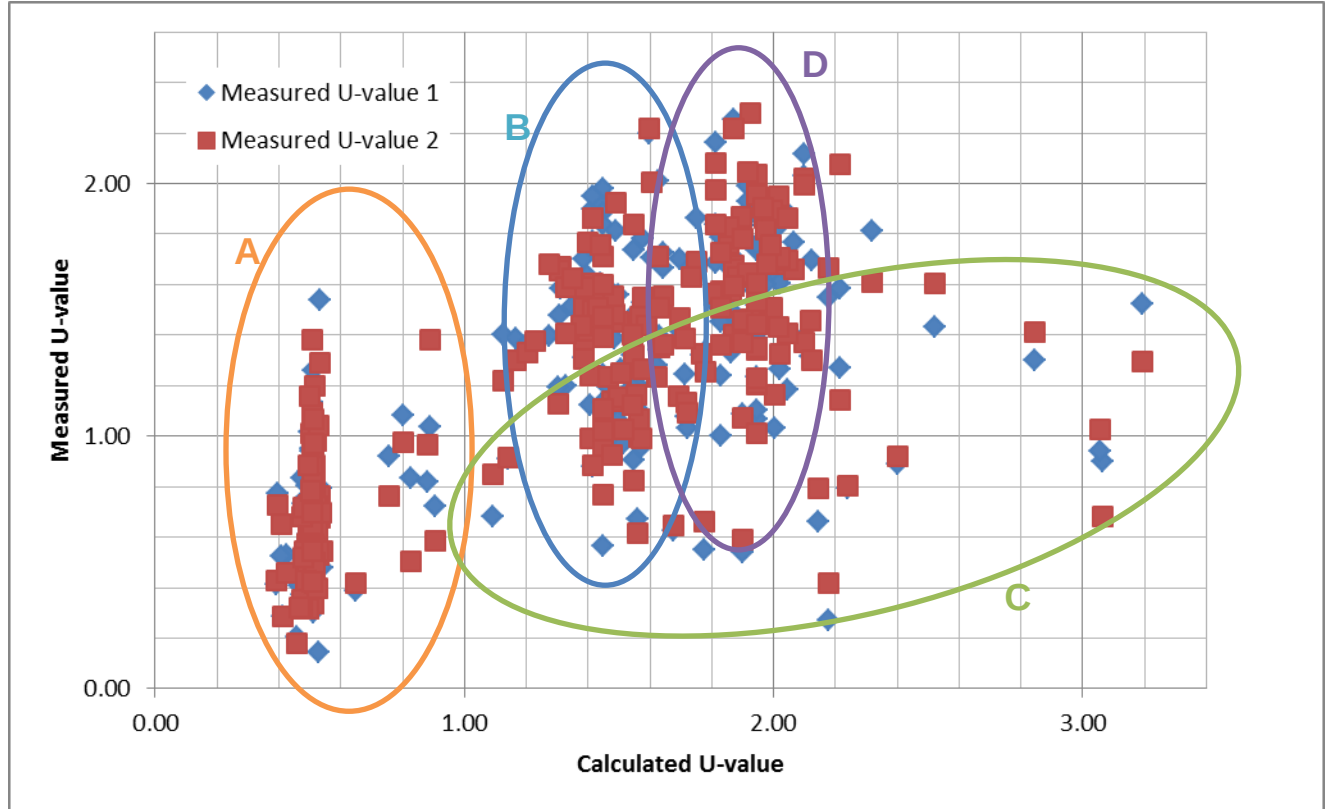


Figure 14: A comparison between measured U-values and calculated U-values (all wall types are shown together. In the calculation of U-values for solid brick walls it is assumed that the vertical joints between stretcher bricks are filled with air).

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

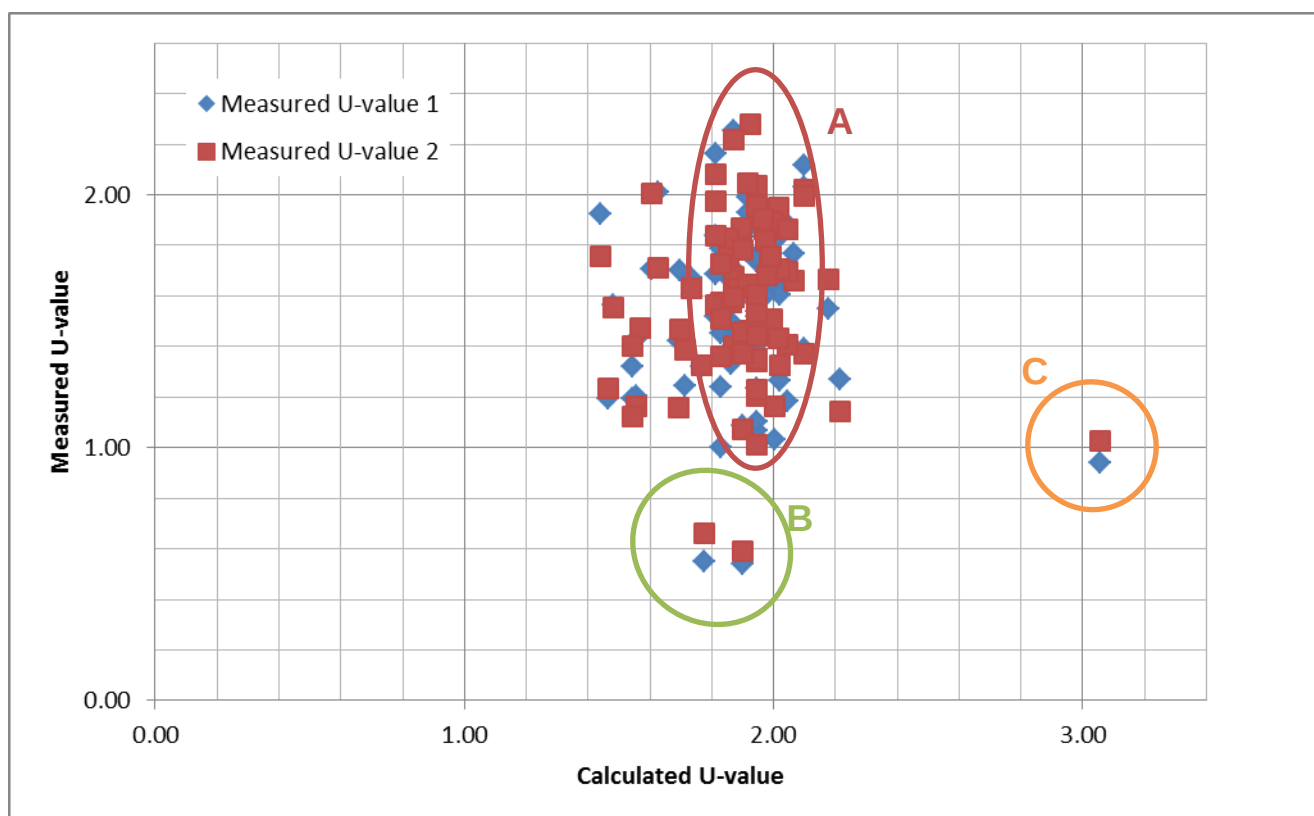


Figure 15: Standard solid walls. A comparison between measured U-values and calculated U-values; the latter taking into account all data from fieldsheets, dust drilling and coring. The outliers in areas B & C are described below.

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.

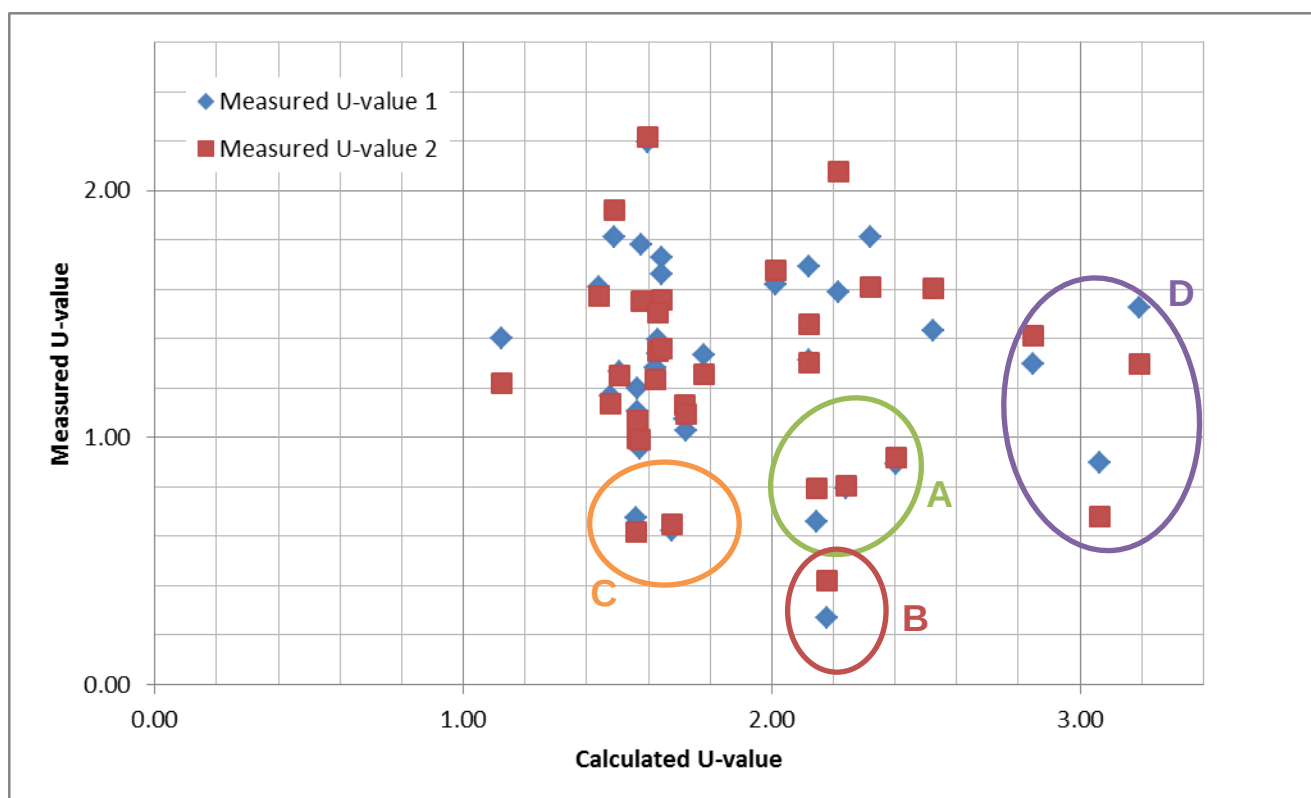


Figure 16: Non-standard solid walls. A comparison between measured U-values and calculated U-values; the latter taking into account all data from fieldsheets. Outliers in groups A, B, C and D are discussed below.

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 ($\geq 330\text{mm}$) 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 ($>500\text{mm}$) 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.

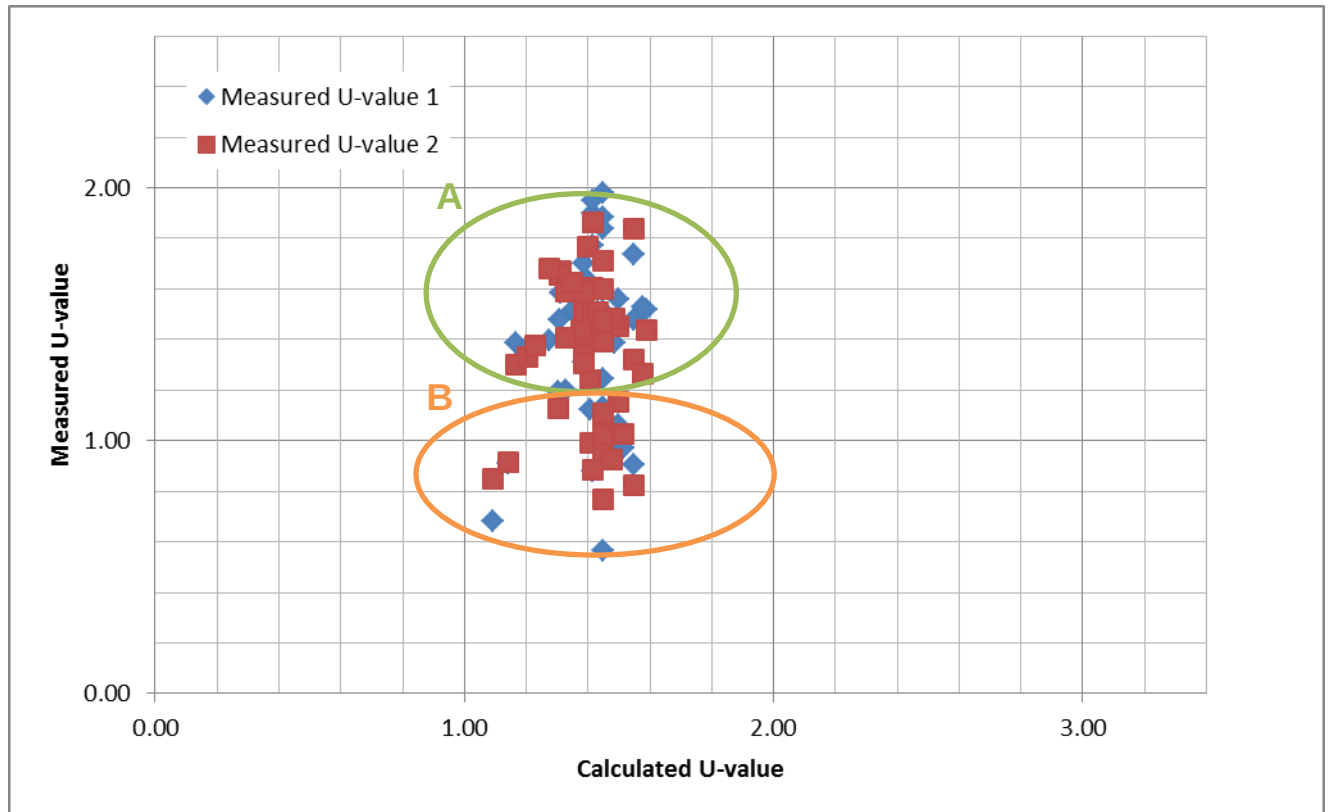


Figure 17: Uninsulated cavity walls: A comparison between measured U-values and calculated U-values; the latter taking into account all data from fieldsheets and boroscopic investigations. Groups A and B are discussed in the paragraph below.

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.

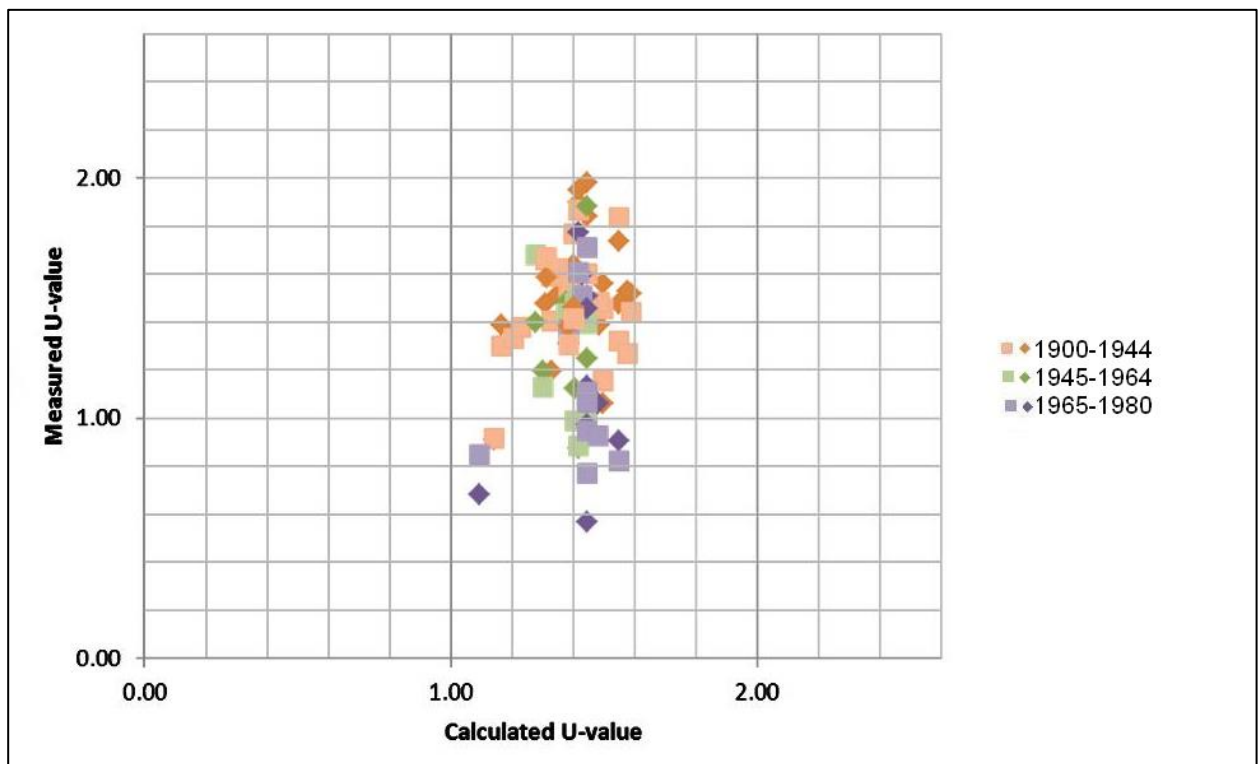


Figure 18: Uninsulated cavity walls marked by age of dwelling (dwellings built between 1900 and 1980): A comparison between measured U-values and calculated U-values; the latter taking into account all data from fieldsheets and boroscopic investigations.

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

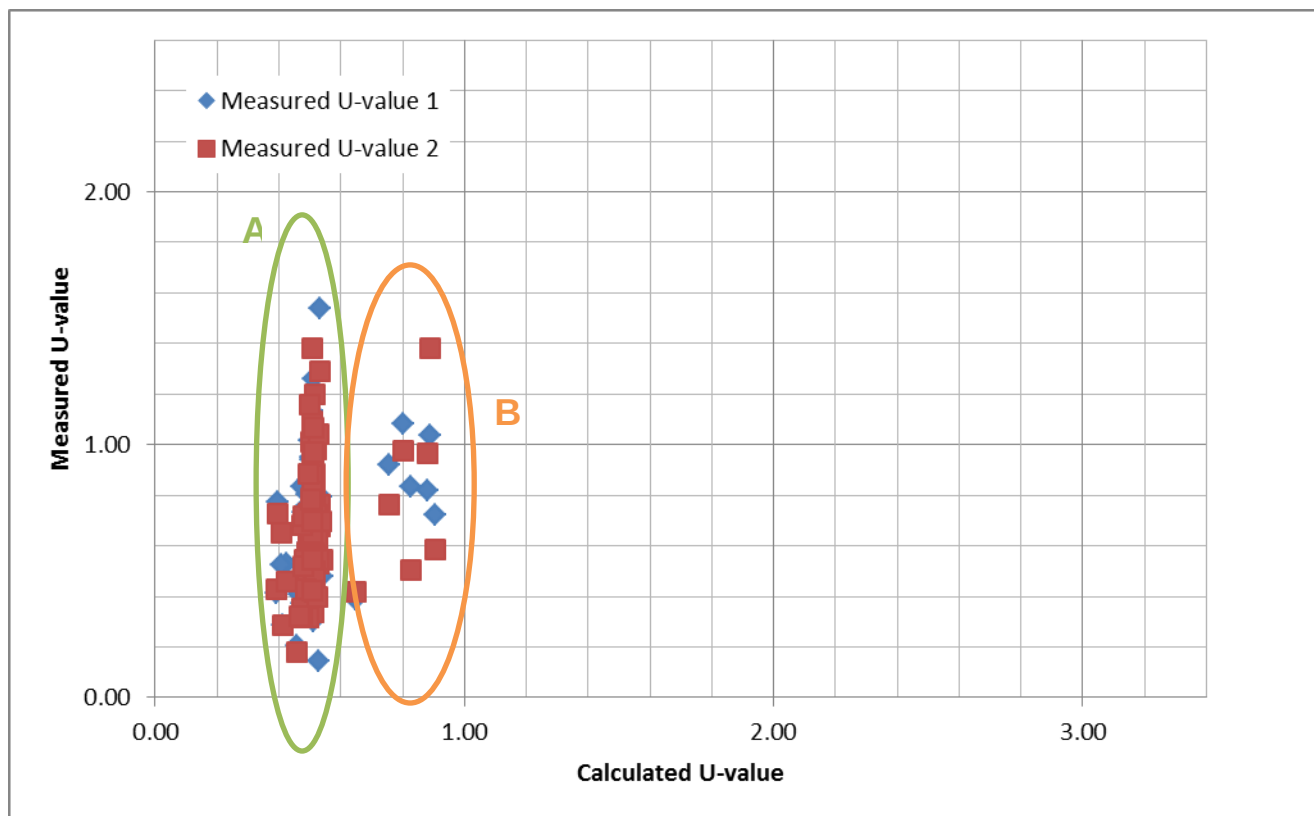


Figure 19: Insulated cavity walls. A comparison between measured U-values and calculated U-values; the latter taking into account all data from fieldsheets and boroscopic investigations. Groups A and B are discussed in the paragraph below.

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/m ² K	W/m ² K	W/m ² K
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
R² (compared to mean measured results)	-	0.0003	0.3836

¹In 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 walls⁹ 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/m ³	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/m³ to the densest sample of 1973 kg/m³. 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/m³ 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/m²K 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 measurements 2012	Original 2012 calculated values	Original 2012 difference	Mean of four measurements 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/m ² K)	Measured U-value, Feb-Mar 2013 (average of four measurements) (W/m ² K)	Difference between measurements years (W/m ² K)
	$U_{m,2011-12}$	$U_{m,2013}$	$U_{m,2013} - U_{m,2011-12}$
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 measurements (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

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).

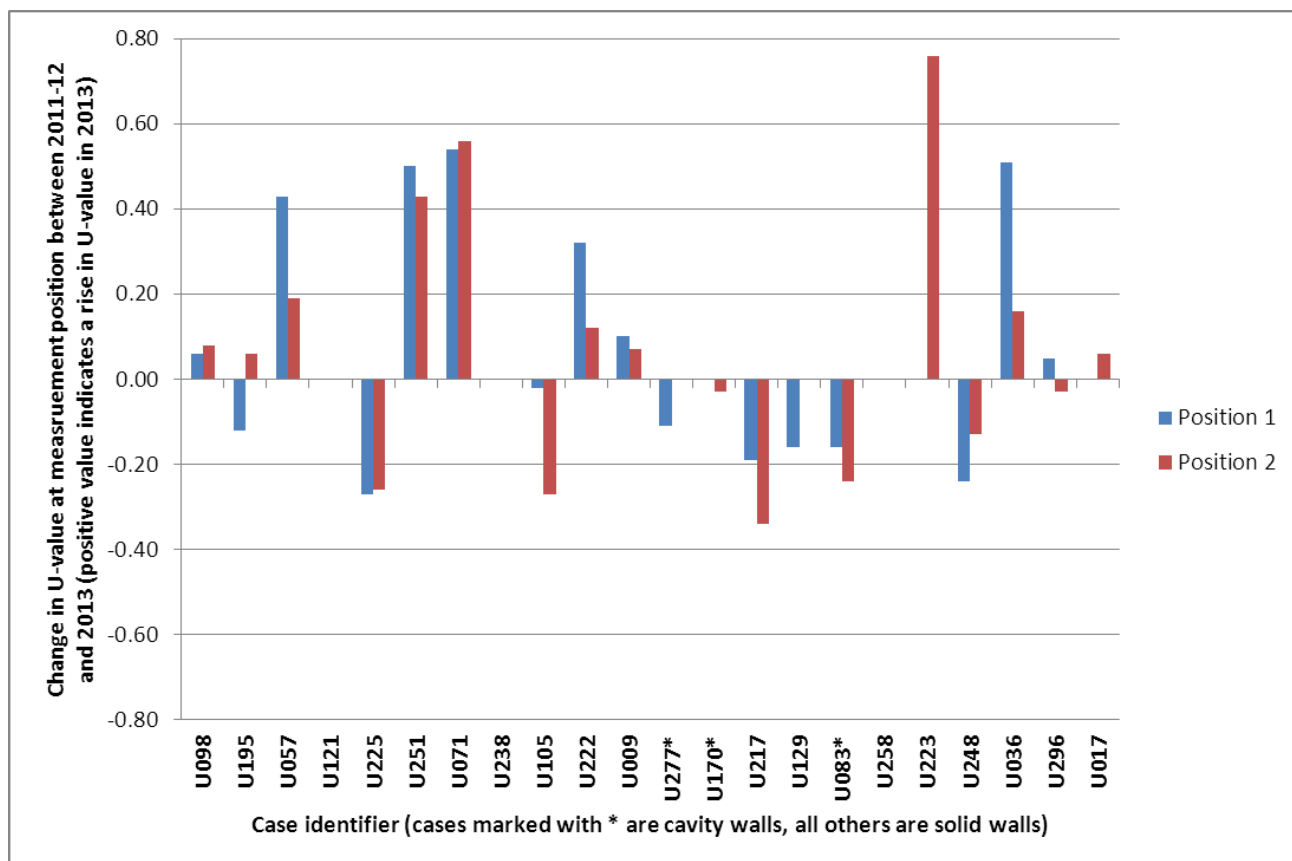


Figure 20 - Change in U-values between winter 2011-12 and 2013 at approximately equivalent positions.

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/m²K. Some measured results, however, were more varied. Case U248 showed the greatest variation in U-value with a range of 0.88 W/m²K. 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.

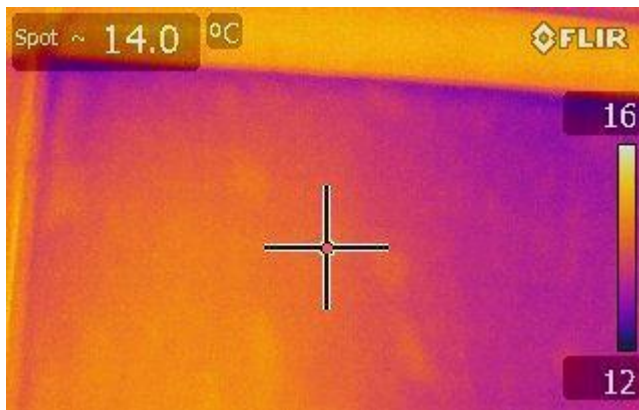


Figure 21: Inhomogeneous wall temperatures (shown by the variation in colours) in case U248, revealed by IR thermography.

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/m ² K	Measured U-values: median W/m ² K	Calculated U-values: mean (standard deviation), W/m ² K	Calculated U-values: Median W/m ² K	RdSAP U-values ^a W/m ² K	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 solid 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, $q_1, q_2, \dots, q_n$ (in W/m^2), n corresponding internal temperatures, $T_{i,1}, T_{i,2}, \dots, T_{i,n}$ (in $^\circ\text{C}$) and n corresponding external temperatures, $T_{e,1}, T_{e,2}, \dots, T_{e,n}$ (in $^\circ\text{C}$), (each taken at times $t_1, t_2, \dots, t_n$) then the U-value will be calculated as follows:

$$U = (\sum_k q_k / n) / [(\sum_k T_{i,k} / n) - (\sum_k T_{e,k} / n)] \quad \text{Equation A1}$$

Where $(\sum_k q_k / n)$ is the mean heat flux, $(\sum_k T_{i,k} / n)$ is the mean internal temperature (measured in the air close to the heat flux plate) and $(\sum_k T_{e,k} / n)$ 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

$$q_k = \epsilon_k / C$$

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

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

$$U(t_1, t_n) = (1 / C) (\sum_k \epsilon_k / n) / [(\sum_k T_{i,k} / n) - (\sum_k T_{e,k} / n)]$$

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

$$U'(t_1, t_n) = (1 / C') (\sum_k \epsilon'_k / n) / [(\sum_k T'_{i,k} / n) - (\sum_k T'_{e,k} / n)]$$

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	m ² K/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

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

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:

$$\lambda_L = \lambda_{L0}(\rho) F_T F_m F_a$$

Where $\lambda_{L0}(\rho)$ 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_{L0} 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_{L0}) 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

$$\lambda_{L0}(\rho) = (0.00038017 \text{ W.m}^2/\text{kg.K} \times \rho) - 0.19617 \text{ W/mK}$$

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 m ² K/W	0.05 W/mK
10 mm	0.15 m ² K/W	0.07 W/mK
15 mm	0.17 m ² K/W	0.09 W/mK
20 mm	0.18 m ² K/W	0.11 W/mK
50 mm	0.18 m ² K/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, $u=(\rho-\rho')/\rho$	Moisture content, volume by volume, $\Psi=(\rho-\rho')/\rho_{\text{water}}$	Predicted thermal conductivity, λ , BS EN ISO 10456	Predicted U-value of typical solid wall
kg/m ³	kg/m ³	%	%	W/mK	W/m ² K
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, $u=(\rho-\rho')/\rho$	Moisture content, volume by volume, $\Psi=(\rho-\rho')/\rho_{\text{water}}$	Predicted thermal conductivity, λ , BS EN ISO 10456	Predicted U-value of typical solid wall
kg/m ³	kg/m ³	%	%	W/mK	W/m ² K
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 ($\geq 0.5 \text{ W/m}^2\text{K}$) between the U-values returned by the HFPs and or between the monitored temperatures ($> 2^\circ\text{C}$). 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/m ² K	Calculated U-values: mean (standard deviation), W/m ² K
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/m ² K*	Calculated U-values: mean (standard deviation), W/m ² K
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)

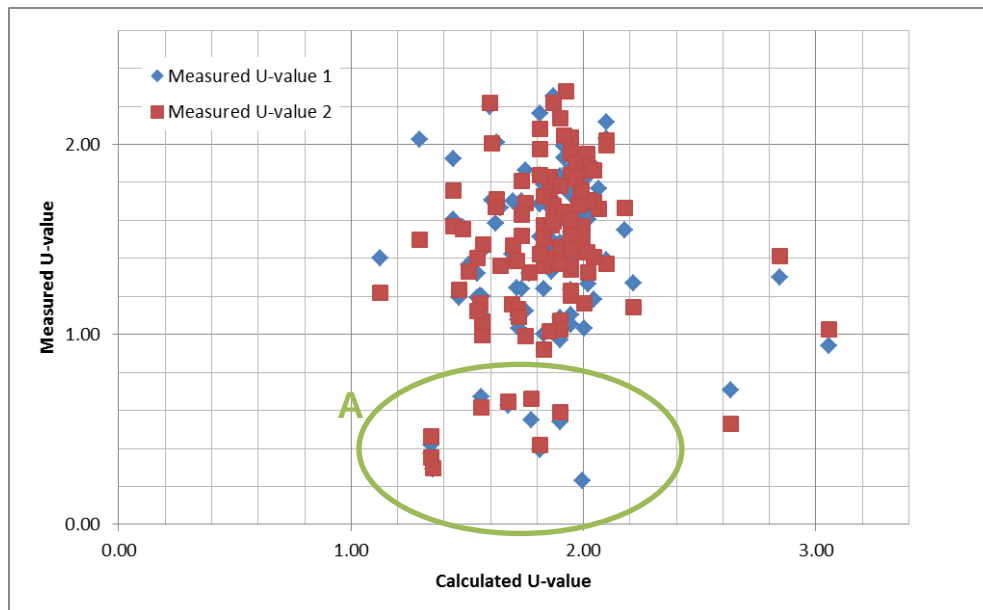


Figure C1: Scatterplot of measured against calculated U-values using the EHS predominant wall type classification of standard solid walls and prior to the filtering of data for low temperature differentials etc. Group A indicates properties which are predominantly standard solid walls, but where the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

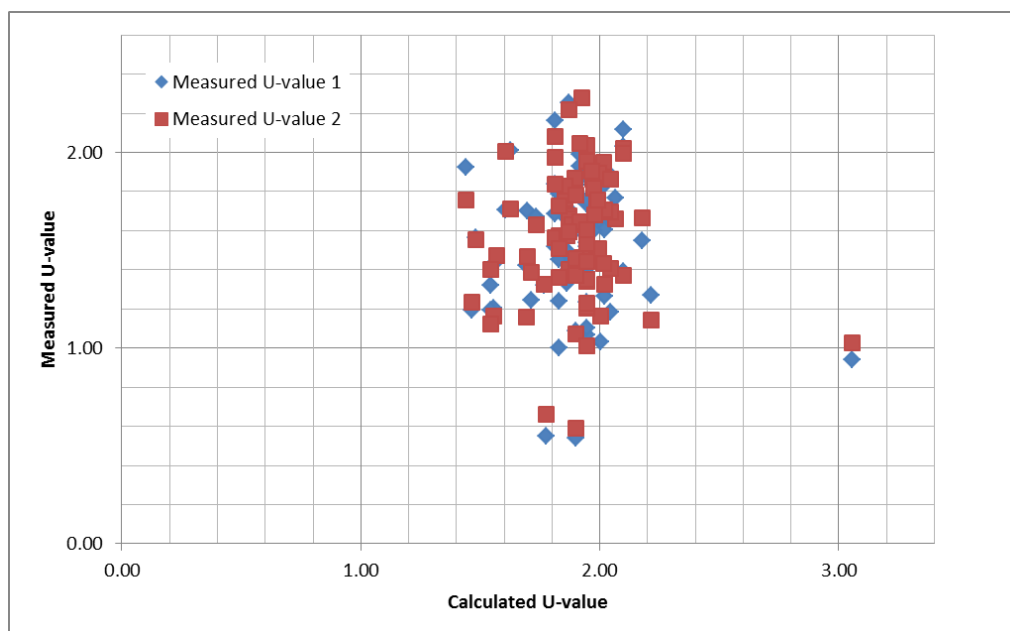


Figure C2: Scatterplot of measured against calculated U-values of standard solid walls using the final wall type classification and filtering data for low temperature differentials etc. Note that the majority of outliers visible in Group A of Figure C1 have now been reclassified as having been in insulated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

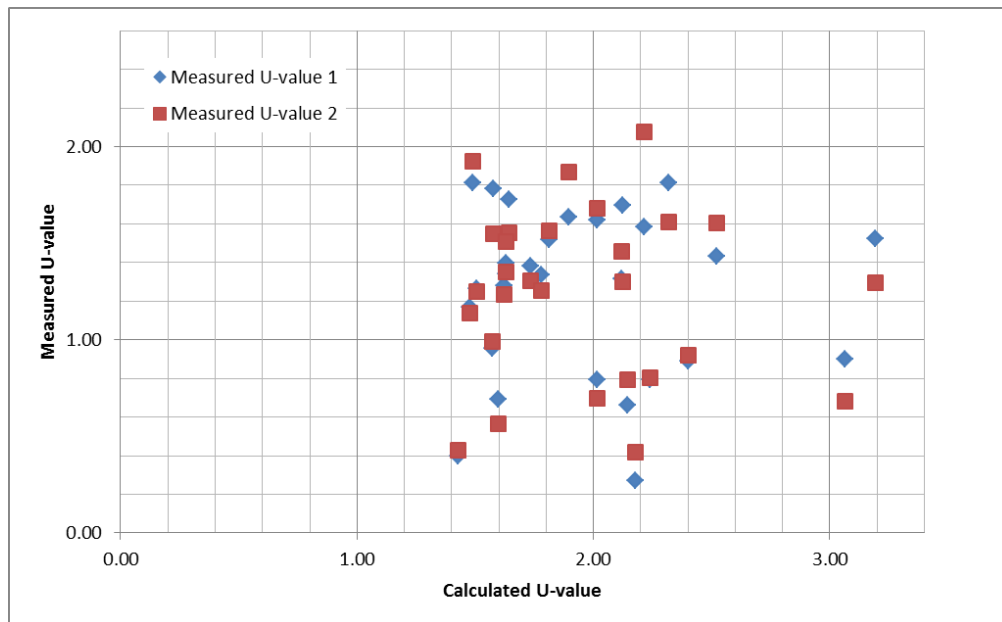


Figure C3: Scatterplot of measured against calculated U-values using the EHS predominant wall type classification of non-standard solid walls and prior to filtering of data for low temperature differentials etc. Some of these properties required reclassification or other adjustments to calculations based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

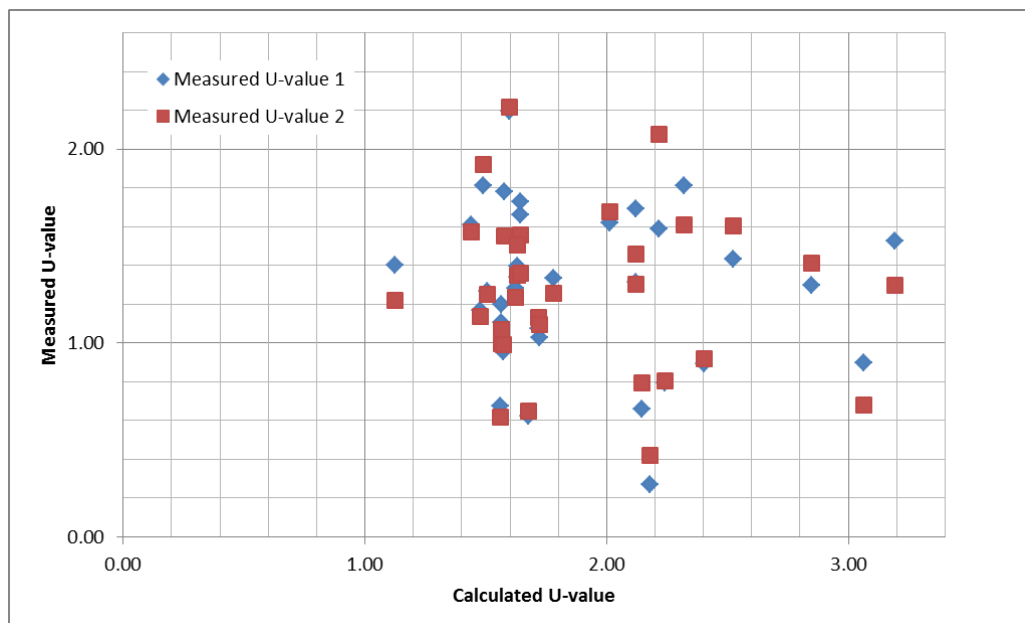


Figure C4: Scatterplot of measured against calculated U-values for non-standard solid walls using the final wall type classification and filtering data for low temperature differentials etc.

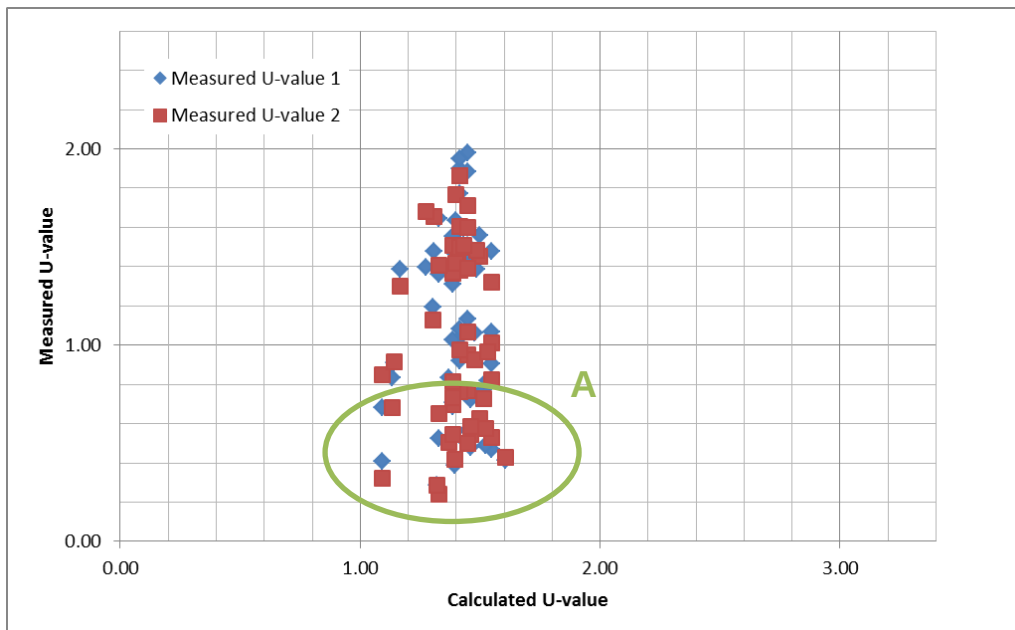


Figure C5: Scatterplot of measured against calculated U-values using the EHS predominant wall type classification of un-insulated cavity walls and prior to the filtering of data for low temperature differentials etc. Several of the properties in group A were re-classified as insulated cavity walls based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

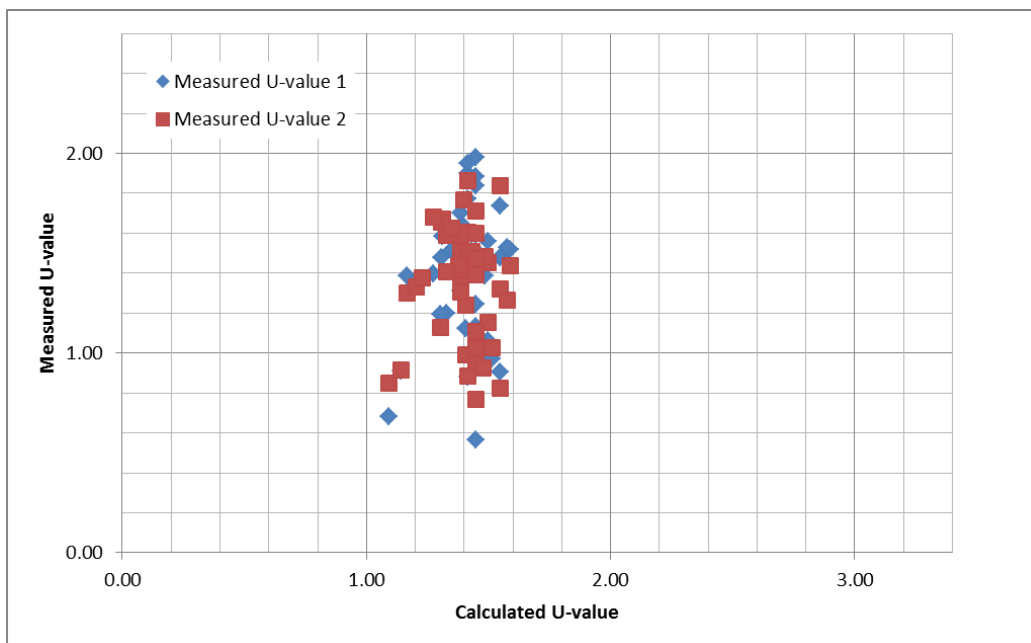


Figure C6: Scatterplot of measured against calculated U-values of un-insulated cavity walls using the final wall type classification and filtering data for low temperature differentials etc. Note the removal of several properties identified in group A of Figure C5 from this group.

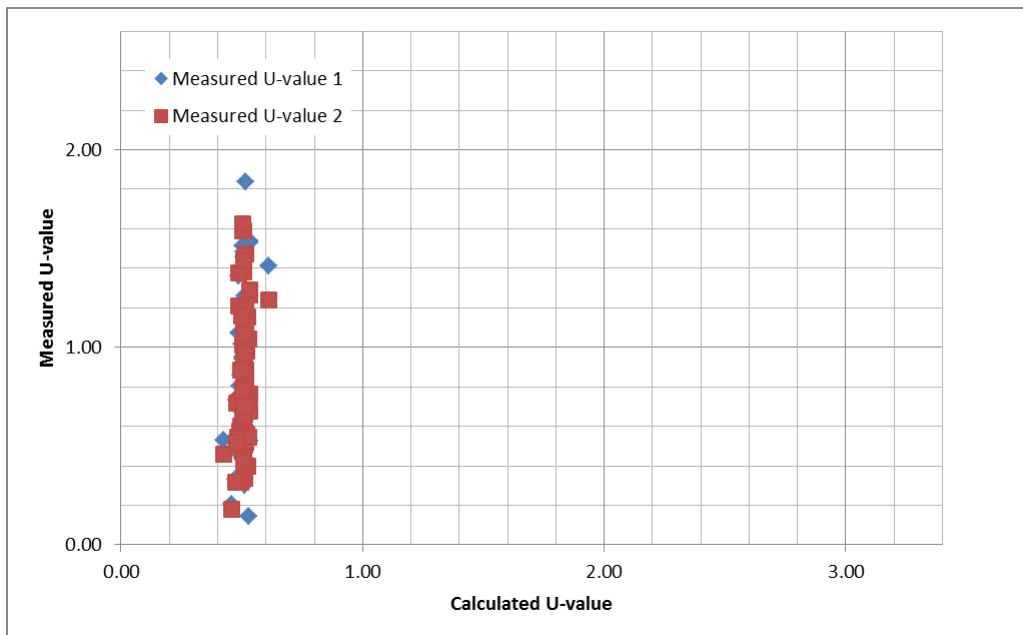


Figure C7: Scatterplot of measured against calculated U-values using the EHS predominant wall type classification of insulated cavity walls and prior to the filtering of data for low temperature differentials etc. These data do not also include the adjustments to the calculations made based on the boroscopic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

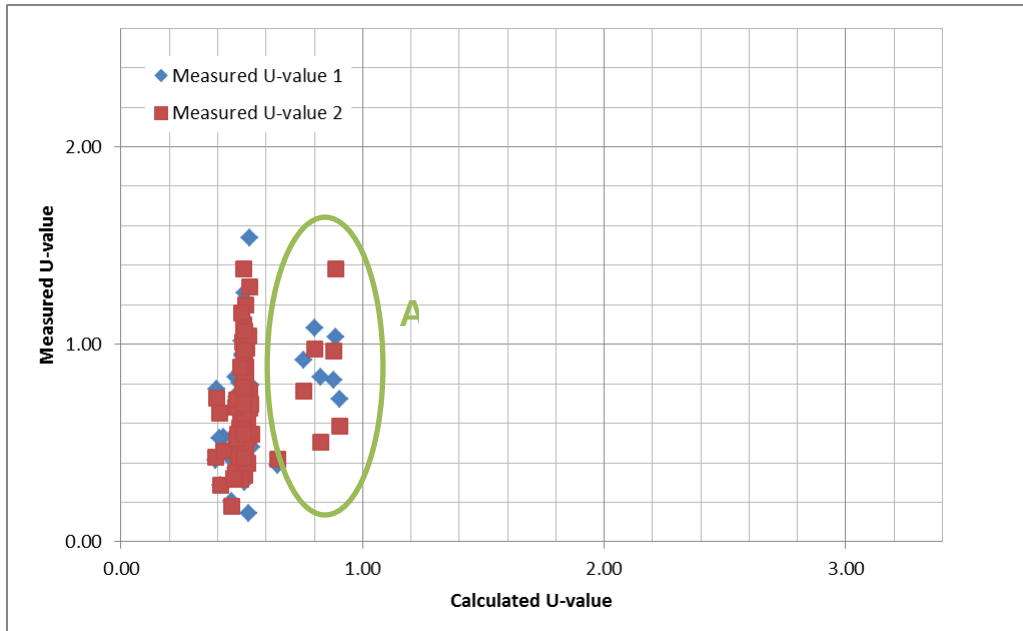


Figure C8: Scatterplot of measured against calculated U-values of un-insulated cavity walls using the final wall type classification and filtering data for low temperature differentials etc. Note the adjusted calculated values informed by the boroscopic investigations in the area marked A.

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

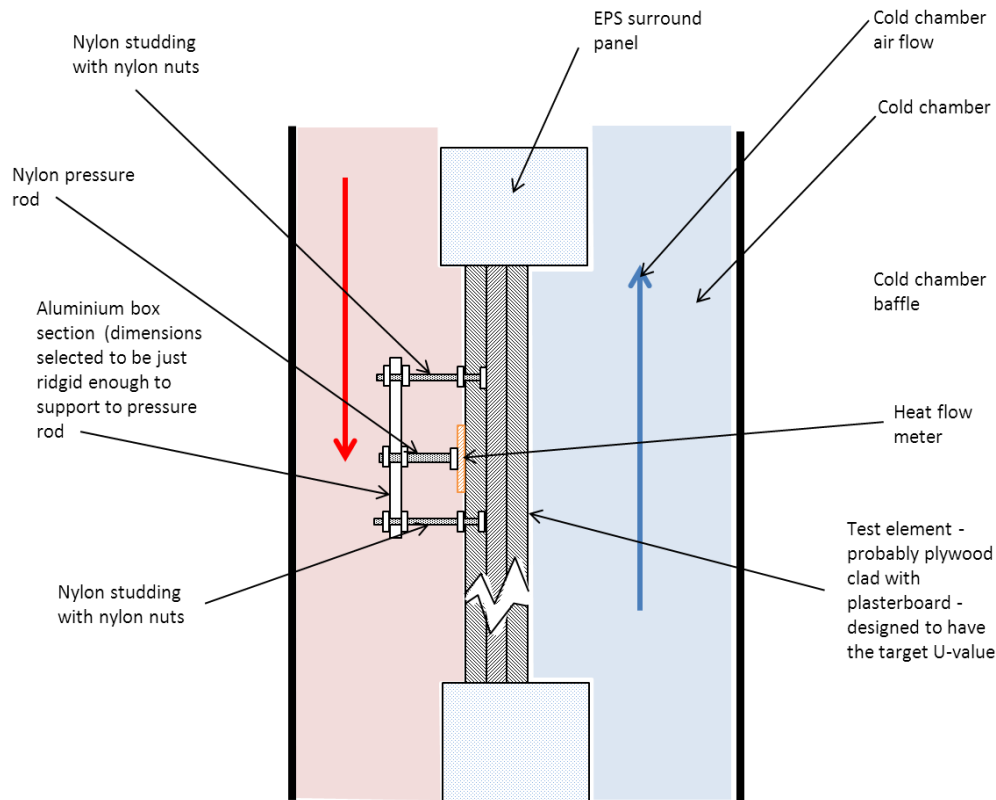
The measurements were conducted at the NPL Rotatable Wall Guarded Hot Box, described in NPL Report CBTL M 25. Where relevant, the equipment and measurement procedures were in accordance with the requirements of BS EN ISO 8990:1996. The main features of the equipment are summarised below:

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.



Arrangement for applying pressure to HFM to ensure it is in good contact with test element and to mimic method used in practice

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.

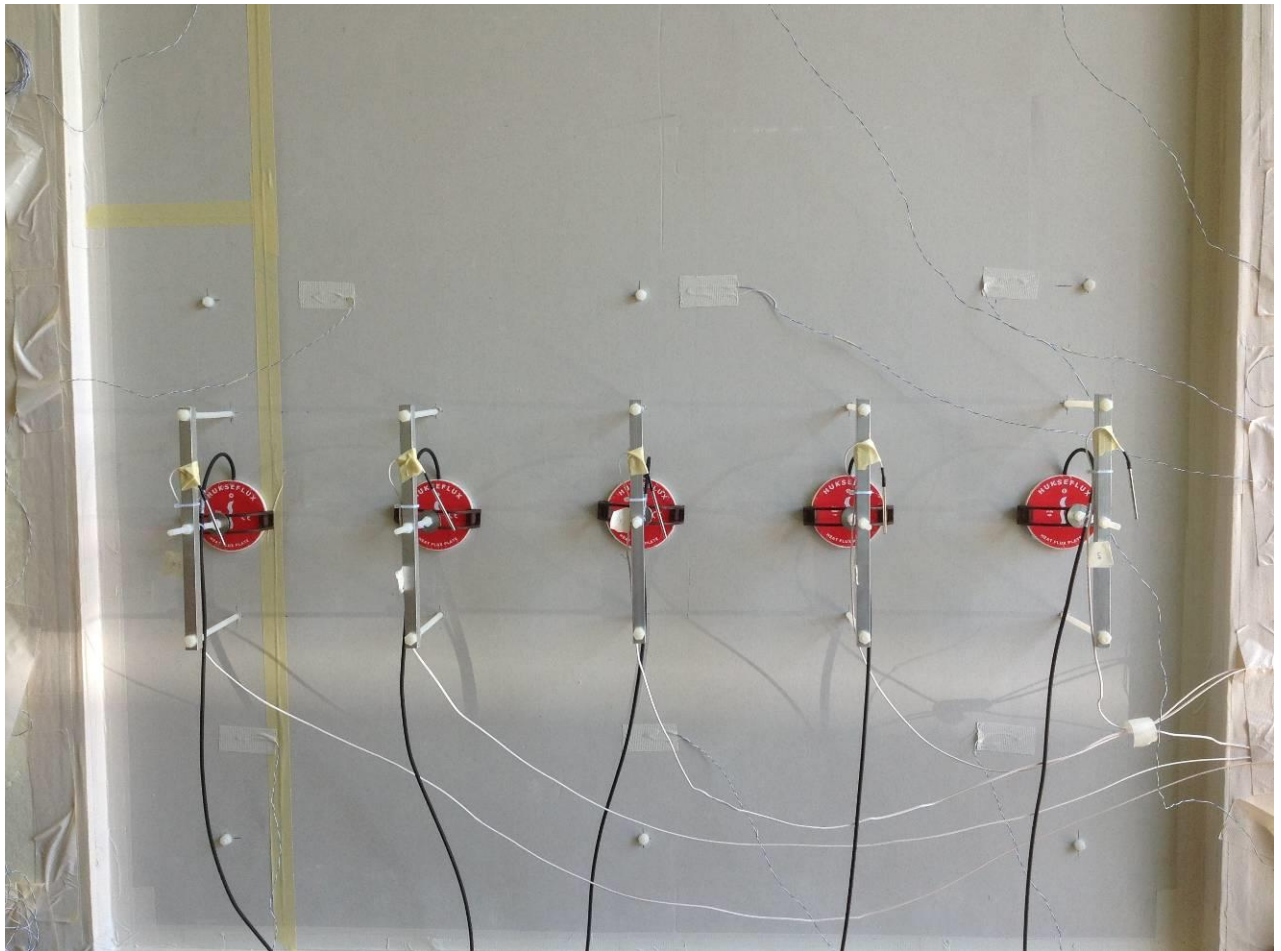


Figure E2 – photograph of in-situ setup of equipment fixed to test panel

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/m^2) 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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Appendix B

Report 2: Hulme, J. (2016) Solid wall heat losses and the potential for energy saving: The nature of solid walls *in situ*.

Solid wall heat losses and the potential for energy saving

The nature of solid walls in situ

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Notes

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

The lead author for this report was Jack Hulme of BRE. Other contributors from BRE include Sean Doran, Tim Ward, Ian Murray, Matt Custard, John Riley, Helen Foster, Jon Whiteley and Mike Kay. Thanks are also extended to Ray Williams, Clark Stacey and Graham Ballard of NPL, and to the householders, local authorities and housing associations who made their homes available for the fieldwork.

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Executive Summary

Previous work by BRE and others has identified that U-values of solid wall dwellings measured in situ are lower than the generally assumed value of $2.1 \text{ W/m}^2\text{K}$.

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

Following this work, we can conclude that there is now good evidence to support a revision to the assumed U-value for uninsulated solid walls to approximately $1.75 \text{ W/m}^2\text{K}$. The lower U-values seem likely to result from the following factors, which are supported by evidence from this research:

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

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

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

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

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

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



- b) Perpend joints were also seldom fully filled with mortar. The median percentage of the exposed perpend area estimated to be filled with mortar was 70%. The air spaces in these joints will lead to lower U-values.
- c) Where a brick contained a frog, if it was found on the top face of the brick (brick laid “frog-up”) then it was almost always fully filled with mortar. If it was found on the bottom face of the brick (brick laid “frog-down”) it was very seldom filled with mortar. The air space created by the frogs will lead to lower U-values.
- d) Broken or damaged bricks forming part of the wall were relatively common. Snapped header bricks or partial or deformed bricks forming the inner leaf were revealed in approximately 1 in 10 cases. These generally resulted in additional air cavities, which will lead to lower U-values.
- e) Bricks were generally very dry. The median moisture content of brick and dust samples by volume was 0.7%. Some bricks, however, were extremely wet with a median moisture content of over 15%. Typical assumptions in calculations are that bricks have a moisture content of 5% by volume. If bricks are significantly drier than this, it will act to reduce their conductivity and the U-value of the wall.
- f) Mortar was slightly wetter, although generally also dry. The median moisture content of mortar by volume was ~2.8%. Some mortar, however, was also extremely wet with a median moisture content of over 15%. Mortar is generally assumed to have a moisture content of 5% by volume. If mortar is, in reality, drier than this, it will act to reduce its conductivity and the U-value of the wall.
- g) The median dry density of bricks was higher than the generally assumed value. The median measured density was 1,804 kg/m³ rather than the often assumed 1,750 kg/m³. There is a general relationship between density and thermal conductivity, with denser bricks likely to be more conductive giving rise to walls with a higher U-value.

The testing of the built walls in the hot box provided some laboratory validation of the U-values of solid wall structures which we had built. The walls that we had built in order to replicate many of the features observed in the fieldwork had U-values of between 1.69 W/m²K and 1.96 W/m²K.

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

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

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

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

The first part of this has examined the effect of including the fieldwork and laboratory observations within the calculation of a typical solid wall; i.e. one with a typical thermal conductivity, moisture content and internal structure, to determine a new average value for a solid brick wall. The fieldwork has provided strong evidence to suggest refinements to the calculation of U-values to incorporate additional air cavities within the wall, and refined default moisture and density values. This has the effect of reducing the theoretical U-value from 2.1 W/m²K to 1.77 W/m²K for a typical wall, of the sort identified in the fieldwork.



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



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1 Introduction

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

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

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

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

1.1 Background

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

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

2.1 W/m²K as the default for solid wall U-values

Recent editions of key guidance documents, such as CIBSE guides [14] and RdSAP Appendix S [15], all list the U-value of a wall as 2.1 W/m²K. This value has a long heritage, and has been broadly supported by some theoretical calculations, and some experimental work.

The earliest work of this sort focussed on experiment. This includes tests undertaken in the 1920s on behalf of the Government's Building Research Board (the predecessor to the Building Research Station (BRS), and subsequent Building Research Establishment). One of these publications includes an assessment of the thermal properties of a solid brick wall, which had been produced by BRS



scientists in conjunction with the National Physical Laboratory (NPL) [2]. The ‘hot box’ work which we have recently undertaken and present here, bears many similarities to these early tests.

Slightly later work, undertaken by BRS in the 1930s in its specifically designed “Wall Laboratory”, also aimed to measure the thermal conductivity of solid brick walls. This work, produced by Dufton, provided measured U-values of between 2.2 and 2.6 W/m²K [1].

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

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

Loudon proposed updated methodologies for various elements of the calculation, including the assumed moisture content of bricks (5% by volume for exposed, and 1% for sheltered) which are generally used today. In the 1970 IVHE guide, based on these assumptions, a value of 2.1 W/m²K was proposed for the U-value of a solid wall.

Later editions of the guide [e.g. 5, 14] (now the CIBSE guide) continued to employ theoretical assumptions, maintaining the modern value for the U-value of a solid wall of 2.1 W/m²K. This was taken into RdSAP Appendix S when this was first produced in 2005 in support of the introduction of Energy Performance Certificates (EPCs).

The assumption that 2.1 W/m²K is a suitable representation of the U-value of solid walls appears to have remained unchallenged until fairly recently. Although some very early unpublished work undertaken in the BRS Experimental House in 1935, using an ‘in situ’ technique, measured U-values of between 1.5 and 1.8 [12] these findings appear to have been soon superseded by the Wall Laboratory findings [1] measuring higher U-values, and which were later compared to the theoretical assumptions in the 1970 IVHE guide. In 1993, Ward [6] produced some in situ U-value measurements which were below 2.1 W/m²K, but the number of measurements made was relatively small. It was not until larger scale work, in anticipation of a programme of solid wall insulation being rolled out in the UK, that the value first began to be seriously challenged. Initial work undertaken by BSRIA and the Energy Saving Trust [7], measured U-values in solid wall dwellings in advance of a programme of insulation. These measurements indicated a significantly lower U-value than the default value of 2.1 W/m²K. Other work, for example, Rhee-Duverne & Baker [8] and SPAB [9] indicated similar findings, although often on unusual dwelling types (e.g. historic buildings).

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

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

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



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

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

Wall type	Number of cases	Measured U-values: mean (95% CI) W/m ² K*	Measured U-values: median W/m ² K	Calculated U-values: mean (standard deviation) W/m ² K	Calculated U-values: Median W/m ² K
Solid wall, standard ^a	85	1.65 (+/- 0.07) (1.57 excluding +5% correction)	1.67 (1.59 excluding +5% correction)	1.90	1.92
Solid wall, non-standard ^a	33	1.34 (1.28 excluding +5% correction)	1.34 (1.28 excluding +5% correction)	1.91	1.68

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

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

1.2 The solid wall insulation research project

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

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

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



adjustment alone, however, is insufficient to explain the gap between the average measured and calculated U-values of solid walls.

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

The programme included the following items:

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

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

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

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

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

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

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

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



Part A: Fieldwork and laboratory experiments



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

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

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

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

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

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

2.1 Fieldwork methodology

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

2.1.1 Heat flux and U-values

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

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



The equipment used in the fieldwork

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

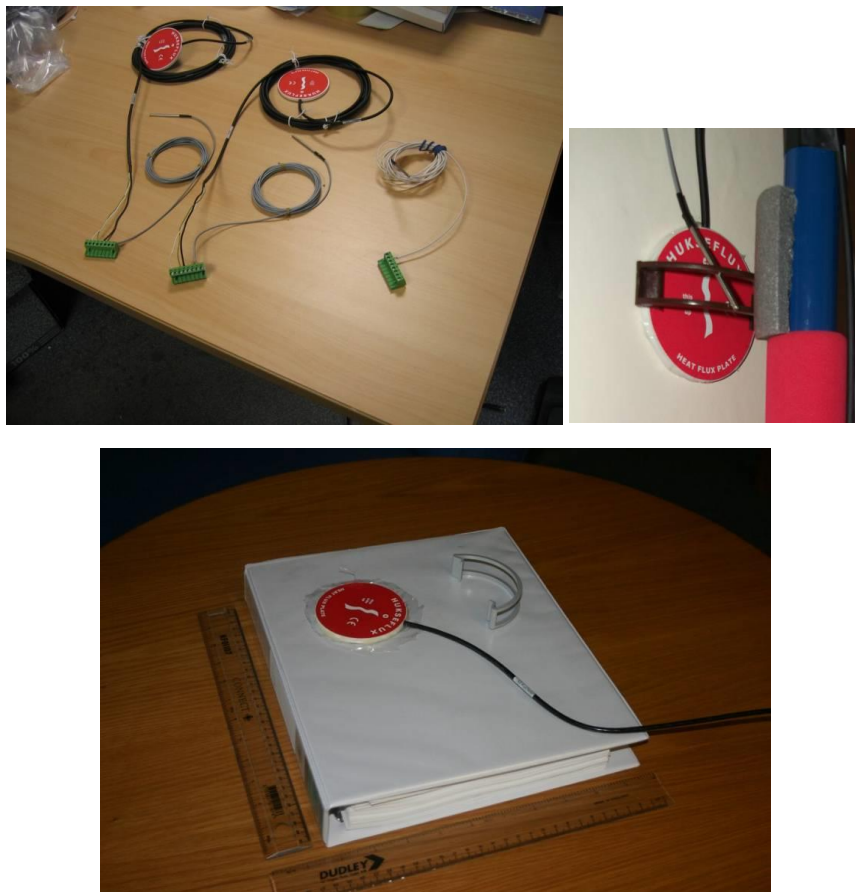


Figure 1: The sensing equipment used for monitoring the heat flux and temperatures. The Hukseflux heat flux plates (circular plates) measure heat flux (in watts per square metre) and the thermistor sensors (silver tubes) measure temperature.



Mounting the heat flux plates

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

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

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

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

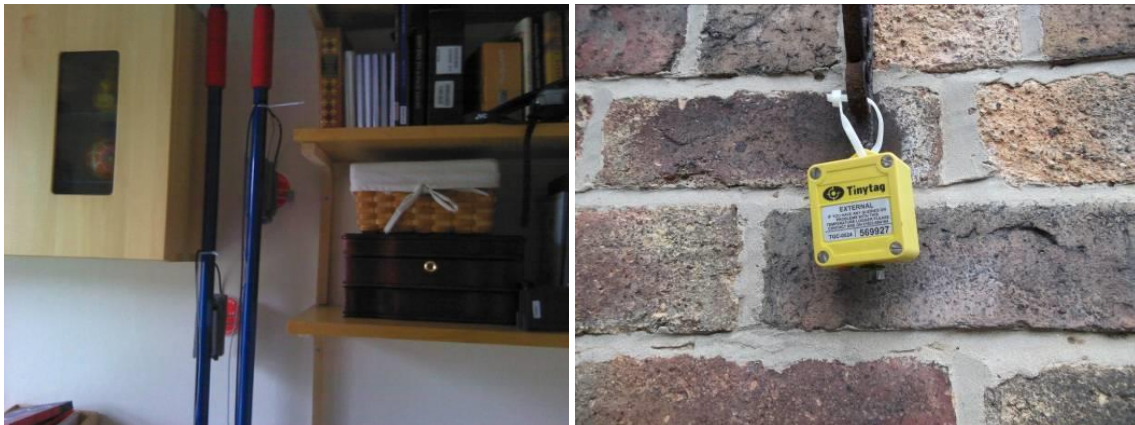


Figure 2: The equipment installed in an occupied dwelling (left hand picture) showing the heat flux plates (red discs) and indoor temperature sensors supported by teleprops (blue poles) and clamps. Also shown is a Tinytag datalogger (right hand picture) attached to the outside wall (in a location out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



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

Selecting a suitable location

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

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

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

Thermal bridging at junctions and around openings

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

Duration of monitoring

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



2.1.2 Additional investigations to refine calculated U-values

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

Investigations of the internal structure of the walls

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

- a) The proportion of the joint between stretchers, known as the collar joint, filled by mortar.
- b) The width of the collar joint.
- c) The proportion of the vertical joints (perpend joints) filled by mortar.
- d) The presence of any frogs or drillings in the bricks, and whether laid frog-up or frog-down.
- e) The dimensions of any frog within the brick and the proportion of the frog filled with mortar.
- f) The presence of any snapped headers or broken bricks within the inner leaf of the wall.
- g) Any other observations.



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



2.1.3 Obtaining samples to provide information on density and moisture content

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

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



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

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

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

2.1.4 Results

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



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

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

2.1.5 Measured U-values results

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

2.1.5.1 Analysis of the U-values data

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

The format of the field data

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

Obtaining the U-value

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

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

$$U = (\sum_k q_k / n) / [(\sum_k T_{i,k} / n) - (\sum_k T_{e,k} / n)] \quad \text{Equation 1}$$

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

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

$$U(t_1, t_2)$$

For an accurate U-value, the value of $(t_2 - t_1)$ should be at least two weeks (in the case of an occupied dwelling) and at least a few days (in the case of a hot box with steady temperature conditions),



although examination of the data over shorter periods can provide a useful check on the quality of the data.

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

$$q_k = \epsilon_k / C$$

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

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

$$U(t_1, t_n) = (1 / C) (\sum_k \epsilon_k / n) / [(\sum_k T_{i,k} / n) - (\sum_k T_{e,k} / n)] \quad \text{Equation 2}$$

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

$$U'(t_1, t_n) = (1 / C') (\sum_k \epsilon'_k / n) / [(\sum_k T'_{i,k} / n) - (\sum_k T'_{e,k} / n)] \quad \text{Equation 3}$$

Thermal mass

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

Resistance of heat flux plate and substrate

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

Therefore, the final U-value becomes:

$$U_{\text{FINAL}} = U * 1.05 \quad \text{Equation 4}$$

2.1.5.2 Obtaining a quality dataset

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

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

- U-value measurements are particularly dependent on cold weather maintaining a sufficient difference between internal and external temperatures. For the survey period, however, two



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

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

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

2.1.5.3 Headline results

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

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

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

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

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

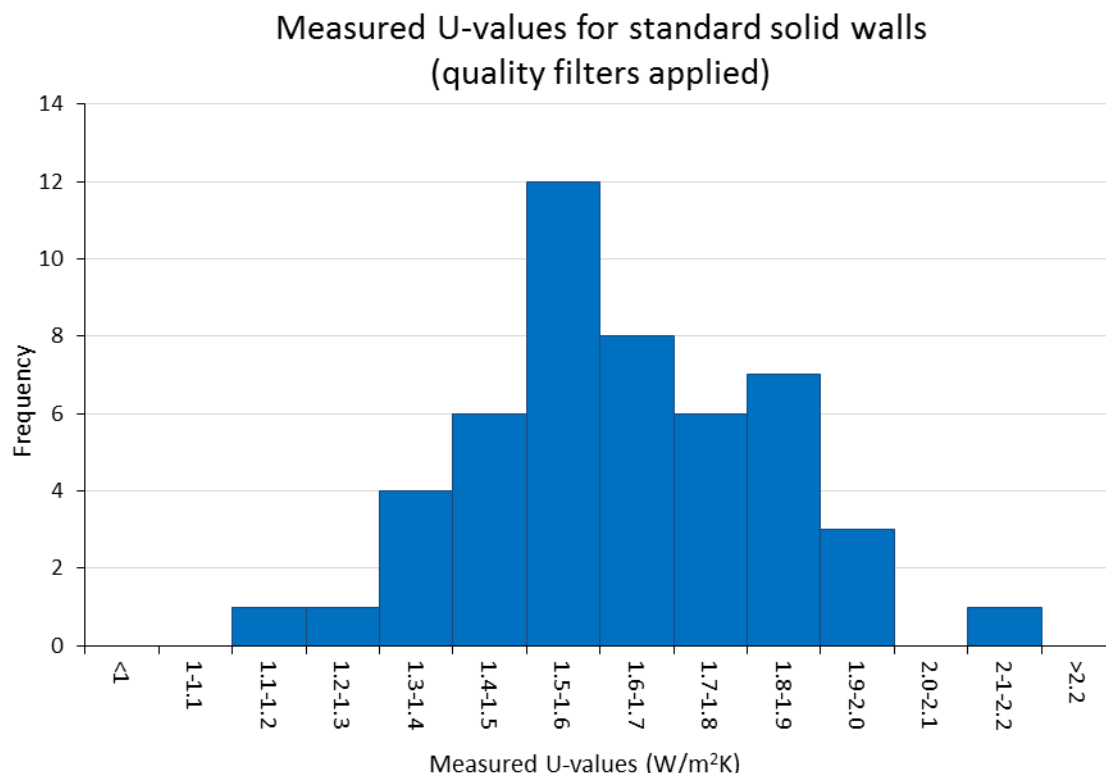


Figure 7: Distribution of measured U-values for standard solid walls, as measured in the fieldwork.

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

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

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

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



Collar joints

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

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



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

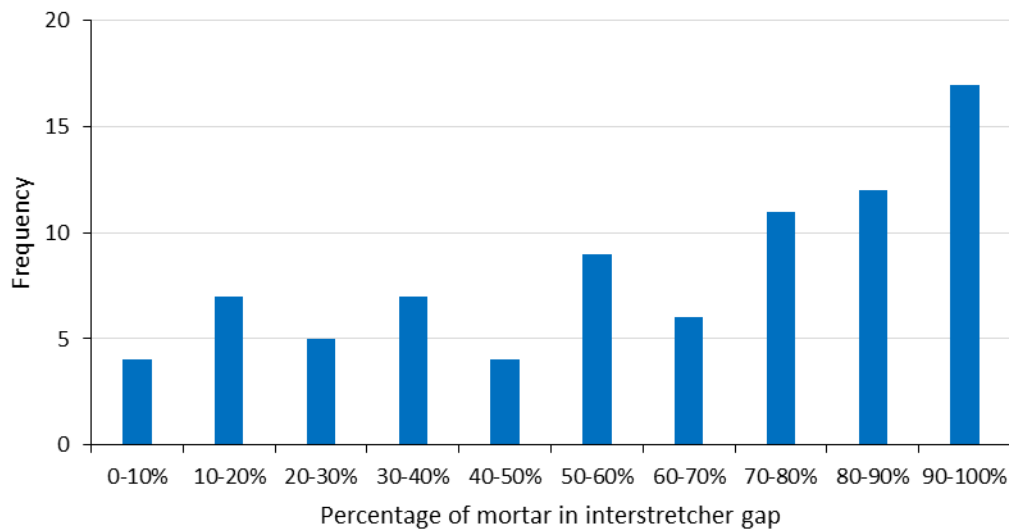


Figure 9: Percentage of mortar in collar joint, as observed in fieldwork

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

Perpend joints

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



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

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

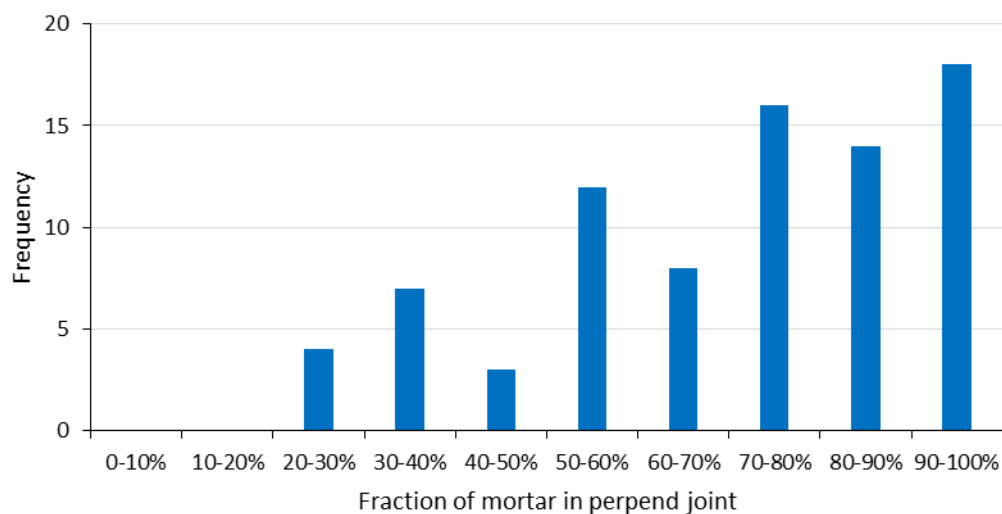


Figure 11: Percentage of mortar in perpend joints, as observed from fieldwork



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

Bed joints

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

Frogs

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

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



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

Overall, 45% of the 82 bricks removed contained frogs. Generally, only a single frog was present (only 12% of all bricks contained two frogs – one on each side of the brick). Of all bricks with a single frog, 52% of bricks were laid frog-up, and 48% laid frog-down (note that, because only a single brick



was removed it is not possible to tell if the wall was built with a mixture of frog-up and frog-down bricks). Frog-up bricks were almost always fully filled with mortar whereas frog-down were very seldom fully filled with mortar. The distributions of mortar fill for frog-up and frog-down bricks are shown in the Figures 13 and 14 below.

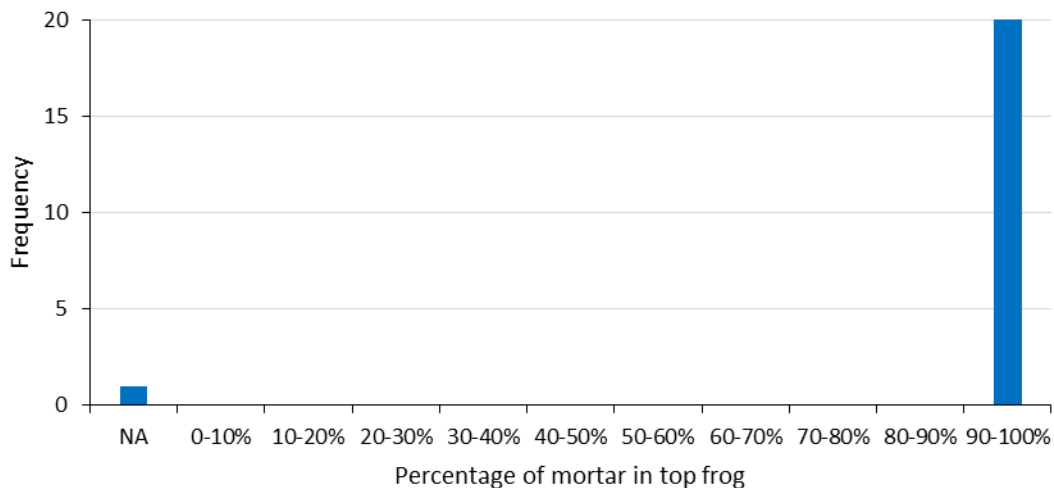


Figure 13: Percentage of mortar in frogs found on the top face of bricks, from fieldwork

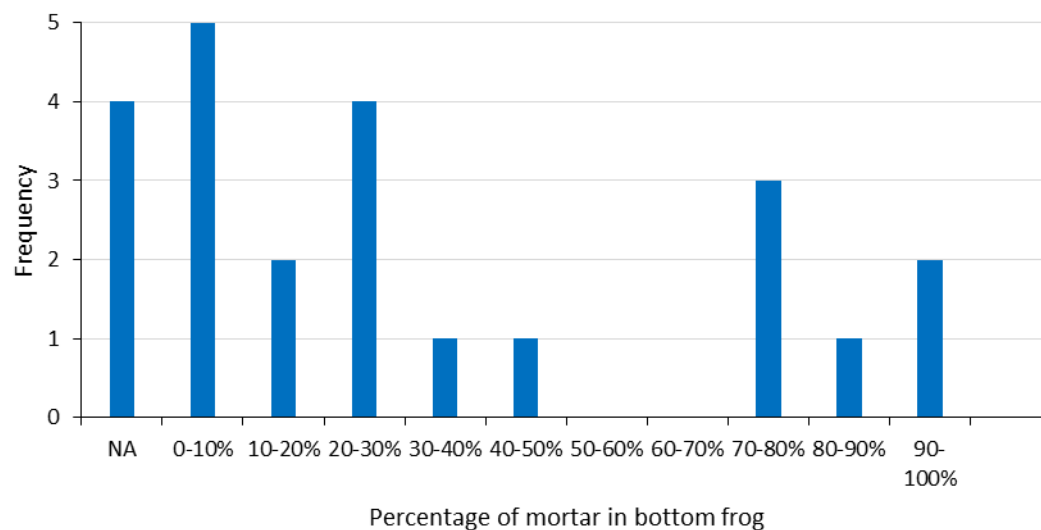


Figure 14: Percentage of mortar in frogs found on the bottom face of bricks, from fieldwork

The dimensions of frogs also varied, for those cases where measurement was possible (mortar or other practical reasons sometimes prevented this). The median volume of the frogs where measurements were taken was 76 cm³. The distribution of frog volumes is shown in Figure 15 below.

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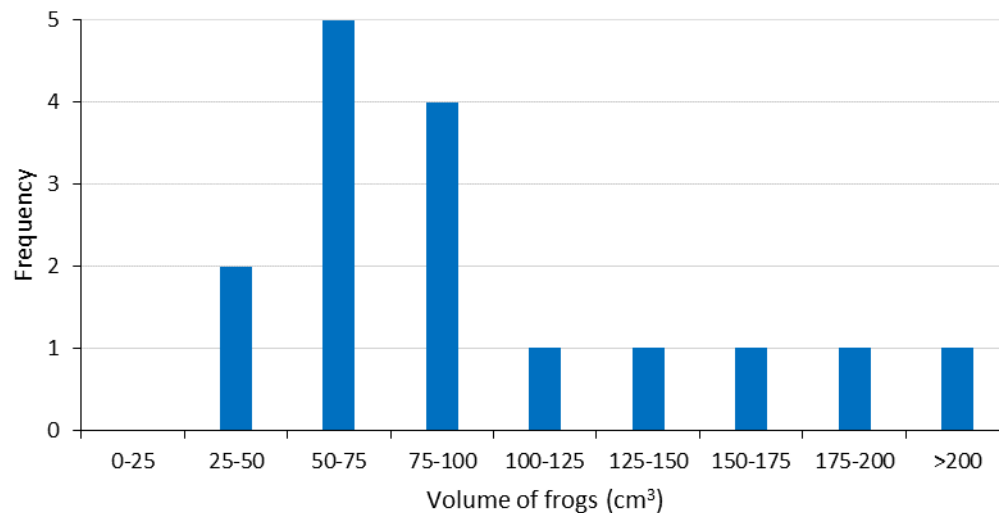


Figure 15: Volume of frogs for those where measurement was possible in the field

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

Brick bats and imperfect bricks

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

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



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



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

Perforated bricks

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



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

Moisture content of bricks

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

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

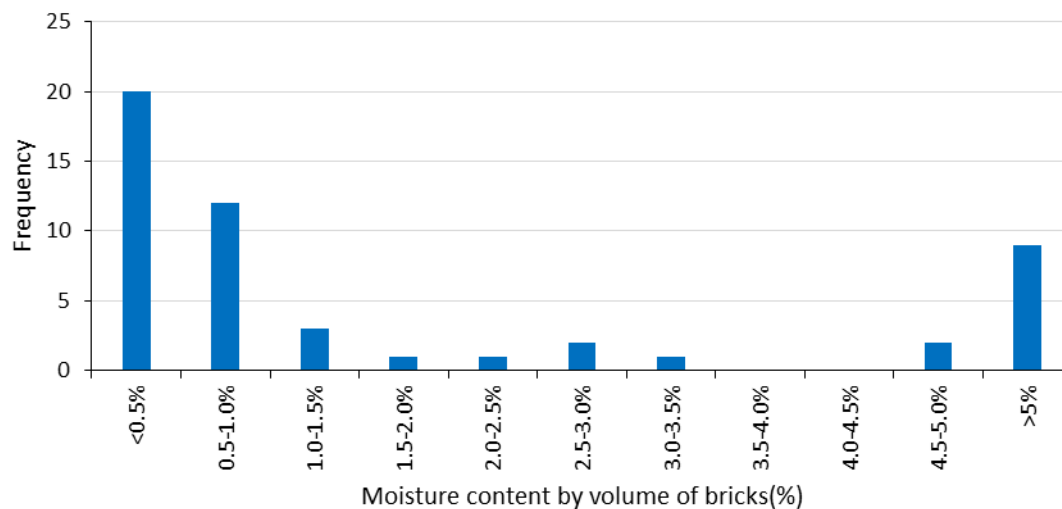


Figure 19: Distribution of moisture content by volume of brick samples.

Moisture content of mortar

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

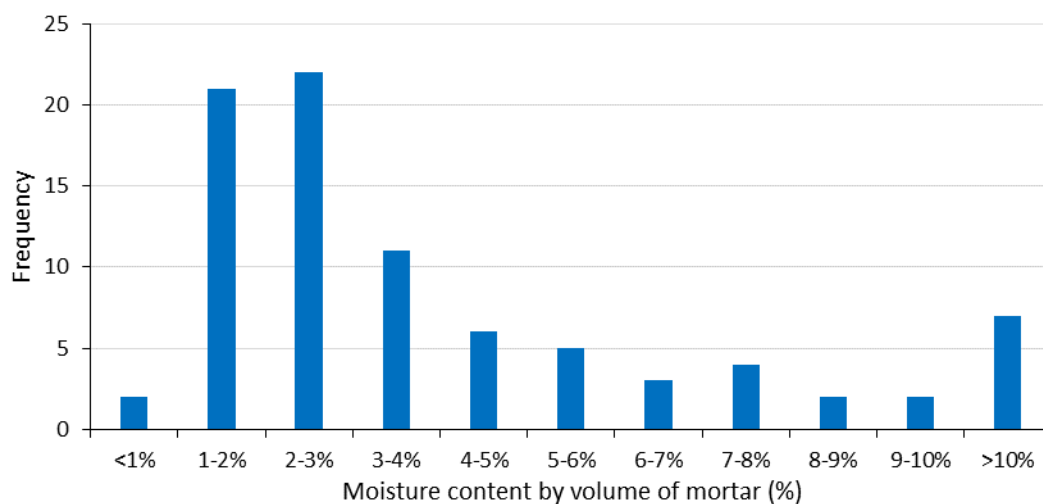


Figure 20: Distribution of moisture content by volume of mortar samples



Brick density

The bulk density¹ of the bricks was determined using the methodology outlined in BS EN 993-1 [25]. Higher density bricks are likely to be more conductive, and will result in higher U-values.

The median bulk density of bricks was higher than that generally assumed in theoretical calculations. The median measured density was approximately 1,805 kg/m³ rather than the often assumed 1,750 kg/m³. There was also considerable variation in the density of the samples. The interquartile range of densities was 135 kg/m³, with the 25th percentile at 1,726 kg/m³ and the 75th percentile at 1,861 kg/m³. The distribution of brick densities is shown in Figure 25 below.

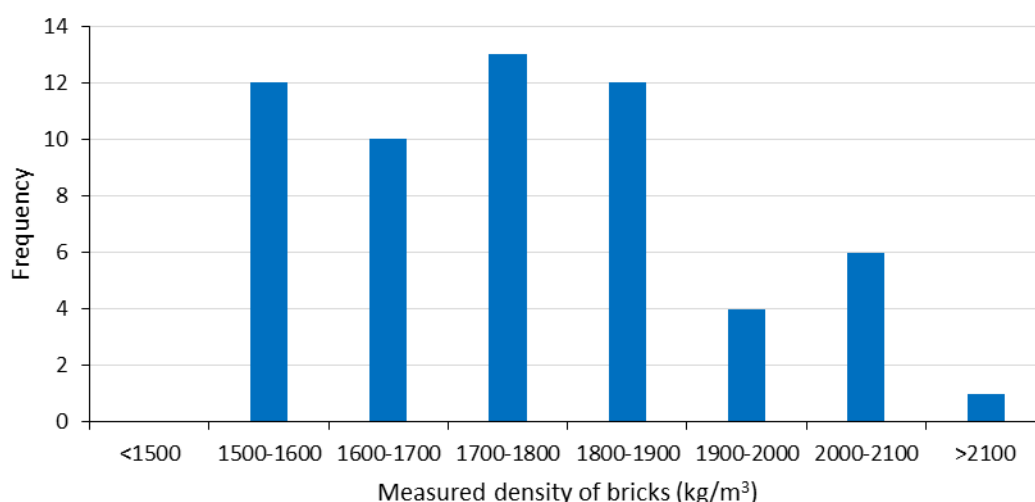


Figure 25: Distribution of brick densities from fieldwork samples

Brick dimensions

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

Wall thickness

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

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



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

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

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

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

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

Average U-values were compared for groups with different thermal conductivity values, brick densities and moisture content. For cases where the measured density of a brick sample from the test wall was greater than 1850 kg/m³, the measured U-value was higher (mean U-value = 1.83 W/m²K +/- 0.12) than bricks with lower density values (mean = 1.70 W/m²K +/- 0.06). Because of the relatively small sample sizes the confidence intervals between these estimates overlap, but it suggests that a higher rate of heat loss may be occurring in walls with bricks of high density which would be in line with our expectations. Additional measurements, particularly in walls of high density bricks, would be required to confirm these results.

Thermal conductivity is also dependent on the moisture content of bricks, however, the measured U-value did not vary as might be expected with brick moisture content where investigations of this type were carried out. The mean U-value was 1.75 W/m²K +/- 0.07 when moisture content by volume was less than 1%, and the mean U-value was 1.70 W/m²K +/- 0.07 when the moisture content was greater than 1%. The reason for this could be due to natural variation within the wall (see section 6 for additional evidence relating to this), where the brick sample tested is not representative of other bricks in the same wall, or that other aspects of the wall also vary in an inconsistent way (e.g. brick density). Further work on the effect of moisture content on conductivity for walls of this type is recommended.

The proportion of air within perpend and inter-stretcher gaps, and the orientation of the wall, may also be influencing factors on the U-value, and would be worth further investigation with a larger sample size. Results indicate that the measured U-value may be greater when the proportion of air gaps in both perpend and collar joints is less than 25% (mean U-value = 1.78 W/m²K +/- 0.09), compared with walls where that proportion is greater than 50% (mean U-value = 1.7 W/m²K +/- 0.11).

2.1.7 Limitations of the fieldwork

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

Sample

The sample chosen for detailed investigation is a combination of owner-occupied cases visited as part of the EHS, with additional dwellings provided by housing associations. Certain dwelling types have



been excluded. In particular, this includes all mid-terrace and those with very small floor areas (for practical reasons of measuring U-values), leasehold properties and flats (which are generally too difficult to obtain the necessary permissions for sample removal work) and rendered dwellings (because of difficulties in obtaining samples and removing bricks). The sample cannot, therefore, be said to be truly representative of all dwellings in the stock. Having said this, with the possible exception of moisture content, the likelihood of the sample differing greatly from the stock as a whole seems low.

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

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

Measurements

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

2.1.8 Discussion of fieldwork results

The results from the fieldwork have revealed significant new information about the nature of solid walls in situ. The measurements of U-values have confirmed the previous U-value results undertaken in 2012, and supports a default U-value of approximately 1.75 W/m²K for solid brick walls of a single-brick thickness. The internal examination of the wall has revealed a number of interesting features, which can help explain why the U-value is lower than the originally assumed value of 2.1 W/m²K.

Wall cavities

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



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

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

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

Brick density and moisture content

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

Summary

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





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

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

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

3.1 Research questions for hot-box work

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

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

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

3.2 Measuring U-values in the hot-box

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

The measurement uncertainty using this apparatus has been calculated using the methodology specified in the BIPM document; *Evaluation of measurement data - Guide to the expression of uncertainty in measurement* (often referred to as the GUM) [21]. For measurements on test elements mounted in an expanded polystyrene surround panel (as our measurements were) the overall



expanded uncertainty is estimated to be within $\pm 5.5\%$, based on a standard uncertainty multiplied by a coverage factor $k = 2$, providing a coverage probability of approximately 95 %.

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

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

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

Equation 5

T_n = Environmental temperature ($^{\circ}\text{C}$)

T_a = Air temperature ($^{\circ}\text{C}$)

ϕ = Power through the test element (W)

A = Area of the test element (m^2)

E = Emissivity of surface

h_r = Radiant heat transfer coefficient ($\text{W/m}^2\cdot\text{K}$)

T_r = Mean radiant temperature of surroundings (baffle temperature)

T_s = Surface temperature ($^{\circ}\text{C}$)

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

- a) Hot and Cold test element surface (9 thermocouples)
- b) Hot and Cold baffle surfaces (16 thermocouples)
- c) Hot and Cold air (16 thermocouples)
- d) Heat flux density through the test element (the apparatus is designed such that when operated correctly the total power supplied to the hot chamber heater is all transferred through the test element and surround panel with negligible losses and gains).

The boundary conditions that were established for the measurements were:

- Warm air temperature (approximately) 22.5°C
- Cold air temperature (approximately) 2.5°C
- Total surface resistance $0.17 (\text{m}^2\cdot\text{K})/\text{W}$

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



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

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

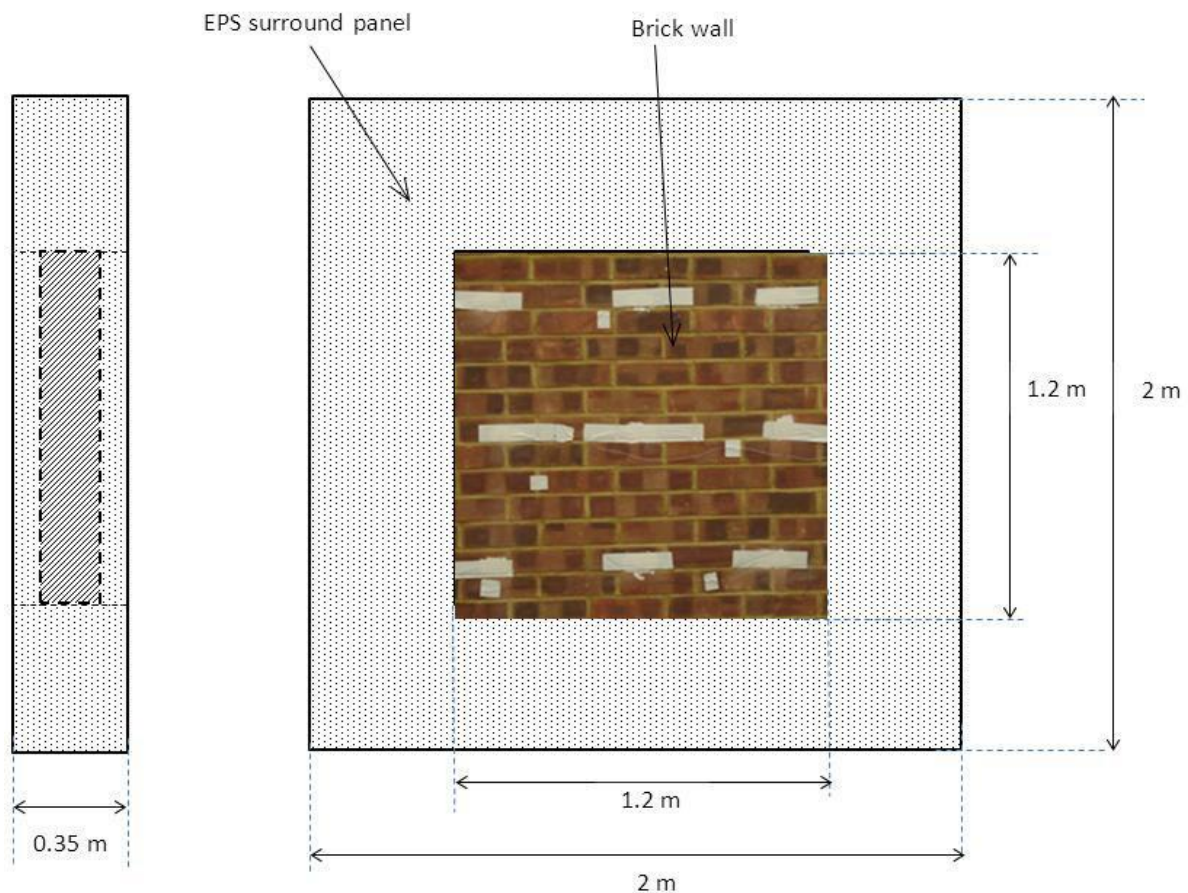


Figure 26: A wall and EPS surround assemblage used within the hot-box apparatus.

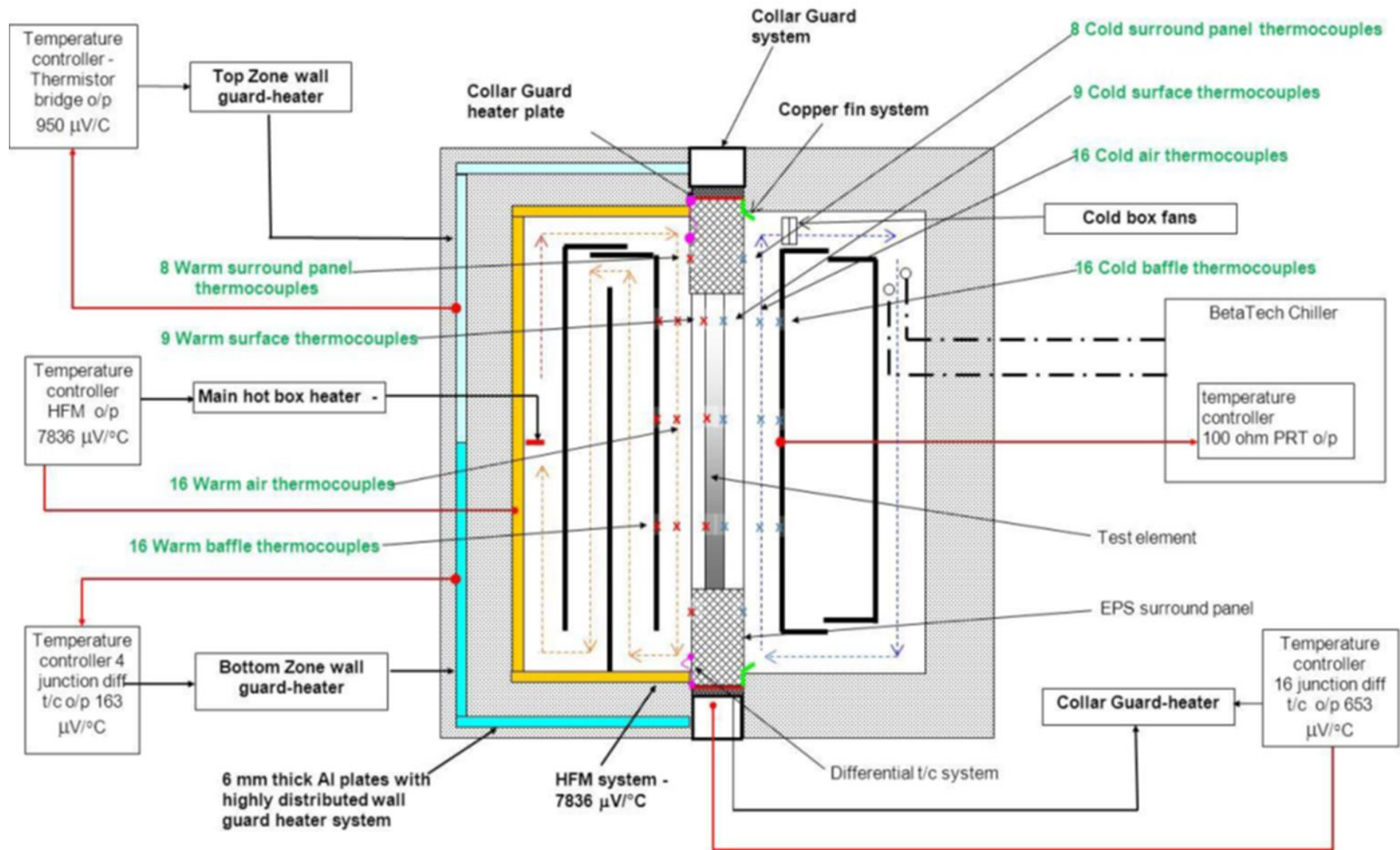


Figure 27: Schematic diagram of the NPL Wall Hot-Box Apparatus

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



3.2.1 Constructing the walls and placing within the hot-box

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

3.2.1.1 Building the walls

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

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

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

Some characteristics of the construction were identical for all walls:

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

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

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



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

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

Table 4: Walls configurations tested in the NPL hotbox.

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

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



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



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



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



Figure 35: Wall 1



Figure 36: Wall 2



Figure 37: Wall 3



Figure 38: Wall 4



Figure 39: Wall 5



Figure 40: Wall 6



3.2.1.2 Moving the built walls into the hot box

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

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

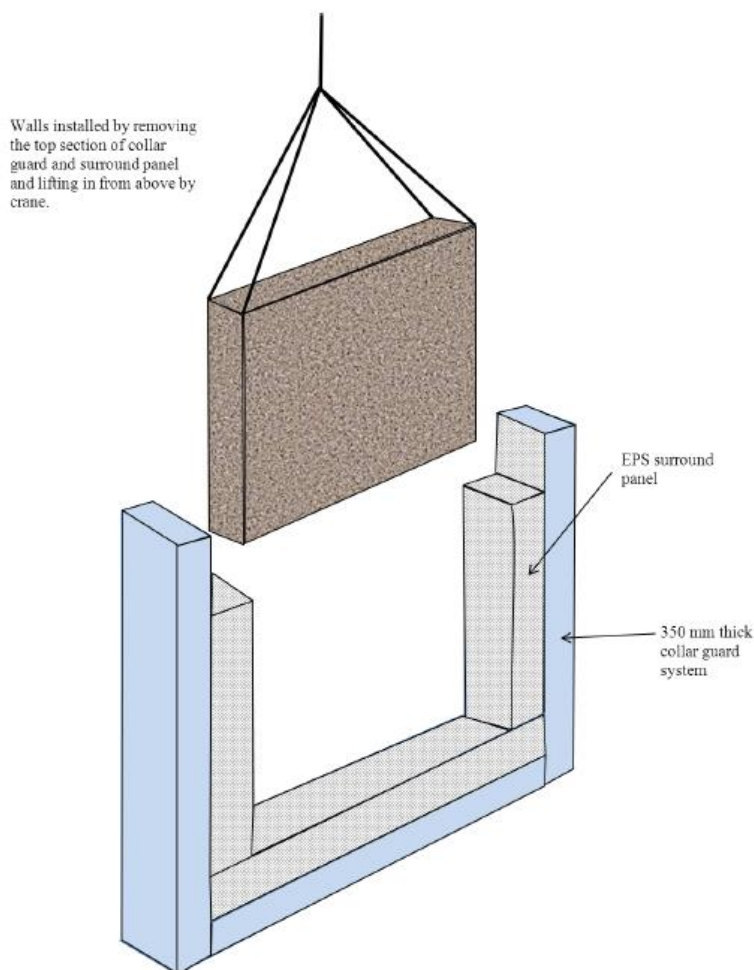


Figure 42: A completed wall, within the EPS guarding, ready to be placed into the hot-box. Once in this position the wall could be rolled into place on castors.

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



3.3 Controlling for differential moisture contents between walls

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

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

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

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

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

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

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



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

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

3.4 Results

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



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

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



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

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



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

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



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

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



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

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



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

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

Table 12: Hot box results for all walls.

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



3.5 Interpretation of hot box results

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

In general, the measured U-values are close to where we would expect from theoretical calculations for these walls. For walls 1 & 2, the measured U-value is very close to 2.1 W/m²K which is the U-value assumed in RdSAP, and historic theoretical calculations, for solid walls - but which is not supported by in situ measurements, as outlined in section 1 above. The original experimental basis for this value [1, 3] used a laboratory test of a brick wall, which seems likely to have been constructed in a similar way to our walls. The density of the bricks used for walls 1 and 2 (approximately 1,750 kg/m³) is equivalent to that used in the traditional calculations of U-values. The overall moisture content of the wall is unknown, but we can assume it to be relatively high, due to the walls being relatively recently built prior to testing. The majority of the moisture will have originally have been in the newly applied mortar, and an unknown quantity of this moisture will have transferred into the bricks since the time of construction.

Walls 3 to 6 were all built with small cavities 'designed' within them. For those built with Bedfordshire Red Bricks (variations of Wall 3) it is noticeable that the built walls still return U-values which are slightly *above* the mean U-values recorded in situ, (although close to this at the bottom of the confidence interval for the wall at moisture equilibrium). This may be because we have not adequately accounted for the cavities within the wall (e.g. no brick bats or imperfect bricks were used), or it may be for another unknown reason. The difference, however, is not unduly large and provides additional evidence in support of a value less than 2.1 W/m²K for walls of this type.

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

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

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

Both walls measured almost identical U-values – i.e. approximately 2.0 W/m²K. We can therefore conclude that there is no evidence from these measurements that different mortar bed thicknesses significantly affect the U-value. In these cases, although the thermal conductivity is expected to be different to that of brick, the additional mortar from the thicker joints has a very small effect on the overall U-value. This is also the results expected by theoretical calculations which indicate that it would have an effect of the order 0.02 W/m²K.

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

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

In the construction of walls 1 and 2, all joints were fully filled with mortar across their full extent – i.e. no gaps were left in perpend joints, bed joints, or between stretcher bricks. In walls 3 to 6, however, gaps were left in the joints to reflect the building practices believed to be in place at the time solid wall dwellings were being built. These gaps attempted to replicate the extent of mortar fill seen in the fieldwork (see section 2). To consider the effect of the introduction of these small cavities, we can compare wall



tests 2 and 3A, which were identical in other regards. The wall weight data, however, suggests that there remains approximately 8kg of water in wall 2, compared to only 4kg in wall 3A. There should have been less water used in the construction of wall 3A than in wall 2 as much less mortar was used (creating the cavities), which may help explain these differences. There is, therefore, a need to have additional caution in this specific comparison. The measured U-value of wall 3A is approximately 1.96 W/m²K compared to 2.03 W/m²K in wall 2. This difference is not significant given the uncertainty of the measurement itself, and given the additional uncertainties we cannot say with confidence that this difference is due to the introduction of the cavities.

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

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

Three different brick types were used, all of which had been reclaimed from old solid wall dwellings following demolition. Studying the wall weight data, we can choose the most appropriate comparisons. The London Stock built wall (wall 5) reached equilibrium more quickly than the other walls (which is probably related to the brick density, porosity and permeability) and is best compared with the test 3C which is the Bedfordshire Red Brick wall at equilibrium. This comparison is of U-values from wall 3C (Bedfordshire Red Brick) at 1.88 W/m²K and wall 5 (London Stock) at 1.69 W/m²K. This comparison is close to what we would expect for these brick types, although the confidence intervals for these measurements do overlap and we cannot therefore say this difference is significant.

Wall 6 (the Wolverton perforated brick) is best compared to wall 3B. The wall 3B U-value was 1.95 W/m²K and the wall 6 U-value was 1.92 W/m²K. Although the Wolverton brick is the most dense brick of the three examined, it incorporates large perforations within it, which may be acting to reduce the overall U-value of the wall and bring it closer to the U-value of the wall built with the less dense Bedfordshire brick. This would be in line with our understanding of the thermal performance of perforated bricks [34]. The wall built with this brick acts as a good example of where a wall may look like a “standard” solid wall from the outside, but other invisible internal features (in this case holes within the brick itself) can act to reduce its thermal transmittance.

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

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

Five of the six walls were built with Flemish bond, which consists of alternate stretcher and header bricks along every course of the wall. This bonding pattern was identified as the most common binding pattern in use in solid wall dwellings in England, following re-analysis of the 2012 U-values study data referred to above in section 1. We would expect the greater proportion of stretcher bricks in the English Garden Wall Bond wall to reduce the U-value of the wall, because of the increased likelihood of cavities being present within walls with this type of bond pattern (recall that both walls incorporate cavities through incomplete mortar fill). Wall 4 was built with an English Garden Wall (3-stretcher) bond, to investigate the effect of this alternative bonding pattern, which could be compared with wall 3B which was built in an otherwise identical way. English Garden Wall (3-stretcher) bond consists of a full course of header bricks, separated by three full courses of stretcher bricks. This can be seen in the photographs of wall 4 above. The measured U-value of the English Garden Wall (3-stretcher) bond wall was 1.89 W/m²K, compared to 1.95 W/m²K for the Flemish Bond wall. This difference is in the direction and of a magnitude expected although this difference cannot be said to be significant.

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



4 Measured thermal conductivity of bricks

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

In particular, following discussions between BRE and NPL, there are significant concerns that many historic measurements of thermal conductivity may not be valid. NPL's thermal conductivity experts believe that, in the past, it is extremely unlikely that many historic measurements of brick thermal conductivity dealt with important issues such as thermal contact resistance issues in a way that would be considered acceptable within the current framework of international measurement standards. As a result, we might expect that historic measured values may be significantly lower than the true thermal conductivity values².

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

4.1 Existing relationships

There are two main sources which are used when attempting to infer a thermal conductivity from a brick density. The first of these is the Jakob relationship [35] which is described in his work published in 1949. This is shown in the Table 19 below. The second of these is the relationship described in the 1999 Thermal Values report [36] developed for the production of ISO 10456, which drew together numerous measurements from across Europe. Due to the nature of the Thermal Values data (which were compiled from numerous sources in different countries) it is not possible to identify the provenance of many of the measurements. It does seem likely, however, that many of the data items used in this report are quite old³.

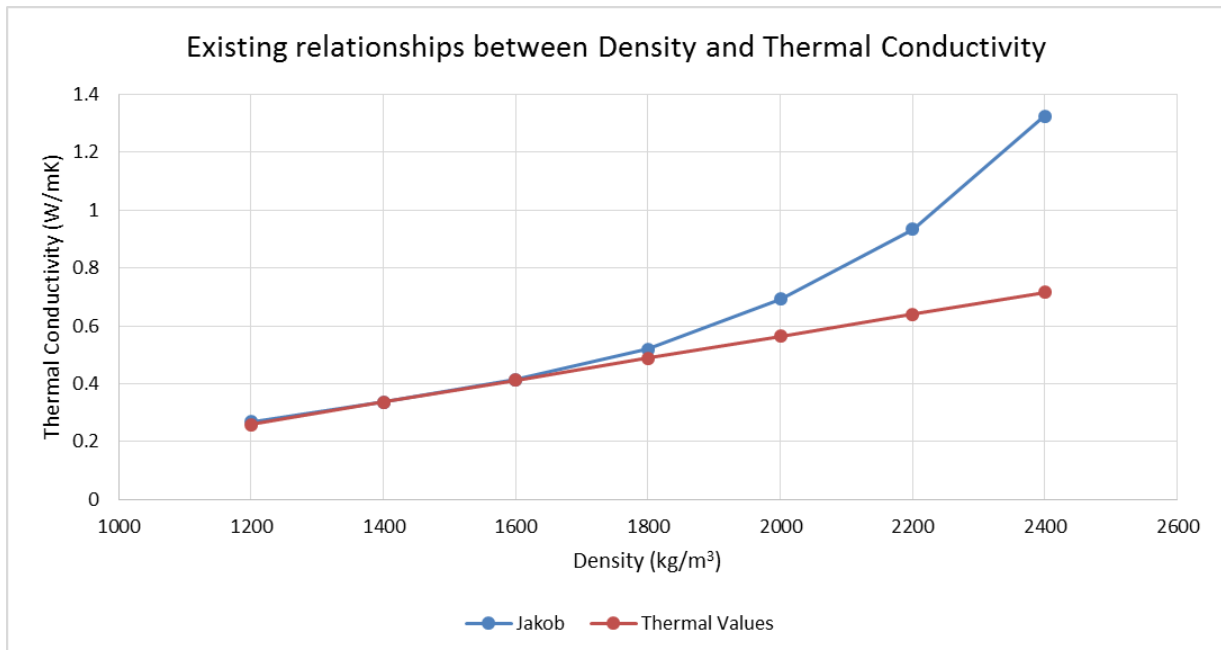
² See NPL statement here: <http://www.npl.co.uk/news/understanding-thermal-performance-of-buildings>

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



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

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





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

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

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

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

- a) Thickness: 20 mm.
- b) Diameter: 50.8 mm. (Within the range 50.6 mm to 51.0 mm)
- c) Parallelism: Variation in thickness was required to be less than 0.025 mm.
- d) Flatness: Both round faces were required to be flat, to better than 0.025 mm.

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

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

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

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



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

Reference	Density (kg/m ³)	Measured Thermal Conductivity (W/mK)
Bedfordshire Red - B1A Long side face	1,748	0.792
Bedfordshire Red -B1B Small header face	1,759	0.793
Bedfordshire Red - B2A Long side face	1,754	0.653
Bedfordshire Red - B3A Long side face	1,748	0.711
Bedfordshire Red - B4A Long side face	1,731	0.614
London Stock - Long side face	1,410	0.595
Wolverton (non-perforated section) - Long side face	2,046	0.955
E140	1,729	0.763
E142	1,768	0.635
E188	1,736	0.588
E189	1,755	0.585
E190	1,706	0.585
E215	1,491	0.685
E222	1,686	0.667
E225	1,844	0.669
E269	1,800	0.733
E171	1,688	0.649
E205	1,567	0.635
E227	1,812	0.504
E285	1,631	0.604
E296	1,820	0.658
E299	1,850	0.763
E301	1,756	0.522
E305	2,169	1.053



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

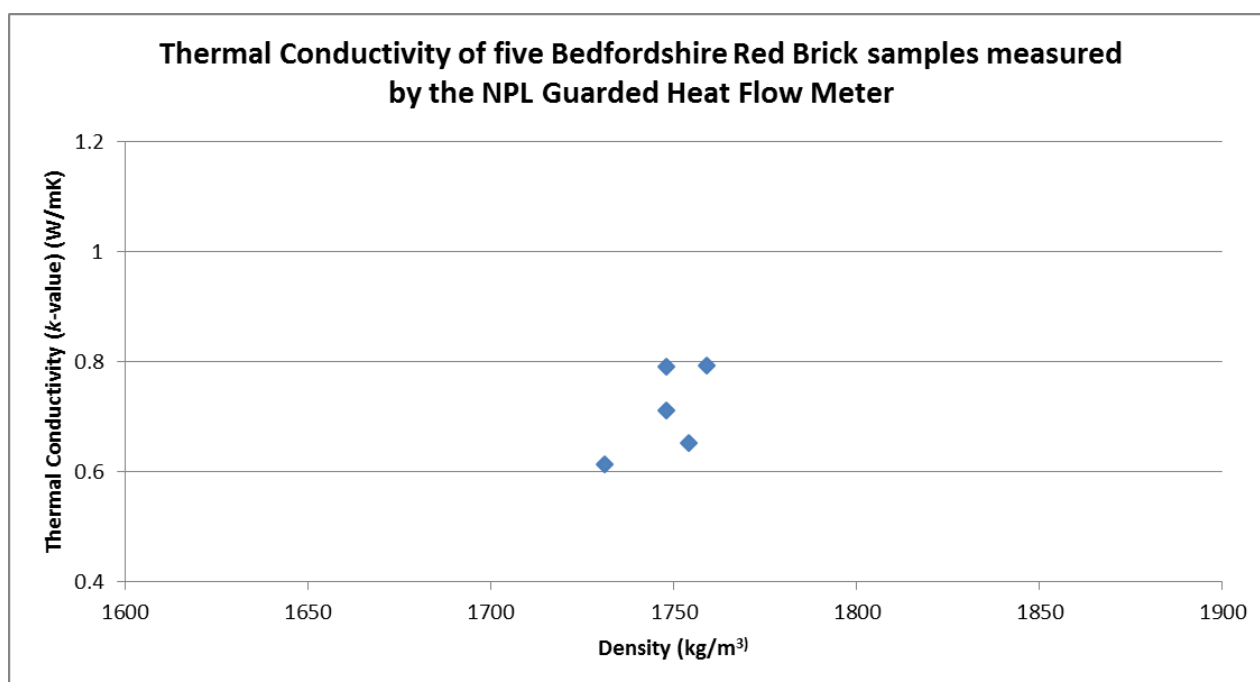


Figure 44: Variation in thermal conductivity within Bedfordshire Red Bricks, as measured by the NPL guarded hot plate apparatus.

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

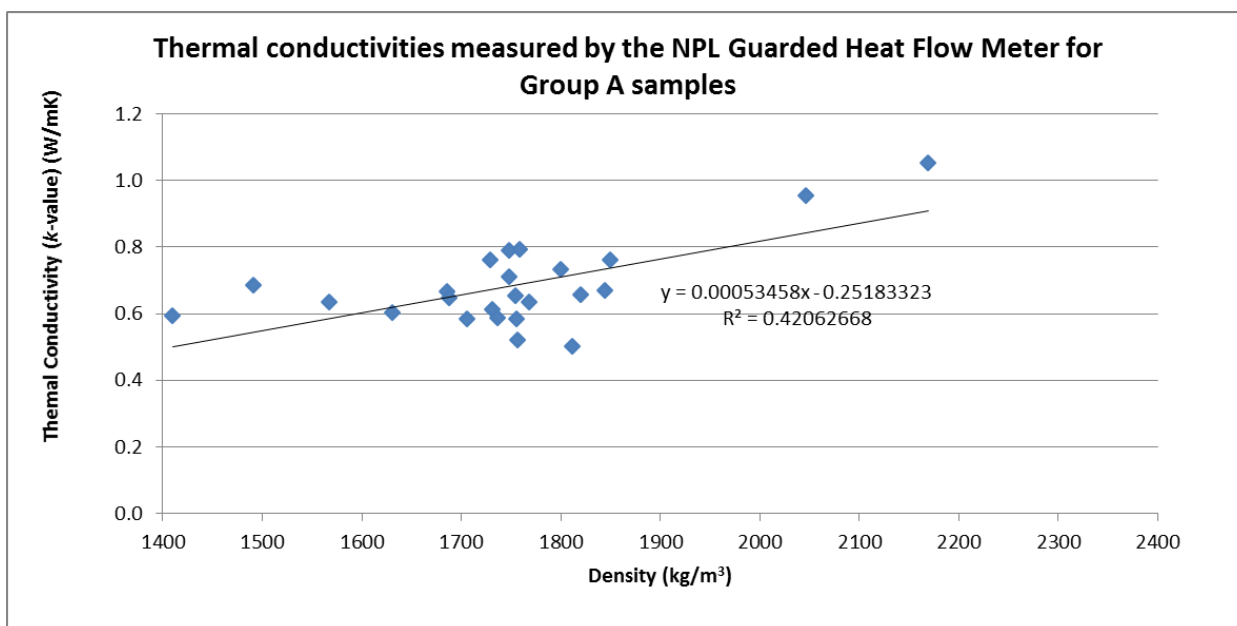


Figure 45: All results measured using the NPL guarded heat flow meter apparatus (Bedfordshire Red Bricks disaggregated).

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

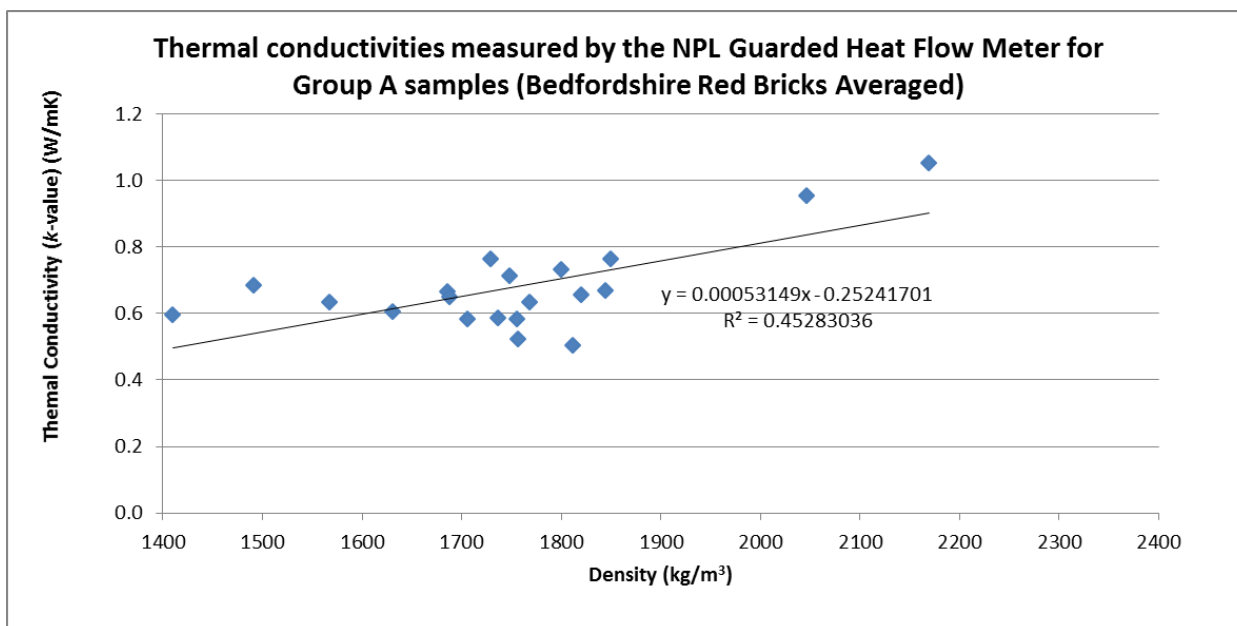


Figure 46: All results measured using the NPL guarded heat flow meter apparatus (Bedfordshire Red Bricks averaged).



Although a best fit line is shown for both these charts, the line of best fit is heavily influenced by the effect of the two densest bricks examined (densities 2,046 and 2,169 kg/m³). Excluding these two single observations results in a much weaker correlation, and a different relationship. As a result, we are reluctant to use this relationship without more data. Such data can be provided through an alternative measurement technique which is able to test smaller samples.

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

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

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

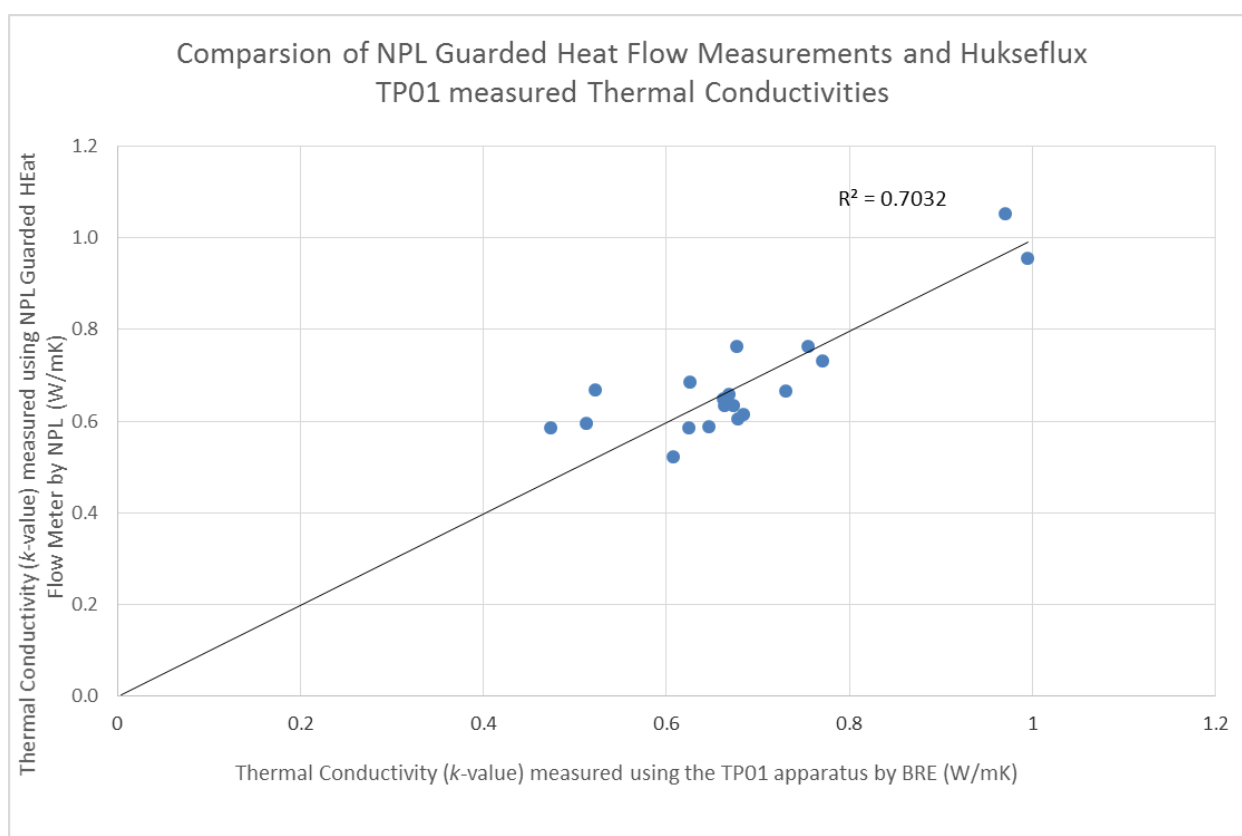


Figure 47: Comparison between the NPL guarded heat flow meter measurements and the TP01 apparatus measurements for sample Group A. A good correlation can be seen.

We can also plot the relationship between the sample density and thermal conductivity for sample Group A, which is derived using the TP01 apparatus. This is shown in figure 48 below. The best fit line



produced from the TP01 results, and the best fit line produced from the NPL guarded heat flow meter data shown in Figures 46 above, are very similar. These two comparisons provide us with some confidence in the results from the TP01 apparatus.

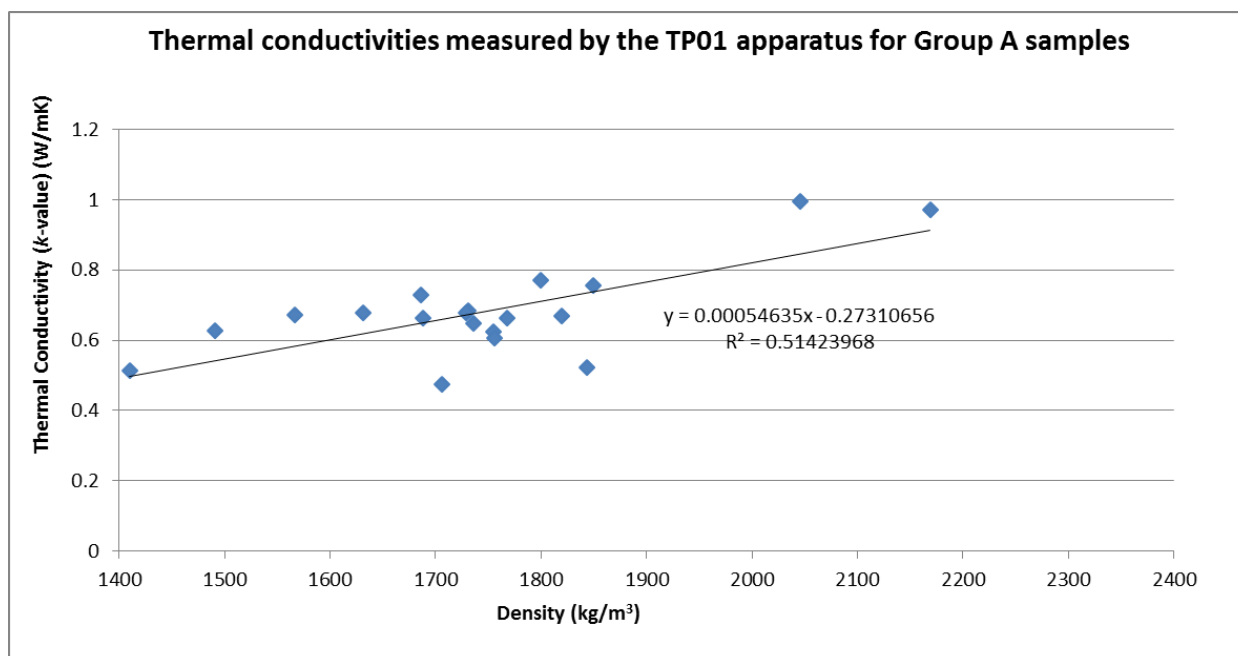


Figure 48 Thermal conductivities measured using the TP01 apparatus for Group A samples (Bedfordshire Red Bricks disaggregated). The chart is very similar to the results tested using the NPL guarded heat flow meter shown in Figure 45.

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

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

Reference	Bulk density (kg/m³)	Measured Thermal Conductivity using TP01 apparatus (W/mK)
Wall 4 (TT382) - Bedford Red - B4A Long side face	1731	0.685
Wall 5 (TT383) - London Stock - Long side face	1410	0.513
Wall 6 (TT384) - Wolverton (with holes) - Long side face	2046	0.995
E140	1729	0.677
E142	1768	0.664



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



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

The results from all samples tested using the TP01 apparatus are plotted in Figure 49 below (this includes the TP01 results from Group A samples – i.e. those also tested using the NPL guarded heat flow



meter). The chart below this, Figure 50, uses the guarded heat flow meter data for those samples where it is available, and HP01 apparatus data where it is not. Also plotted on all charts are linear lines of best fit. The charts are very similar, with similar best fit lines.

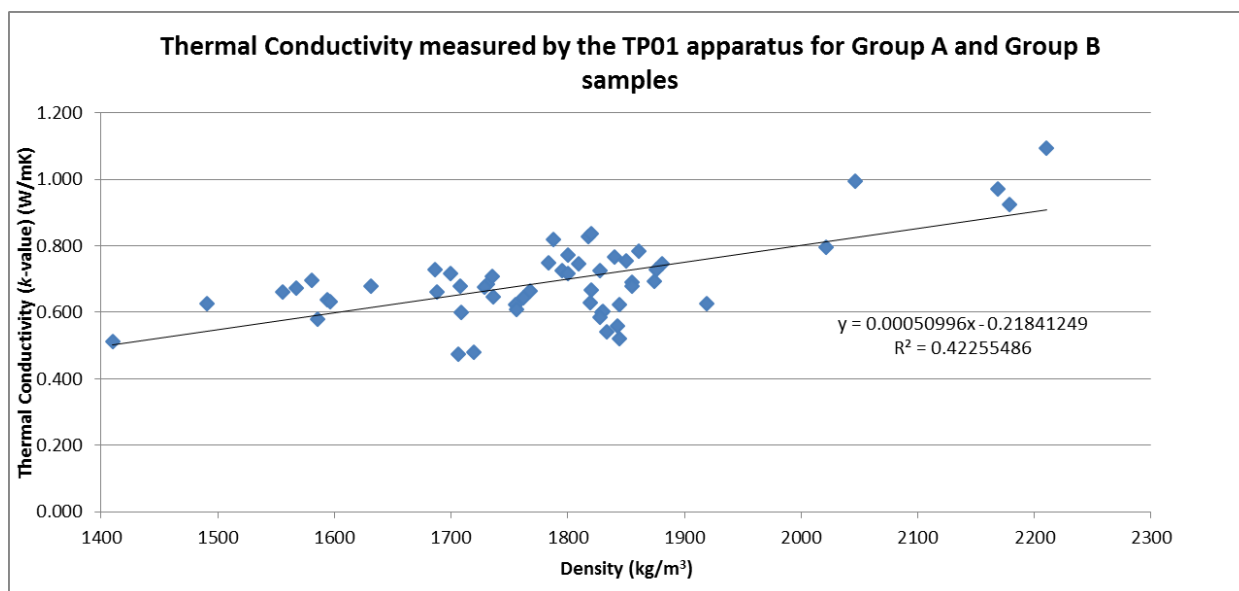


Figure 49: All measurements made using the TP01 apparatus (Bedfordshire Red Bricks disaggregated).

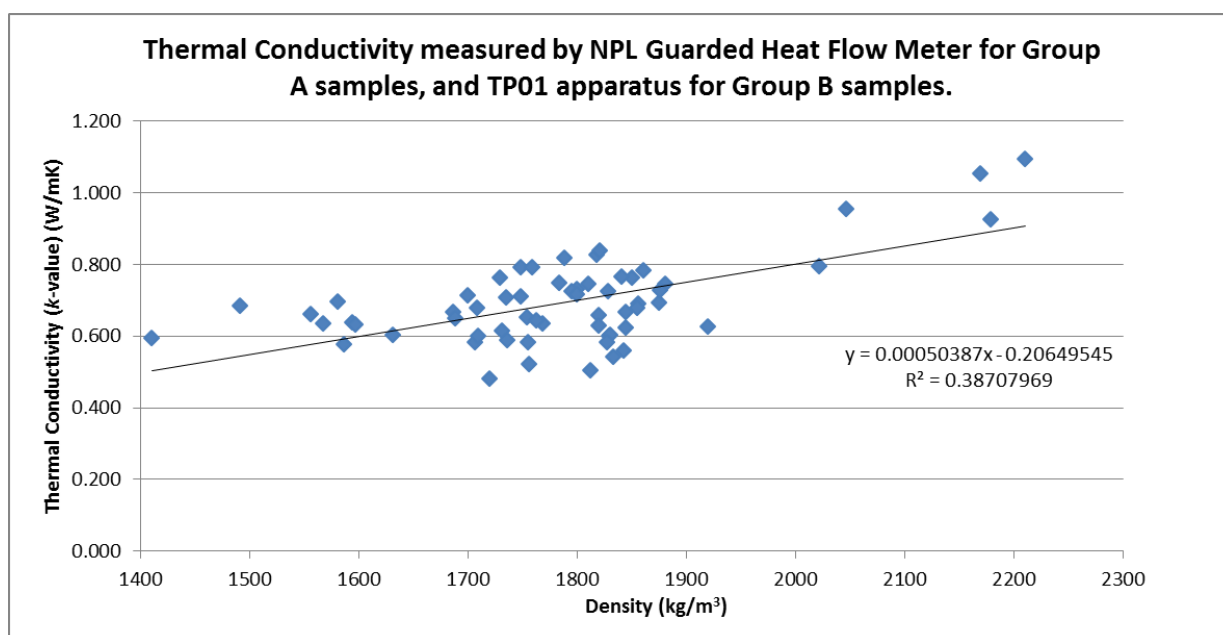


Figure 50: Combination of measurements made using the NPL guarded heat flow meter from Group A samples (Bedfordshire Red Bricks disaggregated), and TP01 apparatus for Group B samples.

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



A value for brick density of 1,750 kg/m³ is generally assumed in U-value calculations, and was supported by the fieldwork undertaken for this project. Data from this project suggests a dry conductivity of ~0.68 W/mK may be appropriate as a default assumption for this type of brick.

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

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

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

This relationship is expressed as:

$$\lambda = 0.00050387\rho - 0.20649545 \quad \text{Equation 6}$$

Where λ is thermal conductivity (W/mK) and ρ is density (kg/m³)

Earlier in this section we raised questions about whether historic relationships between density and thermal conductivity can be considered valid, given known deficiencies in some of the methodologies used in the past. In particular, experts at NPL are of the opinion that old measurements of thermal



conductivities may be too low. It is, therefore, of great interest to compare the relationship described above to the historic relationships. Shown in Table 17 are the results obtained using the newly derived relationship and the Jakob and Thermal Value curves. It can be seen that the newly derived relationship gives higher thermal conductivities than the existing curves, for bricks below 2,200 kg/m³, supporting the hypothesis that older measurements may be too low. Above this density, however, the Jakob curve predicts higher conductivities, but the Thermal Values continues to predict lower than the newly derived relationship. It should be noted, however, that bricks greater than 2,200 kg/m³ in density are relatively rare according to our fieldwork findings (see Section 2).

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

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

4.1.1 Thermal conductivity of mortar

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

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

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

Table 18: Measured Thermal Conductivity of Lime Mortar sample

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

5 In situ measurements of Thermal Conductivity using a needle probe

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

Advantages of using a thermal probe system are:

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

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

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

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

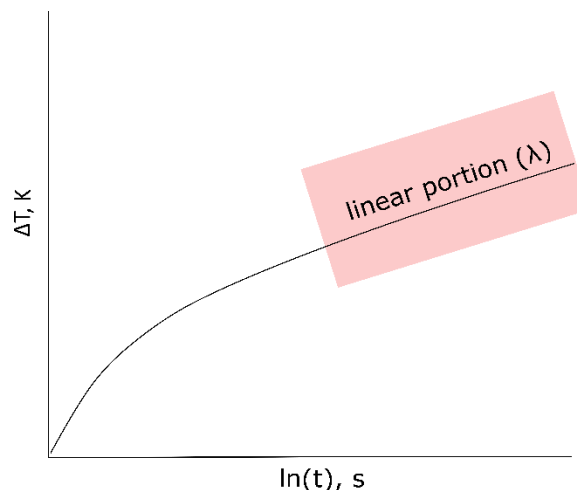


Figure 51 – Relationship between the change in temperature and time.

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

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



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

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

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

5.1 Method

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

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

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

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

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



5.2 Results and discussion

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

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

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

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

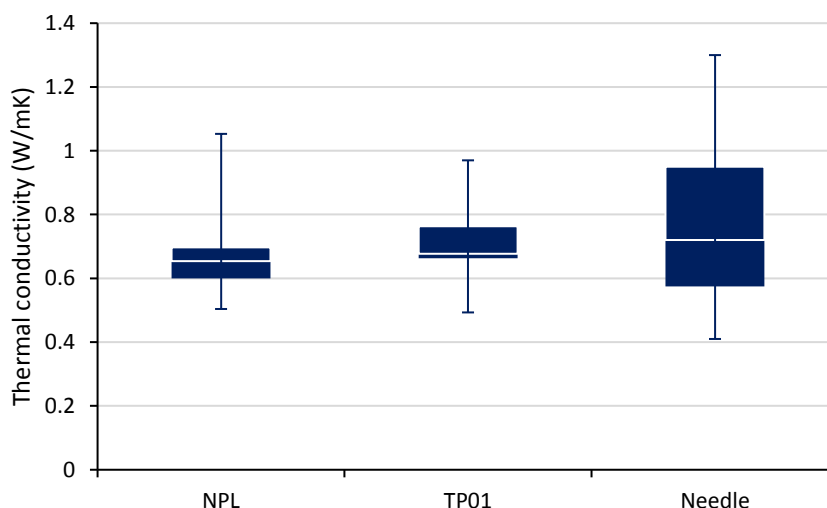


Figure 52 – Boxplot of the measured thermal conductivity, from NPL, TP01 and thermal needle methods. Note that the NPL and TP01 results are in the dry state, and the thermal needle in wet in situ state.

Thermal conductivity measurements from the NPL guarded heat flow meter and TP01 sensor were conducted in the dry state. Therefore, results have been displayed below for all cases, and for only those cases with low moisture content which may provide a better comparison with the measured thermal conductivity data (Table 19). In addition, the correlation between the thermal conductivity measurements



from the thermal needle and the measurements conducted in the dry state, are indicated by the R^2 value, which shows how much variance the two methods share. The R^2 values are high (at approximately 0.5), indicating a strong relationship between the different methods of determining thermal conductivity of brick samples.

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

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

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

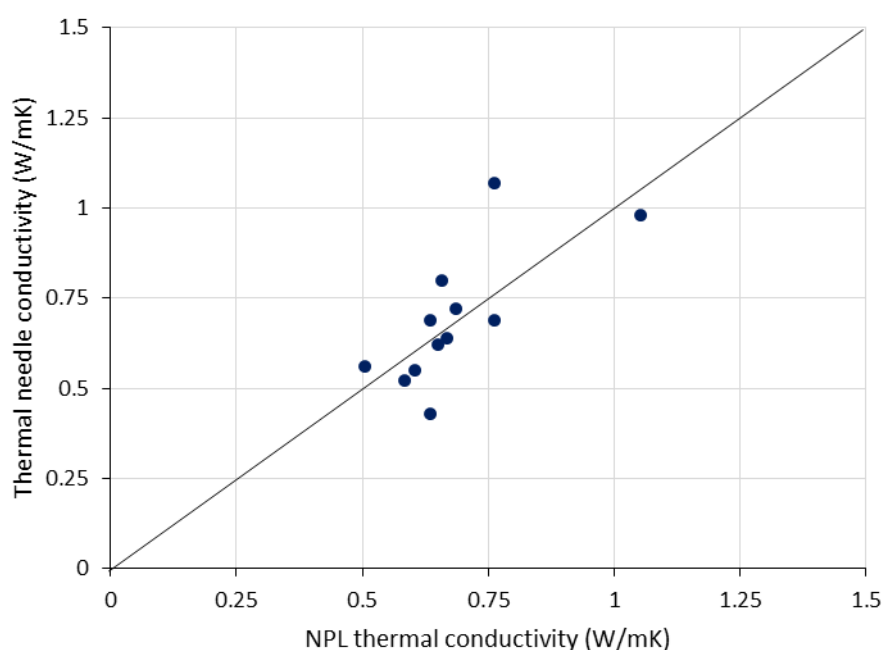


Figure 53 - Thermal conductivity values from NPL and thermal needle measurements.

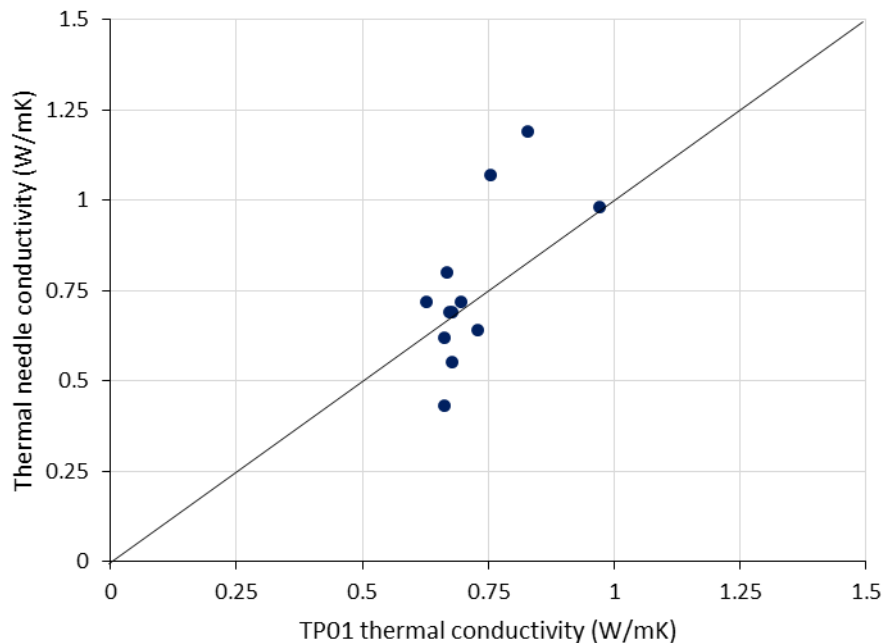


Figure 54 - Thermal conductivity values from TP01 and thermal needle measurements.

5.3 Conclusions

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

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



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

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

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

6.1 Results from investigations

Dwelling 1

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

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

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

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

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

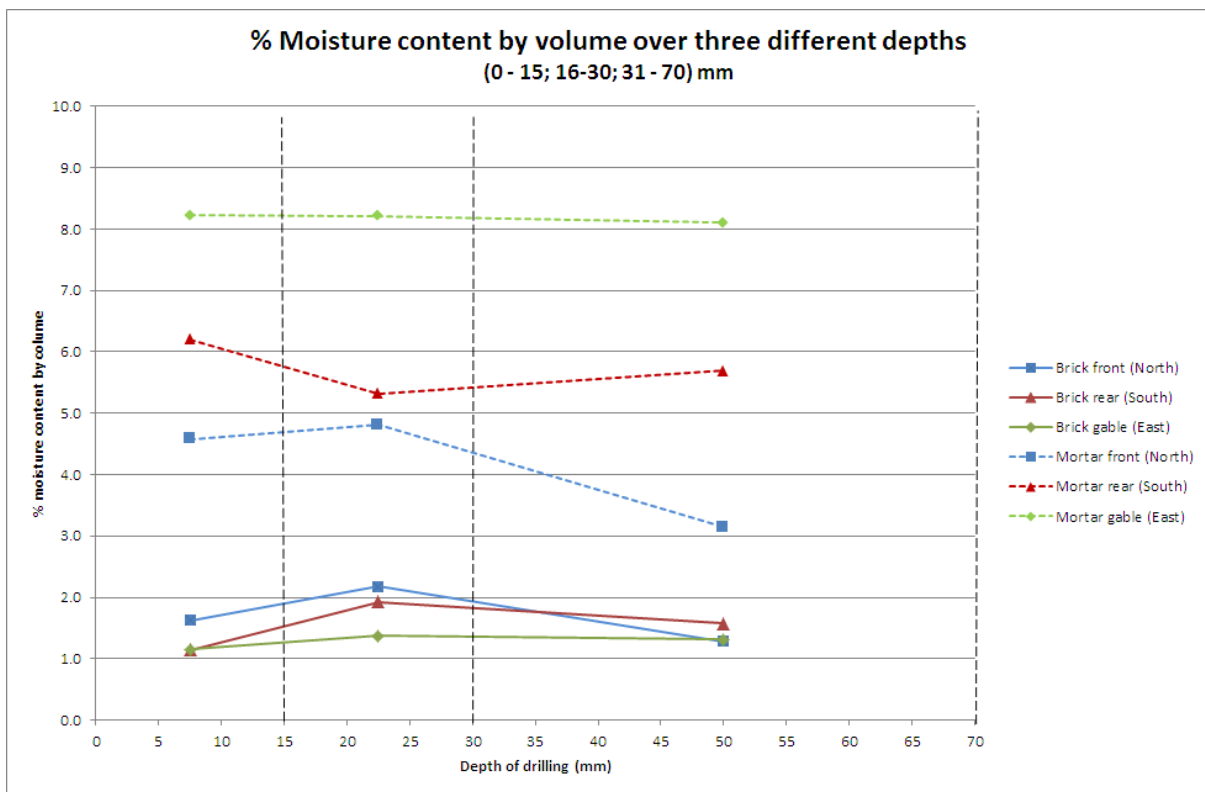


Figure 58: Variation in moisture content by volume at different drilling depths.

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



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

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

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

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



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

Dwellings 2 & 3

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

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

Dust sampling at the properties

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

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

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

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

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

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

**Front view****% Moisture content by Volume**

Mean	6.11
S.D.	9.38
Median	1.90

Level

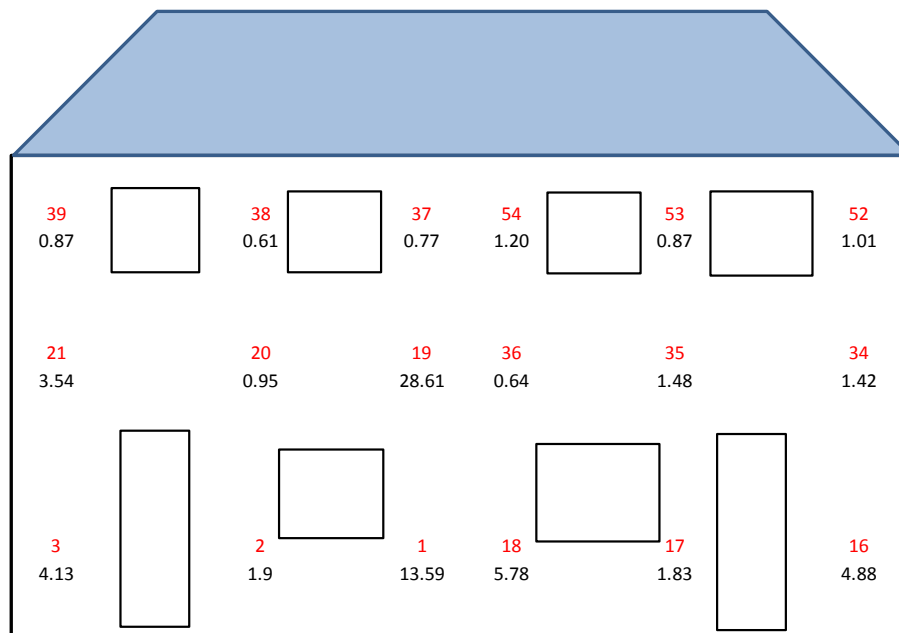
Eaves Mean S.D.
Brick 0.89 0.20

First Mean S.D.
Brick 6.11 11.07

Ground Mean S.D.
Brick 5.35 4.34

Total
(vertical)

Mean	2.85	1.15	14.33	2.54	1.39	2.44
S.D.	1.74	0.67	13.94	2.82	0.48	2.13

**Rear view****% Moisture content by Volume**

Mean	2.92
S.D.	3.56
Median	1.62

Level

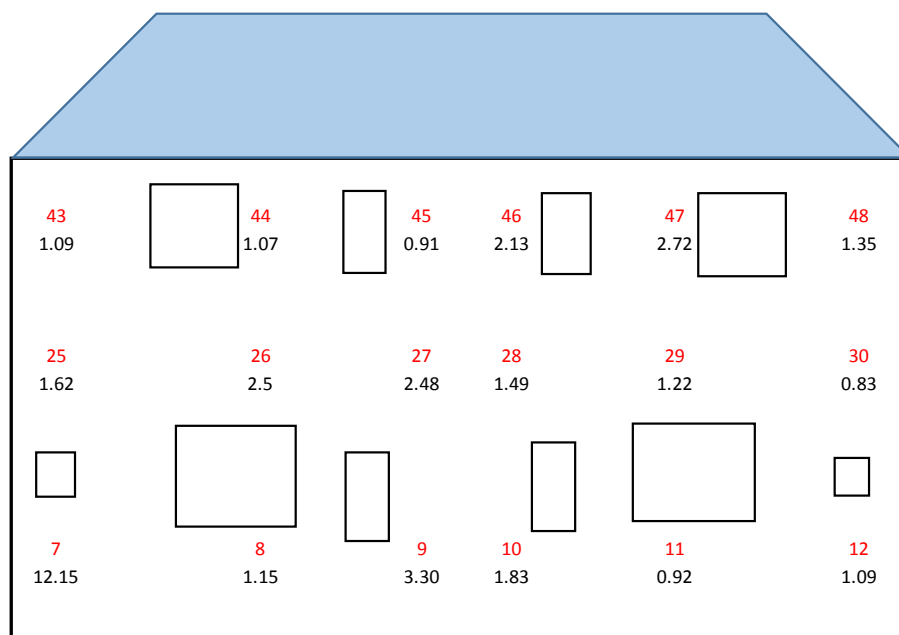
Eaves Mean S.D.
Brick 1.54 0.72

First Mean S.D.
Brick 1.69 0.68

Ground Mean S.D.
Brick 3.41 4.37

Total
(vertical)

Mean	4.95	1.58	2.23	1.82	1.62	1.09
S.D.	6.24	0.81	1.21	0.32	0.97	0.26



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

Left hand semi - flank wall
% Moisture content by Volume

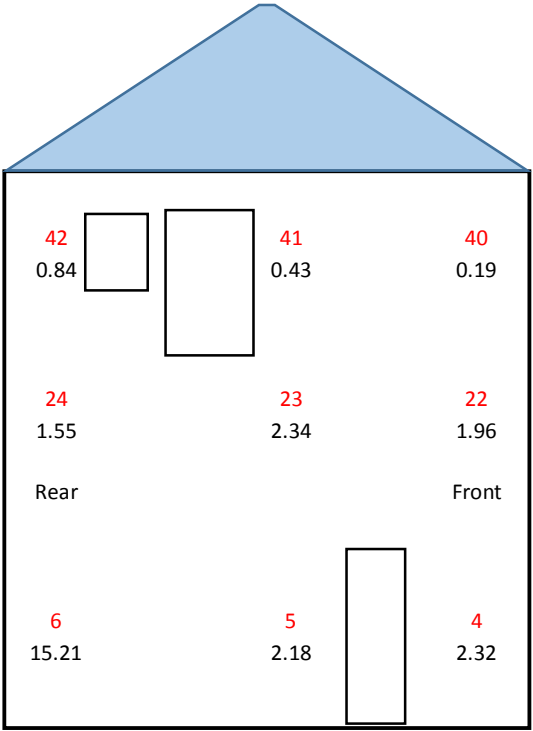
Mean	3.00
S.D.	4.65
Median	1.96

Level

Eaves Mean S.D.
Brick 0.49 0.33

First Mean S.D.
Brick 1.95 0.40

Ground Mean S.D.
Brick 6.57 7.48



Total Mean S.D. 5.87 8.10
(vertical) S.D. 1.65 1.06 1.49 1.14

Right hand semi - flank wall
% Moisture content by Volume

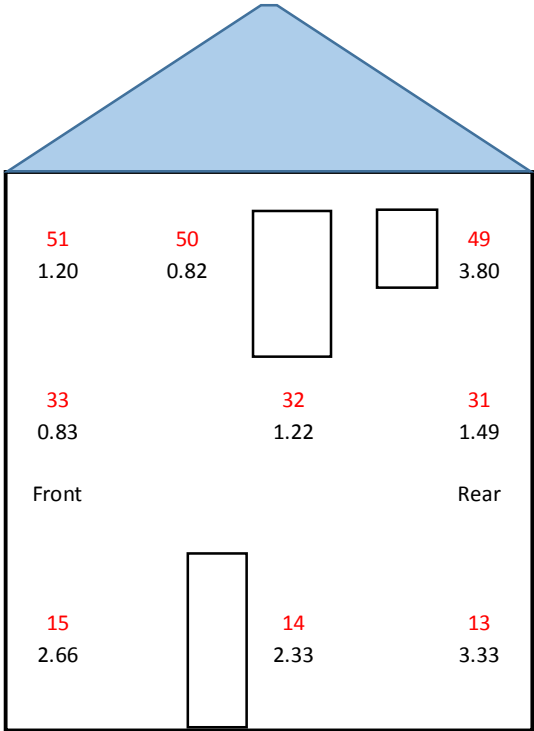
Mean	2.11
S.D.	1.09
Median	1.91

Level

Eaves Mean S.D.
Brick 2.50 1.84

First Mean S.D.
Brick 1.18 0.33

Ground Mean S.D.
Brick 2.77 0.51



Total Mean S.D. 1.56 0.97
(vertical) S.D. 1.77 0.79 2.87 1.22

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



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

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

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

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

6.2 Discussion

The effect of varying moisture content on wall U-values

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

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

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

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Brick Front (North)			U-values (W/m ² K)				Max	16%
							Min	-6%
							+/- S.D.	7%
Brick								
Mean								
S.D.								
Position:			A	B	C	D		
Level								
Second	Mean	S.D.	20	9	18			
Brick	1.58	0.05	1.55	1.56	1.64			
First	Mean	S.D.	19	4	17			
Brick	1.69	0.18	1.88	1.53	1.65			
Ground	Mean	S.D.	12		1			
Brick	1.59	0.00	1.59		1.59			
Total	Brick	Mean	1.67	1.55	1.59			
(vertical)		S.D.	0.18	0.02	-			

Rear (South)			U-values (W/m ² K)				Max	11%
							Min	-6%
							+/- S.D.	6%
Brick								
Mean								
S.D.								
Position:			A	B	C	D		
Level								
Second	Mean	S.D.	28	7		26		
Brick	1.60	0.04	1.64	1.56		1.60		
First	Mean	S.D.	27	6		25		
Brick	1.64	0.16	1.55	1.55		1.82		
Ground	Mean	S.D.	16	3	11	15		
Brick	1.65	0.12	1.63	1.55	1.76	1.78		
Total	Brick	Mean	1.61	1.55	1.76	1.73		
(vertical)		S.D.	0.05	0.01		0.12		

Brick Gable (East)			U-values			Max	24%
	Brick					Min	-8%
Mean	1.66					+/- S.D.	11%
S.D.	0.18						
Level		Position:	A	B	C		
Chimney			29	10	30		
			-	-	-		
Second	Mean	S.D.	24	8	22		
Brick	1.58	0.06	1.53	1.65	1.56		
First	Mean	S.D.	23	5	21		
Brick	1.57	0.02	1.59	1.55	1.56		
Ground	Mean	S.D.	14	2	13		
Brick	1.83	0.25	2.06	1.57	1.86		
Total	Brick	Mean	1.73	1.59	1.66		
(vertical)		S.D.	0.29	0.05	0.17		

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



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



7 Revising theoretical U-value calculations following the fieldwork observations

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

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

7.1 A choice of moisture corrections

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

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

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

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

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

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



This section of this report examines the likely effect of these changes on the theoretical calculated U-value for a typical wall, and compares the typical assumptions which result in a U-value of 2.1 W/m²K (the standard value in the CIBSE guide, and RdSAP) with a revised calculation which uses inputs into the calculation which are much more closely aligned with our fieldwork observations⁴. Note that this section of the report looks at the effect on an example wall only. The effect of applying each individual field observation to the relevant fieldwork case is described in Section 8 below.

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

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

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

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

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

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



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

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

Example 1

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

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

Table 21: Heat flow paths for Example 1

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

In the above table;

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

The thermal conductivities are as follows in Table 22:



Table 22: Thermal conductivities for example 1.

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

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

Table 23: Thermal resistances for Example 1.

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

The sum of the values of (fraction/R) is therefore 2.0935 W/m²K, and this value is considered to be the upper limit of thermal resistance (as defined in BS EN ISO 6946).

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



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

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

The lower limit (as defined in BS EN ISO 6946) is therefore 2.094 m²K/W

From the above, the overall thermal transmittance of the wall is 2.094 W/m²K. By standard rounding conventions, this gives a U-value of **2.1 W/m²K**. This agrees with the U-value that has traditionally been assumed in the CIBSE guides and used in RdSAP for solid walls [see Table S6, Appendix S of RdSAP 2009 version 9.91 (January 2012)]. This example is included in order to understand how a value of 2.1 W/m²K is achieved, and for comparison with a value which incorporates the field observations described below.

Example 2

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

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

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

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

Table 26: Thermal conductivities for Example 2.

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

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

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

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

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

Thermal conductivity values are as follows:

Table 28: Thermal conductivity values for Example 2.

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

Thermal resistance values are as follows:

Table 29: Thermal resistance values for Example 2

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

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

The values of f/R are as follows:

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

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



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

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

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

This gives a lower limit of thermal resistance for the wall of 0.5496 m²K/W.

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

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



8 Theoretical calculated U-values for the fieldwork cases

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

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

8.1 The default assumption for calculating U-values

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

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

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

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

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



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

Wall type	Number of cases	Measured U-values: Mean and SD ($\text{W/m}^2\text{K}$)	Measured U-values: Median ($\text{W/m}^2\text{K}$)	Calculated U-values under default conditions: Mean (standard deviation) ($\text{W/m}^2\text{K}$)	Calculated U-values under default conditions Median ($\text{W/m}^2\text{K}$)
Standard solid wall (brick) – quality filters applied	50	1.74 +/- 0.05 SD = 0.18	1.72	2.01 (0.05)	2.00

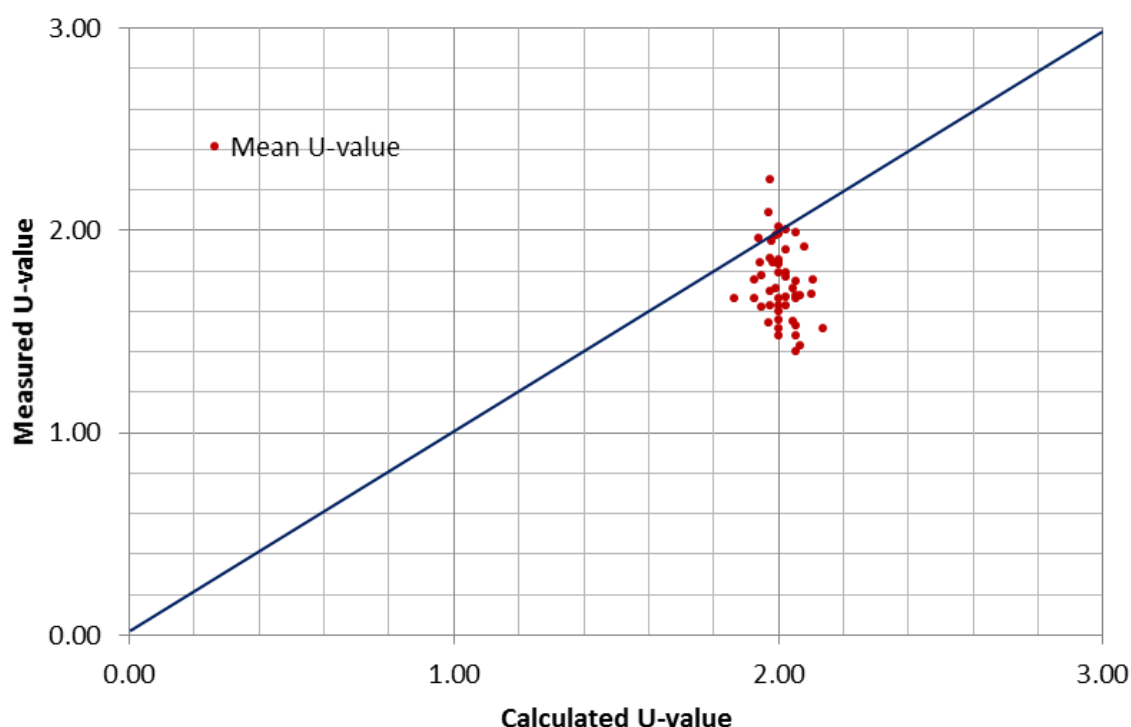


Figure 70 Measured and calculated values for the 50 cases used for comparison using the default calculation assumptions.

The results from this type of calculation show an average calculated value approximately $0.25 \text{ W/m}^2\text{K}$ above the average measured value⁶, and a strong clustering of all calculated values around single value (approximately 2.0). There is little or no variation between the different walls measured because of the absence of any additional data included in the calculation. Any variation observed is a result of the different wall thicknesses of the dwellings measured.

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



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

8.2 Inclusion of the observations

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

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

- a) The space between stretchers, known as the collar joint, was seldom fully filled with mortar. The median percentage of the exposed area estimated to be filled with mortar was 67%.
- b) Perpendents were also seldom fully filled with mortar. The median percentage of the exposed perpend area estimated to be filled with mortar was 70%.
- c) Where a brick contained a frog, if it was found on the top face of the brick (brick laid “frog-up”) then it was almost always fully filled with mortar. If it was found on the bottom face of the brick (brick laid “frog-down”) it was very seldom filled with mortar.
- d) Broken bricks, known as brick bats, and imperfect bricks forming part of the wall were relatively common. These type of bricks were revealed in approximately 9% cases. These generally resulted in additional air cavities.
- e) Perforated bricks in walls of this type were very rare.
- f) Bricks were generally very dry. The mean moisture content of brick samples and dust samples was ~0.7% by volume. Some bricks, however, were extremely wet with a median moisture content of >15%.
- g) Mortar was slightly wetter than the brick samples, although generally also dry. The mean moisture content of mortar was ~2.8% by volume. Some mortar, however, was also extremely wet with a median moisture content of >15%.
- h) The median dry density of bricks was higher to that generally assumed. The median measured density was approximately 1,805 kg/m³ rather than the often assumed 1,750 kg/m³.

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

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

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



different wall types and brick types are larger than the variation within each wall, however, we might expect to see better levels of correlation.

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

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

Wall type	Number of cases	Measured U-values: Mean (standard deviation) (W/m ² K)	Measured U-values: Median (W/m ² K)	Calculated U-values using all observed data: Mean (standard deviation) (W/m ² K)	Calculated U-values using all observed data: Median (W/m ² K)
Standard solid wall (brick) – quality filters applied	50	1.74 +/- 0.05 (0.21)	1.72	1.81 (0.22)	1.77

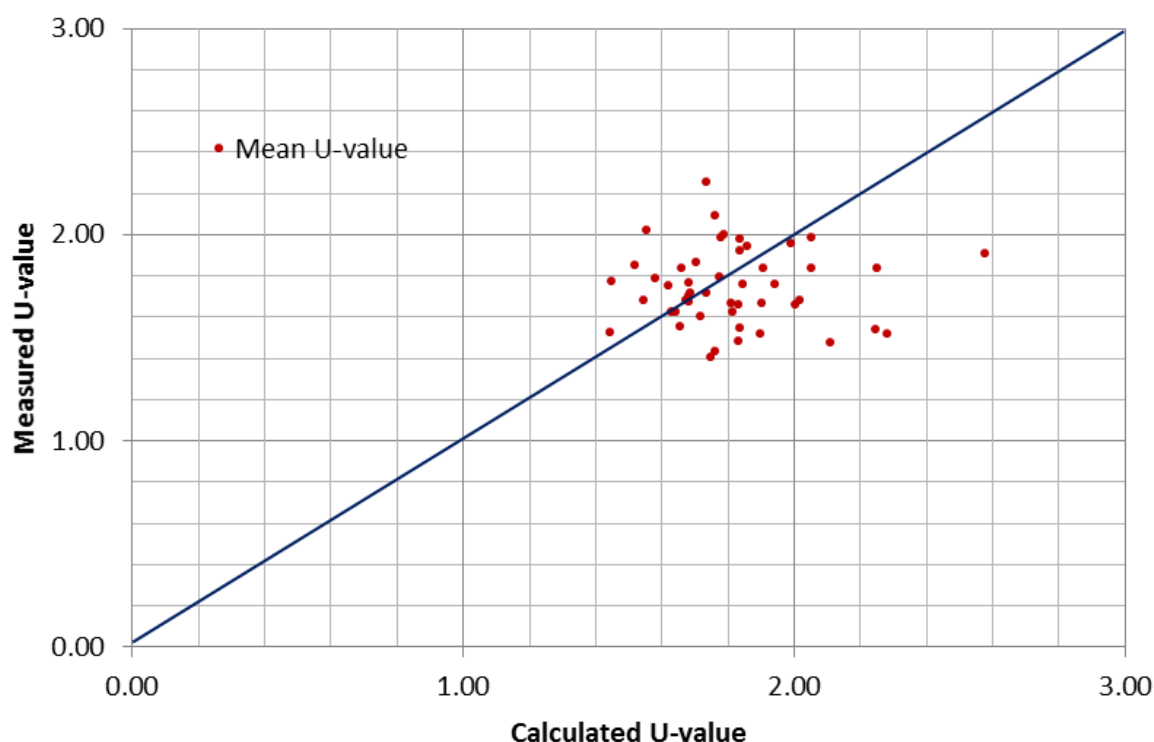


Figure 71 Measured and calculated values for the 50 cases used for comparison using the refined calculation assumptions.

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

The chart of measured against calculated values also shows a significantly increased scatter in the calculated U-values. Whereas the basic calculated values shown in Figure 70 show very little variation



between cases, the variation in density, moisture content and the internal structure of the walls results in much more variation in calculated values shown in Figure 71.

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

8.3 Extending the observations to all walls

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

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

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

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

Wall type	Number of cases	Measured U-values: Mean (standard deviation) (W/m ² K)	Measured U-values: Median (W/m ² K)	Calculated U-values using all observed data: Mean (standard deviation) (W/m ² K)	Calculated U-values using all observed data Median (W/m ² K)
Standard solid wall (brick) – quality filters applied	23	1.82 +/- 0.10 (0.24)	1.85	1.75 (0.05)	1.77

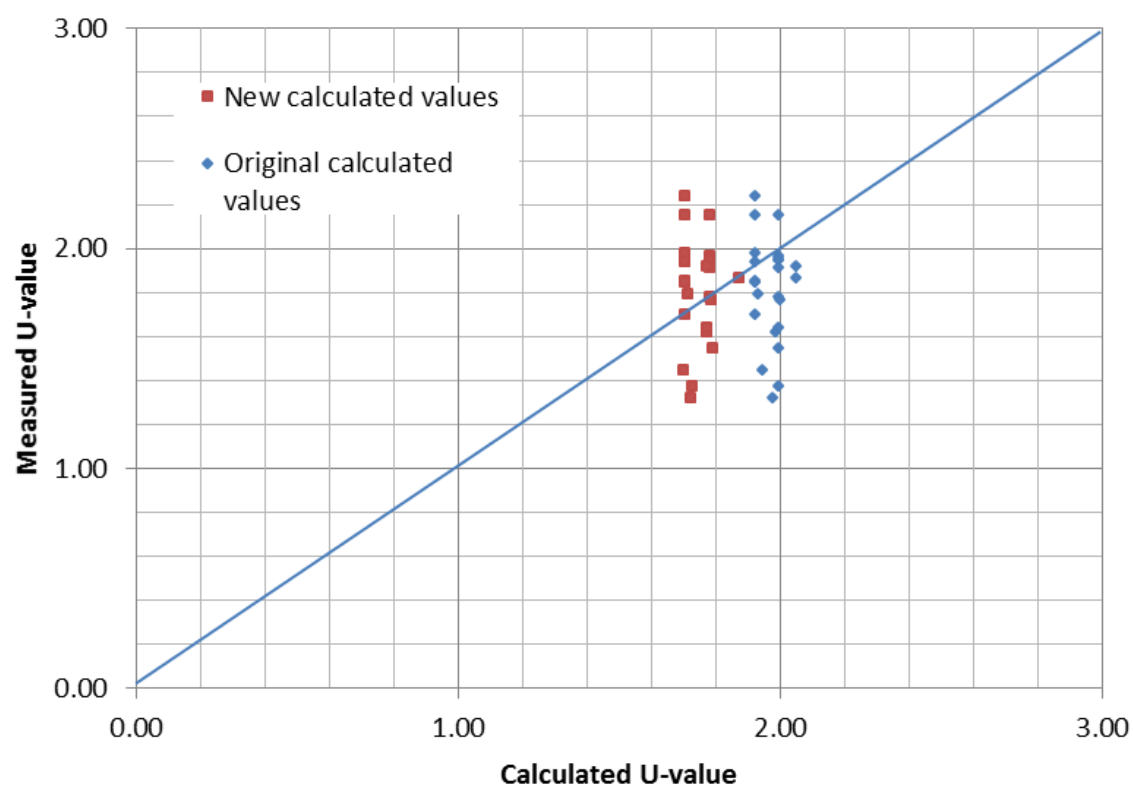


Figure 72: Comparison of measured and calculated values for the 23 cases which did not have additional observations under the original and revised calculations



9 Conclusions and discussion

9.1 Summary of findings

Previous work by BRE and others has identified that U-values of solid wall dwellings measured in situ are lower than the generally assumed value of $2.1 \text{ W/m}^2\text{K}$. This research has provided evidence in support of a U-value of $1.75 \text{ W/m}^2\text{K}$ for solid walled dwellings.

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

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

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

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

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

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

- a) The space between stretcher bricks, known as the collar joint, was seldom fully filled with mortar. The median percentage of the exposed area estimated to be filled with mortar was 67%.
- b) Perpendes were also seldom fully filled with mortar. The median percentage of the exposed perpend area estimated to be filled with mortar was 70%.
- c) Where a brick contained a frog, if it was found on the top face of the brick (brick laid "frog-up") then it was almost always fully filled with mortar. If it was found on the bottom face of the brick (brick laid "frog-down") it was very seldom filled with mortar.
- d) Broken bricks, known as brick bats, and imperfect bricks forming part of the wall were relatively common. These type of bricks were revealed in approximately 9% cases. These generally resulted in additional air cavities.
- e) Bricks were generally very dry. The median moisture content of brick and dust samples by volume was 0.5%. Some bricks, however, were extremely wet with a median moisture content of >15%.



- f) Mortar was slightly wetter, although generally also dry. The median moisture content of mortar by volume was ~2.7%. Some mortar, however, was also extremely wet with a median moisture content of >15%.
- g) The median dry density of bricks was higher than generally assumed. The median measured density was approximately 1,805 kg/m³ rather than the often assumed 1,750 kg/m³.

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

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

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

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

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

9.2 Discussion

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

The standard U-value assumed for solid walls, a value of 2.1 W/m²K has been used since the initial definition of these quantities through calculation in the 1960s, ahead of the publication of the 1970 CIBSE Guide [3]. At this time the use of calculated U-values, rather than those derived through experiment, was promoted as it offers comparability across different materials, as well as the ability to adjust for different conditions of moisture (and other characteristics) as required. This value appears to have remained relatively unchallenged until recent experimental work to establish a baseline ahead of insulation work.

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

Our new research has provided strong evidence to support a revision to the assumed U-value for uninsulated solid walls, and supported our original findings measuring U-values in situ [10]. For solid



walls, a U-value of approximately 1.75 W/m²K seems appropriate, and we would suggest that this value is taken forward as the default value in RdSAP. For other uses, boiler sizing for example, a higher value may be appropriate. The original value of 2.1 W/m²K is approximately two standard deviations above the new measured mean value and may be suitable to prevent undersizing of heating systems.

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

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

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

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

9.3 Further work

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

1. Confirmation of the newly derived thermal conductivity-density relationship, and extension to other materials. This work has proposed a new relationship between thermal conductivity and density for bricks. It has highlighted the age of many of the basic 'book values' which are widely used, and the potential errors that may exist with these old measurements. We would recommend additional testing to both confirm the relationship which has been derived, and extend the research to new measurements of other basic building materials (including mortar), for which the book values may be equally historic.
2. Additional investigations of the effect of brick moisture. The measurements of brick moisture were from a single location, and from the back of the facing stretcher brick only. Moisture dust drillings have indicated the extent that moisture may vary across a wall, and it would be of great interest to understand how this may vary at different locations in different bricks. This would include the moisture content of the inner leaf.
3. Investigation of moisture correction. Numerous alternative methods of correcting for moisture exist – e.g. Jakob corrections, ISO10456, DIN 51692. The choice of correction will affect the final calculated U-value. As with the thermal conductivity-density relationship, much of the data on these corrections



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

4. One area which has not been explored in detail in this work is the nature of the plasterwork. It was noted when plasterboard was present (and this is accounted for in the calculations) but types and thicknesses of plaster (except for the presence of plasterboard) were not measured for practical reasons of householder acceptance. Delamination of the plaster was also not accounted for.
5. The data on the distribution of different brick types within the housing stock is very limited. Additional knowledge of the types of bricks which are likely to be located in different locations may help to better define U-values at a local level. A survey could be designed to map the distribution of different brick types, which could be supplemented by laboratory (or in situ) measurements of the thermal performance of each different type.
6. Continuing investigation of the use of thermal probes for in situ measurements. Initial results from the use of a thermal needle probe are promising, with a good correlation between the measurements taken with the probe, and the measurements of thermal conductivity obtained in the laboratory. Further investigation of this technique is recommended, which ultimately may require the definition of a standard method for use of this equipment for the measurement of thermal conductivity in situ.



10 References

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Appendix A Wall weights for Hot Box test walls

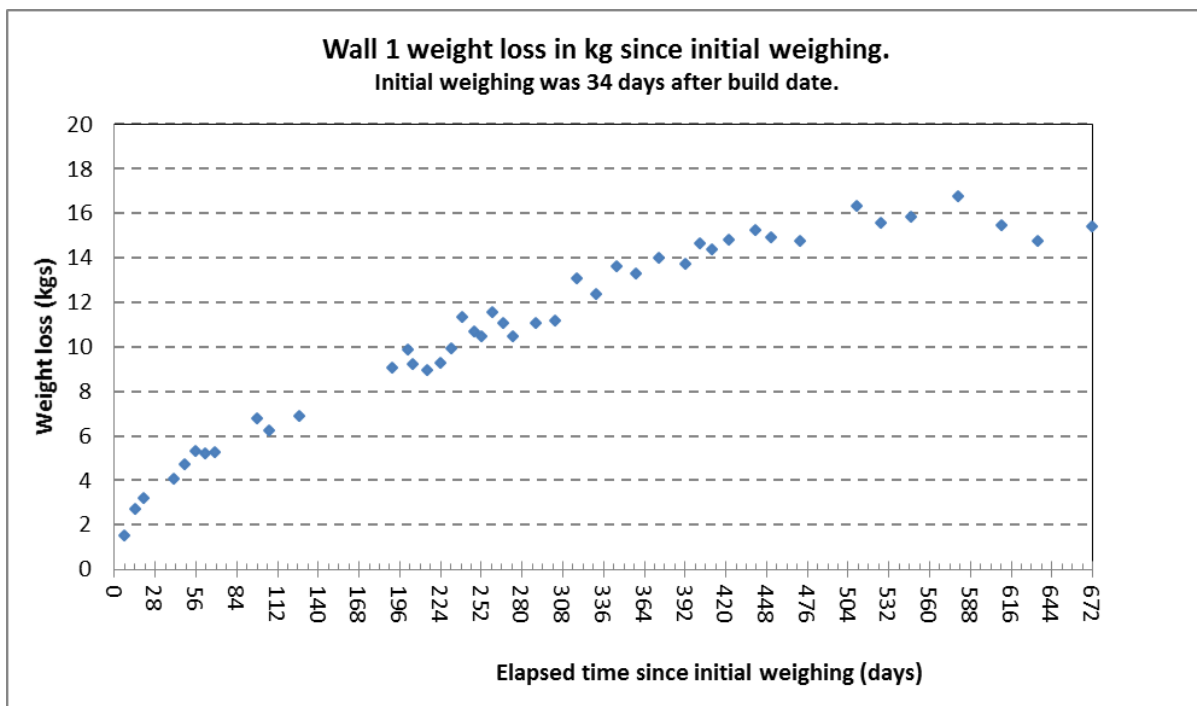


Figure A1: Wall weight loss for Wall 1.

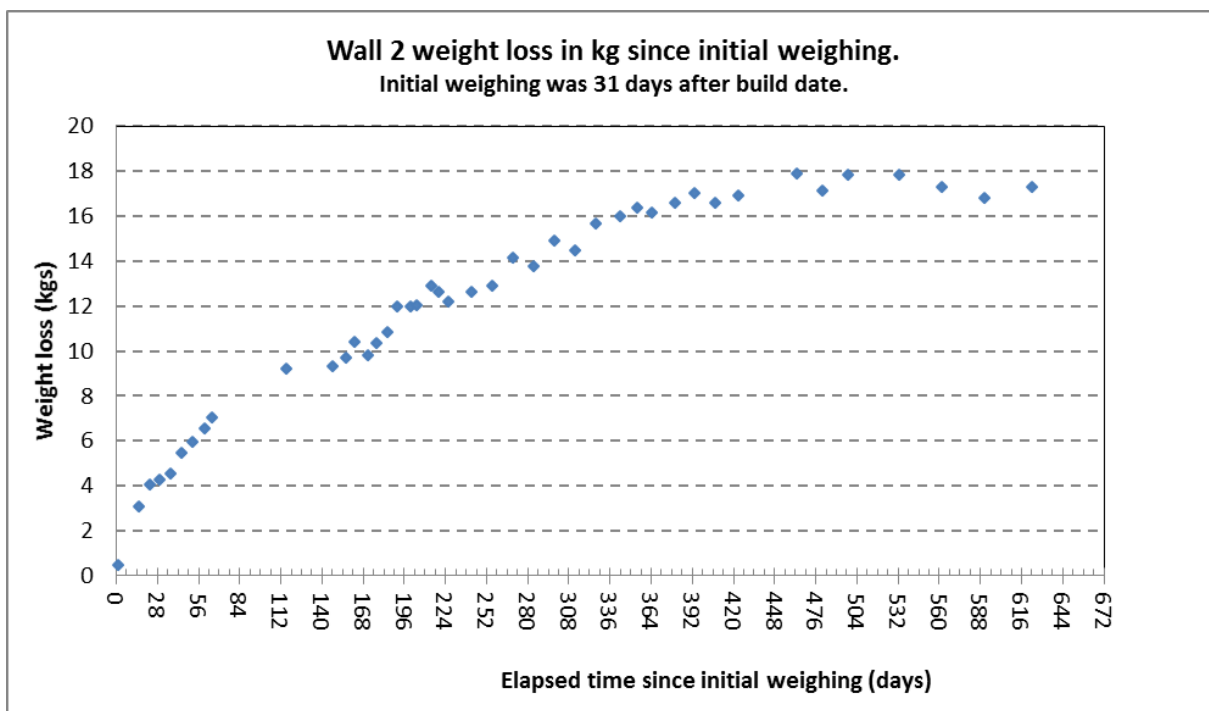


Figure A2: Wall weight loss for Wall 2.

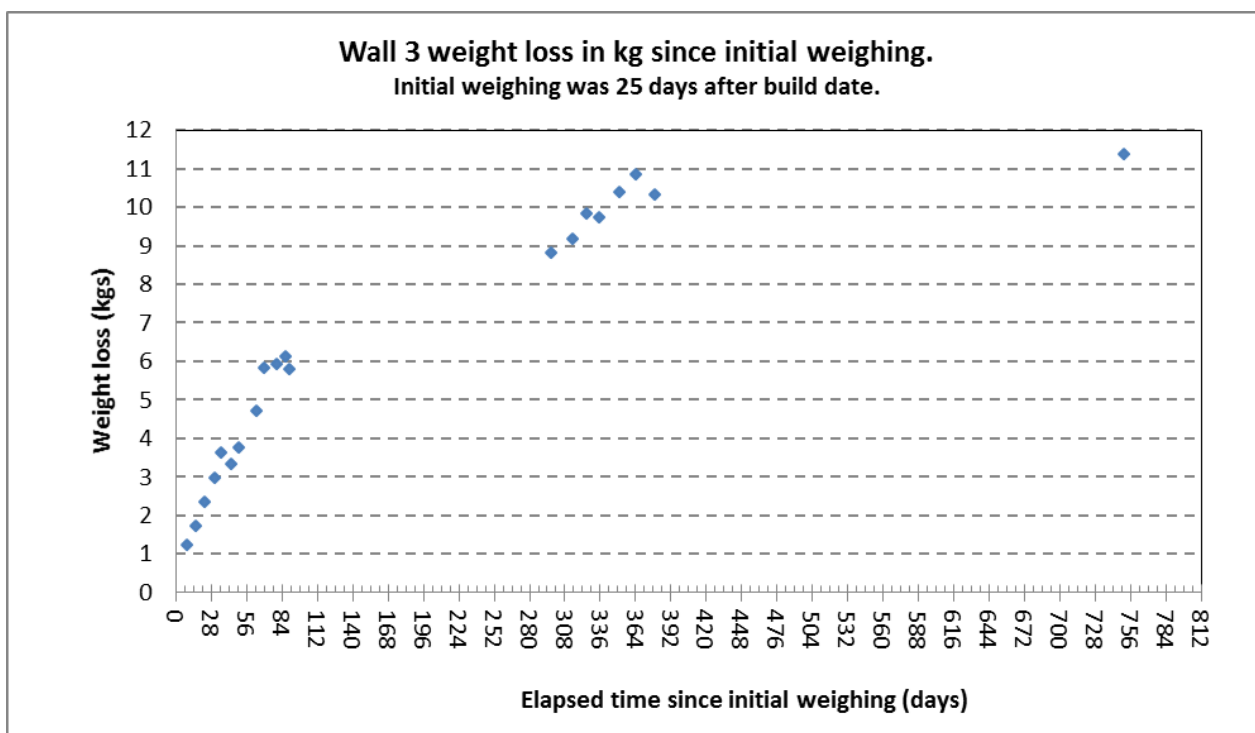


Figure A3: Wall weight loss for Wall 3.

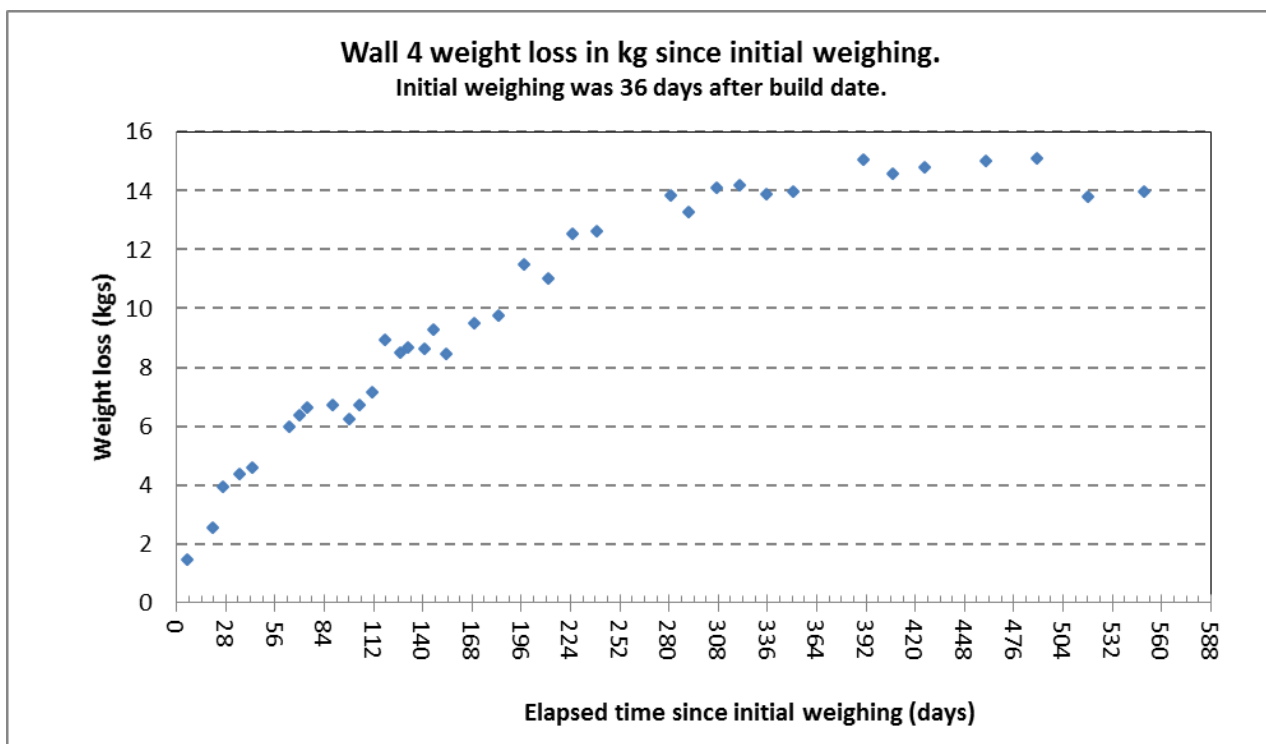


Figure A4: Wall weight loss for Wall 4.

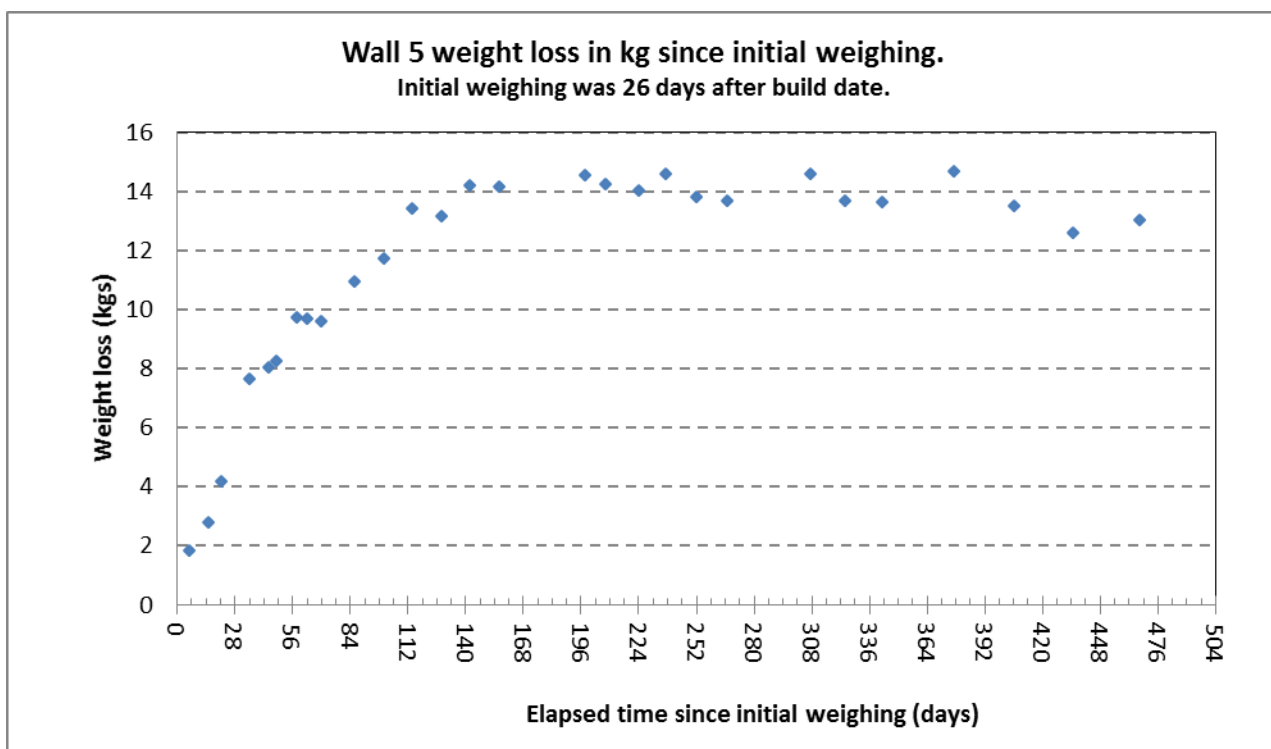


Figure A5: Wall weight loss for Wall 5.

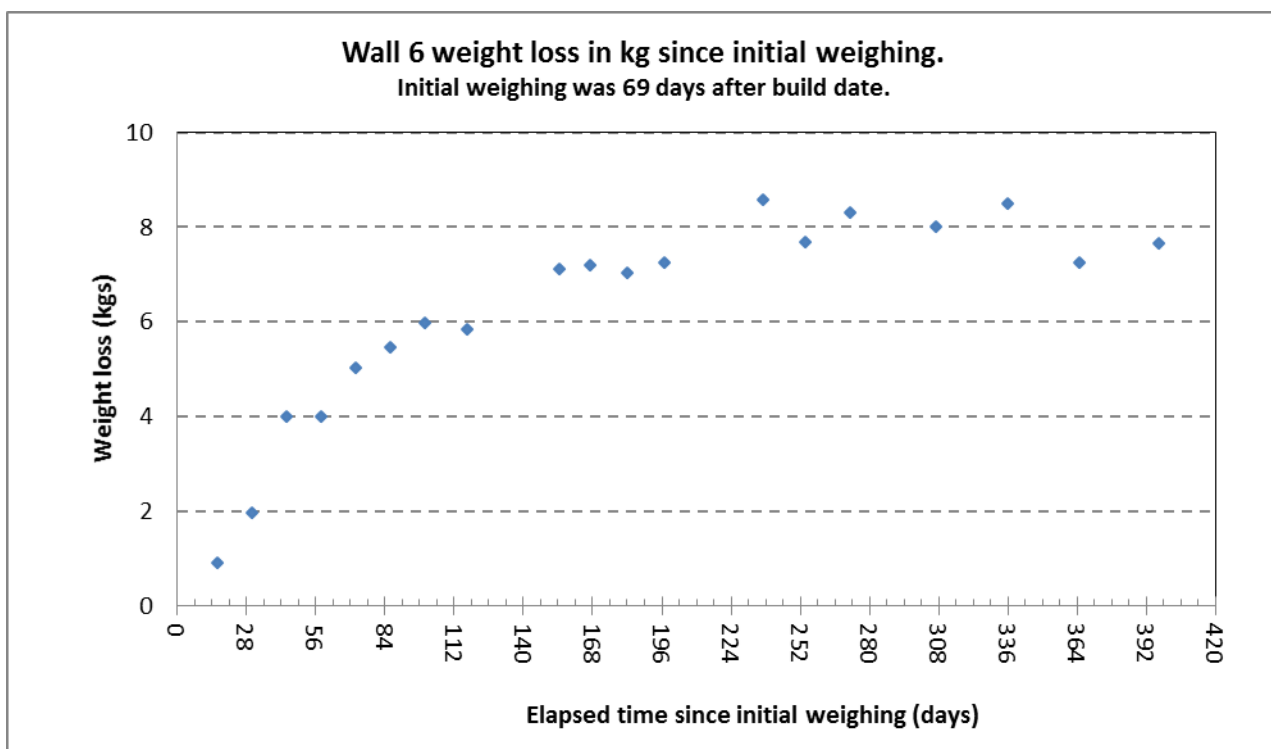


Figure A6: Wall weight loss for Wall 6.

Appendix B The Hukseflux TP01 Sensor

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

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

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

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

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

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

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

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

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

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

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

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

Figure B1 below shows the TP01 sensor.

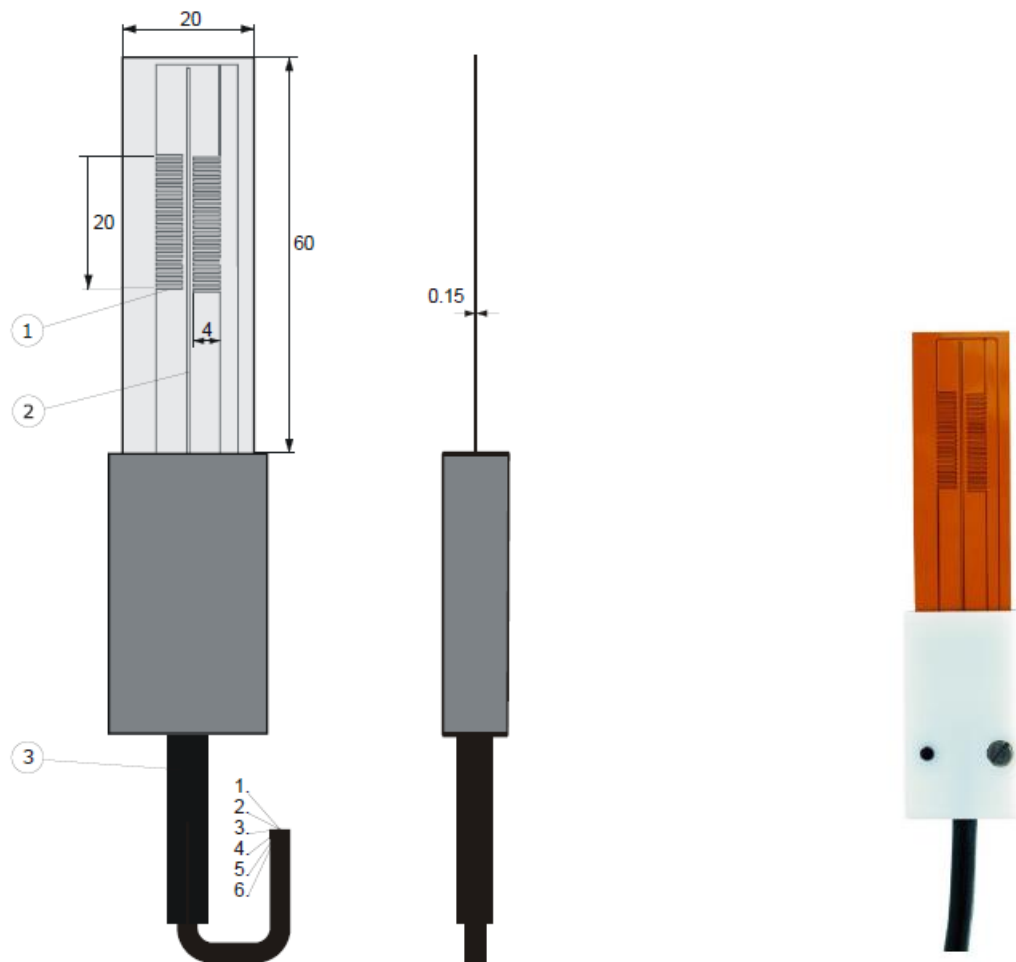


Figure B2: The TP01 Sensor.

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

Appendix C

Report 3: BRE (2016) Review of default U-values for existing buildings in SAP. Consultation paper CONSP:16.

Consultation Paper: CONSP:16

Review of default U-values for existing buildings in SAP

Issue 1.0

DOCUMENT REVISIONS

Documents will be revised by issue of updated editions or amendments. Revised documents will be posted on the website at www.bre.co.uk/sap2016.

Technical or other changes which affect product recognition requirements (for example) will result in a new issue. Minor or administrative changes (e.g. corrections of spelling and typographical errors, changes to address and copyright details, the addition of notes for clarification etc.) may be made as amendments.

The issue number will be given in decimal format with the integer part giving the issue number and the fractional part giving the number of amendments (e.g. Issue 3.2 indicates that the document is at Issue 3 with 2 amendments).

Users of this document should ensure that they possess the latest issue.

DOCUMENT REVISION LOG

DATE	VERSION NO.	AMENDMENT DETAILS	APPROVED BY
28/06/16	1.0	First issue	Paul Davidson

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1. INTRODUCTION

For new homes the U-values of walls are calculated specifically using the procedure described in BS EN ISO 6946. However, for existing dwellings a detailed calculation is not generally possible because the precise wall construction is usually unknown and a quicker assessment is used (RdSAP). In this case default U-values are used based on the type and age of wall, taken from tables in Appendix S of SAP. This appendix cannot be updated until after the full SAP procedure is complete, hence it will be left blank in the first edition of SAP 2016 then added later, as in previous iterations. However, it has been decided to include a proposed updated table of default wall U-values for existing buildings in the SAP 2016 consultation on the basis that this is a potentially significant change and because there is no separate RdSAP consultation process. The values are provided to give a sense of the likely direction and scale of change; however, research is continuing on this subject, so it is possible there will be further refinements before these figures are used for RdSAP.

DECC has commissioned a significant amount of work looking at wall U-values over the last few years after earlier studies found that in-situ wall U-values did not always agree well with those assumed in SAP calculations¹, potentially leading to a significant 'performance gap'. This is particularly relevant when it comes to calculating the savings from wall insulation, which appear to have been overestimated in the past, at least in part due to the use of pessimistic U-values for uninsulated walls and optimistic U-value for insulated walls. This has resulted in the application of large 'in-use' correction factors being applied to modelled savings in schemes where savings from energy efficiency measures are calculated, like Green Deal and the Energy Company Obligation.

The proposed amendments to tables S6, S7 and S8 presented in this document aim to bring the default U-values assumed in RdSAP assessments into line with the findings

¹ The most recent report on that work is available here:

https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/409428/In-situ_u-values_final_report.pdf

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from the latest studies. Further work is continuing on wall U-values (focussing on new age bands), so it is possible further updates will be made in future.

2. EVIDENCE FOR CHANGE

The default wall U-values in RdSAP calculations are based on either building regulations requirements for particular eras, or typical building practices at the time of construction. In the former case (i.e. for pre-1976 dwellings) standard thermal properties of construction materials are assumed in order to calculate the U-values. The materials data this relies on was derived a number of years ago, and appears to have been intended originally for use in 'design heat loss' calculations for sizing heating system components. For such calculations it is generally preferable where there is uncertainty or variability in material performance to assume conservative (higher) U-values to avoid under-sizing. Therefore it is thought that thermal properties at the worse end of the range would have been chosen which then became established as normal. This was a reasonable assumption to make at the time, but the data is now being used for a different purpose, such that median values may be more appropriate.

The DECC report *In-situ measurements of wall U-values in English housing* (referenced earlier), describes work undertaken over the last few years to measure the in-situ performance of a large number of walls in UK dwellings. Comparing these with the default values in RdSAP suggests that some values may need to be updated. The following table summarises the key results for walls built before 1976:

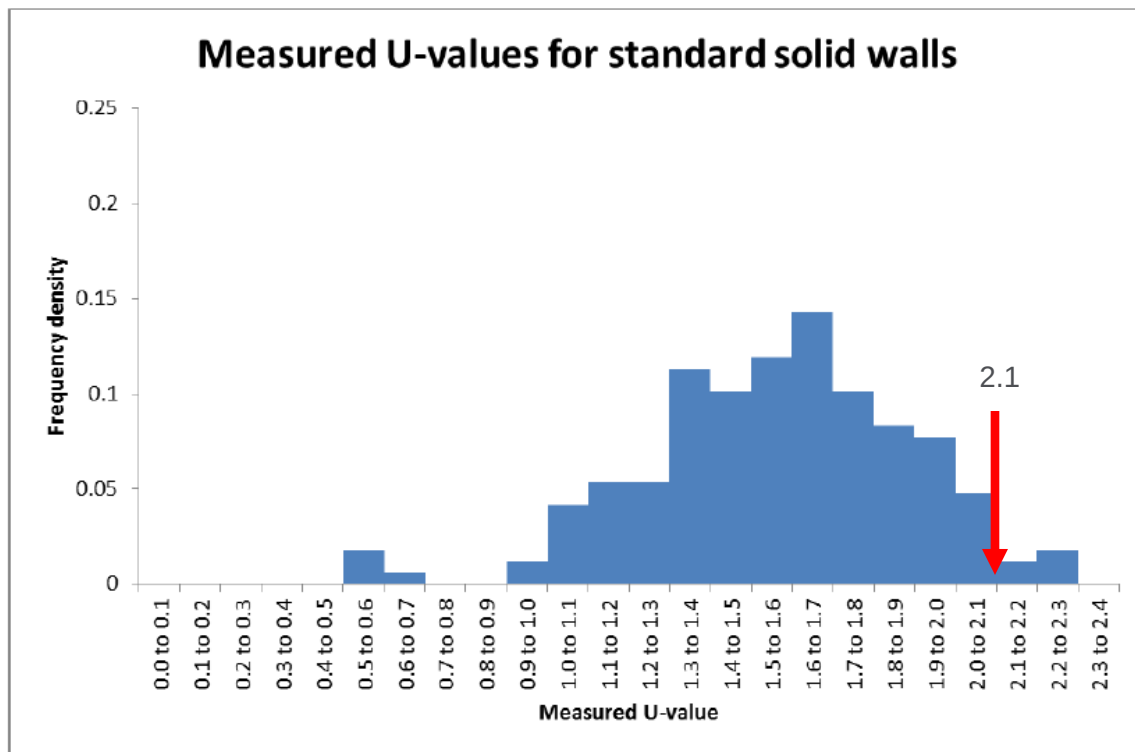
Wall type	Cases	Measured U-value (median)	Corrected* measured U-value (median)	RdSAP assumed U-value
Solid wall	85	1.59	1.69	2.1
Uninsulated cavity	50	1.43	1.52	1.6
Insulated cavity	109	0.63	0.67	0.5

* A 6% increase in U-value was applied based on the finding, after the DECC report was published, that the heat meters used read between 4 and 8% low because of their own thermal resistance.

This suggests that the U-values currently assumed in RdSAP are pessimistic in the case of uninsulated solid walls and uninsulated cavity walls, but optimistic in the case of insulated cavity walls. In particular the U-value assumed for a solid wall is around 24% higher than the median value found in the field study.

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It should be noted that a large range of results was found for each wall type (for example see distribution below for solid walls), implying that there are limitations in using a single figure for each wall type. In future it may be sensible to further subcategorise wall types if this is found to be practical for assessors.



It can be seen that the existing U-value assumed in RdSAP for a solid wall (2.1 W/m²K) is within the spread of values found in the study², but at the upper end of the range. This is consistent with the hypothesis that a conservative value has traditionally been used to avoid under-sizing heating systems in design heat loss calculations. There are also likely to be other factors, such as air-voids in nominally 'solid' walls leading (fortuitously) to better U-values. However, given that SAP is now being used to underpin financial incentives, placing greater demands on the accuracy of input values, it is prudent to use

² The values in the graph have not been corrected for the 6% measurement offset. If they were the whole distribution would be shifted slightly to the right making the figure of 2.1 slightly less peripheral.

a value, or values, that are nearer the median found in practice. There is, therefore, a rationale for updating the default wall U-values in RdSAP to better reflect the findings from the field trials.

3. PROPOSED AMENDMENTS TO TABLES

On the basis of the evidence accumulated so far, updates are proposed to the default U-values for solid and cavity walls for older (pre-76) dwellings in tables S6, S7 and S8 in Appendix S of SAP, which describes how to use RdSAP data to perform a SAP calculation. Updated figures are proposed in the following tables – the same changes are made in each.

The proposed changes to the U-values of uninsulated walls has a consequent (small) effect on the U-value of the same walls once retrofitted with insulation, hence slight adjustments to those values are also proposed.

Ongoing fieldwork may suggest changes to figures in newer age bands are required in future.

[Tables begin on next page, with proposed amended values highlighted]

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Table S6 : Wall U-values – England and Wales

Age band	A	B	C	D	E	F	G	H	I	J	K	L
Wall type												
Stone: granite or whinstone as built	a	a	a	a	1.7 b	1.0	0.60	0.60	0.45	0.35	0.30	0.28
Stone: sandstone or limestone as built	a	a	a	a	1.7 b	1.0	0.60	0.60	0.45	0.35	0.30	0.28
Solid brick as built	1.7	1.7	1.7	1.7	1.7	1.0	0.60	0.60	0.45	0.35	0.30	0.28
Stone/solid brick with 50 mm external or internal insulation	0.55	0.55	0.55	0.55	0.55	0.45*	0.35*	0.35*	0.30*	0.25*	0.21*	0.21*
Stone/solid brick with 100 mm external or internal insulation	0.32	0.32	0.32	0.32	0.32	0.28*	0.24*	0.24*	0.21*	0.19*	0.17*	0.16*
Stone/solid brick with 150 mm external or internal insulation	0.23	0.23	0.23	0.23	0.23	0.21*	0.18*	0.18*	0.17*	0.15*	0.14*	0.14*
Stone/solid brick with 200 mm external or internal insulation	0.18	0.18	0.18	0.18	0.18	0.17*	0.15*	0.15*	0.14*	0.13*	0.12*	0.12*
Cob (as built)	0.80	0.80	0.80	0.80	0.80	0.80	0.60	0.60	0.45	0.35	0.30	0.28
Cob with 50 mm external or internal insulation	0.40	0.40	0.40	0.40	0.40	0.40	0.35*	0.35*	0.30*	0.25*	0.21*	0.21*
Cob with 100 mm external or internal insulation	0.26	0.26	0.26	0.26	0.26	0.26	0.24*	0.24*	0.21*	0.19*	0.17*	0.16*
Cob with 150 mm external or internal insulation	0.20	0.20	0.20	0.20	0.20	0.20	0.18*	0.18*	0.17*	0.15*	0.14*	0.14*
Cob with 200 mm external or internal insulation	0.16	0.16	0.16	0.16	0.16	0.16	0.15*	0.15*	0.14*	0.13*	0.12*	0.12*
Cavity as built	1.5	1.5	1.5	1.5	1.5	1.0	0.60	0.60	0.45	0.35	0.30	0.28
Unfilled cavity with 50 mm external or internal insulation	0.53	0.53	0.53	0.53	0.53	0.45	0.35*	0.35*	0.30*	0.25*	0.21*	0.21*
Unfilled cavity with 100 mm external or internal insulation	0.32	0.32	0.32	0.32	0.32	0.30	0.24*	0.24*	0.21*	0.19*	0.17*	0.16*
Unfilled cavity with 150 mm external or internal insulation	0.23	0.23	0.23	0.23	0.23	0.21	0.18*	0.18*	0.17*	0.15*	0.14*	0.14*
Unfilled cavity with 200 mm external or internal insulation	0.18	0.18	0.18	0.18	0.18	0.17*	0.15*	0.15*	0.14*	0.13*	0.12*	0.12*
Filled cavity	0.7	0.7	0.7	0.7	0.7	0.40	0.35	0.35	0.45†	0.35†	0.30†	0.28†
Filled cavity with 50 mm external or internal insulation	0.37	0.37	0.37	0.37	0.37	0.27	0.25*	0.25*	0.25*	0.25*	0.21*	0.21*
Filled cavity with 100 mm external or internal insulation	0.25	0.25	0.25	0.25	0.25	0.20	0.19*	0.19*	0.19*	0.19*	0.17*	0.16*
Filled cavity with 150 mm external or internal insulation	0.16	0.16	0.16	0.16	0.16	0.16	0.15*	0.15*	0.15*	0.15*	0.14*	0.14*
Filled cavity with 200 mm external or internal insulation	0.13	0.13	0.13	0.13	0.13	0.13	0.13*	0.13*	0.13*	0.13*	0.12*	0.12*
Timber frame as built	2.5	1.9	1.9	1.0	0.80	0.45	0.40	0.40	0.40	0.35	0.30	0.28
Timber frame with internal insulation	0.60	0.55	0.55	0.40	0.40	0.40	0.40†	0.40†	0.40†	0.35†	0.30†	0.28†
System build as built	2.0	2.0	2.0	2.0	1.7	1.0	0.60	0.60	0.45	0.35	0.30	0.28
System build with 50 mm external or internal insulation	0.60	0.60	0.60	0.60	0.55	0.45	0.35*	0.35*	0.30*	0.25*	0.21*	0.21*
System build with 100 mm external or internal insulation	0.35	0.35	0.35	0.35	0.35	0.32*	0.24*	0.24*	0.21*	0.19*	0.17*	0.16*
System build with 150 mm external or internal insulation	0.25	0.25	0.25	0.25	0.25	0.21*	0.18*	0.18*	0.17*	0.15*	0.14*	0.14*
System build with 200 mm external or internal insulation	0.18	0.18	0.18	0.18	0.18	0.17*	0.15*	0.15*	0.14*	0.13*	0.12*	0.12*

Table S7 : Wall U-values – Scotland

Age band	A	B	C	D	E	F	G	H	I	J	K	L
Wall type												
Stone: granite or whinstone as built	a	a	a	a	1.6 b	1.0	0.60	0.45	0.45	0.30	0.25	0.22
Stone: sandstone or limestone as built	a	a	a	a	1.5 b	1.0	0.60	0.45	0.45	0.30	0.25	0.22
Solid brick as built	0.7	0.7	0.7	0.7	1.7	1.0	0.60	0.45	0.45	0.30	0.25	0.22
Stone/solid brick with 50 mm external or internal insulation	0.55	0.55	0.55	0.55	0.55	0.45*	0.35*	0.30*	0.30*	0.21*	0.19*	0.17*
Stone/solid brick with 100 mm external or internal insulation	0.33	0.33	0.33	0.33	0.33	0.28*	0.24*	0.24*	0.21*	0.19*	0.17*	0.14*
Stone/solid brick with 150 mm external or internal insulation	0.23	0.23	0.23	0.23	0.23	0.21*	0.18*	0.18*	0.17*	0.15*	0.14*	0.12*
Stone/solid brick with 200 mm external or internal insulation	0.18	0.18	0.18	0.18	0.18	0.17*	0.15*	0.15*	0.14*	0.13*	0.12*	0.10*
Cob as built	0.80	0.80	0.80	0.80	0.80	0.80	0.60	0.60	0.45	0.30	0.25	0.22
Cob with 50 mm external or internal insulation	0.40	0.40	0.40	0.40	0.40	0.40	0.35*	0.35*	0.30*	0.21*	0.19*	0.17*
Cob with 100 mm external or internal insulation	0.26	0.26	0.26	0.26	0.26	0.26	0.24*	0.24*	0.21*	0.19*	0.17*	0.14*
Cob with 150 mm external or internal insulation	0.20	0.20	0.20	0.20	0.20	0.20	0.18*	0.18*	0.17*	0.15*	0.14*	0.12*
Cob with 200 mm external or internal insulation	0.16	0.16	0.16	0.16	0.16	0.16	0.15*	0.15*	0.14*	0.13*	0.12*	0.10*
Cavity as built	0.5	0.5	0.5	0.5	0.5	1.0	0.60	0.45	0.45	0.30	0.25	0.22
Unfilled cavity with 50 mm external or internal insulation	0.53	0.53	0.53	0.53	0.53	0.45	0.35*	0.30*	0.30*	0.25*	0.19*	0.17*
Unfilled cavity with 100 mm external or internal insulation	0.32	0.32	0.32	0.32	0.32	0.30	0.24*	0.21*	0.21*	0.19*	0.17*	0.14*
Unfilled cavity with 150 mm external or internal insulation	0.23	0.23	0.23	0.23	0.23	0.21	0.18*	0.17*	0.17*	0.15*	0.14*	0.12*
Unfilled cavity with 200 mm external or internal insulation	0.18	0.18	0.18	0.18	0.18	0.17*	0.15*	0.15*	0.14*	0.13*	0.12*	0.10*
Filled cavity	0.7	0.7	0.7	0.7	0.7	0.40	0.35	0.45†	0.45†	0.30†	0.25†	0.22†
Filled cavity with 50 mm external or internal insulation	0.37	0.37	0.37	0.37	0.37	0.27	0.25*	0.25*	0.25*	0.25*	0.25*	0.17*
Filled cavity with 100 mm external or internal insulation	0.25	0.25	0.25	0.25	0.25	0.20	0.19*	0.19*	0.19*	0.19*	0.19*	0.14*
Filled cavity with 150 mm external or internal insulation	0.19	0.19	0.19	0.19	0.19	0.16	0.15*	0.15*	0.15*	0.15*	0.15*	0.12*
Filled cavity with 200 mm external or internal insulation	0.16	0.16	0.16	0.16	0.16	0.13	0.13*	0.13*	0.13*	0.13*	0.12*	0.10*
Timber frame as built	2.5	1.9	1.9	1.0	0.80	0.45	0.40	0.40	0.40	0.30	0.25	0.22
Timber frame with internal insulation	0.60	0.55	0.55	0.40	0.40	0.40	0.40†	0.40†	0.40†	0.30†	0.25†	0.22†
System build as built	2.0	2.0	2.0	2.0	1.7	1.0	0.60	0.45	0.45	0.30	0.25	0.22
System build with 50 mm external or internal insulation	0.60	0.60	0.60	0.60	0.55	0.45	0.35*	0.30*	0.30*	0.21*	0.19*	0.17*
System build with 100 mm external or internal insulation	0.35	0.35	0.35	0.35	0.35	0.32*	0.24*	0.24*	0.21*	0.19*	0.17*	0.14*
System build with 150 mm external or internal insulation	0.25	0.25	0.25	0.25	0.25	0.21*	0.18*	0.18*	0.17*	0.15*	0.14*	0.12*
System build with 200 mm external or internal insulation	0.18	0.18	0.18	0.18	0.18	0.17*	0.15*	0.15*	0.14*	0.13*	0.12*	0.10*

Table S8 : Wall U-values – Northern Ireland

Age band	A	B	C	D	E	F	G	H	I	J	K	L
Wall type												
Stone: granite or whinstone as built	a	a	a	a	1.6 b	1.0	0.60	0.45	0.45	-	0.30	0.28
Stone: sandstone or limestone as built	a	a	a	a	1.6 b	1.0	0.60	0.45	0.45	-	0.30	0.28
Solid brick as built	1.7	1.7	1.7	1.7	1.7	1.0	0.60	0.45	0.45	-	0.30	0.28
Stone/solid brick with 50 mm external or internal insulation	0.55	0.55	0.55	0.55	0.55	0.45*	0.35*	0.30*	0.30*	-	0.21*	0.21*
Stone/solid brick with 100 mm external or internal insulation	0.32	0.32	0.32	0.32	0.32	0.28*	0.24*	0.24*	0.21*	-	0.17*	0.16*
Stone/solid brick with 150 mm external or internal insulation	0.23	0.23	0.23	0.23	0.23	0.21*	0.18*	0.18*	0.17*	-	0.14*	0.14*
Stone/solid brick with 200 mm external or internal insulation	0.18	0.18	0.18	0.18	0.18	0.17*	0.15*	0.15*	0.14*	-	0.12*	0.12*
Cob as built	0.80	0.80	0.80	0.80	0.80	0.80	0.60	0.60	0.45	-	0.30	0.28
Cob with 50 mm external or internal insulation	0.40	0.40	0.40	0.40	0.40	0.40	0.35*	0.35*	0.30*	-	0.21*	0.21*
Cob with 100 mm external or internal insulation	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26	-	0.21*	0.16*
Cob with 150 mm external or internal insulation	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	-	0.20	0.14*
Cob with 200 mm external or internal insulation	0.16	0.16	0.16	0.16	0.16	0.16	0.15*	0.15*	0.14*	-	0.12*	0.12*
Cavity as built	1.5	1.5	1.5	1.5	1.5	1.0	0.60	0.45	0.45	-	0.30	0.28
Unfilled cavity with 50 mm external or internal insulation	0.53	0.53	0.53	0.53	0.53	0.45	0.35*	0.35*	0.30*	-	0.21*	0.21*
Unfilled cavity with 100 mm external or internal insulation	0.32	0.32	0.32	0.32	0.32	0.30	0.24*	0.24*	0.21*	-	0.17*	0.16*
Unfilled cavity with 150 mm external or internal insulation	0.23	0.23	0.23	0.23	0.23	0.21	0.18*	0.18*	0.17*	-	0.14*	0.14*
Unfilled cavity with 200 mm external or internal insulation	0.18	0.18	0.18	0.18	0.18	0.17*	0.15*	0.15*	0.14*	-	0.12*	0.12*
Filled cavity	0.7	0.7	0.7	0.7	0.7	0.40	0.35	0.45 [†]	0.45 [†]	-	0.30 [†]	0.28 [†]
Filled cavity with 50 mm external or internal insulation	0.37	0.37	0.37	0.37	0.37	0.27	0.25*	0.25*	0.25*	-	0.25*	0.21*
Filled cavity with 100 mm external or internal insulation	0.25	0.25	0.25	0.25	0.25	0.20	0.19*	0.19*	0.19*	-	0.19*	0.16*
Filled cavity with 150 mm external or internal insulation	0.19	0.19	0.19	0.19	0.19	0.16	0.15*	0.15*	0.15*	-	0.15*	0.14*
Filled cavity with 200 mm external or internal insulation	0.16	0.16	0.16	0.16	0.16	0.13	0.13*	0.13*	0.13*	-	0.12*	0.12*
Timber frame as built	2.5	1.9	1.9	1.0	0.80	0.45	0.40	0.40	0.40	-	0.30	0.28
Timber frame with internal insulation	0.60	0.55	0.55	0.40	0.40	0.40	0.40 [†]	0.40 [†]	0.40 [†]	-	0.30 [†]	0.28 [†]
System build as built	2.0	2.0	2.0	2.0	1.7	1.0	0.60	0.45	0.45	-	0.30	0.28
System build with 50 mm external or internal insulation	0.60	0.60	0.60	0.60	0.55	0.45	0.35*	0.30*	0.30*	-	0.21*	0.21*
System build with 100 mm external or internal insulation	0.35	0.35	0.35	0.35	0.35	0.32*	0.24*	0.24*	0.21*	-	0.17*	0.16*
System build with 150 mm external or internal insulation	0.25	0.25	0.25	0.25	0.25	0.21*	0.18*	0.18*	0.17*	-	0.14*	0.14*
System build with 200 mm external or internal insulation	0.18	0.18	0.18	0.18	0.18	0.17*	0.15*	0.15*	0.14*	-	0.12*	0.12*

4. CONSEQUENCES OF CHANGES

The energy consumption of a dwelling predicted using SAP is very sensitive to wall U-value. The proposed changes to the default wall U-values will therefore result in significant changes to the predicted building performance and in particular to the savings from insulating walls. Since the savings from insulation are, to a good approximation, proportional to the change in U-value which results from the addition of insulation, it is possible to estimate the impact for a given scenario directly from the change in U-values, as shown in the following example.

Example: Insulation of solid brick walls

Using existing RdSAP default U-values:

U-value before = 2.1, U-value after (100mm) = 0.35

Improvement in U-value = $2.1 - 0.35 = 1.75 \text{ W/m}^2\text{K}$

Using proposed U-values:

U-value before = 1.7, U-value after (100mm) = 0.32

Improvement in U-value = $1.7 - 0.32 = 1.38 \text{ W/m}^2\text{K}$

Reduction in expected savings as a result of changes to wall U-values proposed

= $1 - (1.38 / 1.75) = \textbf{21\%}$

Other potentially significant impacts are:

- The SAP rating and EPC band for existing dwellings with uninsulated walls will improve. For example, solid walled homes in bands F or G will rise to a higher band in some cases. This could be significant in relation to the planned policy to prohibit the rental of properties rated worse than band E.
- The apparent cost-effectiveness of insulating walls will be made worse. However, for purposes where 'in-use factors' are applied to savings these should be relaxed to compensate for the use of corrected U-values, so any impact will be negated.

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Appendix D

Report 4: Hulme, J. (2015) Energy use and home temperatures in English housing: results from the energy follow-up survey.

Energy use and home temperatures in English housing: results from the energy follow-up survey

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Keywords

space heating, water heating, residential buildings, measurements, data collection, lighting, housing, home temperatures

Abstract

The Energy Follow-Up Survey (EFUS) is a large survey which was undertaken in England to collect new data on domestic energy use. The survey provided crucial new information which is being used to update the current assumptions about how energy is used in the home, and to inform energy efficiency policy.

The EFUS consisted of a follow-up interview survey of approximately 2,616 households first visited as part of the 2010/2011 English Housing Survey (EHS). Additionally, sub-samples of these households were selected to have temperature loggers (823 households) and electricity consumption monitors (79 households) installed. Approximately 50 % of the EFUS sample allowed the compilation of gas and electricity consumption data from meter readings (1,345 households).

The survey provides valuable new quantitative data on heating patterns, hours of heating, secondary heating systems and other aspects of energy use in the home.

This paper outlines the main results from this survey, and summarises the implications for energy efficiency modelling and policy.

Introduction

This paper describes the key findings from a large survey of domestic energy use undertaken by BRE, on behalf of the UK Department of Energy and Climate (DECC). This survey was called the 2011 Energy Follow-Up Survey (EFUS) and was designed to collect new data on domestic energy use, in order to

update the current modelling assumptions about how energy is used in the home, and to inform energy efficiency policy.

This paper summarises the results of this work, highlighting those of principal relevance, and discusses the implications of the findings. Full details of the survey, and further results can be found in the 11 reports (Hulme et al., 2013) found here <http://www.gov.uk/government/statistics/energy-follow-up-survey-efus-2011>. The survey had several components:

1. A follow-up interview survey of approximately 2,600 households first visited as part of the 2010/2011 English Housing Survey (EHS¹) (see e.g. DCLG, 2011).
2. Sub-samples of these households were then selected for
 - a. temperature monitoring
 - b. whole-house electricity consumption
 - c. compilation of gas and electricity consumption data from meter readings.

The principal objectives of the analysis to date are to inform energy efficiency policy, and provide data to update the assumptions in the key energy modelling methodologies in use in the UK: the BRE Domestic Energy Model (BREDEM) (Henderson, J & Hart, J 2015) and its derivative the UK Standard Assessment Procedure (SAP) (DCLG, 2013). BREDEM and SAP are widely used to predict the annual energy consumption in dwellings,

1. The English Housing survey is an annual survey undertaken by the UK Department of Communities and Local Government (DCLG). It collects information about people's housing circumstances and the condition and energy efficiency of housing in England. It has 2 component surveys: 1) a household interview and 2) a physical inspection of a sub sample of the properties.

and housing-related CO₂ emissions. The EFUS provides essential new data on the following aspects of energy use.

- How many hours are households heating their homes for on weekdays, and at weekends during the winter? How do these heating hours compare to those typically used as inputs into modelling?
- How many rooms are unheated in winter? What rooms are unheated?
- How are secondary heating systems being used?
- What average 24hr temperatures are found in homes? How do these compare to those typically calculated by the models?
- What temperatures are being achieved during periods of heating? How do these compare to those typically used as inputs into the models?
- How are conservatories being used? Are they being heated?
- How much lighting is found in homes, and how is it being used?
- What electrical appliances are found in homes, and how are they being used?

Background to the survey

The requirement for the 2011 EFUS was first highlighted by BRE in 2007 and 2008 as part of the ongoing development programme for the BREHOMES energy model (Shorrock, 1997), Energy Use In Homes analysis for Government (BRE, 2008) and Domestic Energy Factfile publications (Utley and Shorrock, 2008). At this point it was identified that a detailed survey was required to reflect changing patterns in home energy use and to update the evidence base underpinning modelling and policy. Developments in technology would also allow for the collection of detailed monitored data on home temperatures and electricity consumption for the first time.

A previous survey of this type was undertaken in 1998 (the 1998 EFUS) with results informing policies such as fuel poverty and SAP (see for example DTI/Defra 2001 and BRE, 2005) and it was considered that this evidence base needed to be updated. In particular, data on internal temperatures was particularly outdated with the most recent comprehensive survey over 30 years old (Hunt and Gidman, 1982).

The need for the EFUS was confirmed by a Public Accounts Committee report in 2009 (Public Accounts Committee, 2009) stating that UK Government departments were not gathering enough data from real homes to evaluate the impact of programmes on consumer behaviour and household energy efficiency. It recommended that the (newly formed) Department of Energy and Climate Change and the Department for Communities and Local Government should set out and implement strategies for evaluating and learning from the environmental and financial impact of their programmes, distinguishing the programme impacts from those of other factors, such as energy prices and household growth. The strategies should address how energy-use data will be obtained to:

- understand, monitor and respond to changing patterns of energy use in households, including appliance use and wastage;

- understand the impact in real homes of installing energy efficiency measures, and understand and improve the actual energy performance of new homes built to standards set out in the current and future Building Regulations.

Against this background, the EFUS was specified and developed.

The Energy Follow-Up Survey is so called because it revisits dwellings and households first visited as part of the 2010 English Housing Survey (EHS) (DCLG, 2011). By revisiting EHS properties, the data from the earlier survey (for example on the household type, or physical characteristics of the dwelling) can be combined with the data from the EFUS. This provides a much richer data source for analysis.

The EFUS consisted of an interview survey and several subsets

1. Interview Survey (2,616 homes): The EFUS 2011 interview survey was undertaken by interviewers from the market research organisation GfK NOP between December 2010 and April 2011. A total of 2,616 interviews were completed, drawn from a sample of addresses provided from the first three quarters of the 2010/11 English Housing Survey (EHS). These data were then weighted to account for survey non-response and to allow estimates at the national level to be produced.
2. Temperature monitoring survey (a sub-sample of 823 homes): During the interview survey, householders were invited to take part in a temperature monitoring study. This required the placement of up to three temperature monitors in three rooms of the home, which would record room temperatures every twenty minutes for around one year.
3. Meter readings (a sub-sample of 1,345 homes): To provide information on how much electricity and gas was actually being used, meter readings were also taken as part of the EFUS, and matched with original readings taken as part of the EHS. These readings provide data on annual gas and electricity consumption.
4. Electricity profiling (a sub-sample of 79 homes): Finally, a small number of properties had electricity profiling equipment installed to examine patterns of lighting, appliance and electrical cooking use. This equipment collected data at rapid intervals on how much electricity was being used in the home.

The EFUS data have been scaled up to represent the national population (and to correct for non-response) using weighting factors. The results presented in this report are therefore representative of the English housing stock, with a population of 21.9 million households.

Methodology

The EFUS interviews were carried out by GfK NOP between December 2010 and April 2011 with a total of 2,616 interviews being completed.

BRE supplied 3,288 addresses drawn from the first two quarters of the EHS (April to November 2010) to GfK. This represented all cases from these quarters where the respondent had previously agreed to a further interview (84 % of cases). The EHS 2010 is a simple random sample of addresses from

across England, with each quarter being a random quarter of the full sample (i.e. there is no clustering by survey period). The quarters passed to the EFUS survey team were chosen as they were available in time to conduct the survey, and were as close as possible to the start of the EFUS interview to minimise the chance of changes to the dwelling or household.

When this sample was considered to be exhausted, BRE supplied an additional 400 cases from the third quarter of the EHS. As the number of interviews had been capped at approximately 2,600, this second sample was not fully utilised before fieldwork was complete. In all 135 interviewers were used on the project, and they were allocated cases based on proximity to where they lived. Interviewers were supplied with names, addresses and telephone numbers for the households in their assigned sample.

To enable the EFUS data to be scaled up to represent the national population and to correct for non-response, weighting factors have been calculated to align with national totals for tenure, Government Office Region and dwelling type.

During the survey, householders were invited to take part in a temperature monitoring study. The temperatures collected can be used to produce a temperature profile for the household and investigate overheating issues and provide accurate information for updating assumptions within SAP and BREDEM. This provides additional information in support of the reported data.

The temperature loggers used were modified TinyTag Transit 2 data loggers, produced by Gemini Data loggers. Each logger was marked for use in specific rooms. The loggers store temperature data internally, with a memory capacity of 32,000 readings, an accuracy of ± 0.2 °C and a resolution of 0.01 °C. The temperature range of the loggers is from -70 °C to +40 °C. To maximise the number of readings possible in a period of a year, each logger was programmed to record data every 20 minutes until reaching capacity. All loggers were new and calibrated at manufacture, but BRE performed some additional tests on a sample of loggers before the survey began. This included testing of battery life, recording frequency and verification that the loggers had been set up with the correct starting dates and recording frequencies. All of the tested loggers operated as expected.

Of the 2,616 households interviewed, around 943 households received three temperature loggers to be placed in the living room, hallway and bedroom. A small number of households without all three rooms (e.g. bedsits) received only two loggers.

Interviewers were given instructions on proper placement of the loggers during the interview briefings, this was essentially emphasising the need for the loggers to be placed on an internal wall, away from heat sources and out of direct sunlight and at a height that could be reached by the occupant for removal of the logger (but out of the reach of small children). Because of practical issues placing loggers into the diverse circumstances found in homes, guidance on logger placement could not be overly prescriptive. Occasionally, the householder put the loggers up with instruction from the interviewer, for example in a private room like a bedroom which they were unwilling to allow access to.

A total of 118 sets of loggers failed to be returned by householders and two sets were returned with all three loggers faulty. Thus the total number of sets of loggers adequate for analysis is 823.

In a total of 79 homes, short time-step data on electricity consumption was obtained. This was collected using the Micro

Amper digital voltage data logger. This is a stand-alone battery powered single channel data logger with a 0–1.5 V input signal range and a accuracy of 0.15 %. It was combined with a 0 to 50 Amp split-core current clamp (current transformer) to record whole house electricity consumption. The current clamp was placed around the red 'live' cable between the household electricity meter and the consumer unit and a thin data cable connected it to the monitor.

The current clamps used were ACT050-10-S (ACT 0 to 50 A). The clamp has an output signal 0 to 10 V AC, but the cabling was modified to include a resistor to ensure that the output of the current clamp did not overload the monitor. Configured and set-up with the 100 k Ω series resistor, the current measurement range is 0 to 82 Amps representing approximately 0 to 20 kW. Spot readings of consumption were recorded every 10 seconds with the data stored on a 2 GB Secure Digital Flash Memory Card. Each daily file comprises 8,640 data readings for each full day.

The final data collected related to actual consumption. During the EHS 2010/11 physical survey, EHS surveyors read the gas and electricity meters where possible. This reading forms the first (initial reading) of the EFUS meter reading dataset and were taken during the period April to September 2010.

To obtain the second (final) reading, a number of approaches were taken. At the end of the EFUS interview the householders were asked if they would consent to a further reading taken by a professional meter reader and around two thirds of the sample agreed to this. Follow up readings were attempted for all households by G4S, a meter reading company, in two batches: the first between February and March 2012 and the second in November 2012. A high number of readings were unobtainable in the first batch of data collection, necessitating a two stage process.

Alongside this second reading attempt by G4S, a number of further approaches were made to households to increase the size of this dataset:

1. Self-read cards were sent to remaining households.
2. During the EFUS interview, households were asked if they would consent to DECC obtaining information of electricity and gas consumption directly from their energy supplier, with over 60 % of all EFUS cases agreeing. Two major energy suppliers supplied initial and final meter reading data. Other suppliers were unable to assist with this task.
3. A small number of meters were read by BRE staff (with the householder's permission) while installing and removing other monitoring equipment

In order to obtain a final set of cases for reporting, a validation process was applied to the meter readings from all sources. This process was assisted by comparison with the Meter Point data (a national data set of consumption) provided to the survey team by DECC for comparison purposes. Cases with a missing first or second reading were removed and the remaining data were inspected to decide on the validity of their consumption data, including day and night rates of electricity where applicable. Cases were dropped where the consumption was implausibly high or produced a negative figure, although in a number of cases the data could be consolidated and retained where there was clear evidence for the source of the

discrepancy, e.g. a negative value resulting from a meter passing through 9,999 during the consumption period. Implausibly high consumptions were identified by examination of the data close to and above 70,000 kWh for gas and 30,000 kWh for total electricity (by inspecting plots of the data, these extreme values became apparent above these points). Values at the top end of this range were then checked, looking for possible errors in the actual meter readings along with comparisons against the meter point estimates and dwelling and household size. Similar checks were done for apparently valid consumptions close to 0. These checks lead to around 40 cases (approx. 3 %) being dropped. Following this validation process a complete set of initial and final electricity meter readings was obtained for 1,345 cases (51 % of total EFUS sample). Of these, 1,197 cases had a mains gas supply and produced valid gas consumption values (89 % of the meter reading sample, and 45 % of the total EFUS sample).

Summary of key survey findings

The EFUS has provided a wealth of new information about how energy is being used in English homes. Presented below are summaries of the key findings for modelling and policy in a number of key areas.

MEAN HOUSEHOLD TEMPERATURES

Average internal temperatures (i.e. the average temperatures in a dwelling over a 24 hr period) are of importance when quantifying energy consumption within dwellings. Average internal temperatures are key quantities in calculations of the energy requirement of homes, and it is valuable to compare the averages calculated by the models in use in the UK to the average temperatures observed by the EFUS.

Mean household temperatures have been produced from the EFUS using data collected during February 2011 to January 2012 inclusive. These give a dataset of monthly mean temperatures in the three rooms monitored (living room, main bedroom and hallway). Data from individual rooms have also been combined to produce proxies for the BREDEM (Henderson, J & Hart, J 2015) zone 1 and zone 2 (BREDEM zone 1, the living room, is generally considered to be heated to a higher temperature than BREDEM zone 2 which is the rest of the heated space) and the whole dwelling.

The mean monthly room temperatures recorded are shown in Figure 1. During the heating season (October to April) these are 19.3 °C for the living room, 18.8 °C for the hallway and 18.9 °C for the bedroom, from which heating season mean temperatures of 18.8 °C for zone 2 and 19.0 °C for the dwelling have been derived. These temperatures are significantly higher than those recorded in a previous national survey of home temperatures from 1978 (Hunt & Gidman, 1982).

The differences between the zone 1 (living room) and zone 2 temperatures are less than those typically calculated through SAP (the UK's energy rating system). The EFUS suggests differences of approximately 0.6 °C, whereas the difference calculated for a typical semi-detached house in SAP is approximately 1.3 °C in the heating season. This provides some evidence that the SAP model in use in the UK may need to be recalibrated, if it is to match actual temperature differences between different zones in the home.

There are no statistically significant differences seen between weekday and weekend monthly mean temperatures in the living room, bedroom, zone 2 or the dwelling as a whole. The difference between weekday/weekend mean temperatures currently calculated in SAP is not observed in the monitored data. This supports the results of analysis of main heating patterns (see section below) in which householders reported no change in the number of hours that their heating was on between weekdays and weekends.

The variation in average heating season temperatures for different dwelling and household characteristics has also been investigated. Dwellings that are fully double glazed, those with someone in during the day during a weekday, and those in which the occupants are not under-occupying show both living room and zone 2 mean heating season temperatures that are significantly *higher* than their alternative category.

Some groups of dwellings have significant differences in the mean heating season temperatures in one or other of the zones but not both. For example, flats are seen to have *higher* living room mean heating season temperatures than detached or semi-detached dwellings but no difference is seen between dwelling types for zone 2 mean heating season temperatures.

METERED ENERGY CONSUMPTION

Annual consumptions have been produced using gas and electricity meter readings collected as part of the EHS and EFUS.

The median annual mains gas consumption determined using the EFUS meter reading data is around 14,000 kWh, with a median value of around 3,700 kWh for electricity².

Significant differences are found in the median consumption levels for different categories of dwelling and household types. Gas use appears closely associated with dwelling floor area and type as well as household size, with detached houses having a median gas consumption more than twice that found in flats. Electricity use appears to be more strongly affected by the number of people in the household, with the data showing a median consumption of around 2,400 kWh for single people, compared with a figure of around 6,000 kWh where there are at least 5 people in the household.

Households living in dwellings built between 1919 and 1944 show a significantly higher median gas consumption than those from other periods with a median of 17,100 kWh per year. These households also have a higher median electricity consumption than households living in dwellings built between 1965 and 1980.

There is no statistically significant difference in the median gas consumption of households living in rural or urban areas. However, median electricity consumption is significantly higher in households in rural areas compared to urban areas, related to the large number of dwellings without a gas supply in these areas.

There is some evidence of lower median gas consumption with increasing levels of different insulation measures, although

2. The data used to produce these estimates have been adjusted using degree days to represent the core period of meter reading data collection (the period November 2010 to November 2011). They have not, however, been weather corrected to a standardised temperature profile. It should be noted that the core period includes the very cold period in December 2010, which acts to raise consumption of the EFUS data when compared to other estimates, such as Energy Consumption in the UK (DECC, 2014a) which do not include this month.

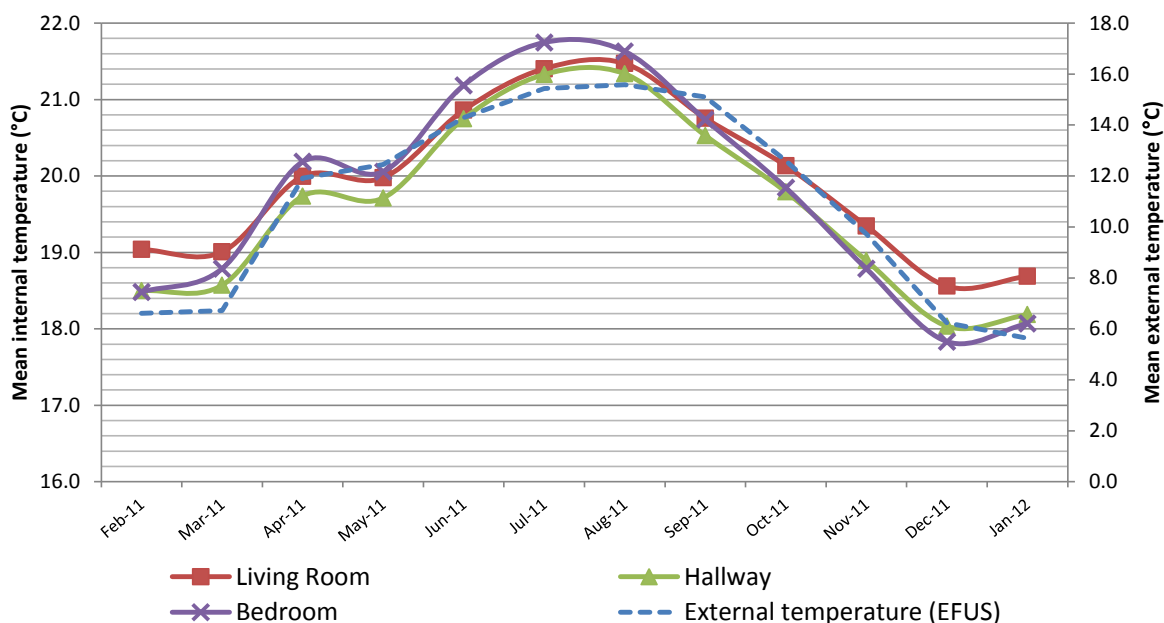


Figure 1. Monthly mean room temperatures (left y-axis) and external temperature (right y-axis) recorded during EFUS 2011. Base: All households in EFUS 2011 temperature sub-sample ($n=823$).

the only statistically significant difference can be seen between those households living in 'well insulated' dwellings who have both lower gas and electricity consumption than households living in 'poorly insulated' dwellings. Owner occupiers tend to consume more gas than households in all other tenures and more electricity than households in the private rented or local authority tenures. For both fuels, households in the private rented, local authority and Registered Social Landlord (Housing Association) tenures show no significant differences in their median annual consumption rates.

MAIN HEATING SYSTEMS

Domestic energy use is dominated by energy used by the main heating systems in homes. (Shorrock & Utley, 2009). Understanding how these systems are used is of great importance to energy efficiency policy and modelling. The analysis of these data examines the heating patterns of households, and the temperatures achieved when the main heating system is on (as opposed to the 24 hr average temperatures described under the mean household temperatures section above), providing new data in this area.

The EFUS collected detailed information on the type and use of main heating systems. Data were obtained on the months that heating took place, and the times that heating was used on different days of the week. Table 1 provides a summary of the use patterns of the main heating system reported by households.

Households that are in during the day on weekdays report heating their homes for a longer period of time (median 9.4 hours per day) than households that are not in during the day on weekdays (median 8 hours per day). This difference is lower than the typically assumed standards in many energy modelling applications which attempt to account for household occupancy.

Households report that they heat their homes regularly for a period of 6 to 7 months (the EFUS temperature data suggests a similar length). This is 1–2 months shorter than currently assumed in SAP (DCLG, 2013).

Mean achieved temperatures (i.e. those temperatures achieved at the end of the longest period of heating within the dwelling) in the living room (zone 1) fall within the range of 19.7–20.4, with the mean being 20.2 °C, and the mean temperature achieved for the (hallway and bedroom) zone 2 within the range of 18.7–19.4, with the mean being 19.1 °C. The zone 1 temperature used in SAP is approximately 0.8 °C higher than the mean living room achieved temperature derived from the EFUS temperature data. Higher achieved temperatures are observed in the living room in the homes of older households (approximately 22 °C in those households with a Household Reference Person aged over 75, compared to 20–21 °C for those younger than 75) and in dwellings with insulation present (20–21 °C for those with at least one insulation measure, compared to 19 °C for those with none).

Around 65 % of households (14.3 million households) have one or more rooms that are not heated by the main heating system. Conservatories, separate WCs, bedrooms, hallways and kitchens are more likely not to be heated by the main heating system than living rooms, dining rooms, studies and bathrooms. The only significant difference in the likelihood of a certain household characteristic group having one or more rooms not heated by the main heating system is seen for fuel poverty status; households that are calculated to be fuel poor are more likely to have one or more rooms not heated by the main heating system than those households that are not fuel poor.

The 9 hours of heating on weekdays, currently used in SAP, is supported by the analysis of the both the EFUS interview and temperature data for centrally heated dwellings. Non-centrally heated households, however, may be heating for significantly longer than this (10 to 15 hours). The EFUS interview and tem-

Table 1. Summary of the key findings reported by households with respect to the heating patterns used.

Type of main heating system	Regularity of heating	Number of heating periods		Boost heating (asked of households with CH controlled by timer to give regular heating) (12.2 m households; n=1,399)			Daily heating hours (including source of data)
Centrally Heated 19.7 m households (90 %) (n=2,356)	Regular heating 14.7 m households (75 %) (n=1,715)	0 heating periods	*1 % (n=20)	Use boost heating at least once per week?	Yes	7.5 m households (61 %) n=850)	95 % C.I. of median daily heating hours
		1 heating periods	21 % (n=395)				8.4–8.8 (Householder responses)
		2 heating periods	69 % (n=1,158)		No	3.2 m households (26 %) n=378)	8.8–9.5 (Temperature data derived)
		3+ heating periods	8 % (n=142)				
	Non-regular heating 5 m households (25 %) (n=641)	Heating periods N/A	N/A	Use boost heating?	N/A	N/A	95 % C.I. of median daily heating hours
					N/A	N/A	4.0–5.1 (Householder responses)
							9.8–11.3 (Temperature data derived)
Non-Centrally heated 2.2 m households (10 %) (n=260)	Regular heating 1.3 m households (60 %) (n=158)	0 heating periods	*8 % (n=15)	Use boost heating?	N/A	N/A	95 % C.I. of median daily heating hours
		1 heating periods	81 % (n=128)				10.7–15.3 (Householder responses)
		2 heating periods	*9 % (n=14)		N/A	N/A	9.1–16.5 (Temperature data derived)
		3+ heating periods	*1 % (n=1)				
	Non-regular heating 0.9 m households (40 %) (n=102)	Heating periods N/A	N/A	Use boost heating?	N/A	N/A	95 % C.I. of median daily heating hours
					N/A	N/A	2.3–4.6 (Householder responses)
							15.6–23.4 (Temperature data derived)

Base: All dwellings in EFUS 2011 Interview Survey representing 21.9 million households in England (n=2,616).

perature data suggest that the total number of hours heating are approximately the same on weekends as they are on weekdays.

Currently, SAP implements a heating pattern of 9 hours for weekdays and 16 hours for weekends in the living room for all heating system types. These assumptions may need to be reviewed in light of these results.

Currently, SAP implements a demand temperature of 21 °C in zone 1 and 18–21 °C in zone 2. The results from the EFUS suggest mean achieved temperatures of 20.2 °C in zone 1 (living room) and 19.1 °C in the zone 2 proxy (mean of hallway and bedroom) – i.e. the zone 1 temperature in SAP is 0.8 °C higher than the average living room achieved temperature from the EFUS temperature data. The zone 2 temperatures are within the expected range.

Interesting patterns are seen in the temperatures achieved by different types of households. There is a clear pattern of higher achieved temperatures in older households (approximately 22 °C for those aged over 75). Similarly, higher achieved temperatures are seen in dwellings with insulation present (20–21 °C) than in those with no insulation (19 °C).

The temperature data show that for those households heating twice a day, the first period of heating is typically for a short interval, and the time that the heating is on for in many households may not be sufficient to bring the room temperatures to the thermostat set-point temperature. In general, most models (including SAP and BREDEM) assume that temperatures demanded by households are reached in all periods of heating. The fact that many households are not achieving these temperatures may be resulting in an overestimate of energy consumption by these models.

SECONDARY HEATING SYSTEMS

Secondary heating systems are those that provide space heating which is in addition to that provided by the main heating. This can be as heating in rooms where the main heating is not present or not used (referred to in this analysis as alternative heating); or as ‘top-up’ heating in rooms where the main heating is used (referred to in this analysis as supplementary heating). Prior to the EFUS, little was known about the use of these systems. Currently SAP and BREDEM modelling simply assigns a proportion of total energy use to secondary heating systems. New SAP and BREDEM algorithms could potentially be developed using these data, to more appropriately model the use of different types of heating systems. This analysis examines how these systems are used in homes, providing valuable new data in these areas.

Two types of secondary heating are considered by the analysis:

1. Alternative heating – defined as heating that is used *instead* of the main heating in a room. This could either be where the main heating is turned off or does not extend into this room.
2. Supplementary heating – defined as heating that is used in *conjunction* with the main heating in a room.

Approximately 65 % of all households have one or more rooms not heated by the main heating system. Of these, 26 % (17 % of all households) use alternative heating to heat these rooms. Alternative heating is typically used in one room per household,

and the predominant type of alternative heater used is electric (74 % of households with alternative heating). Households using storage radiators as their main heating are most likely to use an alternative heater.

Close to half of all households (48 %) indicate that they have supplementary heating in one or more rooms. Approximately 79 % of households using supplementary heating use it in only one room per dwelling, with a further 17 % using it in two rooms per dwelling. Of households with supplementary heating, 83 % use it in living rooms and 12 % in bedrooms. Supplementary heating is rarely used in other room types. Typically supplementary heaters are either electric (46 %) or mains gas (41 %).

On average, households use alternative heating for 17.5 hours per week (median) during their heating season. Supplementary heating is typically used for a shorter period of 8 hours per week (median).

Almost half (47 %) of all households using supplementary heating indicate that they use their heaters ‘to provide extra heat when the heating system is on’, about a quarter (26 %) state that it is used ‘to provide heat when the heating system is not on’, 18 % say that it is used for both these reasons.

No heating is provided from the main or alternative heating system (including main heating turned off) in one or more rooms in 48 % of all households. The majority of these households (60 %) report less than a fifth of all rooms in the dwelling are unheated. Typically, circulation spaces, WCs and ‘other’ rooms (which include rooms such as utilities etc.) are much more likely to be unheated than other types of rooms. Approximately 23 % of households with at least one bedroom have one or more bedrooms that are not heated by the main or alternative heating system. The most common responses from households to the question of why they do not heat specific rooms were that the room is warm enough already (41 % of households), the room does not have a heater (36 % of households) or that the room does not need a heater as the room is not used (33 % of households). Only 5.2 % of households reported that they do not heat a room due to expense.

CONSERVATORIES

Conservatories are increasingly common additions to homes in England. In general, however, no additional energy losses are assigned to homes with conservatories under standard energy modelling assumptions (as it is presumed that they are thermally separated from the dwelling, and unheated). The EFUS collected data on thermal separation (the presence and use of a door) and heating in conservatories.

Conservatories are found in approximately 18 % of households in England. Most conservatories (95 %) open on to the living room, kitchen or dining room.

Around 77 % of conservatories have heating. Just over half of those with heating (55 %) are connected to the central heating system, and 42 % have storage or direct acting electric heaters. In winter, 56 % of conservatories with heating are heated every day. Most occupants report that they heat the conservatory to the same (45 %), or a lower (39 %) temperature than the house.

In approximately 91 % of dwellings with conservatories there is a separating door. Most households with a conservatory with a separating door (83 %) keep it shut in winter. This is mainly to keep heat in the room, and also for security. Of the small

proportion (17 %) of households who report the door is kept open, it is reported to be mainly for convenience.

In summer 81 % of households report that they keep the door to the conservatory open for a period of time. This is reported to be mainly for convenience and to let heat into the adjoining room, and also to make the room feel more spacious.

These results demonstrate that a significant proportion of conservatories are heated, with potentially important implications for domestic energy modelling methodologies. Under the SAP methodology, a conservatory is currently ignored (i.e. no energy use is assigned) if it is 'thermally separated'. While 91 % of conservatories studied by the EFUS have a separating door (and it is likely that most of these may be included in the definition of 'thermally separated'), the EFUS results indicate that the majority of these conservatories will actually be heated. The thermal separation may, therefore, be irrelevant in many cases. In light of these results consideration should be given to amending SAP to assign energy usage to conservatories whether or not thermal separation exists. Any changes to SAP should also note that most households report heating the conservatory to the same or a lower temperature than the rest of the dwelling.

There are further potential implications for Building Regulations. Under current Building Regulations guidance, conservatories are exempt from energy efficiency requirements given certain conditions, one being that the heating system is not extended into the conservatory. This does not cover the case of conservatories in which portable heaters are used, which this report indicates is about half of heated conservatories. Consideration should therefore be given to including conservatories under Building Regulations under other circumstances, perhaps where there are gas or electric points that portable heating may be connected to.

LIGHTING

Information was collected in the EFUS 2011 Interview Survey about the number of sets of lights, the number of bulbs per set, the types of bulbs in each set and the length of time each set is used, in three of the main rooms of the house (living room, main bedroom and kitchen), as well as lights left on overnight and outside lights powered from the household electricity supply.

In the living room and main bedroom approximately 40 % of light bulbs are tungsten (traditional light bulbs – not of a low-energy type), and 30 % low energy compact fluorescents (CFLs). In the kitchen however, halogen bulbs (50 %) and fluorescent strip lighting (15 %) are the dominant type of lighting. Lighting is reported to be used for about 2 to 3 times as long in winter as summer (5–8 hours per day in the winter compared to 2–3 hours per day in the summer).

Lights are reported to be left on in one or more rooms overnight by 17 % of households. Of these households, 92 % leave a light on in just one room and a further 7 % in two rooms. These rooms are typically the hallway/landing, bathroom with a WC or the second bedroom. For the households that leave lights on in either of the hall/landings overnight, just under 60 % of them use low energy CFLs. This may reflect the fact that households value the energy savings these bulbs provide for this type of usage. However, just over 20 % of households leaving lights on in hallways overnight use tungsten bulbs.

Approximately 62 % of households have outside lights powered by their mains electricity supply. Of these, almost half

(47 %) have one bulb and a further 37 % have two or three bulbs. The most commonly-used type of bulb in outside lights was described as tungsten. This may indicate a preference for instant, brighter light for this purpose. Manual switching is the most usual form of control with more than 60 % of lights being switched manually.

DOMESTIC APPLIANCES, COOKING AND COOLING EQUIPMENT

The EFUS 2011 has revealed detailed information on patterns of ownership and use of key domestic appliances, including cooking and cooling equipment, which is of use for the development of energy efficiency policy and refinement of energy modelling methodologies such as SAP and BREDEM.

Almost all households own a washing machine (97 %), a fridge (99 %), a freezer (93 %), a television (98 %), an oven (95 %) and a hob (93 %). Other appliances are less universally owned. Almost 80 % of households own a grill, 80 % a microwave, 62 % a tumble dryer, and 41 % a dishwasher. The EFUS has identified differences in patterns of ownership and use among different household groups. Owner occupiers are more likely to own washing machines and tumble dryers compared to the other tenures. Single person households, households without any children, households in which the HRP (Household Reference Person) is 75 years old or more, households in which none of the occupants is working, households with incomes in the lowest income quintile and households that are not under-occupying are all *less likely* than their counterpart groups to own a washing machine or tumble dryer. There are no apparent differences in fridge ownership across the different household groups suggesting that this appliance is considered a necessity. Freezer ownership and dishwasher ownership across the different household groups is more variable with similar differences in the patterns of ownership as those seen for the laundry appliances. There is a particularly strong relationship between dishwasher ownership and income.

The median number of washing loads per week is 4 and the median number of drying loads per week is 3 in the winter. Approximately 59 % of households report typically running their washing machine at 40 °C; 27 % report typically washing at 30 °C, and 8 % report typically using temperatures hotter than 40 °C. As to be expected, there is a pattern of more frequent washing machine use among large households, particularly those with children. The median number of loads per week also increases as household income increases. However, households with at least one pensioner present, and households that are considered to be under-occupying, use their washing machines less than their counterpart groups.

Electricity is the dominant fuel used in ovens (almost 70 % of households with ovens have electric ovens and just under 30 % have gas ovens). For hobs, the prevalence of fuels is reversed with gas being the dominant fuel (38 % of households have electric hobs, whereas 61 % have gas hobs). Households use their hobs and microwaves more frequently than their ovens or grills.

The number of televisions in homes ranged from 0 to 9, with a mean number of 2.3 televisions per household. Owner occupiers typically have more televisions than any of the other tenures. Additionally, the mean number of televisions in a household increases as household size increases. Households in the lowest income quintiles have fewer televisions on average than households in any of the four high income quintiles.

Households with children present, and households where no pensioners are present, also report owning more televisions compared to their counterpart groups.

The main (most used) television in the home is likely to be a flat screen type. Owner occupied households are *more likely* to have a flat screen television than a standard cathode-ray tube (CRT) type as the most used television compared to households in the social rented sector, whereas households in the lowest income quintile are *less likely* to have a flat screen model as the television used the most compared to households with higher incomes. Additionally, single person households are *also less likely* to have a flat screen television as the most used television compared to larger households.

The television used most often in the house is reported to be used for approximately 5 to 6 hours per day. The average number of hours is greater for households that are in the social rented sector compared to owner occupiers or private renters, and higher for households with children, containing someone of pensionable age, where someone is in during the day and households that are not under-occupying.

43 % of all households report using portable fans. Other fixed fans are reported to be in use by around 9 % of households. Air conditioning use is very rare with less than 3 % of households using fixed or portable air conditioning units during the summer months. Around 17 % of households use portable fans on a daily basis during the summer months. Just under 40 % of households with portable fans use them more than once per week but not every day, and a further 39 % of households use them less than once a week.

Considerable scope has been identified for the replacement of older appliances in the stock which may represent a significant potential for energy saving. The survey suggests that over 2.1 million washing machines, and 2.6 million tumble dryers, are more than 10 years old. A large number of refrigeration appliances are more than 10 years old, including around 24 % of standalone fridges and 24 % of standalone freezers (equivalent to around 2.5 million of each of these types of appliance). Approximately 22 % of ovens are over 10 years old (equivalent to around 4.5 million ovens).

HOUSEHOLD UNDERSPEND

The methodology used to produce estimates of fuel poverty in England defines a regime which is considered sufficient to provide adequate energy for heating and other uses in the home. This includes energy for heating, lighting, appliance use and cooking. A household is said to be “underspending” when its actual fuel expenditure is below that predicted by this theoretical regime.

Approximately 67 % of all households are underspending to some degree. Around 35 % of all households are underspending by more than 25 % of the required fuel bill, and approximately 8 % of all households are underspending by more than 50 % of the required fuel bill.

Households that are underspending have lower mean internal temperatures, and lower achieved temperatures, than those that are not. Households exhibiting the highest levels of underspend also report heating for fewer hours per day than households that are not underspending.

Fuel poor households (using the Low Income High Costs definition – see DECC, 2014b) are more likely to be under-

spending than non-fuel poor households. Around 80 % of those in fuel poverty are underspending, compared to 65 % of households not in fuel poverty underspending.

There is no clear relationship between underspending and income. High income households are as likely to be underspending as low income households. Similarly, the likelihood of underspend is not directly influenced by other household factors including household type, age of household or employment status. However, a clear relationship exists with the energy efficiency of the property as defined by the SAP rating. Those households living in higher energy efficiency properties are less likely to be underspending than those in lower energy efficiency properties. Approximately 90 % of those living in the least energy efficient properties (below a SAP rating of 30) are underspending (relative to the modelled requirement for those dwellings), compared to 47 % underspending in the most energy efficient properties (SAP >70). This is shown in Figure 2.

This relationship with energy efficiency is reflected in the fact that households in older properties are more likely to underspend, as are those without gas central heating systems, and in poorly insulated properties. The may have significant policy implications as improvements made to poorly performing properties may simply reduce the level of underspend, rather than deliver reductions in consumption.

Conclusions and discussion

The EFUS has provided a wealth of new data on energy use in English households. The results summarised above from the survey provide essential new information to assist in the development of energy efficiency policies, and to enhance the energy models which underpin them.

The purpose of the EFUS was to challenge existing ideas and concepts, many of which have been established for several years (indeed, in many cases decades) and to provide new data to develop enhanced methods.

The data supports many of the conventional heating assumptions in key areas such as the number of hours that heating is on weekdays. In other areas, it provides evidence to vary from the existing assumptions. In particular, differences have been identified in the hours heated at the weekend (fewer than generally assumed), internal temperatures (slightly lower in the living room, but higher in the other areas than generally assumed), and the widespread heating of conservatories (generally these are assumed unheated). These are important inputs into our calculations and models. Heating is the largest end use of energy in the home (DECC, 2014a) and any variance in the hours or temperature of heating can significantly affect the final energy consumed by a household. Similarly, a heated conservatory may be a significant source of additional heat losses. We are now able to take these data into our models and calculations as both direct inputs, or quantities to control and calibrate our outputs against, and have some increased confidence that they and their results represent reality.

Novel data have also been collected that may allow the construction of completely new algorithms and methods for modelling appliance use, and secondary heating use. This work has not yet begun, but the EFUS data allows this to proceed.

One of the principal aims of producing this paper for the ECEEE is to highlight to international colleagues that primary

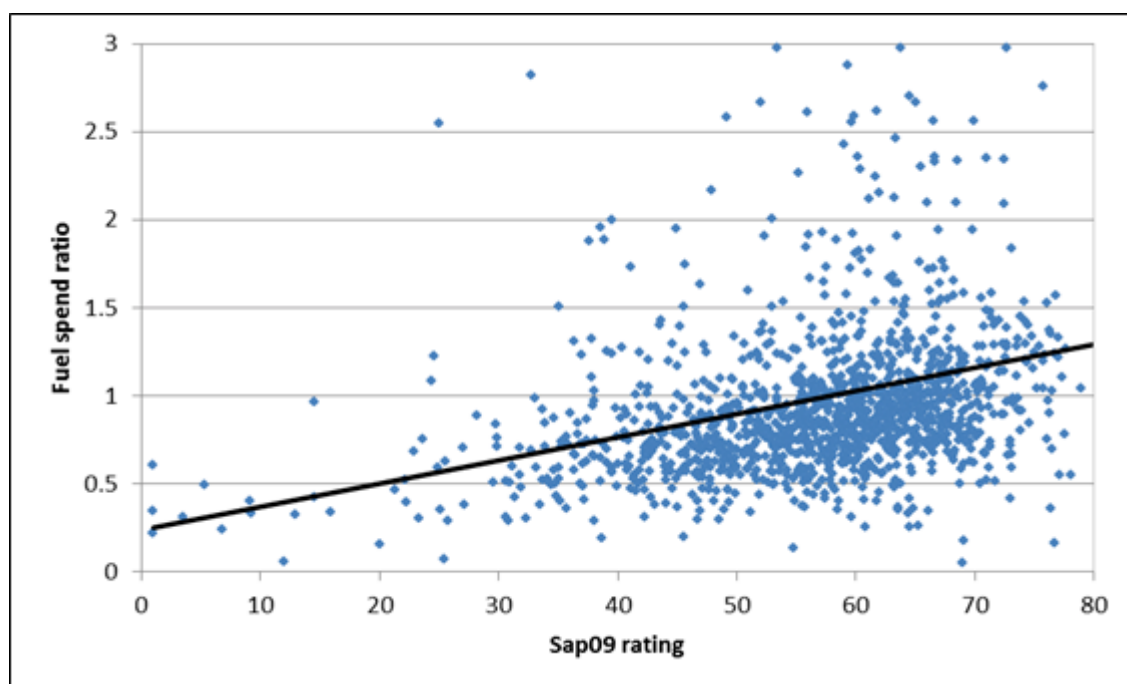


Figure 2. Relationship between SAP rating and fuel spend ratio. SAP ratings run from 1 (lowest energy efficiency) to >100 (highest energy efficiency). A fuel spend ratio of >1 represents an actual spend above the requirement, a ratio <1 represents an actual spend below the requirement.

data collection is essential if we are to understand how energy is being used in the domestic sector, and provide an example of how this has been done in the UK. These types of data both challenge and support the conventional assumptions used and allow us to check that our models are adequately representing reality. The English statistician George Box stated that “essentially, all models are wrong, but some are useful” (Box & Draper, 1987). While more data is always required, and all models will only ever be able to simulate the real world imperfectly, primary data such as from the EFUS help to ensure they are at least wrong but remain as useful to us as possible.

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