RESEARCH INTO THE THERMAL PERFORMANCE OF TRADITIONAL BRICK WALLS

ENGLISH HERITAGE
RESEARCH REPORT

RESEARCHING THE THERMAL PERFORMANCE OF TRADITIONAL BUILDINGS

The national and global imperative to improve energy security and reduce carbon emissions is turning the spotlight onto the existing building stock.

Traditional and historic buildings can often adopt modern technologies, such as more efficient boilers, lamps, control and management techniques, and low-carbon energy supplies. Changing the building fabric is more difficult, particularly for walls, windows and doors, which give the building so much of its character. This is not just an aesthetic concern: changing balances between heat, air and moisture movement may also affect the integrity of the building and the health of its occupants.

There is often a presumption that old is bad and new is good. This is not necessarily so: historic and traditional buildings have stood the test of time, demonstrating their sustainability in an ever-changing world. With hindsight, many well-meaning interventions in the 20th century have turned out to have been mistaken. For example, harder and less permeable paints, coatings, mortars, and renders often accelerated the deterioration of the fabric they were expected to protect, while new windows and pointing have taken the character out of many well-loved buildings and streetscapes.

To better understand the performance of traditional and historic buildings and elements, and the need and scope for upgrading, English Heritage has been commissioning a series of research projects, on which it reports as soon as results come available. Each report includes a technical summary of the research, and an executive summary that puts the work into a broader context.

ENGLISH HERITAGE

RESEARCH INTO THE THERMAL PERFORMANCE OF TRADITIONAL BRICK WALLS

EXECUTIVE SUMMARY

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SOME USEFUL DEFINITIONS

Heat flux: The flow of energy through a surface, per unit of area. Expressed as W/m^2.

RdSAP: The Reduced Data Standard Assessment Procedure is a lower-cost calculation tool based on the SAP, and approved by the Government to assess the energy performance of existing buildings for the production of Energy Performance Certificates.

SAP: The Standard Assessment Procedure [SAP] is the methodology used by the UK Government to assess and compare the energy use and environmental performance of dwellings. The SAP gives a rating to the building's performance based on its energy use per unit floor area, a fuel-cost-based energy-efficiency rating, and estimated carbon emissions.

SBEM: The Simplified Building Energy Model is a government-defined process in accordance with Part L of the Building Control Regulations, and is used to calculate the performance of new commercial and industrial buildings.

Thermal conductivity: A measure of a material's inherent ability to transfer heat (the lower the thermal conductivity, the greater the insulating effect). Expressed as W/mK.

U-value: A measurement of heat flux through a particular thickness of material(s); it does not take account of the mechanism by which heat is transferred. Commonly used to assess the insulating effect of composite building systems such as walls (the lower the U-value, the slower the rate of heat transfer through the system, and therefore the better the insulating quality). Expressed as (W/m^{2}K).

1. INTRODUCTION

Global pressures to reduce energy use and greenhouse gas emissions are increasing. The UK Government's commitment to an 80% reduction by 2050 from 1990 levels means that efforts to improve the energy efficiency of our existing buildings are intensifying. Buildings make a significant contribution to greenhouse gas emissions: the way they are heated, lit and used accounts for about 40% of all the UK's carbon emissions. In 2009 it was reported that 25% of total emissions was attributable to domestic buildings.[1]

Traditional buildings account for about 21% of the UK's housing stock.[2] They are an important resource, and form an integral part of our built heritage. The majority were constructed with solid walls and were built using permeable materials capable of absorbing and releasing moisture. Most date from before 1919, when cavity wall construction and the use of damp-proof membranes and vapour barriers to control moisture movement became widespread.

Traditional buildings have proved to be robust, durable, adaptable and relatively easy to maintain. Nevertheless, there is a common perception that their thermal performance is poor. Pre-1919 buildings with solid walls are assumed to be the least energy-efficient, particularly when compared with new buildings, and are perceived as being major contributors to greenhouse-gas emissions.[3]

The pervasive viewpoint that older buildings are inherently energy inefficient has occurred largely because of shortcomings in the method used to assess energy performance. There is evidence that RdSAP frequently over-estimates energy use in traditional buildings, sometimes by as much as 40%.[4] This is undoubtedly due in part to certain incorrect assumptions about the construction of traditional buildings inherent in the RdSAP assessment method.

A further issue is the accuracy of available standard design data on the thermal transmittance of traditional building elements. Thermal transmittance, expressed as U-values, forms the basis for assessing energy performance using RdSAP, SAP and SBEM calculations. U-value calculations are also used when designing fabric improvements to enhance thermal performance. If the thermal performance of a building element is under estimated, the likelihood is that the fabric improvements will be over-designed. This is not only wasteful of resources, but could lead to inappropriate and potentially harmful work being carried out.

The walls of a building can account for a large proportion of the heat lost through its fabric, and the accurate thermal transmittance of the wall is critically important when assessing energy performance. With ever tighter Building Regulation targets being demanded, there are pressures to adapt traditional buildings to improve their thermal performance. However, increasing the thermal resistance of traditional solid walls can be problematic. This is not just an aesthetic concern; changing balances between heat, air and moisture movement may also affect the integrity of building and the health of its occupants.

Therefore, before any intervention can be considered, it is essential to obtain accurate data on the thermal performance of the building walls, and to better understand the factors that influence it.

To this end, English Heritage has undertaken research to obtain measurements *in situ* of the actual thermal performance of traditional solid walls, and to compare these with the results obtained by calculation.

The report presents the findings of two studies undertaken during 2010–12 by Dr Paul Baker, from Glasgow Caledonian University. The project has focussed on brick walls, as this is the form of construction most commonly encountered in traditional buildings in England. Detailed analysis of the thermal characteristics of eighteen solid-walled brick properties was carried out by *in-situ* U-value measurements, and the thermal conductivities of three types of brick were obtained by laboratory testing.

2. ASSESSING THERMAL PERFORMANCE

Conservation of energy is dependent on the ability of a wall (or other building element) in reducing the rate of heat escaping from the inside of the building to the outside. This ability is described in terms of its thermal transmittance or U-value, which is expressed as the transfer of heat in watts per square metre of area per degree difference in temperature (W/m^{2}K). This is defined in *ISO 7345* as the *"heat flow rate in the steady state divided by area and by the temperature difference between the surroundings on each side of a system"*.[5] Steady state assumes that the flow of heat is in a straight line and that the measured element consists of plane, parallel or uniform layers.[6] The lower the U-value of a building element, the better will be its thermal performance, indicating higher levels of insulation.

U-values may be calculated where the thermal conductivity and thickness of each material in a building element is known, according to standard procedures. The thermal conductivity or lambda (λ) value, of a material is expressed in watts per metre per degree kelvin (W/mK). The better a material is in resisting the conduction of heat, the lower its lambda value will be. Thermal conductivity data for many materials may be obtained from published guidance, or manufacturers' technical literature. Alternatively, thermal conductivity can be measured in the laboratory using heat flow meter apparatus as described in *ISO 8301*.[7]

Where the U-value of a building element cannot be calculated with certainty, because of a lack of information on construction details and/or material properties, it can be measured *in situ* in accordance with procedures set out in *ISO 9869*.[8] This involves measuring the flow of heat (heat flux) through the building element when there is a sufficient temperature difference between the inside and outside of the structure.

The methods described in *ISO 8301* and *ISO 9869* were used in the investigations described in this report.

3. WHAT ARE U-VALUES USED FOR, AND WHY ARE STANDARD VALUES PROBLEMATIC?

U-values are used in calculations to assess the energy performance and carbon emissions from buildings. They form the basis of calculations in SAP, RdSAP energy assessments for domestic buildings and SBEM assessments for non-residential buildings. Most of the external elements of new buildings are required to meet the thermal standards set out in the Building Regulations Part L, which are expressed in terms of maximum U-values. Existing buildings may also be required to meet these standards when certain works are carried out, or when the use of the building changes.

In general standard U-values are obtained from recommended industry guides such as *CIBSE Guide A: Environmental Design* (2006) or by calculation using software programmes such as BuildDesk U 3.4 or the BRE Calculator. The basis for all of these is *BS EN ISO 6946:2007* (the main standard for calculating U-values of walls) and *BR443 Conventions for U-value Calculations*.[9] These standards are most suitable for modern construction and very limited provisions have been allowed for traditional constructions and the different properties of traditional materials.

Though a range of thermal conductivity values for brick are available from various sources, without actual measurement it is difficult to ascertain which value is the most appropriate for a traditional solid brick wall. The BuildDesk U 3.4 calculator gives two values suggested by *BR433* for outer and inner leaves of brick of 0.77 W/mK and 0.56 W/mK respectively, and *Everett* (1986) and *CIBSE* (2006) provide a wide range of values based upon the different densities and moisture contents of brick.[10] The wide range of values available is problematic, since there can be significant variations in calculated U-values depending on the value chosen for the brick thermal conductivity.

This potential for error is a concern, since energy-performance rating systems for buildings in the UK relies on a set of assumptions about building performance that are often obtained by standard calculations, or from default values given by industry guides. A recent study by University College London has estimated that the uncertainties in U-values and heat loss coefficients may sometime result in an overestimate of heat loss by 30-50% because of the variability in traditional building construction (something that these models are unable to take into account).[11]

4. RESEARCH UNDERTAKEN

A combination of fieldwork, modelling with software applications, and laboratory testing was used to investigate the thermal performance of a range of traditional solid brick walls. The approach was designed to enable the findings from each method to be validated, and to develop a sound evidence base to better understand the thermal performance of this type of construction. The research is presented as two reports.

- The first report describes the work undertaken to determine the U-values of the walls, both by *in-situ* measurement, and by calculation using four thermal conductivities obtained from industry standard design values. It compares the results obtained, and considers reasons for the discrepancies between measured and calculated values.
- The second report focuses on thermal conductivity tests, undertaken in laboratory conditions, of dry and wet samples of three bricks. Samples were obtained from two of the houses tested in the field, and were a soft porous brick and a hard dense brick; the third sample was taken from a separate English Heritage case study in New Bolsover, Derbyshire, which was also a hard dense brick. The tests aimed to determine how well the calculated U-values agreed with the in-situ results when the thermal properties of the bricks were known, and to compare the thermal conductivities between wet and dry samples of brick.

5. WHAT WAS MEASURED AND HOW?

In-situ U-value measurements of walls were made in eighteen houses in three locations in England between February and April 2010. The types of solid wall measured ranged from walls 12 inches thick built of soft, fine and homogenous bricks dating from 18th and 19th centuries in Berkshire, to 9-inch thick walls built with hard, dense bricks, of uneven quality used typically in the Midlands and North of England in the late 19th century. Most of the internal finishes were painted or wall-papered plaster, with the exception of two walls, one of which was bare painted brick and the other of which was finished in cement render. Several walls were dry-lined with plasterboard. It was not possible to ascertain the exact build-up of the dry-lined walls, as the testing was a non-invasive procedure, but given the results achieved at these sites it may be assumed that some form of insulation had been used.[12]

The U-value measurements were carried out using heat flux sensors attached to the test walls with adhesive tape. The walls were monitored for 3–4 weeks to allow for the impact of thermal mass and for fluctuations in temperature and heat flow as the measurements are based on a steady-state analysis.[13] The effects of exposure, orientation, and thermal bridging were not allowed for, but considerable care was taken when positioning the sensors to minimise these factors, and where possible to provide consistency.[14]

Before attaching the sensors, thermal imaging of the wall was carried out to ensure that the surface temperatures of the locations selected were uniform, that areas of high thermal bridging were avoided, and that the measurements were unaffected by hidden services or construction anomalies that would give unrepresentative values. Two measurements were taken on each wall, and hourly heat flow data, together with internal and external surface temperatures of the walls, were collected and averaged out over the monitoring period. In addition, ambient room humidity and temperature, and the external environmental conditions were also recorded. Further detail on the testing and analysis procedure is described in *Report 1: Appendix 1*.

All the houses were occupied during the period of testing.

For each measurement a comparison was made with calculated methods using the BuildDesk U 3.4 software programme. Assumed thermal conductivities for the modelled values were based on both known reference materials, and on the values given in the software programme.

For the thermal conductivity tests, four samples of each brick were cut for testing, and their thermal conductivities were measured under laboratory conditions after drying, and then again after wetting. Further detail on test method is given in *Report 2*.

6. KEY FINDINGS

Thermal performance for traditional walls is underestimated

- The average U-value of walls measured *in situ* at the eighteen properties was 1.4 W/m^{2}K. This indicates that the industry-standard default U-value of 2.1 W/m^{2}K for a solid (9-inch) brick wall, used in energy-performance assessments, underestimates the thermal performance of the wall by approximately one third.

Accurate thermal conductivity data is vital for U-value calculations

- The results suggest that U-value calculations using software applications can be inaccurate where reliable data on the thermal properties of historic materials are not available. This is because one of the key parameters used in the calculations is the thermal conductivity of the material. Comparison of the four assumed thermal conductivity calculations (based on the BuildDesk 3.4 default values and *Everett* (1986)) showed significant variation from the modelled values. Comparison with the results measured *in situ*, made it clear that in some cases the calculated values underestimated the thermal performance of the walls.
- Where the thermal property of the brick is known, and the construction of the wall can be deduced with sufficient accuracy, the use of software programmes to calculate U-values of a traditional solid brick wall can be reasonably reliable. Follow-up U-value calculations with Build Desk U 3.4 using the measured dry thermal conductivity values were in better agreement with the in-situ U-values, validating the field results. This suggests that, provided that the data input is correct, the modelling method given in the BuildDesk calculator is reliable.
- Calculated U-values using the wet brick thermal conductivity values were significantly higher than the in-situ values, except in the case of the dry-lined walls. This indicates that the thermal conductivity of the brick has less influence on calculated U-values where walls have been insulated (for which assumptions were made regarding the likely type and thickness of insulation used).

Comparison with CIBSE design values shows significant variation between published and measured results for thermal conductivity

- There was reasonable agreement between the measured dry thermal conductivity results and the design values assuming 'standard' moisture content (1% for 'protected' conditions).
- There was less convergence between measured results and the published design values for the wet thermal conductivity tests. The moisture contents of the tested brick samples were both much higher than the assumed 'standard' moisture content of 5% for 'exposed' conditions, and more variable. Note that the samples were very wet, having been immersed in water.
- Of the three samples of brick tested, the New Bolsover brick – which has the highest density – was found to have the best agreement with the published design values, and appeared to follow the trend given in *CIBSE* (2006).

The physical properties of the brick have a strong influence

- The results suggest that the thermal conductivity of bricks, and the *in-situ* U-values of walls, is affected by variations in the material characteristics of the bricks (reflecting the variations in locally-sourced raw materials, and in manufacturing processes). The laboratory tests showed that variations in brick texture, density and structure could influence dry thermal conductivity; in particular, the results show a correlation between lower density and lower dry thermal conductivities suggests that softer and more porous hand-made bricks provide higher levels of insulation than dense engineering bricks. A comparison with the values given in *Everett* (1986) and *CIBSE* (2006) appears to support a correlation between lower densities and better thermal insulation.[15] On the other hand, more porous bricks have a greater capacity to absorb water. In the tests they attained higher capillary moisture contents, and higher wet thermal conductivity values than the denser, less porous bricks.

Moisture affects thermal conductivity

- The wet thermal conductivity values obtained indicated a clear relationship between moisture content and poor thermal insulation, with wet values being 1.5 to 3 times higher. However, the wet thermal conductivity values obtained in the tests would apply where water can travel through the wall as a liquid; for example, where there has been prolonged ingress from wind-driven rain, faulty rainwater goods or drains. This highlights the importance of maintaining a building in a good state of repair. Problems could be exacerbated if incoming water is prevented from evaporating by an impermeable surface such as impermeable wall insulation.

7. CONCLUSIONS

The findings from the research indicate that *in-situ* U-value measurements are a relatively quick, effective and accurate method for assessing the thermal performance of solid brick walls provided that monitoring is sufficiently prolonged. Monitoring the U-values over several weeks and then averaging the measurements obtained minimises the impact of fluctuations in environmental conditions and the thermal inertia of the wall.

In-situ U-values can help to quantify the real (as opposed to theoretical or modelled) performance of traditional wall constructions. Standard default values for brick walls underestimated their thermal performance by a third.

Calculation methods based on *BS EN ISO 6946:2007* can be unreliable where accurate data on material properties is lacking, but if the thermal conductivity values are known, calculations made using software programmes can be in reasonable agreement with the actual measured U-values. This suggests that much of the unreliability of calculating u-values lies with the low quality of input data.

The follow-up calculations using the measured thermal conductivities in dry bricks not only validated the field results, but also indicated that the main discrepancy between the in-situ measurements and the calculated values was due to the physical properties of traditional bricks. Other possible contributory factors are the moisture content of the walls, and incorrect assumptions about the construction of the walls (which may be more complex than is apparent at the surface). For some walls, the ratio of mortar to masonry may also have an influence.[16]

Industry-standard design values are used as the basis for energy performance assessments, planning energy efficiency measures, and also to demonstrate compliance with the Building Regulations; however, they are more appropriate for modern buildings, and are designed for 'ideal' construction, with limited provisions made for older buildings.

The potential ramifications of underestimating the thermal performance of brick walls are considerable:

- Government strategies for reducing emissions of greenhouse gases in the UK (such as the Green Deal) could lead to a performance gap between predicted and actual savings, resulting in failure to meet carbon-emission reduction targets set out in the Climate Change Act (2008);
- It is likely that energy efficiency measures will be over-designed, which is not only wasteful of money and resources, but increases the potential for harm to the character and significance of the built environment, and heightens the risk of unintended consequences for the condition of the buildings and the health of the occupants.

8. RECOMMENDATIONS

- The substantial differences in thermal conductivities obtained for dry and wet (saturated) samples of brick suggest that further thermal conductivity testing should be carried out on bricks to test a range of moisture dependencies.[17]
- The effect of moisture on the U-value of traditionally constructed walls should be investigated and quantified.
- Since the thermal conductivity tests indicated that variations in brick density and structure may have an influence on the thermal conductivity, further investigation of the effect of porosity and permeability would be of value.
- The research has highlighted the importance precise data on the thermal properties of traditional building materials, to enable energy performance to be calculated accurately. Further thermal conductivity testing of a range of brick types and other traditional building materials is to be highly recommended.

NOTES

1. DECC (2011), *The Carbon Plan: Delivering Our Low Carbon Future*, p.29.

2. CLG (2013), *English Housing Survey 2010: Homes Report.*

3. CLG (2006), *Review of Sustainability of Existing Buildings*.

4. Findings from a whole-house thermal performance test of a Victorian end of terrace house in New Bolsover undertaken by English Heritage have shown that a SAP (2009) assessment over-estimated the whole-house heat loss coefficient by 40%. This work will be published in summer 2013.

5. *BS EN ISO 7345:1996, Thermal insulation – Physical quantities and definitions.*

6. In actual practice, real buildings have many non-uniformities and areas, which are non-planar and non-parallel resulting in heat flowing dynamically. This involves a dynamic analysis using a numerical calculation allowing for multi-dimensional heat flow, which is beyond the scope of this study. For further information, see: Anderson, B. (2006), *Conventions for U-value Calculations*, BRE Scotland.

7. *ISO 8301:1991, Thermal insulation – Determination of steady state thermal resistance and related properties – Heat flow apparatus.*

8. *ISO 9869:1994, Thermal insulation – Building elements – In situ measurement of thermal resistance and thermal transmittance.*

9. *BS EN ISO 6946:1997, Building components and building elements – Thermal resistance and thermal transmittance – Calculation methods*; Anderson, B. (2006), *Conventions for U-value Calculations*, BRE Scotland.

10. Everett, A. (1986), *Materials (Mitchells Building Series)*, London: The Mitchell Publishing Co.; CIBSE (2006), *Guide A: Environmental Design*.

11. Shipworth, D. and Gentry, M. (2010), *English Heritage Hearth and Home Scoping Study*, unpublished study commissioned by English Heritage from the Energy Institute, University College London.

12. Private communication with Accord Housing in Walsall indicated that insulated plasterboard had been installed during the 1980s in the dry-lined houses.

13. BRE states that if the monitoring period is shorter such as five days, the results can be adjusted by allowing for thermal storage corrections. However, they note that there is some uncertainty as accurate wall constructions would need to be identified.

14. Further, it is arguable that the effect of thermal bridging would have greater impact on insulated walls rather than on uninsulated walls.

15. See Table 3.1 in CIBSE (2006), *Guide A: Environmental Design*, p.3-5.

16. Masonry-to-mortar ratio has been investigated by Paul Baker: Baker, P.H. (2011), *Historic Scotland Technical Paper 10: U-values and Traditional Buildings.*

17. A range of moisture dependencies will be in the hygroscopic region. This is where a material has reached moisture equilibrium under a range of relative humidities (from a dry state to equilibrium moisture of about 95% relative humidity). This is expressed in moisture sorption isotherm curves and this sorption behaviour describes the ability of a hygroscopic material to absorb and release water vapour or into the air until a state of equilibrium is reached.

ENGLISH HERITAGE

RESEARCH INTO THE THERMAL PERFORMANCE OF TRADITIONAL WALLS: SOLID BRICK WALLS

Prepared for English Heritage by Dr Paul Baker

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CONTENTS

This report summarises the results of research on the use of in-situ measurements to determine the as built thermal transmittances (U-values) of solid brick walls, and how these test results compare with predicted performance using a standard U-value calculation software program.

The objectives of the study were as follows:

- *To provide a better understanding of the thermal performance of such buildings, for example, variations which may result from local construction details, such as brick type, wall thickness and internal finish.*
- *To assess the capability and applicability of U-value calculation methods for traditionally constructed buildings.*

The report presents a comparison of the in-situ U-values results with the historical U-value requirements of the Building Regulations for walls since 1965.

The research was carried out by the School of Engineering and Built Environment, Glasgow Caledonian University, on behalf of English Heritage. The in-situ U-value measurements were carried out between February and April 2010 on 18 houses with solid brick walls in three locations.

1. INTRODUCTION

The thermal performance of pre-1919 dwellings with solid wall constructions is perceived as poor, for example, the CIBSE Guide suggests the use of a U-value of 2.09 W/m²K for a 220-mm solid brick wall with 13-mm dense plaster (*Anderson, 2006b*). On the other hand, the estimated U-value of post-1919 cavity wall constructions (*Energy Saving Trust, 2008*) is 1.7 W/m²K until the introduction of the 1976 English and Welsh Building Regulations, when the requirement was reduced to a maximum of 1.0 W/m²K in response to the oil crisis of the early 1970s. However, previous investigations (*Baker, 2011*) have shown that the actual thermal performance of solid wall constructions is often better than that assumed for energy assessment purposes. Establishing the actual performance can contribute towards a more rational approach to improving the energy efficiency of solid-wall traditional buildings in the UK.

2. THE BUILDINGS

Descriptions of the buildings are given in *Table 1*. The distribution of wall finishes is shown in *Figure 1*.

The buildings in each of the locations had distinctive brick types and wall thicknesses:

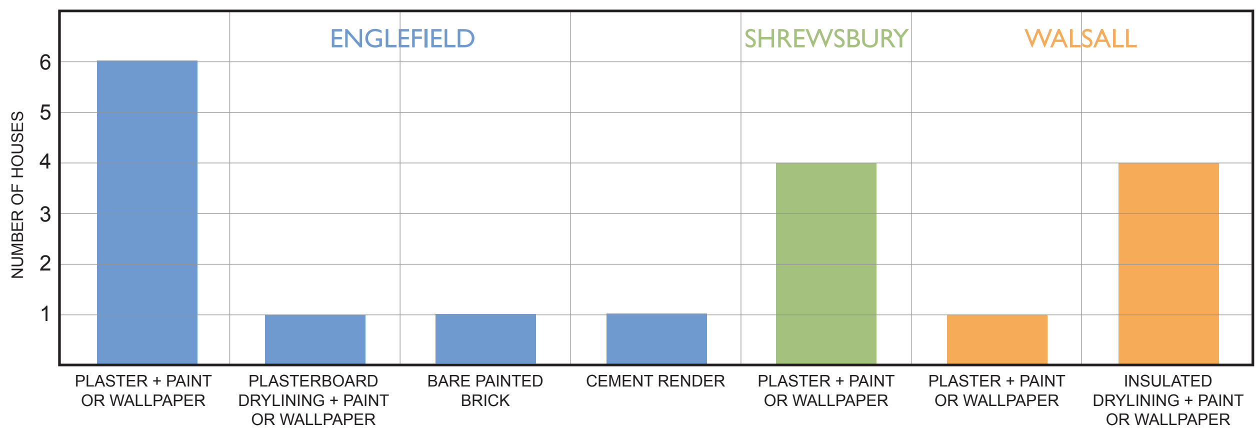
- The Englefield Estate: soft, porous 12-inch brick
- Shrewsbury: soft, medium, porous 9-inch brick
- Walsall: hard, dense 9-inch brick.

The majority of the houses had a plastered internal finish with paint or wallpaper. One of the Englefield houses (*Table 1*: E4) was drylined with plasterboard. Four houses in Walsall (*Table 1*: W1, W3, W4, W5) were drylined with plasterboard, which is understood to be backed with insulation, however no details of the actual materials and their thicknesses were available. Measurements were made in a room of one building on the Englefield Estate with painted bare brick (*Table 1*: E5). One building (*Table 1*: E6) on the Englefield estate had internal walls rendered with cement.

TABLE 1: DESCRIPTION OF THE BUILDINGS STUDIED

ID	BRICK TYPE	INTERNAL FINISH	CONSTRUCTION	PERIOD	ORIENTATION	EXPOSURE
ENGLEFIELD						
E1	12 inch Soft, porous	Plaster + paint	Timber frame; detatched	Multi-period 17th -19th century	NE facing	Sheltered
E2	12 inch Soft, porous	Plaster + paint	Detached	Mid 19th century	NW facing	Sheltered
E3	12 inch Soft, porous	Plaster + wallpaper	Semi-detached	Mid 19th century	E facing	Sheltered
E4	12 inch Soft, porous	Plasterboard drylined + wallpaper	Timber frame; semi-detached	Mid 19th century	SE facing	Semi-exposed
E5	12 inch Soft, porous	Bare painted brick	Detached	Mid 19th century	N. facing	Sheltered
E6	12 inch Soft, porous	Cement render	Detached	Multi-period (Grade II) 17th -19th century	E facing	Sheltered
E7	12 inch Soft, porous	Plaster + paint	Detached	Mid 19th century	NE facing + N facing	Exposed
E8	12 inch Soft, porous	Plaster + paint	Semi-detached	Mid 19th century	W facing	Exposed
E9	12 inch Soft, porous	Plaster + textured wallpaper	Semi-detached	Mid 19th century	S facing	Exposed
SHREWSBURY						
S1	9 inch Medium soft porous	Plaster + paint	Terrace	Mid 19th century	NE facing	Sheltered
S2	9 inch Medium soft porous	Plaster + paint	Terrace	Mid 19th century	SW facing	Sheltered
S3	9 inch Medium soft porous	Plaster + paint	Terrace	Mid 19th century	NE facing	Semi-exposed
S4	9 inch Medium soft porous	Wallpaper + paint	Timber frame; semi-detached	Mid 19th century	NE facing + SE facing	
WALSALL						
W1	9 inch Hard, dense	Insulated drylined + painted	End terrace	1917	SE facing	Sheltered
W2	9 inch Hard, dense	Plaster + paint	Terrace	Early 20th century	NW facing	Sheltered
W3	9 inch Hard, dense	Insulated drylined + painted	Almshouse; terrace	1886	N facing	Semi-exposed
W4	9 inch Hard, dense	Insulated drylined + painted	Two-storey terrace	1878	NE facing	Sheltered
W5	9 inch Hard, dense	Insulated drylined + painted	Two-storey terrace	Early 20th century	NE facing	Sheltered

FIGURE 1: DISTRIBUTION OF INTERNAL FINISHES IN THE HOUSES STUDIED



3. MONITORING AND ANALYSIS PROCEDURES

3.1 PRINCIPLES

The monitoring and analysis procedures have been developed during similar projects with Historic Scotland (*Baker, 2011*) and other organisations. The procedures are based on the principles of *prEN 12494:1997*, which are summarised below.

The U-value or thermal transmittance of a building element is defined in the European Standard *EN ISO 7345:1987* as the *"heat flow rate in the steady state divided by the area and the temperature difference between the surroundings on each side of a system."*

In the laboratory, suitable steady-state conditions can be achieved to determine the U-value of a building element for standardised boundary conditions. However, during *in-situ* measurements, the boundary conditions (temperature, wind velocity and solar radiation) change with time. It is therefore recommended that the surface-to-surface thermal resistance of the element is obtained by measuring the heat flow rate through the element and the surface temperatures on both sides of the element for a sufficiently long period of time to give a good estimate of the steady state from the mean values of the heat flow rate and temperatures. The U-value can then be calculated by applying standardised surface heat-transfer coefficients. This averaging approach is valid if:

- the thermal properties of the materials in the element are constant over the range of temperature fluctuations;
- the change in the internal energy of the element is negligible if compared to the amount of heat going through the element.

An alternative is to use a dynamic method to account for the fluctuations in the heat flow and temperature in the recorded data.

It is assumed that the element is sufficiently homogeneous or made of sufficiently homogeneous layers to use a heat-flow meter.

3.2 PROCEDURES

The test and analysis procedures are summarised as follows and explained in greater detail in *Appendix 1*.

Actual measurements, recorded using a data logger(s), were made over a period of at least two weeks of the heat flow through the internal surface of each wall and the internal and external temperatures. The measurement period was found to give a stable average U-value (*Baker, 2011*) which takes into account the thermal inertia of the wall. Sensor locations were chosen to avoid probable thermal bridge locations near to windows and corners, with the heat flow sensor ideally located about half-way between window and corner, and floor and ceiling. Where possible a north-facing or sheltered elevation was selected to reduce the influence of solar radiation on the wall. If possible, both external air and surface temperatures were measured.

The surface-to-surface thermal resistance (R-value) of the wall was generally estimated from the averages of the recorded heat flow and surface temperature difference across the wall over the monitoring period.

The U-value can then be calculated by applying standardised surface heat transfer coefficients. In some cases it was not possible to measure the external surface temperature: therefore the difference between the internal surface temperature and the external air temperature was used, in which case only the standard internal surface heat transfer was applied to obtain the U-value.

The uncertainty of the U-value estimate is estimated from the individual measurement errors and the standard deviation, which is a measure of the spread, of the average value. Whilst the uncertainty of the U-values estimates is generally about ±10%, the level of uncertainty increases where the temperatures difference across the wall or building element is small.

4. RESULTS AND DISCUSSION

4.1 MEASURED RESULTS

The results are summarised in *Table 2* for the two measurements (H1 and HF2) made in each building. The results are also presented by location and internal wall finish in *Figure 2*, where an average value is given for each category and, where appropriate, a standard deviation. The CIBSE Guide suggested value of 2.09 W/m²K is shown for comparison.

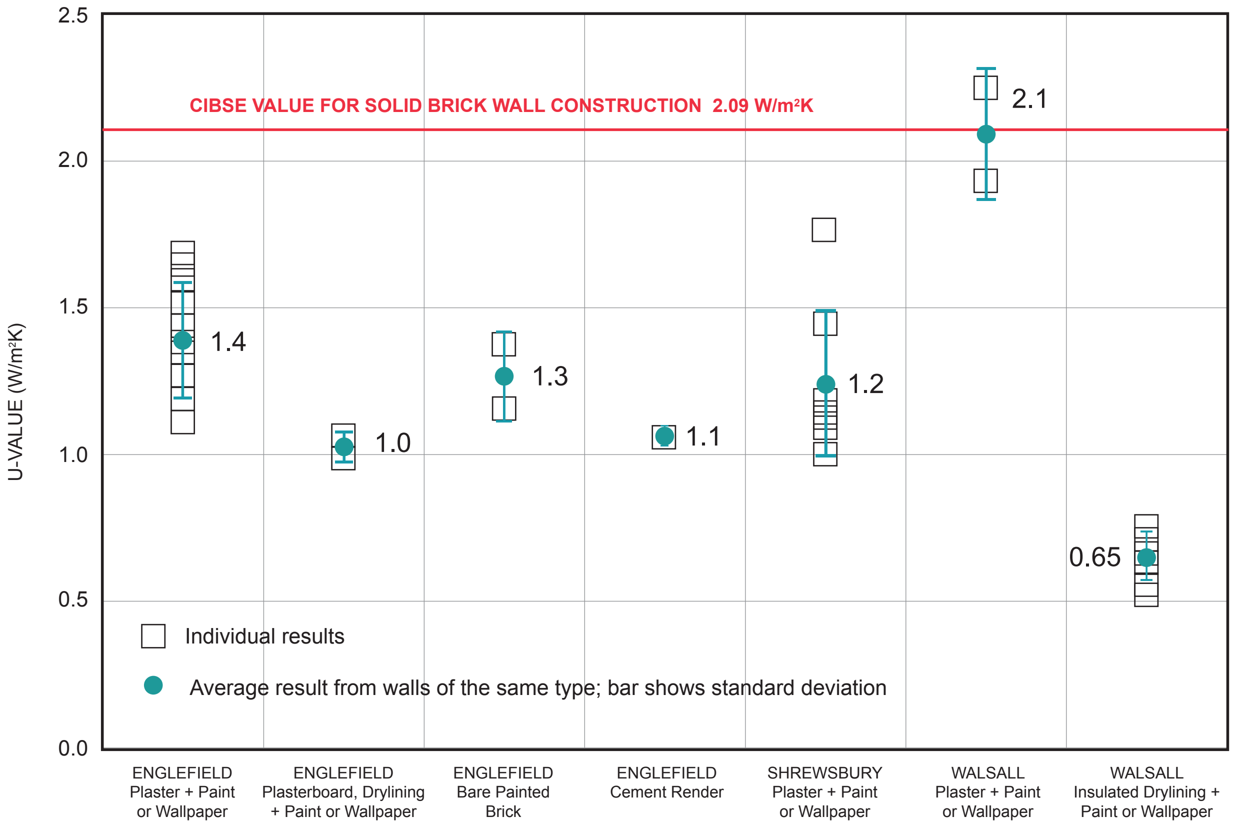
The majority of the measured values are lower than the CIBSE Guide value, except for one of the Walsall results (W2/HF1).

TABLE 2: SUMMARY OF *IN-SITU* U-VALUE RESULTS WITH THEIR UNCERTAINTIES

ADDRESS	MONITORING PERIOD 2010		HF1 U-value [W/m²K]	HF2 U-value [w/m²k]
	From	To		
E1	17 February	5 March	1.3 ± 0.1	1.3 ± 0.1
E2	17 February	6 March	1.4 ± 0.1	1.6 ± 0.1
E3	18 February	5 March	1.4 ± 0.1[1]	1.4 ± 0.1
E4	18 February	5 March	1.0 ± 0.1	1.1 ± 0.1
E5	18 February	5 March	1.2 ± 0.2[1]	1.4 ± 0.2[1]
E6 [1]	5 March	22 March	1.1 ± 0.2[1]	[2]
E7	6 March	22 March	1.2 ± 0.1	1.6 ±0.1
E8	6 March	22 March	1.5 ± 0.1	1.7 ± 0.1
E9	6 March	22 March	1.1 ± 0.1	1.1 ± 0.1
S1	18 March	26 April	1.2 ± 0.1	1.1 ± 0.1
S2	19 March	26 April	1.4 ± 0.2	1.8 ± 0.2
S3	19 March	26 April	1.1 ± 0.1	1.0 ± 0.1
S4	19 March	26 April	1.1 ± 0.1	1.2 ± 0.1
W1[3]	25 March	22 April	0.72 ± 0.12	0.59 ± 0.11
W2	25 March	22 April	2.2 ± 0.3	1.9 ± 0.2
W3	26 March	22 April	0.75 ± 0.13	0.52 ± 0.08
W4	26 March	22 April	0.71 ± 0.07	0.70 ± 0.07
W5	27 March	22 April	0.61 ± 0.07	0.70 ± 0.06

NOTES:
1. Heat flux sensor fell off wall and was then replaced at some stage during test: the data during these periods were identified and have been excluded from the analysis.
2. Heat flux sensor fell off wall and was not replaced: test data unusable.
3. External air temperature data lost. The average of the external temperature measurements in the other four Walsall houses was substituted since W1 was in the same general location as W2–W4. The variation of external air temperature between the four houses was about ±1°C. This was included as an additional error in the calculation of the uncertainties for the U-values measured.

FIGURE 2: RESULTS BY LOCATION AND SURFACE FINISH



4.1.1 Plastered Walls

The results of the plastered walls (either painted or with wallpaper) from Englefield and Shrewsbury are similar with average values of 1.4 ±0.2 W/m²K and 1.2 ±0.2 W/m²K, respectively, although the Englefield walls use a thicker construction with 12-inch brick. The two Walsall results from house W2 with plastered walls are higher, with an average value of 2.1 ±0.2 W/m²K. Although there is no information available for the brick thermal properties, the Walsall bricks are dense compared with the Englefield and Shrewsbury brick, and therefore likely to have a higher thermal conductivity. For example, *Everett 1986* gives a value of about 1.2 W/mK for the thermal conductivity of denser brick engineering brick and a much lower value of 0.44 W/mK for London Stock brick.

4.1.2 Drylined Walls

Whilst the examples of the other surface finishes are limited, drylining appears to give some improvement in the case of the Englefield results for E4, 1.0 ±0.1 W/m²K, compared to the original wall construction with plaster 1.4 ±0.2 W/m²K. Values obtained for stone walls with drylining (*Baker, 2011*) were similar, 0.9 ±0.2 W/m²K.

The Walsall drylined walls (W1, W3, W4, W5) have an average U-value of 0.7 ±0.1 W/m²K from eight heat flow sensor locations, which is lower than the average Englefield value, and appears to be consistent with calculated values assuming an insulating layer behind the plasterboard (see *Section 4.2*).

4.2 COMPARISON WITH CALCULATED VALUES

BuildDesk U3.4 software was used to calculate upper and lower of U-values for the walls. The software performs calculations in accordance with the calculation methods set out in British Standard *BS EN ISO 6946:1997* and the BRE publication *Convention for U-Value Calculations* (*Anderson, 2006a*). The wall constructions or 'build-ups' for the modelling are shown in *Figure 3*, and were selected as follows.

Brick

The main difficulty is selecting the thermal conductivities of the bricks. The software database has two brick types: inner leaf and outer leaf with a thermal conductivity of 0.56 and 0.77 W/m²K, respectively. It is also possible to add user defined materials. After reviewing various sources (e.g. *Everett, 1986*), a range of brick thermal conductivities was identified from 0.44 W/m²K, for London Stock bricks, to about 1.2 W/m²K for denser brick engineering brick. These two extreme values were entered into the database as appropriate alternatives for modelling the walls.

Plasters and Renders

Both lime and gypsum were modelled as possible alternatives, each with a thickness of 25 mm. A 25-mm cement render was also modelled for the Englefield case.

Drylining

A 50-mm layer behind 12.5 mm standard plasterboard was assumed for the Englefield case E4. For the Walsall houses (W1, W3, W4, W5) the build-up behind the plasterboard was modelled as a combination of a 25-mm air gap and 25 mm of phenolic insulation (having a thermal conductivity of 0.025 W/mK).

Table 3 compares the calculated values for the build-ups using the four brick thermal conductivities with the measured results for each wall category, expressed as the range calculated

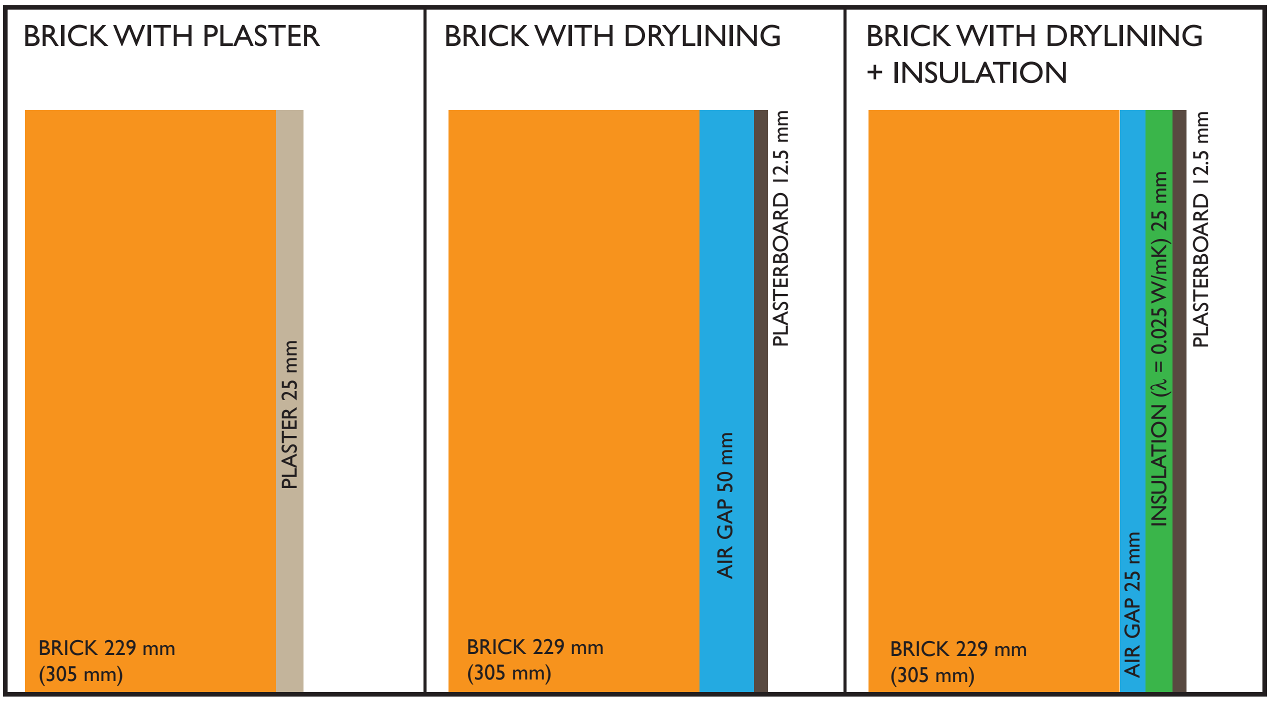


Figure 3: The three basic configurations used for modelling the walls using BuildDesk.

from the average result ± one standard deviation (see *Figure 2*).

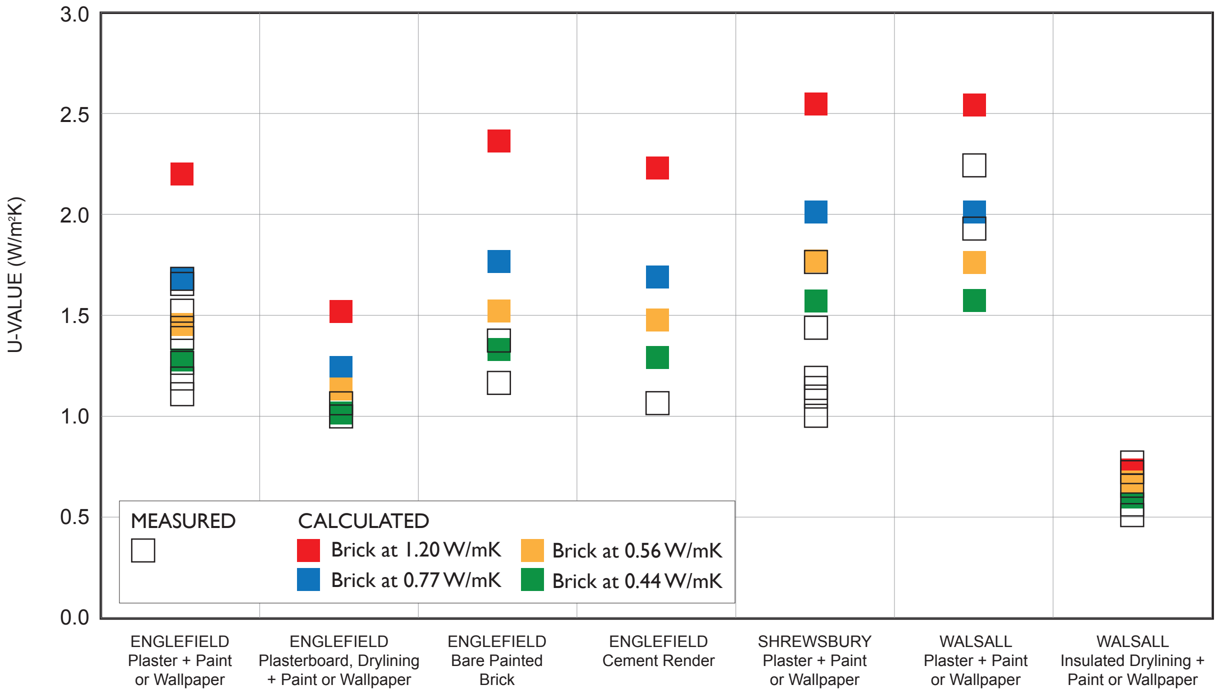
TABLE 3: COMPARISON OF CALCULATED U-VALUES

WALL DESCRIPTION	RANGE OF MEASURED VALUES Average + one standard deviation	CALCULATED U-VALUES Assumed brick thermal conductivities			
		1.2 W/mK	0.77 W/mK	0.56W/mK	0.44W/mK
ENGLEFIELD 12-inch brick wth plaster + wallpaper or paint	1.2 to 1.6	2.2	1.7	1.5	1.3
ENGLEFIELD 12-inch brick drylined with plasterboard + paint or wallpaper	1.0 to 1.1	1.5	1.2	1.1	1.0
ENGLEFIELD 12-inch bare painted brick	1.1 to 1.4	2.4	1.8	1.5	1.3
ENGLEFIELD 12-inch brick with cement render	0.9 to 1.3 [1]	2.2	1.7	1.5	1.3
SHREWSBURY 9-inch brick with plaster + wallpaper or paint	1.0 to 1.5	2.6	2.0	1.8	1.6
WALSALL 9-inch brick with plaster + paint or wallpaper	1.9 to 2.3	2.6	2.0	1.8	1.6
WALSALL 9-inch brick drylined with insulated plasterboard + paint or wallpaper	0.6 to 0.7	0.7	0.7	0.6	0.6

NOTES:
1. One measured result only: the range is expressed as the value ± the measurement uncertainty.

The calculated values are also compared with the measured results in *Figure 4*. The calculated values assume that the plastered walls use lime, and the insulation in the Walsall drylined walls is phenolic insulation.

FIGURE 4: MEASURED AND CALCULATED U-VALUES



Most of the measured values for the Englefield houses are in reasonable agreement with the low to mid-range calculated values.

The measured values for the Shrewsbury walls are generally lower than the lowest calculated result assuming a brick thermal conductivity of 0.44 W/mK.

The Walsall measured values are close to the mid-range to high values calculated using a brick thermal conductivity of 0.77 and 1.2 W/mK for the plastered walls. The range of measured values for the insulated drylining is in agreement with the calculated values across the range of brick thermal conductivities, since the effect of the insulation dominates the overall thermal transmittance value determined by BuildDesk.

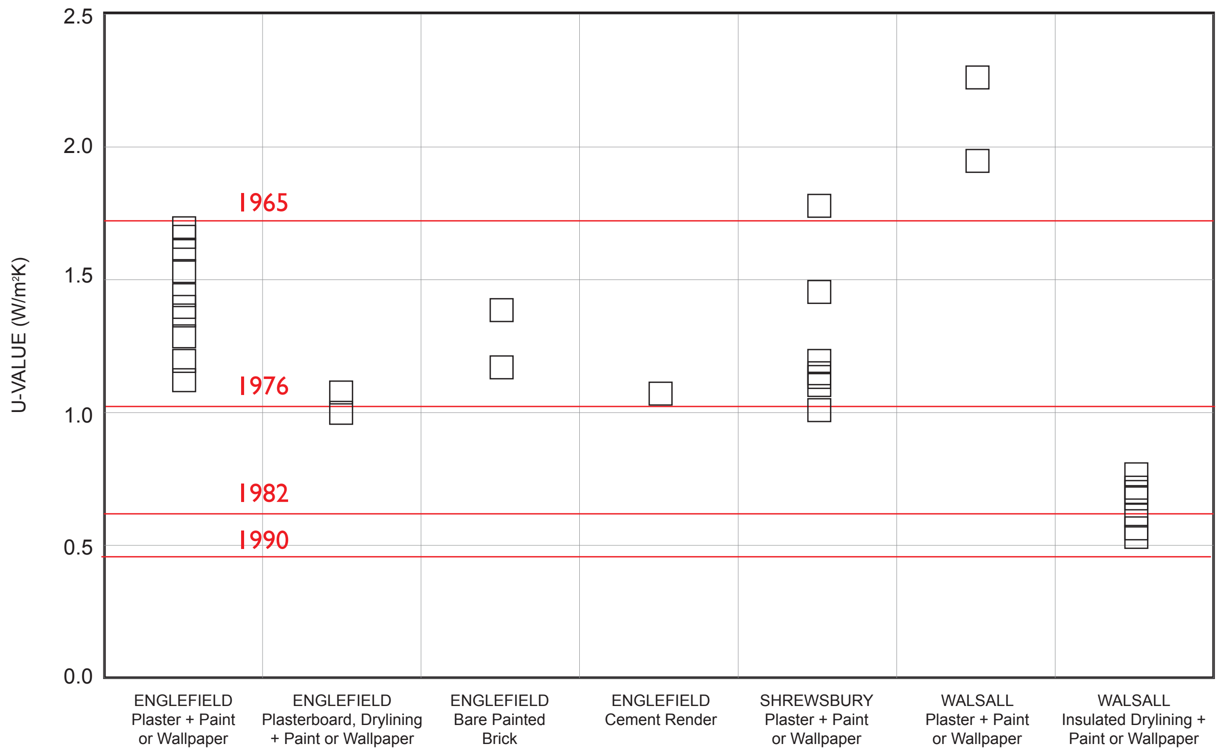
4.3 COMPARISON WITH HISTORICAL BUILDING REGULATIONS

Table 4 gives the maximum U-values for walls for the English and Welsh Building Regulations from 1965 to 1990. The measured results are compared with these values in *Figure 5*.

TABLE 4: MAXIMUM U-VALUES FOR WALLS (BUILDING REGULATIONS FROM 1965 TO 1990)

YEAR REGULATIONS INTRODUCED	MAXIMUM WALL U-VALUE W/m²K
1965	1.7
1976	1.0
1982	0.6
1990	0.45

FIGURE 5: COMPARISON WITH U-VALUES FROM BUILDING REGULATIONS 1965–1990



Of the total of 35 *in-situ* results, 22 of the measurements fit in the U-value range 1.0–1.7 W/m^{2}K: i.e. better than the 1965 value, but not meeting the standard introduced in 1976. Only three measurements are worse than the 1965 value. Two of these results (W2) were made on a wall constructed from hard, dense brick which is likely to have a high thermal conductivity. The third (S2/HF2) is the highest result for the Shrewsbury sample. All walls with insulated drylining in the Walsall sample of houses exceed the requirements of the 1976 Regulations, and three meet the requirements of the 1982 regulations.

5. CONCLUSIONS AND RECOMMENDATIONS

Comparing the results for plastered walls, brick type and thickness both influence the U-value. Variation in brick properties may explain the differences in the results from the three locations:

- The Englefield results for 12-inch brick are similar to the Shrewsbury results for 9-inch brick, which indicates that the Shrewsbury bricks have a lower thermal conductivity than those at Englefield.
- The Walsall results are consistent with a denser, higher thermal conductivity brick.

The results for the walls in the Walsall houses show that significant improvements can be achieved by using internal insulation behind the drylining. The sample sizes of the other types of wall finishes in Englefield (drylined, bare brick and cement render) were too limited to draw significant conclusions.

The majority of the sample of traditional (pre-1919) solid brick wall constructions studied is not inherently worse than most post-1919 houses up to the late 1970s. Generally, comparing the measured results with the CIBSE Guide suggested value for solid brick walls (*Anderson, 2006b*), shows that all but one of the results was lower than the Guide value of 2.09 W/m^{2}K. The majority of the results were also better than the post-1919 cavity wall constructions and 1965 Building Regulations maximum U-value for walls of 1.7 W/m^{2}K, but failed to meet the 1976 requirement of 1.0 W/m^{2}K, apart from the insulated drylined houses in Walsall.

Comparing the measured and calculated U-values, the Shrewsbury results are significantly lower than would be expected from the U-value calculations using the standard database in BuildDesk and modelling a lower thermal conductivity brick (0.44 W/mK). Assuming a range of thermal conductivities for the bricks, the measured and calculated results shows some agreement particularly in the case of the Englefield and Walsall houses:

- The Englefield results are consistent with calculations using lower brick thermal conductivities.
- The Walsall results for plastered walls are consistent with calculated values using higher brick thermal conductivities.
- The influence of the brick thermal conductivity is less in the case of the calculated results for the insulated drylined walls in Walsall and good agreement is generally achieved assuming a build-up using phenolic foamed backed plasterboard.

Briefly reviewing the available information on modern brick properties shows a wide range of reported conductivities (0.44-1.2 W/mK). A wider range for traditional bricks may be expected since they were likely to be produced from locally sourced materials. Mortar composition may also be a variable.

The study highlights some of the problems associated with identifying the build-up of traditional buildings to perform U-value calculations, where there are no records of the original construction details and/or any changes to the building (for example, the case of the drylined walls), and without carrying out invasive surveys. The *in-situ* measurement technique therefore offers a means of determining actual thermal performance.

It is recommended that the thermal conductivities of samples of the bricks from the three locations should be measured in the laboratory. It would then be possible to critically validate the U-value calculations against the *in-situ* results.

APPENDIX 1

TEST AND ANALYSIS PROCEDURES

The monitoring and analysis procedures have been developed during similar projects with Historic Scotland (*Baker, 2011*) and other organisations.

Monitoring

Campbell Scientific CR1000 data loggers equipped with heat flux and temperature sensors were used internal room measurements. Hukseflux HFP01 heat flux sensors were used to measure heat flows through the selected walls (*Figure A1*).

The sensors are 80 mm in diameter and 5 mm thick. The sensors were mounted by firstly applying a layer of double sided adhesive tape to the back of the sensor. Secondly, low-tack masking tape was applied to the wall. Finally, the heat flux sensor was applied firmly to the masked area.

This arrangement was generally satisfactory for two or more weeks monitoring on painted surfaces only. Wallpapered surfaces were not generally used in case of damage. Sensor locations were chosen to avoid probable thermal bridge locations near to windows and corners, with the sensor ideally located about half-way between window and corner, and floor and ceiling (*Figure A2*). Where possible a north-facing or sheltered elevation was selected to reduce the influence of solar radiation on the wall.

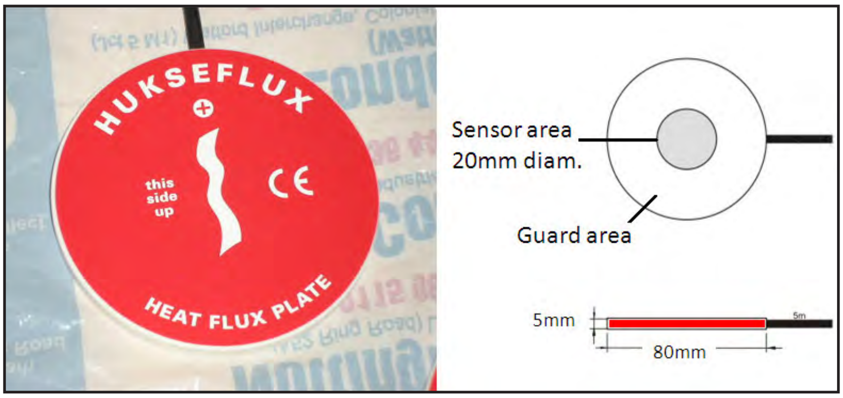


Figure A1: Heat flux sensor

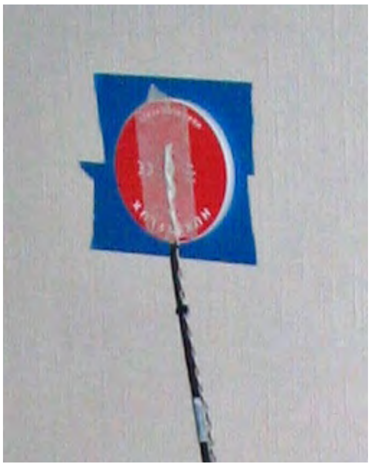
Figure A2: Typical heat flux sensor and room temperature measurement locations.

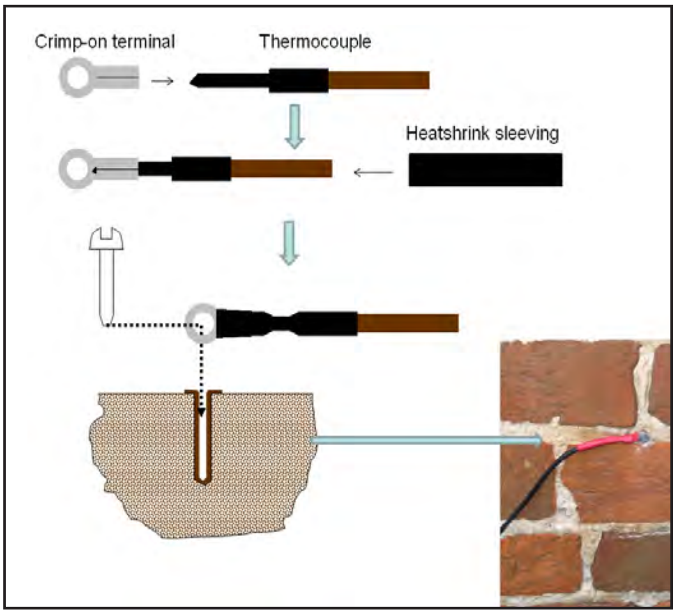
Stainless steel-sheathed thermistors, Campbell Scientific type 107, were used internally to measure room air temperature, mounted within a simple radiation shield in order to minimise the influence of solar radiation and other heat sources (*Figure A3*). The surface temperature of the face of each heat flux sensor was measured using type-T thermocouples taped onto the surface of the heat flux sensor (*Figure A4*).

External temperatures were measured using separate data logger which could be mounted outdoors, as it had been found that during the Historic Scotland project (*Baker, 2011*) it was not always possible or practical to run an external sensor cable back into the building, particularly through sash windows, without leaving the window slightly open to accommodate the cable (in contrast modern windows fitted with a gasket seal can be closed onto a cable).

Dual channel Gemini TinyTag Plus 2 TGP-4520 loggers were used with thermistor probes to measure external air temperature and, generally, external wall surface temperature. Each external temperature sensor was placed in a radiation shield which was generally tied, for example, onto a drainpipe (*Figure A5*). Crimp-on terminals were used to secure surface temperature sensors to mortar joints, by drilling and plugging joints (*Figure A6*).

Room sensors were logged at 5-second intervals and averaged over 10 minutes. External temperatures were logged at 5-minute intervals.





Clockwise from top left:

Figure A3: Room air temperature shield

Figure A4: Type-T thermocouple mounted on surface of heat flux sensor

Figure A5: Mounting of shielded external temperature sensor

Figure A6: Method of mounting external surface temperature sensor to mortar joint

Data Analysis

Given that the monitoring conditions are non-steady state, it is considered necessary to monitor for about two weeks, or preferably longer, in order to collect sufficient data to estimate *in-situ* U-values. The period should be sufficient to take into account the thermal capacity/inertia of the wall. *Figure A7* shows the effect of increasing the length of the monitoring period on the estimate of the U-value using a simple averaging procedure as described below. A period of at least a week is required before the U-value estimate stabilises to within ±5% of the final value determined from about 27 days data.

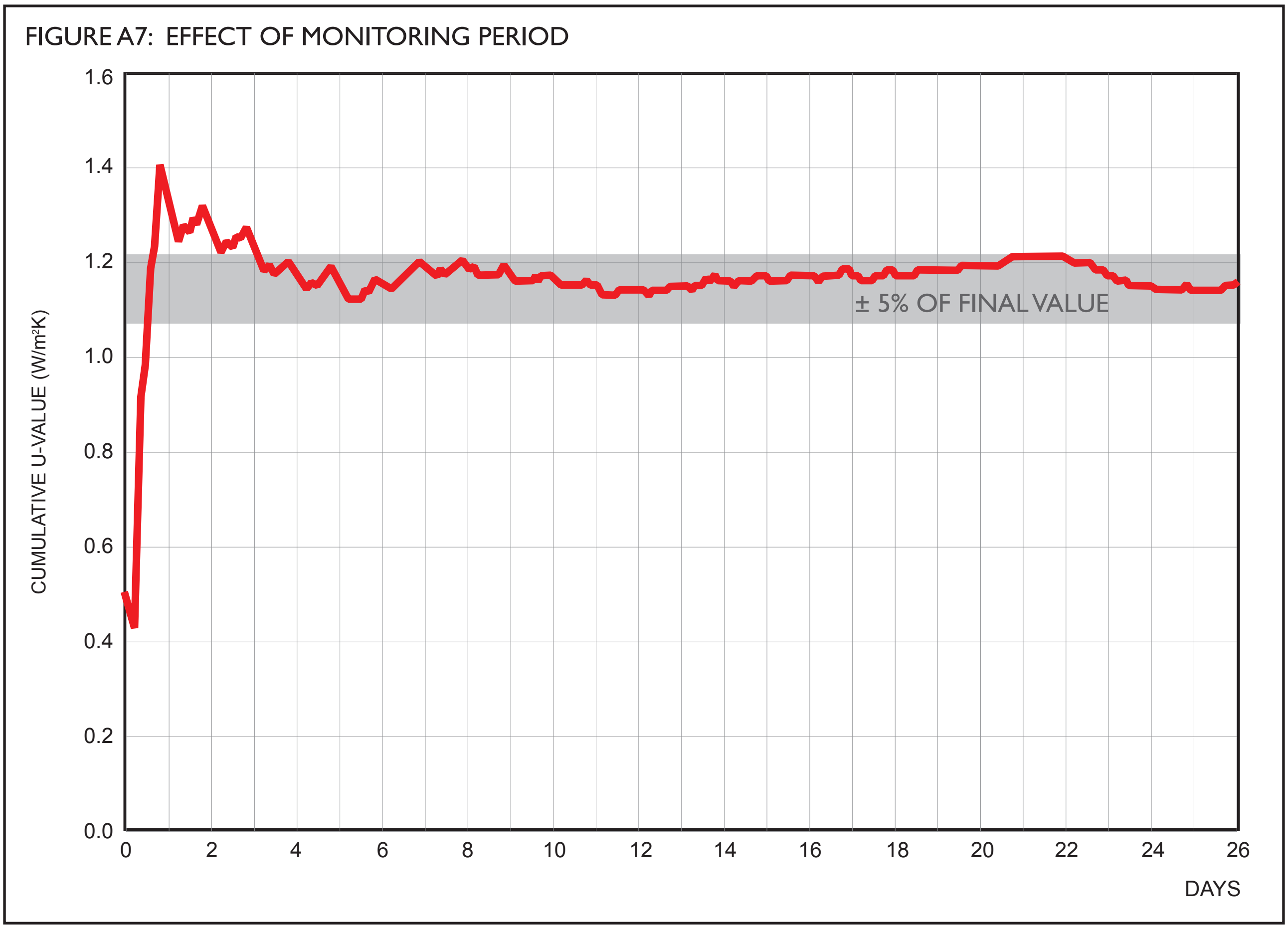


Figure A7: The effect of increasing the monitoring period.

For example, the U-value may be estimated by a simple averaging procedure as follows:

$$U = \frac{\sum_{0}^{i-t} Q_i}{\sum_{0}^{i-t} Ti_i + \sum_{0}^{i-t} Te_i} \quad \text{W/m}^2\text{K} \qquad \textit{Equation A1}$$

where is the average U-value after time t, Q, Ti and Te are, respectively, the heat flux, room temperature and external temperature collected at time intervals of i.

There are drawbacks to using internal and external air temperatures in terms of the uncertainties introduced. In the case of internal air temperature stratification may occur, therefore the measured temperature may not be representative for the location of the heat flux meter. Whilst the external air temperature measurements may be representative for the building, there may be exposure of the external surface to solar radiation and radiative exchange with its surroundings will occur. Therefore an alternative to using air temperatures to calculate U-values using *Equation A1* is to use the surface temperature difference across the wall to determine its thermal resistance, and add the standard internal and external surface resistances (r_{int} = 0.13m²K/W and r_{ext} = 0.04 m²K/W,, respectively) as follows:

$$U_t = \frac{1}{\dfrac{\sum_0^{i-t} Tsi_i - \sum_0^{i-t} Tse_i}{\sum_0^{i-t} Q_i} + r_{\text{int}} + r_{ext}} \quad \text{W/m}^2\text{K} \qquad \textit{Equation A2}$$

where *Tsi* and *Tse* are the internal and external surface temperatures respectively.

In some cases it is not possible to measure the external surface temperature; therefore the difference between the internal surface temperature and the external air temperature can be used as follows:

$$U_t = \frac{1}{\dfrac{\sum_0^{i-t} Tsi_i - \sum_0^{i-t} Te_i}{\sum_0^{i-t} Q_i} + r_{\text{int}}} \qquad \textit{Equation A3}$$

A small correction is applied for the thermal resistance of the heat flux sensor ($<6.25\times10^{3}$ m²K/W).

Error Analysis

The uncertainty of the U-value estimate is derived from the individual measurement uncertainties and the standard deviation (s.d.) of the average value.

For the averaging method the calculated U-value contains all the information available; therefore the uncertainty of this value cannot be easily determined. One approach is to calculate moving averages for, say, weekly periods: i.e. the first period is the average over Day 1 to Day 7; the second period Day 2 to Day 8; and etc. The standard deviation (s.d.) of these N averages can then be calculated, which will give some indication of the uncertainty of the estimated U-value. This approach is justified because a week is the minimum period which may be expected to give a result.

Each of the measured parameters (heat flux, and internal and external temperature) has an associated uncertainty due to the sensor itself (E_S) and the logging system (E_L). These are combined as follows:

$$\sqrt{E_S^2 + E_L^2} \qquad \textit{Equation A4}$$

To determine the error each measurement will have on the U-value estimate, the U-value calculation is repeated with each measured parameter perturbed by its error in turn. For example, in *Equation A5* the error on internal surface temperature (δTsi) measurement is applied to calculate *Uerr_Tsi*:

$$U_{err\_Tsi} = \frac{1}{\dfrac{\sum_0^{i-t}\left[Tsi_i + \delta Tsi_i - Tse_i\right]}{\sum_0^{i-t} Q_i} + r_{\text{int}} + r_{ext}} \qquad \textit{Equation A5}$$

The overall uncertainty on the U-value estimate, δU, is calculated as the root-mean-square value (RMS) of the deviations of each error case from the base case (i.e. the value determined from *Equation A2* or *Equation A3*), and the standard deviation of U as follows:

$$\delta U = \sqrt{\left(U - U_{errQ}\right)^2 + \left(U - U_{errTi}\right)^2 + \left(U - U_{errTe}\right)^2 + (s.d.)^2} \qquad \textit{Equation A6}$$

where U_{errQ}, U_{errTi} and U_{errTe} are the U-values calculated by applying the errors due to heat flux, internal temperature and external temperature, respectively.

Table A1 gives an example of the error analysis.

TABLE A1: ERROR ANALYSIS				
The estimation of the uncertainty of the U-value of a wall in a heated building with a temperature difference of 8.3K Base case U-value = 1.52 W/m²K Standard deviation = 0.02				
SENSOR	AVERAGE VALUE	SENSOR ERROR	U-VALUE W/m²K	
Heat Flux	16.8 W/m²	5 %	U_{errQ}	1.57
Internal Surface Temperature	289.55 K (16.40 °C)	0.5 K	U_{errTi}	1.45
External Surface Temperature	281.15 K (8.00 °C)	0.5 K	U_{errTe}	1.59
	Temperature Difference = 8.3 K		Overall uncertainty δU	0.11 = 8 %

Whilst the uncertainty of the U-values estimates is generally about ±10%, the level of uncertainty increases where the temperature difference across the wall or building element is small. An example is given over the page for a measurement in an unheated building, where the average surface temperature difference across the wall is less than 1K (*Table A2*).

TABLE A2: ESTIMATION OF UNCERTAINTY				
Estimation of the uncertainty of the U-value of a solid stone wall in an unheated building with a temperature difference of 0.9K Base case U-value = 1.83 W/m²K Standard deviation = 0.58				
SENSOR	AVERAGE VALUE	SENSOR ERROR	U-VALUE W/m²K	
Heat Flux	2.5 W/m²	5 %	U_{errQ}	1.89
Internal Surface Temperature	275.75 K (2.6 °C)	0.5 K	U_{errTi}	1.34
External Surface Temperature	274.75 K (1.6 °C)	0.5 K	U_{errTe}	2.87
	Temperature Difference = 0.9 K		Overall uncertainty δU	1.70 = 93 %

Whilst the U-value of the wall in the unheated building appears acceptable (1.8 W/m²K), the result should be rejected since the uncertainty is ±1.7 W/m²K (that is, 93%). The U-value of the wall in the heated building is 1.5±0.1 W/m²K (8%), which is satisfactory.

Dynamic Analysis

An alternative to the averaging method is to use a dynamic analysis method which explicitly takes into account the thermal capacity of the wall. Such a method may be more appropriate if for example there are large diurnal swings in external conditions as may be experienced during spring, or changes in the weather pattern during the test period. An example of such software is the LORD program (2004) which models the wall as a network of conductances and capacitances, analogous to an electrical circuit. *Figure A8* shows an example of this for a simple wall.

The wall is modelled with four nodes: the boundary conditions of the network at Node 1 and Node 4 are the measured temperatures (at Node 1 the outside temperature T_{ext}, and at Node 4 the inside temperature T_{int}). The measured heat flux is applied at the interior node 4. The nodes are connected by thermal conductances (H 1-2, etc.). Each node has a certain thermal capacity (C2, etc.). Storage of heat is only possible at the nodes.

The program calculates the best fit values for the conductances and thermal capacitances. The number of nodes used to model the wall depends on its thermal mass; however the selection of the optimum number of nodes may require a process of trial and error, and can be somewhat dependent on the user's experience of interpreting the output of the program.

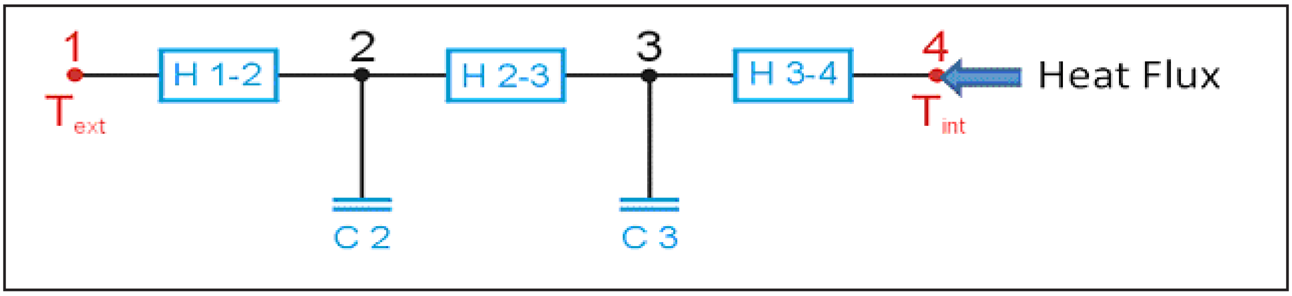


Figure A8: Example of a wall modelled as a network of conductances and capacitances

APPENDIX 2

RESULTS

TABLE OF RESULTS								
ID	LOCATION	CONSTRUCTION	THICKNESS	EXTERNAL FINISH	STUDS / AIR GAP ?	INTERNAL FINISH	U-VALUE (W/m²K)	
							In Situ	Calculated
EH1	DETACHED, ENGLEFIELD ESTATE, MULTI-PERIOD, ORIGINALLY DATING FROM 17TH CENTURY							
EH1.1	Sheltered wall facing NNE	12-inch brick Soft, porous	~300 mm	Brick and mortar	No	Plaster	1.3	1.3–2.2
EH1.2	Sheltered wall facing NNE	12-inch brick Soft, porous	~300 mm	Brick and mortar	No	Plaster	1.3	1.3–2.2
EH2	DETACHED, ENGLEFIELD ESTATE, MULTI-PERIOD, MID 19TH CENTURY							
EH2.1	Sheltered wall facing NW	12-inch brick Soft, porous	~300 mm	Brick and mortar	No	Plaster	1.4	1.3–2.2
EH2.2	Sheltered wall facing NW	12-inch brick Soft, porous	~300 mm	Brick and mortar	No	Plaster	1.6	1.3–2.2
EH3	SEMI-DETACHED, ENGLEFIELD ESTATE, MID 19TH CENTURY							
EH3.1	Sheltered wall facing E	12-inch brick Soft, porous	~300 mm	Brick and mortar	No	Plaster	1.4	1.3–2.2
EH3.2	Sheltered wall facing E	12-inch brick Soft, porous	~300 mm	Brick and mortar	No	Plaster	1.4	1.3–2.2
EH4	TIMBER FRAME, SEMI-DETACHED, ENGLEFIELD ESTATE, MID 19TH CENTURY							
EH4.1	Semi-exposed wall facing SE	12-inch brick Soft, porous	~300 mm	Brick and mortar	Yes	Plasterboard	1.4	1.3–1.5
EH4.2	Semi-exposed wall facing SE	12-inch brick Soft, porous	~300 mm	Brick and mortar	Yes	Plasterboard	1.4	1.3–1.5
EH5	DETACHED, ENGLEFIELD ESTATE, MID 19TH CENTURY							
EH5.1	Sheltered wall facing N	12-inch brick Soft, porous	~300 mm	Brick and mortar	No	Bare painted brick	1.2	1.3–2.4
EH5.2	Sheltered wall facing N	12-inch brick Soft, porous	~300 mm	Brick and mortar	No	Bare painted brick	1.4	1.3–2.4
EH6	DETACHED, ENGLEFIELD ESTATE, MULTI-PERIOD, GRADE II-LISTED: MEDIEVAL, 17TH 18TH 19TH CENTURIES							
EH6.1	Sheltered wall facing E: inner courtyard with farm buildings	12-inch brick Soft, porous	~300 mm	Brick and mortar	No	Cement render	1.1	1.3–2.2
EH7	DETACHED, ENGLEFIELD ESTATE, MID 19TH CENTURY							
EH7.1	Exposed wall facing NE & N	12-inch brick Soft, porous	~300 mm	Brick and mortar	No	Plaster	1.2	1.3–2.2
EH7.2	Exposed wall facing NE & N	12-inch brick Soft, porous	~300 mm	Brick and mortar	No	Plaster	1.6	1.3–2.2
EH8	SEMI-DETACHED, ENGLEFIELD ESTATE, MID 19TH CENTURY							
EH8.1	Exposed wall facing W	12-inch brick Soft, porous	~300 mm	Brick and mortar	No	Plaster	1.5	1.3–2.2
EH8.2	Exposed wall facing W	12-inch brick Soft, porous	~300 mm	Brick and mortar	No	Plaster	1.7	1.3–2.2
EH9	SEMI-DETACHED, ENGLEFIELD ESTATE, MID 19TH CENTURY							
EH9.1	Exposed wall facing S	12-inch brick Soft, porous	~300 mm	Brick and mortar	No	Plaster	1.1	1.3–2.2
EH9.2	Exposed wall facing S	12-inch brick Soft, porous	~300 mm	Brick and mortar	No	Plaster	1.1	1.3–2.2

TABLE OF RESULTS								
ID	LOCATION	CONSTRUCTION	THICKNESS	EXTERNAL FINISH	STUDS / AIR GAP ?	INTERNAL FINISH	U-VALUE (W/m²K)	
							In Situ	Calculated
EH10	TERRACE, 3 STOREYS, SHREWSBURY, MID 19TH CENTURY							
EH10.1	Sheltered wall facing NE	9-inch brick Medium/soft, porous	~230 mm	Brick and mortar	No	Plaster	1.2	1.6–2.6
EH10.2	Sheltered wall facing NE	9-inch brick Medium/soft, porous	~230 mm	Brick and mortar	No	Plaster	1.1	1.6–2.6
EH11	TERRACE, 3 STOREYS, SHREWSBURY, MID 19TH CENTURY							
EH11.1	Sheltered wall facing SW	9-inch brick Medium/soft, porous	~230 mm	Brick and mortar	No	Plaster	1.8	1.6–2.6
EH11.1	Sheltered wall facing SW	9-inch brick Medium/soft, porous	~230 mm	Brick and mortar	No	Plaster	1.8	1.6–2.6
EH12	TERRACE, 3 STOREYS, SHREWSBURY, MID 19TH CENTURY							
EH12.1	Sheltered wall facing NE	9-inch brick Medium/soft, porous	~230 mm	Brick and mortar	No	Plaster	1.1	1.6–2.6
EH12.1	Sheltered wall facing NE	9-inch brick Medium/soft, porous	~230 mm	Brick and mortar	No	Plaster	1.0	1.6–2.6
EH13	TIMBER FRAME, SEMI-DETACHED, 3 STOREYS, WROXETER NEAR SHREWSBURY, MID 19TH CENTURY							
EH13.1	Semi-exposed wall facing NE & SE	9-inch brick Medium/soft, porous	~230 mm	Brick and mortar	No	Plaster	1.1	1.6–2.6
EH13.1	Semi-exposed wall facing NE & SE	9-inch brick Medium/soft, porous	~230 mm	Brick and mortar	No	Plaster	1.2	1.6–2.6
EH14	TERRACE, 3 STOREYS, WALSALL, 1917							
EH14.1	Sheltered wall facing SE	9-inch brick Hard, dense	~230 mm	Brick and mortar	Insulated	Plasterboard	0.7	0.6–0.7
EH14.2	Sheltered wall facing SE	9-inch brick Hard, dense	~230 mm	Brick and mortar	Insulated	Plasterboard	0.6	0.6–0.7
EH15	TERRACE, 2 STOREYS, WALSALL, EARLY 20TH CENTURY							
EH15.1	Sheltered wall facing NW	9-inch brick Hard, dense	~230 mm	Brick and mortar	No	Plaster	2.2	1.6–2.6
EH15.2	Sheltered wall facing NW	9-inch brick Hard, dense	~230 mm	Brick and mortar	No	Plaster	1.9	1.6–2.6
EH16	TERRACE, BUNGALOW, WALSALL, 1886							
EH16.1	Semi-exposed wall facing N	9-inch brick Hard, dense	~230 mm	Brick and mortar	Insulated	Plasterboard	0.8	0.6–0.7
EH16.2	Semi-exposed wall facing N	9-inch brick Hard, dense	~230 mm	Brick and mortar	Insulated	Plasterboard	0.5	0.6–0.7
EH17	TERRACE, 2 STOREYS, WALSALL, 1878							
EH17.1	Sheltered wall facing NE	9-inch brick Hard, dense	~230 mm	Brick and mortar	Insulated	Plasterboard	0.7	0.6–0.7
EH17.2	Sheltered wall facing NE	9-inch brick Hard, dense	~230 mm	Brick and mortar	Insulated	Plasterboard	0.7	0.6–0.7
EH18	TERRACE, 2 STOREYS, WALSALL, EARLY 20TH CENTURY							
EH18.1	Sheltered wall facing NE	9-inch brick Hard, dense	~230 mm	Brick and mortar	Insulated	Plasterboard	0.6	0.6–0.7
EH18.2	Sheltered wall facing NE	9-inch brick Hard, dense	~230 mm	Brick and mortar	Insulated	Plasterboard	0.7	0.6–0.7

ENGLISH HERITAGE

THERMAL CONDUCTIVITIES OF THREE TRADITIONAL BRICKS

Prepared for English Heritage by Dr Paul Baker

Glasgow Caledonian University

INTRODUCTION

Glasgow Caledonian University has carried out thermal conductivity measurements using a heat flow apparatus on dry and wet samples of three bricks obtained from traditionally constructed Victorian dwellings in Englefield and Walsall, where *in-situ* U-value measurements were carried out in 2010, and from New Bolsover, where *in-situ* U-values were measured before and after energy-efficiency improvement works. The thermal conductivities of the wet samples are representative of the extreme case, when bricks are saturated.

The tests on the Englefield and Walsall brick samples provided actual thermal conductivity data to re-calculate U-values for comparison with the *in-situ* measurements carried on walls constructed from the same types of bricks.

The previous study considered that the main difficulty in calculating the U-values of traditional walls in accordance with British Standard *BS EN ISO 6946:1997* (*BSI, 1997*) and the BRE publication *Convention for U Value Calculations* (*Anderson, 2006a*) was that the thermal properties are unknown; therefore four possible thermal conductivities were selected for brick: 0.44, 0.56, 0.77 and 1.2 W/mK. Most of the measured values for the Englefield houses were in reasonable agreement with the lower to mid-range calculated values using 0.44 and 0.56 W/mK for the brick thermal conductivities. The Walsall measured values were close to the mid-range to high values calculated using a brick thermal conductivity of 0.77 and 1.2 W/mK for plastered walls. The range of measured values for walls with insulated drylinings is in agreement with the calculated values across the range of brick thermal conductivities, since the effect of the insulation dominates the overall thermal transmittance value in the calculation procedure.

The objective of these follow-up calculations is to determine how well the calculated values of U-values agree with the *in-situ* results when the thermal properties of the bricks are known.

The brick thermal conductivities of the New Bolsover brick were also used to calculate U-values to compare with the *in-situ* values for walls before and after the installation of three internal wall insulation systems.

METHOD

The measurements were carried out in a Lasercomp Fox 50 apparatus (*Figure 1*). The principle of operation of the apparatus is to apply a temperature gradient across a sample and measure the heat flow through the sample using heat flux transducers.

Tests were carried according to BS EN 12667:2001 (*BSI, 2001*) for a mean temperature of 10°C, with a temperature of 20°C on the warm face and 0°C on the cold face of the sample.

Figure 1: Lasercomp Fox 50 thermal conductivity apparatus

Four samples of each material were cut for testing. The nominal sample size is a square (44.5 × 44.5 mm), with a maximum thickness of 25 mm. The samples were then oven dried at 105°C. After cooling, each sample was smeared with a thin coating of petroleum jelly over both surfaces of the sample in contact with the plates of the apparatus, to ensure good thermal contact.

After completion of the dry tests, the samples were submerged and stored under water and only removed for thermal conductivity testing. The resulting moisture content should be approximately at capillary saturation.

When removed from storage, excess water was removed from each sample using a barely damp sponge, after which the sample was weighed and then wrapped in cling film to prevent evaporation of moisture during testing. The surfaces of the cling film in contact with the plates of the apparatus were smeared with a thin coating of petroleum jelly, prior to testing.

After testing, the samples were again dried at 105°C and then re-weighed to calculate the moisture content.

THERMAL CONDUCTIVITY RESULTS

The average dry densities, moisture contents and dry and wet thermal conductivities (with their standard deviations) of the three traditional bricks are given in *Table 1*. The estimated density from dry weight and sample dimensions and the moisture content by weight and volume after immersion are also shown.

TABLE 1: MEASURED CHARACTERISTICS OF SAMPLES

SAMPLE STATE	DRY DENSITY kg/m^3	AVERAGE MOISTURE CONTENT BY WEIGHT %	AVERAGE MOISTURE CONTENT BY VOLUME %	AVERAGE THERMAL CONDUCTIVITY AT 10°C W/mK
ENGLEFIELD				
Dry	1696 ± 22	0	0	0.55 ± 0.06
Wet	—	18.4 ± 1.6	31.1 ± 2.4	1.56 ± 0.09
WALSALL				
Dry	1912 ± 27	0	0	0.68 ± 0.10
Wet	—	11.1 ± 0.9	21.2 ± 1.7	1.26 ± 0.08
NEW BOLSOVER				
Dry	2191 ± 62	0	0	0.63 ± 0.11
Wet	—	2.4 ± 0.5	5.1 ± 1.0	0.98 ± 0.13

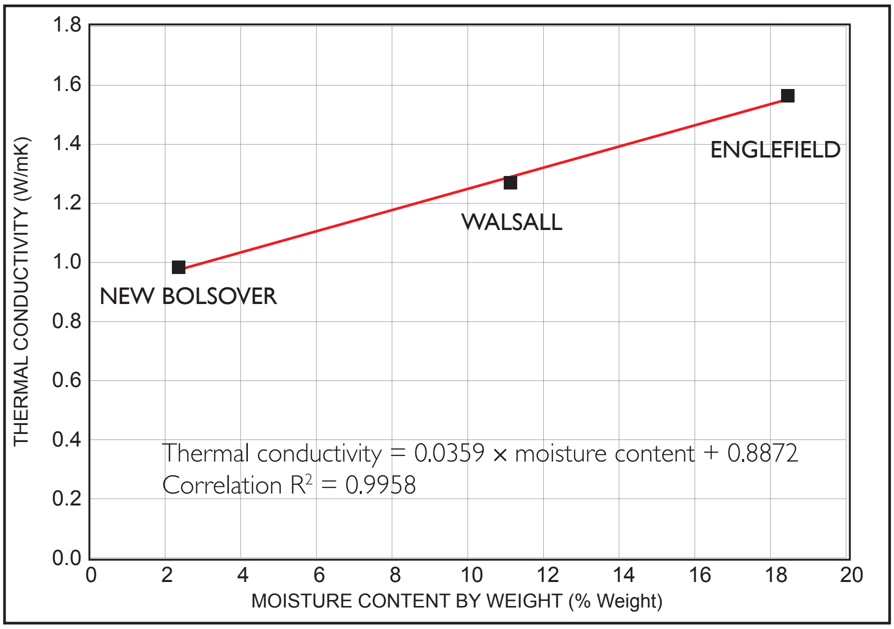
Dry Thermal Conductivity

Each set of brick sample shows a spread of values of, which may be due to the variation in texture, porosity and composition of each brick type (*Figure 2*). The Englefield brick has a fine, homogeneous structure and shows the lowest variation in thermal conductivity. It has the lowest density and average thermal conductivity of the three bricks. The Walsall brick samples have a number of striated cracks/voids, which may correspond to folding of the unfired material during processing. The Walsall brick has the highest average thermal conductivity. The New Bolsover samples show the largest variation; they have a coarse grainy structure with some voids. The New Bolsover brick has the highest density of the three bricks.

Figure 2: Thermal conductivity samples.

Wet Thermal Conductivity

Wetting to achieve capillary saturation produces a significant increase in the thermal conductivity of all the bricks, and there is a clear relationship between the moisture content by weight and thermal conductivity if all three types are considered (*Figure 3*). The Englefield brick has the highest capillary moisture content and wet thermal conductivity, almost three times greater than its dry thermal conductivity. In comparison the New Bolsover brick has a low capillary moisture content and a wet thermal conductivity about 1.5 times its dry value.



Although the graph in *Figure 3* suggests that there is a linear relationship between the capillary-saturation moisture content by weight and the thermal conductivity, this may be fortuitous: it may not be the case that all bricks fit this relationship.

Figure 3: Thermal conductivities of bricks at capillary saturation.

RE-CALCULATION OF U-VALUES

BuildDesk U3.4 software was used to recalculate U-values for the wall build-ups described in the *in-situ* U-values report using both the dry and wet brick thermal conductivity results for Englefield and Walsall from *Table 1*. The new results are given in *Table 2*, and in *Figure 4* and *Figure 5* are compared with the calculated values using the default values used previously (0.44, 0.56, 0.77 and 1.2 W/mK). The results are expressed as a range to reflect the uncertainty (± 1 standard deviation) in the measured thermal conductivities.

TABLE 2: RE-CALCULATED U-VALUES USING DRY & WET THERMAL CONDUCTIVITY

	MEASURED U-VALUES W/m^2K	MEASURED CONDUCTIVITY DRY BRICK W/mK	CALCULATED U-VALUE USING DRY CONDUCTIVITY W/m^2K	MEASURED CONDUCTIVITY WET BRICK W/mK	CALCULATED U-VALUE USING WET CONDUCTIVITY W/m^2K
ENGLEFIELD					
12-inch brick Plaster with wallpaper or paint	1.2–1.6	0.55 ± 0.06	1.2–1.4	1.56 ± 0.09	2.4–2.5
12-inch brick Plasterboard drylining with paint or wallpaper	1.0–1.1	0.55 ± 0.06	1.0–1.1	1.56 ± 0.09	1.6–1.7
12-inch brick Bare painted	1.1–1.4	0.55 ± 0.06	1.3–1.5	1.56 ± 0.09	2.7–2.8
12-inch brick Cement render	0.9–1.3	0.55 ± 0.06	1.2–1.4	1.56 ± 0.09	2.5–2.6
WALSALL					
9-inch brick Plaster with wallpaper or paint	1.9–2.3	0.68 ± 0.10	1.6–2.0	1.26 ± 0.08	2.5–2.6
9-inch brick Plasterboard drylining with insulation and paint or wallpaper	0.6–0.7	0.68 ± 0.10	0.6	1.26 ± 0.08	0.6
All measurements AVERAGE ± 1 STANDARD DEVIATION					

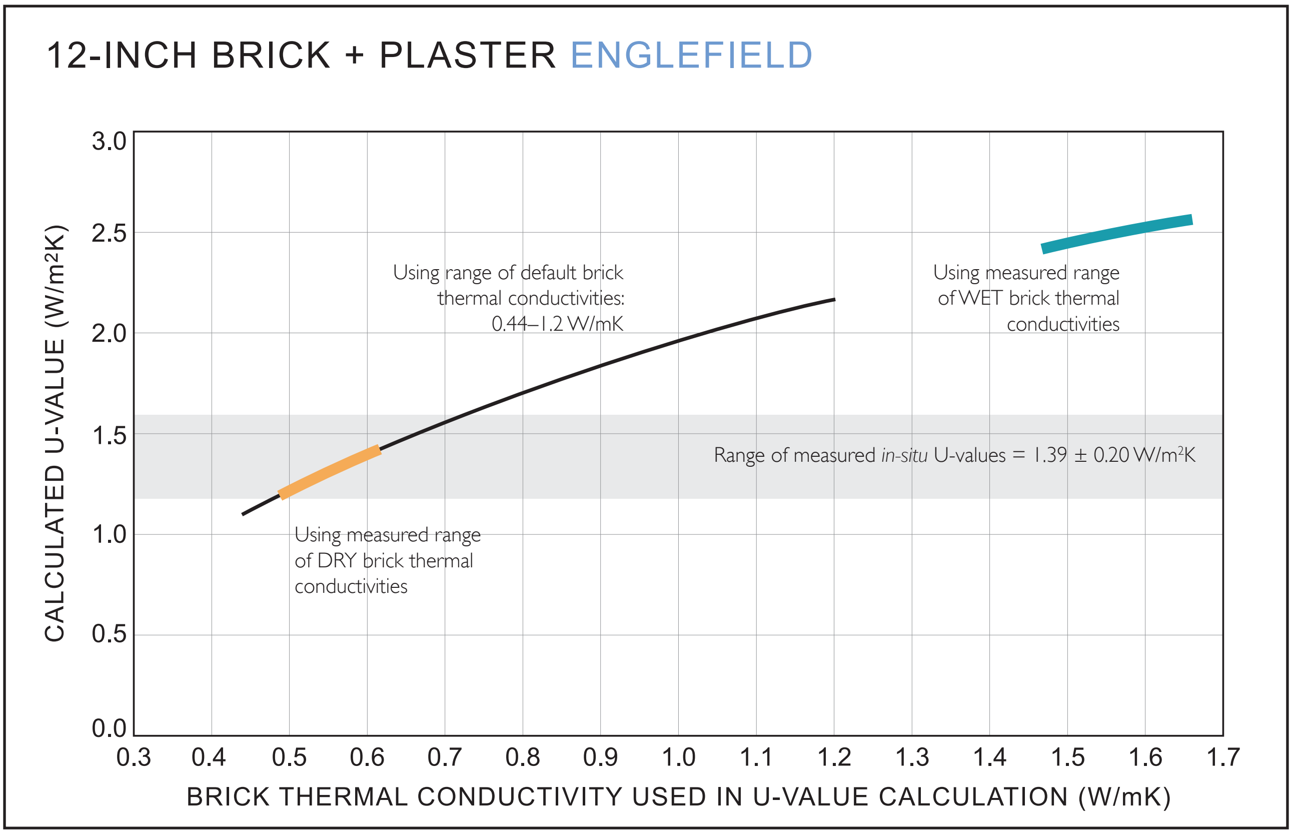
Generally, for the Englefield build-ups the dry range of BuildDesk results fits well with the *in-situ* U-value measurements, as evidenced by the overlapping ranges (*Table 2* and *Figure 4*). The poorest agreement is for the cement-rendered wall; however, only one *in-situ* result was obtained for this wall due to problems with adhesion of the heat-flow meters during testing. The uncertainty of this *in-situ* result may be higher than estimated.

Comparison of Measured U-Values with Calculated Values using BuildDesk Software

The following graphs (*Figures 4a* and *4b*, and *Figure 5*) compare measured U-values to U-values calculated with the BuildDesk software, using measured dry and wet brick thermal conductivities. The graphs may be read as follows:

- The range of *in-situ* measured U-values is shown as a grey band.
- The range of results for the measured thermal conductivities is shown by an orange band (for dry measured values) or a blue-green band (for wet measured values).
- The previous results using a range of default brick thermal conductivities 0.44–1.2W/mK are shown as a solid black line.

The four graphs in *Figure 4a* and *Figure 4b* compare measured U-values to U-values calculated with the BuildDesk software using the measured dry and wet brick thermal conductivities of the Englefield sample.



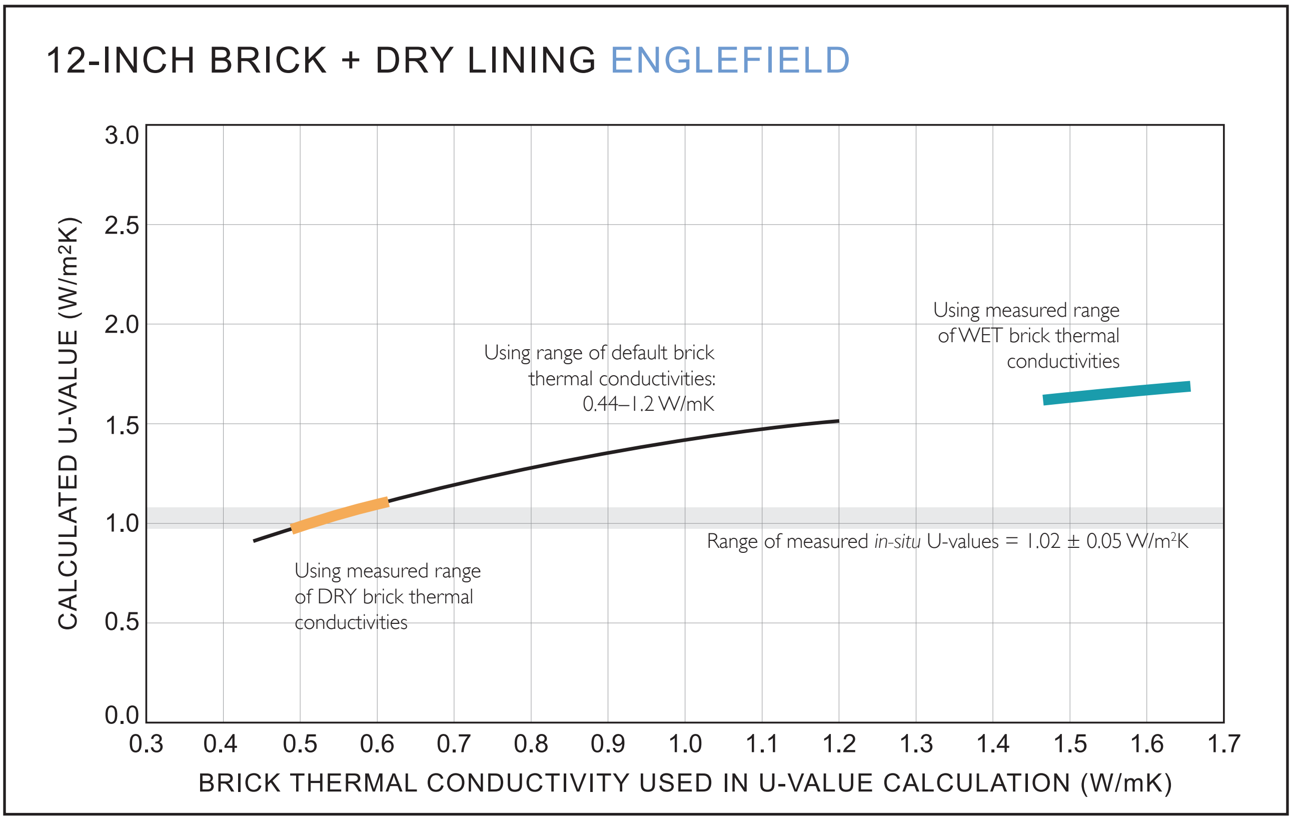
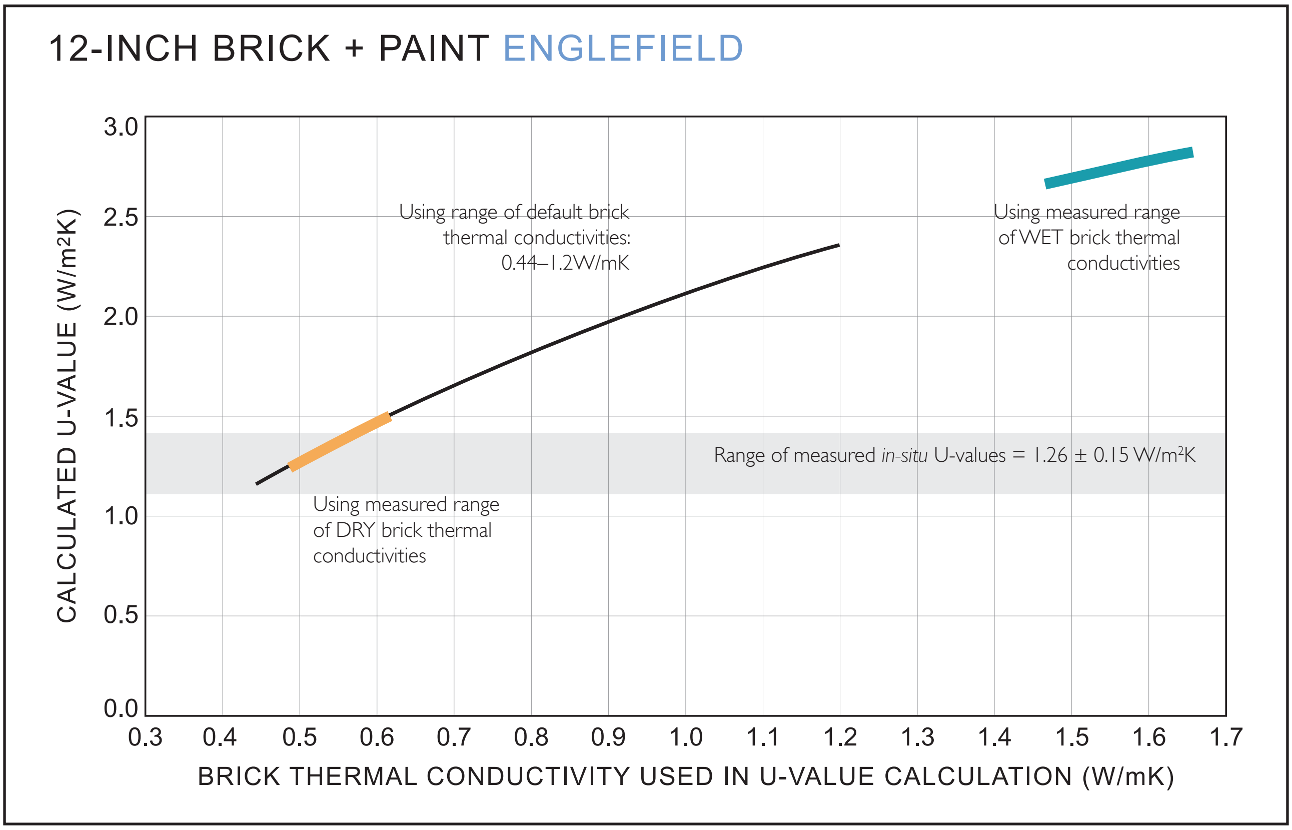


Figure 4a: Comparison of measured U-values with calculated values using the BuildDesk software with measured dry and wet brick thermal conductivities of the Englefield brick sample.



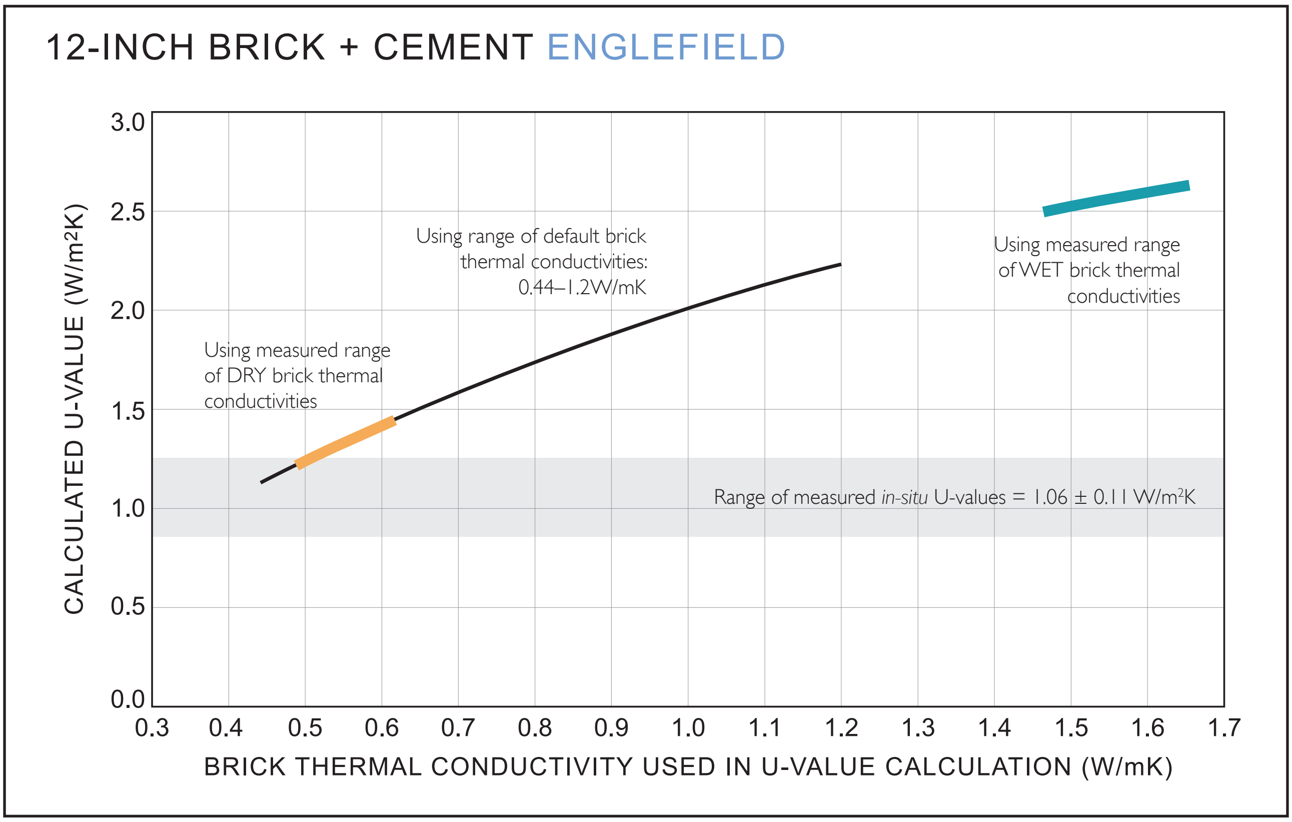
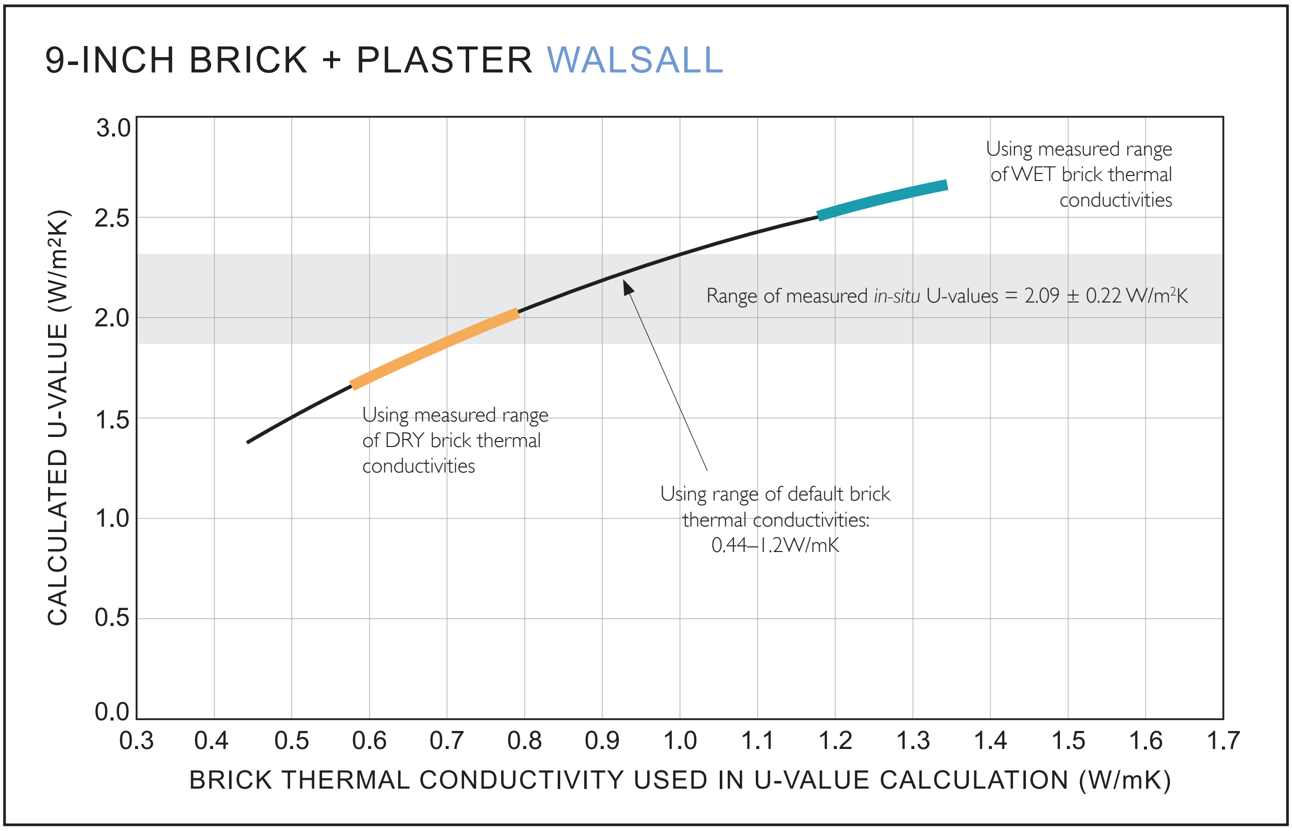


Figure 4b: Comparison of measured U-values with calculated values using the BuildDesk software with measured dry and wet brick thermal conductivities of the Englefield brick sample.

The two graphs in *Figure 5* compare measured U-values to U-values calculated with BuildDesk using the measured dry and wet brick thermal conductivities of the Walsall sample.



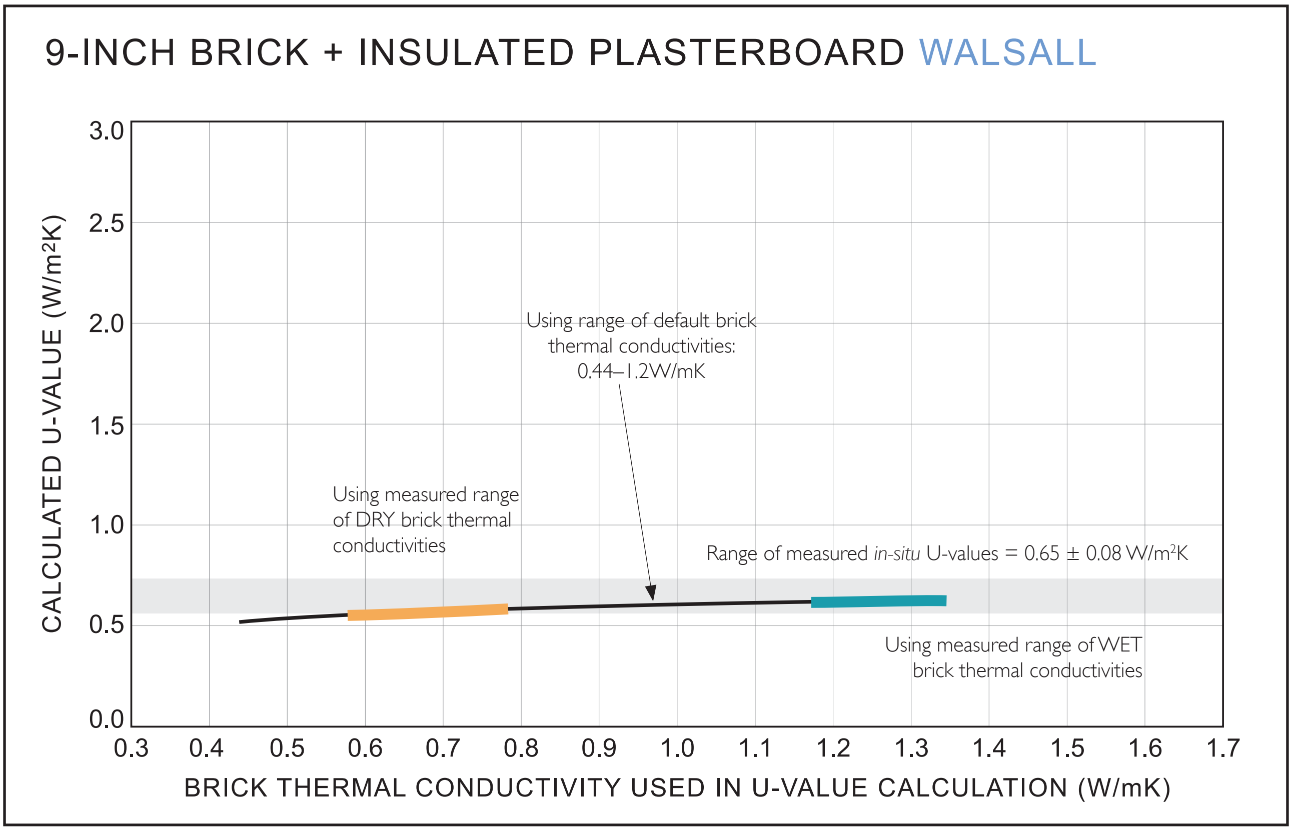


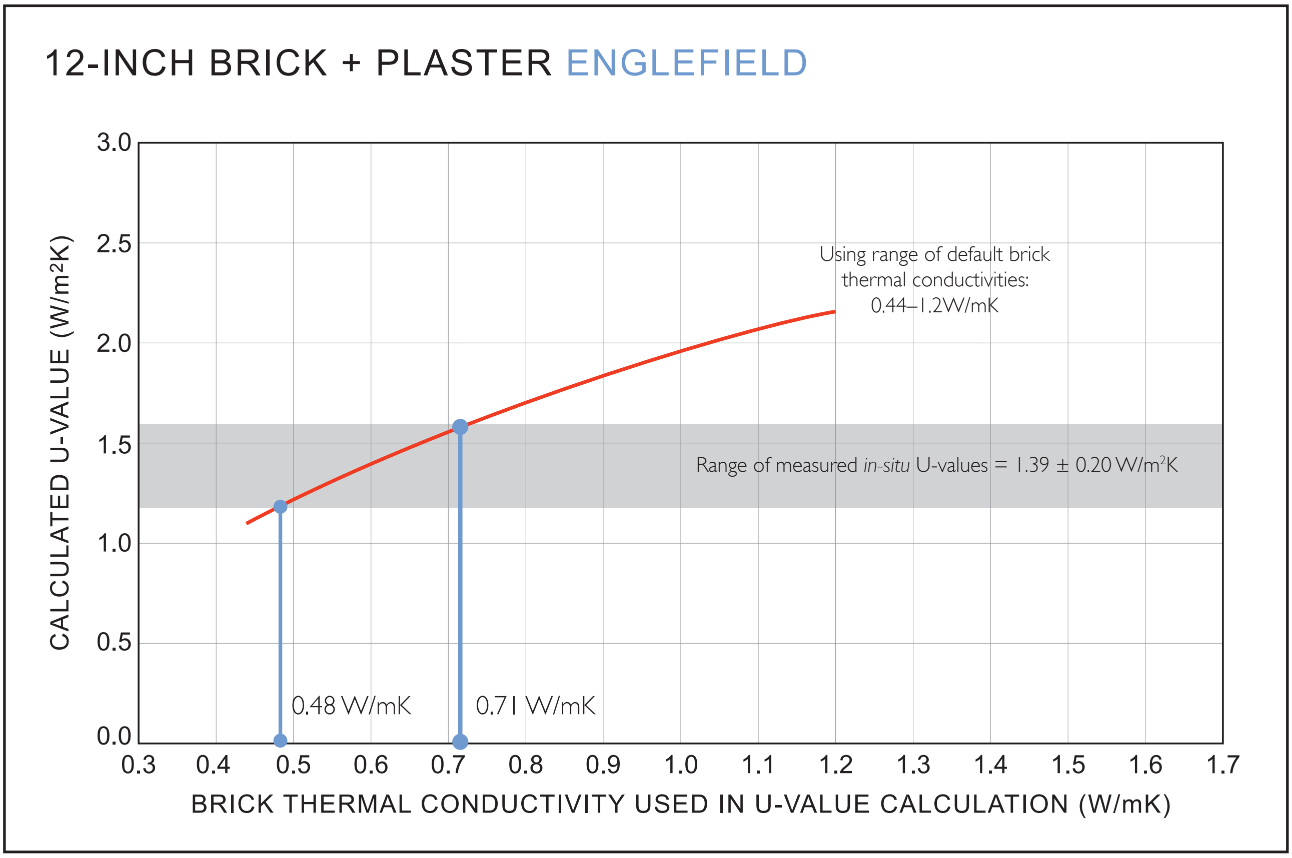
Figure 5: Comparison of measured U-values with calculated values using the BuildDesk software with measured dry and wet brick thermal conductivities of the Walsall brick sample.

For the Walsall results, BuildDesk results using the measured range of dry brick thermal conductivities overlap the lower limits of the *in-situ* measurements (*Figure 5*). For the insulated build-up in Walsall, the wet thermal conductivity results correspond better than the dry range with the *in-situ* results; however the actual build-up of the construction is unknown: it is assumed that plasterboard backed with 25 mm of insulation with a thermal conductivity of 0.025 W/mK has been used.

In general, for both Englefield and Walsall, the calculated U-values using the wet thermal conductivity ranges are significantly higher than the *in-situ* values, excluding the case with insulated plasterboard.

The significance of the differences between the dry range of thermal conductivities and the *in-situ* results may be due to moisture in the walls, increasing the thermal conductivity, and/or incorrect assumptions regarding the build-ups and the thermal conductivities of the other materials. However, a further series of thermal conductivity measurements would be required with samples conditioned at different relative humidities.

An estimate of the brick thermal conductivity range that would produce the range of measured *in-situ* U-values, if used in the calculation procedure, can be obtained from the U-values derived from the default range of brick thermal conductivities for each build-up. An example is shown in *Figure 6*: the range of possible brick thermal conductivities can be read off the x-axis of the graph from the intersection of the blue line drawn through the default U-values calculated using the default brick thermal conductivities (0.44-1.2W/mK) with the upper and lower limits of the *in-situ* values (grey band). For the Englefield brick with plaster this range is 0.49-0.71 W/mK: the measured dry conductivities (0.49-0.61 W/mK) are at the lower end of this range.



Following the above example, the range has been estimated for each of the Englefield and Walsall build-ups and compared with the range of measured dry thermal conductivities. *Table 3* gives the estimated range of brick thermal conductivities which, when used in U-value calculation for each build-up, gives agreement with measured *in-situ* U-values and range of measured dry thermal conductivities.

TABLE 3: RANGE OF THERMAL CONDUCTIVITIES FOR AGREEMENT BETWEEN MEASURED VALUES

	ESTIMATED RANGE OF BRICK THERMAL CONDUCTIVITIES TO GIVE AGREEMENT WITH MEASURED *IN-SITU* U-VALUES W/mK	RANGE OF MEASURED THERMAL CONDUCTIVITY OF DRY BRICK W/mK
ENGLEFIELD		
12-inch brick Plaster with wallpaper or paint	0.49–0.71	0.49–0.61
12-inch brick Plasterboard drylining with paint or wallpaper	0.49–0.59	0.49–0.61
12-inch brick Bare painted	0.42–0.57	0.49–0.61
12-inch brick Cement render	0.30–0.51	0.49–0.61
WALSALL		
9-inch brick Plaster with wallpaper or paint	0.70–1.00	0.58–0.78
9-inch brick Plasterboard drylining with insulation and paint or wallpaper	>0.74	0.58–0.78

COMPARISON WITH DESIGN VALUES

Design values for the thermal conductivities of fired clay bricks are given by *Everett 1986* from *BRE Digest 108* (1984) and *CIBSE Guide A* (2006) for different densities. Values are given for 'standard' moisture conditions: 1% by volume for protected locations (e.g. internal partitions, inner leafs separated from outer leaves by a continuous air space) and 5% by volume for exposed conditions (e.g. directly exposed to rain). The thermal conductivities given in the literature for both protected and exposed conditions are shown in *Figure 7*, with the variation in brick density. The measured values for the bricks tested are shown for comparison.

There is reasonable agreement between the measured dry thermal conductivity results and the design values for protected conditions, although the high density (2191 kg/m^3) New Bolsover brick appears to follow the trend for the CIBSE values if extrapolated to higher densities.

As may be expected, the measured wet thermal conductivities of the Englefield brick with a moisture content of 31% by volume and the Walsall brick with a moisture content of 21% by volume are higher than the exposed design values for bricks of the same density. The New Bolsover brick with a moisture content of 5% by volume again tends to follow the trend for the CIBSE exposed brick values extrapolated to higher densities.

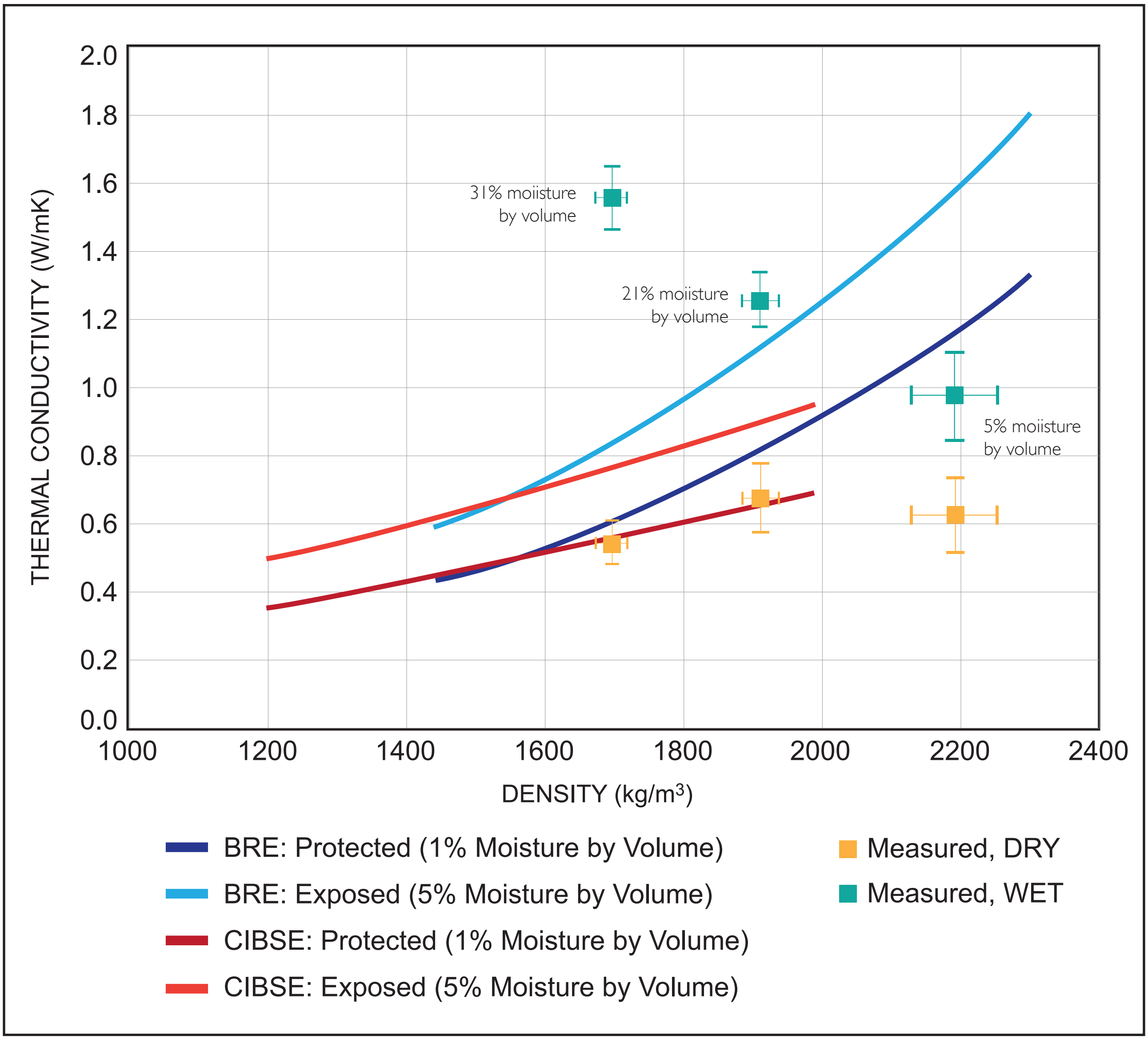


Figure 7: Comparison of measured values with design values from BRE Digest 108 and CIBSE Guide A. Both the Digest and the Guide assume moisture contents of 1% and 5% by volume for protected and exposed brickwork, respectively. The measured wet thermal conductivities range between 5% and 31% by volume.

CONCLUSIONS

The dry and wet thermal conductivities of three traditional bricks have been measured. A range of results were obtained for both dry samples and wet samples at capillary saturation of the bricks (*Table 4*).

TABLE 4: SUMMARY OF TEST RESULTS		
LOCATION	SAMPLE STATE	AVERAGE THERMAL CONDUCTIVITY AT 10°C W/mK
ENGLEFIELD	DRY	0.55
	WET	1.56
WALSALL	DRY	0.68
	WET	1.26
NEW BOLSOVER	DRY	0.63
	WET	0.98

The results indicate that variation in brick texture, density and structure may influence dry thermal conductivity, although additional studies of the microstructure and porosity would be required.

The capillary moisture content, i.e. that resulting from immersion of samples under water, appears to be the major factor in determining the wet thermal conductivity. The wet thermal conductivity was found to be 1.5 to 3 times greater than the dry value. The wet thermal conductivities would generally be applicable only to situations where moisture transport is by capillary action (e.g. rising damp, driving rain penetration, persistent problems such as faulty rain water goods, etc.).

It is recommended that a further series of tests is carried out with the samples conditioned at a high humidity (between 90% and 100% Relative Humidity), where there is the presence of liquid water in the brick pores, but moisture transport would be by vapour rather than capillary action.

Using the dry and wet thermal conductivity test values to calculate U-values using BuildDesk software indicates that:

- Generally the calculated U-values using the range of dry brick thermal conductivities are more consistent with the measured *in-situ* results.
- The influence of the brick thermal conductivity is less in the case of the calculated results for the insulated walls.

Generally, using measured thermal conductivity data improves the convergence between calculated and measured U-values; however, the calculations are based on assumptions about the wall materials and structures (e.g. the type and properties of the insulated plasterboard used in the Walsall houses).

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